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Volume 11

Water Quality Determinations

July 1972

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13. ABSTRACT *(Maximum 200 words)*

This is Volume 11 of the 12 volume report prepared by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers as a contribution to the International Hydrological Decade.

This volume describes the important physical, chemical, and biological water quality parameters, discusses the water quality requirements of the major beneficial uses of water, and discusses the causes of water quality degradation. It also illustrates some numerical techniques pertinent to most water quality studies. Water quality surveys and methods of water quality control are also described. A generalized computer program description useful for evaluating the average monthly release temperatures from large stratified impoundments and a glossary of water quality terms are inclosed.

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US Army Corps of Engineers
Institute for Water Resources
Hydrologic Engineering Center
609 Second Street
Davis, CA 95616

(530) 756-1104
(530) 756-8250 FAX
www.hec.usace.army.mil

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FOREWORD

In the development of the world's water resources in the last half century, the quality of the water resource being developed has often been of minor concern. During recent years, however, the world's mushrooming population, the development of high-production agriculture practices, the development of industries, and a higher expectation in the quality of life have caused the scientific and engineering communities to reassess the role of quality in water resource development and to elevate it to a position of comparable importance with water quantity.

The purpose of this volume will be to examine the technology of the water quality field as it applies to water resource planning in general and to the water problems of developing countries in particular. This subject was originally discussed by Dr. Roy W. Hann, Jr., in "Water Quality Aspects of Water Resource Planning." Dr. Hann's report was funded in 1968 by The Hydrologic Engineering Center for the International Hydrological Decade. This volume, "Water Quality Determinations," was prepared from an extensive edit of Dr. Hann's original text by Mr. R. G. Willey of The Hydrologic Engineering Center. The authors wish to thank Messrs. Leo R. Beard, Herbert W. Hereth, Edward F. Hawkins, and Donald L. Robey for their review of this volume.

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CHAPTER 1. PHYSICAL PARAMETERS

Section 1.01. Introduction

Water quality is often examined from the viewpoint of its physical, chemical, and biological characteristics. In general, physical parameters index or measure the water quality characteristics that affect our senses while chemical and biological parameters index the chemical and biological constituents present in the water resource system. However, these are not independent viewpoints but are actually highly related. For example, chemical waste discharges may affect such physical factors as density and color, may alter chemical parameters such as pH and alkalinity, and may affect the biological community in the water. Even so, the physical, chemical, and biological breakdown is a useful one in considering the effects of water quality.

Section 1.02. Water Temperature

Heat input into aquatic systems and the resultant temperature change significantly affect the biological community and the beneficial use of the water resource system. Undesirable temperature conditions occur naturally in aquatic systems and, with few exceptions, there is little that can be done to change the system. Such temperature conditions occur as a result of seasonal and even daily meteorological fluctuations.

Temperature problems may also develop in industrialized nations as a result of the use of the water resource for cooling purposes. The continuing development of fossil fuel and nuclear power generating facilities throughout the world indicates that temperature management will be of increasing importance in the future.

The solubility of gases in water is dependent on the partial pressure of the gas in contact with the water surface. Temperature is a climatological factor which affects the partial pressure of gases and thus affects the solubility of dissolved gases.

Recent studies in the United States have outlined some of the effects of temperature on the aquatic system. The rate at which organic material decomposes, the rates at which microorganisms die and are replaced by succeeding waves of living things, and the rates at which carbon is consumed and carbon dioxide is substituted are all increased by rising temperature.

Changes in temperature also affect both fish and lower forms of aquatic life. For each organism there is a range of temperature for optimum growth as well as a lethal level. Temperature is one of the environmental factors that determines which organisms will thrive and which will diminish in numbers and size. Water temperatures do not have to reach lethal levels in order to wipe out a species. Temperatures higher or lower than optimum can favor competitors, predators, parasites, and diseases that can destroy a species at levels well within the lower and upper lethal temperature limits. Rapid changes in temperature, even within the lethal temperature limits, may have lethal effects on some species. When defining acceptable temperature limits, consideration must be given to the amount of time the temperature exceeds an acceptable limit as well as the rate at which the temperature change occurs. Many biological communities can adapt to water temperatures exceeding normally acceptable levels if the unsatisfactory condition is not maintained for long periods and the change occurs gradually.

The efficiency of water treatment for domestic and industrial use is temperature dependent. The density of waters above 4°C decline at accelerated rates with rising temperatures. Lower density waters accelerate settling, permit more rapid filtration, and require higher backwash rates. Thus, temperature is basic to most of the quality management requirements of streams and lakes.

Section 1.03. Density Phenomena

Density is important in aquatic systems because of possible vertical stratification induced by density differences. Density difference is generally a result of differences in temperature or dissolved or suspended materials. Tables 1.01 and 1.02 show how density is affected by changes in dissolved solids and temperature.

Table 1.01. Effect of dissolved solids on density*

Dissolved Solids (Grams per liter)	Density (at 4° C)
0	1.00000
1	1.00085
2	1.00169
3	1.00251
10	1.00818
35 (Mean for sea water)	1.02822

Table 1.02. Effect of temperature on density of pure water and ice*

Temperature (°C)	Density	
	Water	Ice
-10	.99815	.9397
- 8	.99869	. 360
- 6	.99912	. 320
- 4	.99945	. 277
- 2	.99970	. 229
0	.99987	.9168
2	.99997	
4	1.00000	
6	.99997	
8	.99988	
10	.99973	
12	.99952	
14	.99927	
16	.99897	
18	.99862	
20	.99823	
22	.99780	
24	.99732	
26	.99681	
28	.99626	
30	.99567	
32	.99505	
34	.99440	
36	.99371	
38	.99299	
40	.99244	

*Data obtained from reference 1.01.

Density is important in analysis of water quality in three major areas. The first is the classical stratification which takes place in both natural lakes and man-made impoundments as a result of water density differences. Fig. 1.01 shows the normal stratification which takes place in reservoirs in summer as a result of warming the water surface. The upper portion of the epilimnion may become well mixed (isothermal) due to internal and external forces such as diurnal air temperature variations, wind action, and internal currents. The density difference at the thermocline can become so significant, energy transfer between the epilimnion and the hypolimnion is inhibited, and the density profile in the hypolimnion will then remain relatively constant with time. Stratification will persist until the stability of the density profile can be overcome by the various external and internal mixing forces. Because the different strata contain drastically different aquatic life communities, the eventual mixing of the entire system can have catastrophic effects on certain biota and temporarily degrade the quality of the water so that it is less desirable for domestic and industrial use.

The second density phenomenon occurs in estuaries in the zone where the fresh water flow of a river encounters the saline waters of the ocean. In a highly stratified estuary, the lighter fresh water slides over a denser wedge of saline ocean water. The upstream movement of saline bottom waters and the downstream movement of the lighter fresh water creates a complex system which is difficult to analyze. In some estuaries, however, forces due to tide and wind have thoroughly mixed the saline and fresh water layers so that there is merely a gradually increasing salinity and density as the river approaches the ocean.

The third density phenomenon of importance is the dispersion of pollutants discharged into an aquatic system where the density of the waste stream differs from that of the receiving aquatic system. Two examples would be the discharge of heated water from a power generation facility into a cooler body of water and the discharge of polluted water into a denser saline estuarine.

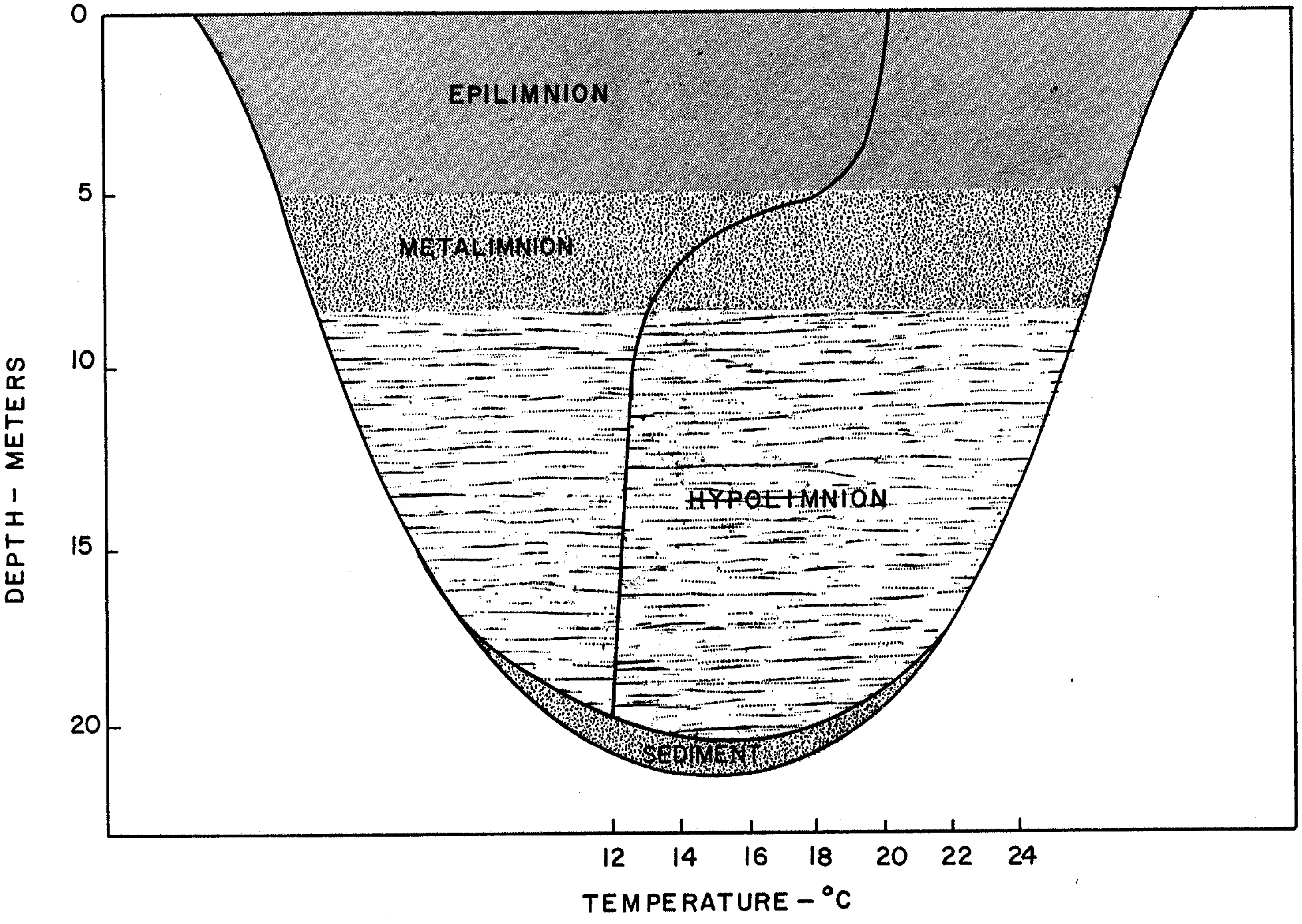

Fig. 1.01. Typical summer temperature stratification in a reservoir

Section 1.04. Turbidity

Turbidity is caused by materials which interfere with the penetration of light and generally disturb the clarity of the water. Turbidity may be caused by microorganisms, silica, iron and manganese compounds, silt, sawdust, fibers, or other suspended materials. These materials may be in the water either as a result of the addition of domestic sewage, industrial wastes, or from natural sources.

Turbidity of a water sample is a measure of the extent to which the intensity of visible light passing through the sample is reduced by suspended matter. It should be noted that turbidity is not a direct quantitative measure of the suspended material but is a measurement of the ability of light to penetrate such material. Since turbidity affects the aquatic system by limiting light transmission into the system, both the biological communities on the bottom of the system and in the system are affected.

Turbidity is also an important parameter in the beneficial uses of water. For domestic uses and for most industries a low turbidity water is highly desirable. In determining usability for industries, turbidity is often used as a broad empirical measure of suspended solids.

Section 1.05. Taste, Odor, and Color

Taste and odor may be the result of biological activity or excessive chemical concentrations. Their primary affect on the beneficial use of water is upon the marketability of the product for domestic and industrial purposes, but may also have a significant effect on the recreational aspects of the water.

Color may be of natural mineral origin, may be caused by metallic substances such as iron and manganese compounds, or may be due to humus material, peat tannins, algae, weeds, and protozoa. Color may also be induced by the wastes from a variety of industries including textile finishing, pulp and paper processing, refining, and chemical plants.

True color is technically defined as that observed after suspended material has been removed by centrifuging. The term apparent color may be used to describe the color of waters prior to removal of suspended matter.

As a quality parameter, color is important in domestic use because it may make water aesthetically undesirable, dull clothes, and stain food and plumbing fixtures. Colored water is undesirable in many industries, particularly those involving products which must be clear, white, or color true.

Chapter 2

Chemical Parameters

CHAPTER 2. CHEMICAL PARAMETERS

Section 2.01. Introduction

Almost any substance, whether active or inert, can be a critical water quality parameter if introduced into water in sufficient quantity. There are, however, a number of chemical parameters which either occur naturally in significant concentrations or which are often introduced into aquatic systems from domestic, industrial or agricultural sources.

The discussion of chemical parameters will be divided categorically into inorganic and organic chemicals. The discussion of organic material has been further divided into discussions on biodegradable and nonbiodegradable chemicals. The former will decay by biochemical means within a reasonable period of time and thus their effect is not permanent. Nondecaying organic materials, on the other hand, may persist for long periods of time and may continue to accumulate in the aquatic system. If the materials are toxic, the long-term effect of such buildups could be catastrophic.

Section 2.02. Inorganic Chemicals

Oxygen. Just as water is necessary to sustain life, so too is molecular oxygen. In its most abundant natural elemental form it consists of diatomic molecules, O_2. Oxygen is found combined in water, most mineral elements, and biological compounds and is an essential element for all plant and animal life.

Dissolved oxygen (DO) is unique as a quality parameter because it is not a pollutant except under very unusual conditions. It is designated as a secondary water quality parameter because it is affected by actual pollutants. The importance of dissolved oxygen can be deduced from the knowledge that a substantial dissolved oxygen level must be maintained in an aquatic system for many organisms to survive and for aerobic decompositions of waste materials. The absence of dissolved oxygen leads to a highly undesirable anaerobic condition. Unfortunately, only a small amount of oxygen will dissolve in water under atmospheric conditions. The saturation levels are dependent on temperature, salinity, and atmospheric pressure. Saturation values of dissolved oxygen are shown in table 2.01. Dissolved oxygen is consumed in the oxidation of waste materials but replenished by processes such as natural stream turbulence and algal respiration. Supersaturation values can occur when replenishment exceeds the amount consumed or when rapid warming of the water occurs.

The demand for oxygen by an aquatic system may be either an instantaneous chemical demand or a long-term biological or chemical demand. The primary demand for oxygen in an aquatic system results from the decay of organic matter that is discharged into the system and may be measured by the biochemical oxygen demand, the chemical oxygen demand, or the total organic carbon test. Each test measures the oxygen demand but does so in a different way.

Biochemical Oxygen Demand. The biochemical oxygen demand (BOD) is a measure of the amount of oxygen needed to oxidize organic material by biochemical means. The biochemical oxidation yields carbon dioxide, water, inorganic chemicals, and new biological cells as products. In time the new biological cells, which are also organic material, will undergo further oxidation until there is almost a complete oxidation of the organic material. Complete oxidation cannot be obtained because some biological cell products are relatively stable and thus are only slowly oxidized. The most common measurement for BOD is an oxygen consumption test in which a water sample is incubated at 20°C for 5 days (reference 2.02). An example is given in Chapter 6.

Chemical Oxygen Demand. Chemical oxygen demand (COD) is an important parameter for stream industrial waste studies. COD is sometimes erroneously considered as indicating the total amount of carbonaceous organic matter present, but, in fact, only indicates a part of the organic matter. The proportion of the organic matter that can be measured by the COD test depends upon the chemical oxidant used, the structure of the organic compounds, and the manipulative procedure.

The COD test does not differentiate unstable from stable organic matter. Therefore, the chemical oxygen consumed is not directly correlated

Table 2.01. Saturation values of dissolved oxygen (in water exposed to an atmosphere containing 20.9% oxygen under a pressure of 760 mm of mercury*)

Calculated by G. C. Whipple and M. C. Whipple from measurements of C. J. J. Fox

Temperature, °C	Dissolved Oxygen (mg/l) for Stated Concentrations of Chloride, mg/l					Difference per 100 mg/l Chloride
	0	5,000	10,000	15,000	20,000	
0	14.62	13.79	12.97	12.14	11.32	0.0165
1	14.23	13.41	12.61	11.82	11.03	.0160
2	13.84	13.05	12.28	11.52	10.76	.0154
3	13.48	12.72	11.98	11.24	10.50	.0149
4	13.13	12.41	11.69	10.97	10.25	.0144
5	12.80	12.09	11.39	10.70	10.01	.0140
6	12.48	11.79	11.12	10.45	9.78	.0135
7	12.17	11.51	10.85	10.21	9.57	.0130
8	11.87	11.24	10.61	9.98	9.36	.0125
9	11.59	10.97	10.36	9.76	9.17	.0121
10	11.33	10.73	10.13	9.55	8.98	.0118
11	11.08	10.49	9.92	9.35	8.80	.0114
12	10.83	10.28	9.72	9.17	8.62	.0110
13	10.60	10.05	9.52	8.98	8.46	.0107
14	10.37	9.85	9.32	8.80	8.30	.0104
15	10.15	9.65	9.14	8.63	8.14	.0100
16	9.95	9.46	8.96	8.47	7.99	.0098
17	9.74	9.26	8.78	8.30	7.84	.0095
18	9.54	9.07	8.62	8.15	7.70	.0092
19	9.35	8.89	8.45	8.00	7.56	.0089
20	9.17	8.73	8.30	7.86	7.42	.0088
21	8.99	8.57	8.14	7.71	7.28	.0086
22	8.83	8.42	7.99	7.57	7.14	.0084
23	8.68	8.27	7.85	7.43	7.00	.0083
24	8.53	8.12	7.71	7.30	6.87	.0083
25	8.38	7.96	7.56	7.15	6.74	.0082
26	8.22	7.81	7.42	7.02	6.61	.0080
27	8.07	7.67	7.28	6.88	6.49	.0079
28	7.92	7.53	7.14	6.75	6.37	.0078
29	7.77	7.39	7.00	6.62	6.25	.0076
30	7.63	7.25	6.86	6.49	6.13	.0075

* For other barometric pressures the solubilities vary approximately in proportion to the ratios of these pressures to the standard pressures.

Reprinted with permission of publisher from Elements of Water Supply Waste-Water Disposal by Fair and Geyer, Table A6 (reference 2.01) with the BOD of industrial wastes, sewage plant effluents or stream samples. The oxygen consumed is of value when estimating the quality of certain trade wastes and sewages.

Total Organic Carbon. The total organic carbon (TOC) test converts the organic material in a water sample to carbon dioxide by combustion. The measurement of the carbon dioxide indicates the amount of organic material present.

Hydrogen. In its elemental form, hydrogen is a diatomic molecule, H_2. However, it does not occur naturally in this form to any great extent. Hydrogen is found combined in more chemical compounds than any other element. Along with carbon, it is a component of all organic compounds.

The ionic dissociation of water is of primary importance to many chemical reactions. Pure water dissociates slightly into ions as follows:

$$H_2O \rightleftarrows H^+ + OH^- \qquad (2\text{-}1)$$

The availability of the hydrogen ion in solution is measured by a chemical parameter called pH. The parameter pH is defined in terms of the hydrogen ion concentration, $[H^+]$, as follows:

$$pH = \log_{10} \frac{1}{[H^+]} = -\log_{10} [H^+] \qquad (2\text{-}2)$$

The pH can range from 0 to 14, with pH = 7 representing absolute neutrality ($[H^+] = [OH^-] = 10^{-7}$).

The pH of a water sample having a hydrogen-ion concentration of 10^{-5} moles per liter can be calculated by equation 2-2 as follows:

$$pH = \log_{10} \left(\frac{1}{10^{-5}}\right) = 5$$

Low pH values are indicative of acid waters and high pH values are indicative of alkaline waters, as shown in fig. 2.01. Most natural waters have a pH in the relatively neutral range from 6 to 8.5.

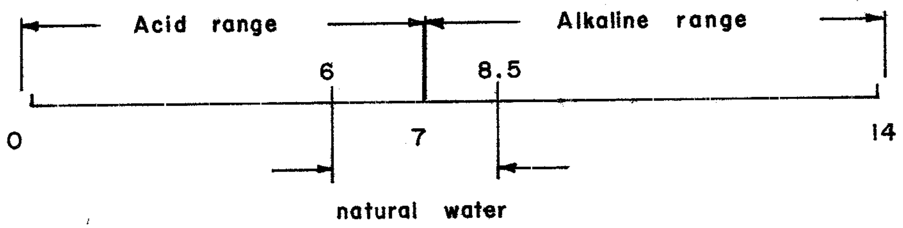

Fig. 2.01. pH scale

The pH is an important measure of water quality because it affects the chemical nature of water (such as its corrosive tendencies) and the biological life which it may support.

Nitrogen. Nitrogen is significant in the aquatic system because it is an essential component of all proteins, chlorophyll, and certain other important biological compounds.

In organic matter nitrogen undergoes changes of decomposition from complex proteins through amino acids to ammonia, nitrites, and nitrates (nitrification); and also changes by synthesis from nitrates into plant and animal forms (nitrogen fixing). This so-called nitrogen cycle in nature is dependent upon bacterial action for decomposition and upon photosynthesis for reconstitution of organic matter. In natural or polluted waters, nitrogen may be present in many forms, but the ones that are measured by the common tests include ammonia, organic nitrogen, nitrites, and nitrates.

Nitrates are the end product of the aerobic stabilization of organic nitrogen, and as such they occur in polluted waters that have undergone self-purification or aerobic treatment processes. Nitrates also occur in percolating ground waters as a result of excessive application of fertilizer or leaching from cesspools. In a few instances nitrates may be added to a stream or ground water by degradation of natural organic material or directly by inorganic industrial wastes, but such sources are relatively insignificant.

Nitrites are generally formed in water by the action of bacteria upon ammonia and organic nitrogen. Owing to the fact that they are quickly oxidized to nitrates, they are seldom present in surface waters in significant concentrations. In conjunction with ammonia and nitrate, nitrites in water are often an indicator of pollution. High nitrogen levels can contribute to the eutrophication (i.e., overenrichment) of the system and thus cause excessive growth of aquatic plants.

Phosphorus. In nature, phosphorus is found in several minerals in the form of phosphates and is a constituent of fertile soils, plants, and the protoplasm, nervous tissue and bones of animal life. It is an essential nutrient for plant and animal growth, and like nitrogen it passes through cycles of decomposition and photosynthesis.

Phosphorus concentrations in excess of about .2 mg/l generally indicate that domestic wastes, industrial wastes, or fertilizers from agricultural use have entered the system.

High levels of phosphorus are believed by many to be the critical parameter in the problem of eutrophication of ponds, lakes, and other aquatic systems. As a result there is now considerable research relating to the removal of phosphorus from waste streams.

Alkali Metals. The elements which make up the group known as the alkaline metals include lithium, sodium, potassium, rubidium, and cesium. Except for complex silicates, virtually all of the salts of the alkali metals are soluble. They are found as ions in natural waters or in large salt deposits formed by the evaporation of brines. Sodium is most abundant, followed by potassium and lithium. Rubidium and cesium are relatively rare and unimportant except for man-made radioactive isotopes of cesium.

As a contaminant, sodium is important for both domestic and agricultural use of water. Sodium in drinking water may be harmful to persons suffering from cardiac, renal, or circulatory diseases. Sodium is extremely important in irrigation water, since high concentrations are toxic to plants. Alkali metals other than sodium do not present water quality problems except in unusual conditions.

Alkaline Earths. The chemical family called the alkaline earths is made up of beryllium, magnesium, calcium, strontium, barium and radium.

The main interest in calcium and magnesium is their adverse affect on household uses such as laundering and bathing, since they combine with soap and leave precipitates, and on cooking and water heating, since they cause incrustations. Calcium and magnesium are often indexed by an empirical parameter called hardness.

For irrigation waters, calcium and magnesium are also important parameters. In some situations they help offset the effects of sodium. Similarly, the toxicity of some chemicals in the aquatic system is reduced when high calcium concentrations are present in the water.

Magnesium is considered nontoxic to man, because even at subtoxic levels the taste becomes intolerable. However, magnesium salts at subtoxic levels have a laxative effect which requires that limits be established.

Beryllium and barium may be considered insignificant as water quality parameters.

Strontium and radium behave like calcium and magnesium in the building of bone cells in the human body. Thus the ingestion of strontium and radium fixes these radioactive materials in the bone structure where they will radiate to adjacent areas of the body.

Sulfur. Sulfur in the form of sulfides, sulfites, and sulfates are important water quality parameters. Sulfates occur naturally in water as the result of leachings from gypsum and other common minerals. They may also occur as the final oxidized stages of sulfides, sulfites, and thiosulfates which have been discharged into the system from natural or man-made sources. In high concentrations sulfate ions may cause the precipitation of calcium ions and lead to sodium poisoning of plants.

Sulfides are constituents of many industrial wastes but they are also generated in sewage and some natural waters by the anaerobic decomposition of organic material. The decay of bottom sludges deposited from natural or man-made organic discharges often generate large quantities of hydrogen sulfide. Hydrogen sulfide is important because of its obnoxious odor, toxicity, corrosion properties and oxygen demand.

Sulfites are often discharged to streams as sulfite waste liquors from the pulping of wood. Such waste material exerts a high oxygen demand on the receiving waters and is considered to be one of the most harmful industrial wastes.

The Halogens. The halogen group of elements includes fluorine, chlorine, bromine, and iodine. Fluorine as fluorides and chlorine as chlorides are abundant and are found in almost all aquatic systems. Bromine and iodine are less abundant and are found as bromide and iodide in sea water and some brines.

Low concentrations (less than 1.5 mg/l) of fluorides may be beneficial to health, particularly for minimizing tooth decay. Higher concentrations can cause mottled teeth.

Chlorine is an important quality parameter in both its elemental and chloride form. Elemental chlorine is very toxic to microorganisms, thus it is used in water purification. A chlorine residual may be toxic to fish and other aquatic life.

Chlorides may be found in practically all natural waters. They may be of mineral origin, may be derived from sea water contamination of underground supplies, agricultural salts, from human or animal wastes or from a variety of industrial wastes including water softening, oil and sulfur production, and oil refining. Chlorides in drinking water are generally not harmful to human beings until high concentrations are reached, although they may be injurious to people suffering from diseases of the heart or kidneys.

The corrosive properties of chlorides are of considerable importance in industry. Even very low concentrations of chlorides may cause corrosion of steel.

Chlorides are troublesome in irrigation water and are generally more toxic than sulfates to plants.

Inorganic Carbon. The most important role of carbon in the water quality field is in its organic form. It does, however, exist in the aquatic system as carbon dioxide, carbonates, and bicarbonates.

High carbonate levels may interfere with industrial processes such as brewing, acid processes, carbonated beverages, and with steam power plants. High bicarbonate levels may cause scale to form at high temperatures. The most significant aspect of carbonates and bicarbonates as water quality parameters is the natural buffering capacity of water in which these compounds exist.

Silica. Silica (silicon dioxide) is the primary compound of silicon. Being relatively insoluble, it is particularly undesirable in boiler feed waters because it deposits on heater tubes and steam-turbine blades.

Metals and Metalloids. Although many metals are needed in trace amounts by humans, the majority of the metal and metalloid group appears as significant water quality parameters only in industrial wastes. The exceptions are iron and manganese which may be induced from natural sources, copper which is used to control aquatic organisms, lead from atmospheric pollution, and arsenic which is used in some agricultural pesticides and herbicides.

Because of extreme effects on the human body, a discussion of mercury pollution deserves special mention. Mercury was first discovered to be a significant pollutant in Japan and Sweden in the 1960's. Prior to this it was thought that any mercury released to an aquatic system would sink to the bottom and be inert. It was found, however, that any form of mercury released can eventually be converted by either microorganisms or fish into the most toxic form, methyl mercury.

Since the human tolerance level for mercury is not known, and the accumulation effect is critical, the World Health Organization recommends that food for human consumption contain no trace whatsoever of mercury.

Iron and manganese are important water quality parameters because of aesthetic degradation of domestic water and associated economic considerations in the use of water for industrial purposes. Only in higher levels are they toxic to fish and aquatic life. Iron and manganese cause unpleasant taste, deposit on food during cooking, and discolor laundry and plumbing fixtures.

Copper may enter the aquatic system in appreciable quantities from the corrosion of copper and brass tubing and from industrial effluents. Copper compounds are frequently used to control undesirable plankton and other aquatic organisms.

Lead compounds are highly toxic, but of even greater concern is the cumulative effect after continuous consumption over a long period. Lead is not considered to be essential to the nutrition of animals or humans. A major source of lead in the aquatic system is from the exhaust of gasoline fueled internal combustion engines.

Arsenic compounds occur naturally in some waters. However, they normally enter streams as industrial wastes or agricultural runoff. Arsenic ingestion, even in small quantities, is critical in human beings and animals because it accumulates in the body. Thus, continual small doses may build to lethal levels. High levels of arsenic in irrigated soils may prove toxic to plants.

Many of the other metals and metalloids are toxic, except in trace amounts, to humans, animals and aquatic life.

Total Dissolved Solids. Dissolved solids consist mainly of inorganic salts and a small amount of organic material. It is a measure of all the nonfilterable solids in solution. Agricultural, domestic, and industrial water users desire water with low concentrations of total dissolved solids (TDS). However, agreement as to an acceptable level for a specific use is not easily obtainable (reference 2.03).

For domestic use, changes in the concentration of TDS in drinking water will usually be more harmful (can cause gastric disturbances) than the actual concentration itself. While drinking water with concentrations in excess of several thousand mg/l is generally not palatable, those accustomed to drinking highly mineralized water often describe water with a low concentration of dissolved solids as "tasting flat."

Agricultural use of water with a high TDS concentration generally causes a salinity problem on irrigated soils. Livestock seem to be less sensitive to the solids concentration.

Industrial tolerances to dissolved solids differ widely, but few industries will use water with concentrations in excess of 1,000 mg/l.

Electrical Conductivity. Electrical conductivity (EC) is a measure of the capability of a water sample to conduct electricity. In many streams there is a direct relationship between electrical conductivity and such parameters as dissolved solids, alkalinity and chloride concentration.

Section 2.03. Biodegradable Organic Chemicals

The list of organic materials which may be considered to be biodegradable includes such natural materials as simple sugars, starch, fats, and proteins. To this may be added more complex organic compounds synthesized by man. The fact that a material is biodegradable indicates that it is not toxic to some microorganisms which carry out the biological oxidation process. However, the decay process requires either dissolved oxygen or combined oxygen, thus the oxygen resource of the aquatic system can be depleted.

If the decay process is anaerobic, the end products such as hydrogen sulfite, ammonia, and methane may be toxic to aquatic life prior to their oxidation to sulfates and nitrates or their dissipation into the atmosphere. If the decay process is aerobic or if the anaerobic end products are oxidized, the phosphates and nitrates may become the fertilizer or building blocks for the growth of new organic material. The new organic material may be a welcome enrichment of the aquatic system or it may cause an overenrichment (eutrophication) which can be detrimental to the system.

Section 2.04. Nonbiodegradable Organic Chemicals

Introduction. The term nonbiodegradable is used to describe those organic materials which persist in the aquatic system for a substantial period of time. All will eventually be broken down, but the rate for the different materials varies widely. The boundary between degradable and nondegradable is not sharp, but it may generally be concluded that those materials which will not decay substantially in a normal secondary waste treatment plant are nonbiodegradable.

Pesticides. Pesticides are a group of chemicals which have become increasingly important to man in his production of food, the control of disease and the achieving of a more pleasant environment. They have also become a water quality contaminant which may ultimately prove to be our most critical group. Pesticides include insecticides, herbicides, rodenticides, miticides, nematocides, and fungicides.

Important insecticides fall into one of two groups of organic chemicals, namely chlorinated hydrocarbons and organic phosphorus compounds. The chlorinated hydrocarbon compounds all contain chlorine, hydrogen, and carbon. Otherwise, they vary widely in their chemical structure and activity. They are known to affect the central nervous system of insects, but the basic mode of toxic action is generally not known for them.

Organic phosphorus compounds all contain phosphorus, oxygen, carbon, and hydrogen. As derivatives of phosphoric acid, they are characterized by similar structure. Their mode of toxic action is to interfere with cholinesterase enzyme activity.

Another important group of pesticides is the herbicides. These compounds include carbamates, chlorophenoxyacetic acids, and other chemical structures. Little is known about their mode of toxic action. Herbicides are used to control undesirable plants.

In water, pesticides are dangerous both for acute and chronic toxicity. Heavy runoff from insecticide production or from agricultural lands may be of sufficient toxicity to wipe out aquatic communities. The long-term effects of low level exposure to both man and the aquatic community are not known and are a cause of concern.

Detergents. During the past two decades the synthetic detergent industry has experienced a rapid growth throughout the world. As the use of these products has mushroomed, an accompanying water quality problem has been generated. Detergents belong to a group of products known as surface-active agents which have the property of lowering surface tension and other interfacial properties of their solvents. Other surface-active agents include soaps, emulsifiers, wetting agents, and penetrants. Detergents, however, are the most important because they are used in the greatest amounts.

The surface-active agent which was most widely used in detergents in the last decade is called alkyl benzene sulfonate (ABS). ABS compounds created a water quality problem because the compound does not degrade to nonactive products in the time span and biological processes found in present day waste treatment facilities. As a result, significant concentrations of ABS were persisting in surface and ground waters where they created foam, made the water more turbid, interfered with coagulation and created taste and odor problems.

In 1965 the detergent industry began a change to a new surface-active agent called linear alkylate sulfonate (LAS) which, because of its molecular structure, can be easily broken down by biological action, thus sharply reducing its capacity to foam after normal waste treatment.

Oil and Petrochemicals. Floating oils and derivatives of petroleum which enter the aquatic system generally decay at such a slow rate that they may be considered nondegradable organic materials. Sources of oil pollution are bilge and ballast waters from ships, oil refinery wastes, industrial plant wastes, and storm drains.

Oil films on the water surface may spoil beaches and coastal resorts, destroy and injure sea birds, foul boats and fishing gear, cause a fire potential in harbors and bays, and damage marine flora and fauna. Dissolved or emulsified oil may coat and destroy fish, algae and other plankton and affect the taste of seafood. Settleable oil substances may coat the bottom and thereby destroy benthal organisms and interfere with spawning areas. Even when deposited on the bottom, oil may continuously yield water soluble substances that are toxic to fish.

Chapter 3

Biological Parameters

CHAPTER 3. BIOLOGICAL PARAMETERS

Section 3.01. Pathogenic Organisms

Intestinal wastes from warm-blooded animals include a wide variety of genera and species of bacteria. Among these may be listed the coliform group, certain spore-forming bacteria, pathogenic bacteria, and other microorganisms.

Disease which may be transmitted to man or livestock by the bacterial organisms in water supplies includes intestinal illnesses such as dysentery, typhoid fever, paratyphoid fever, cholera, and gastroenteritis, but also on infrequent occasion, tuberculosis, anthrax, brucellosis, tularemia, leptospirosis, and other infections. Occasionally, strains of coliforms may be pathogenic although they are normally harmless. Some diseases such as brucellosis, tuberculosis, tularemia, and salmonella are common in animals and could conceivably be transmitted to man by animal-polluted water.

Viruses are infectious agents of both plant and animal cells. Only in the case of infectious hepatitis is the disease known to be waterborne, but there is strong implication that waterborne viruses have transmitted a number of viral diseases. Certain protozoa, which may be transmitted by infected drinking water or by sewage-irrigated food, is the cause of amoebic dysentery.

Section 3.02. Bacterial Indicators

Bacterial indicators of pollution are associated primarily with water polluted by the excreta of warm-blooded animals (including man, domestic and wild animals, and birds). As routinely practiced, bacterial evidence of water pollution of intestinal origin is evaluated by a test for the presence and numbers of bacteria consistently found in wastes. The following indicators may be used on occasion:

- a. Coliform group and certain subgroupings,
- b. Fecal streptococci and certain subgroupings, and
- c. Miscellaneous indicators of pollution.

Evidence of water contamination by intestinal wastes of warm-blooded animals is regarded as evidence of a health hazard in the water being tested.

The most common bacterial indicator used today is the coliform group bacteria which is made up of several different species and, as may be expected, they do not all come from the same source. One separation method is to differentiate the coliform group into fecal and nonfecal groups. A number of tests are available (reference 2.02) to determine the total coliform count and to make the fecal-nonfecal differentiation.

A second indicator used with the coliform group to differentiate a pollution source is that of fecal streptococcus bacteria. The fecal streptococci appear characteristic of fecal pollution, being consistently present in both the feces of all warm-blooded animals and in the environment associated with animal discharges. But because of uncertainties in "die-off" rates, the absence of fecal streptococci does not necessarily signify a safe water.

In samples where the source and significance of the coliform group has been questioned, the presence of the streptococcus group should be interpreted as indicating at least a portion of the coliform group were derived from fecal sources and that the water is therefore a health hazard.

Section 3.03. Eutrophication Organisms

In a terrestrial ecosystem, an increase in fertilizer application generally leads to increased crop production. Similarly, if the rate of eutrophication (the addition of plant nutrients to a body of water) increases, the standing crop of the aquatic environment will usually increase. The process can continue until a threshold level is reached when the penetration of light becomes the limiting factor. The standing crop in a body of water consists of algae, shoreline vegetation, zooplankton, fish, benthic organisms, and bacteria.

One of the symptoms frequently used to distinguish the eutrophic state of a body of water is the algal standing crop. In lakes which are nutrient deficient, there are relatively small standing crops of algae with a large diversity of genera. Highly eutrophic lakes generally have large quantities of algae and few genera. The type of intensity of the eutrophication problem depends on the frequency of occurrence of algal blooms and on the genera and species of algae present. In the littoral region, a sign of eutrophic conditions is the presence of prolific quantities of aquatic weeds along the shoreline.

In lakes that thermally stratify, the lack of oxygen in the bottom waters is also a possible symptom of eutrophic conditions. Under the proper temperature and light conditions, considerable plant productivity will be found in the epilimnion of a eutrophic lake, where the water is well oxygenated. However, the hypolimnion is cut off from the atmosphere so that its dissolved oxygen cannot be replenished during the period of stratification.

Section 3.04. Aquatic Indicators

Various species of fish, shellfish, plankton, and bottom organisms are sensitive to water quality parameters such as dissolved oxygen, temperature, salinity, suspended solids, and toxic materials. The absence or presence of these organisms in the system under varying physical conditions, size variation of the population, and specific knowledge of water quality parameters in relation to massive kills can often give insight into the behavior of the system.

The bioassay technique subjects fish or other organisms to waters of suspected or known contamination and the behavior of the test species is noted. If the test specimens survive, certain insight is gained into the quality of the system or the tolerance of the species. It is necessary, of course, to keep such empirical tests in their proper perspective but much useful information can be gained from their proper execution and evaluation.

A second type of survey is a periodic examination of the type and quantity of organisms in an aquatic system. Such studies may indicate biological change which has taken place in the time period evolved and this may be presumptive of evidence of water quality change depending on the circumstances and available experimental control on the surveys. The establishment and execution of such surveys usually belong in the realm of the skilled aquatic biologist.

Chapter 4

Water Quality Requirement for Beneficial Uses

CHAPTER 4. WATER QUALITY REQUIREMENTS FOR BENEFICIAL USES

Section 4.01. Introduction

A wide variety of demands are made for the use of water resources. Water of a quality that is unsatisfactory for one use may be perfectly acceptable for another. The level of acceptable quality is often governed by the scarcity of the resource or the availability of water of better quality.

Section 4.02. Water Quality Requirements for Municipal and Domestic Use

The use of water for domestic purposes such as drinking, culinary use, and bathing is generally considered to be the most essential use of our water resources. The standards for the quality of this water are likewise higher than for most (but not all) other beneficial uses of water.

In early times, the quality of the water supply source and the quality at the delivery point were synonymous; but the general degradation of both surface water quality and shallow ground-water quality has made it necessary, in most cases, for some degree of water treatment to be used to produce an acceptable water for domestic use. In recent years, there has been a strong trend (which is likely to continue) for the quality of the source waters throughout the world to decline as a result of increased urbanization and industrialization and as a result of changes in agricultural practices. At the same time, populations are coming to expect a higher standard of health and well-being; and as a result, the standards for acceptable domestic water continue to rise and enlarge the role of water treatment.

Section 4.03. Drinking Water Standards

Drinking water standards for the world as a whole have been set by the World Health Organization (WHO). One should keep in mind that these standards do not describe an ideal or necessarily desirable water, but are merely the maximum values of contaminant concentration which may be permitted. It is highly desirable to have water of much better quality.

In the United States, the United States Public Health Service (USPHS) set standards (reference 4.01) that legally apply only to drinking water and water supply systems used by interstate carriers and others subject to Federal quarantine regulations. However, they have been accepted by the American Water Works Association and by most of the state departments of public health as criteria for all drinking water supplies.

Generally the standards are divided into three categories, namely: bacterial, physical, and chemical characteristics.

Bacterial quality is defined by establishing the sampling sequence, the method of analysis and the interpretation of test results for the coliform organisms which serve as presumptive evidence of bacterial contamination from intestinal sources. Analysis is generally made for total coliform, fecal coliform, and streptococci coliform. In the European standards of the WHO, the arithmetic mean coliform density is specified to not exceed one per liter. The USPHS and the International Standards of the WHO establish an arithmetic mean density of one per 100 ml of water.

Such physical parameters as turbidity, color, odor, and temperature are specified to the extent that they can be evaluated.

The limits for chemical elements or compounds in water are divided into mandatory requirements for certain substances and recommended criteria for others. Table 4.01 compares the USPHS and the WHO standards for 25 chemical contaminants.

Radioactivity became an official parameter in the USPHS standards in 1962. The establishment of standards for radioactivity from various sources depends on the chemical nature of the radioactive material and its function in the human body.

Section 4.04. Quality of Source Waters

The drinking water standards are the end product of a production line which begins with the source water as a raw material and proceeds

Table 4.01. Comparison of chemical constituents in the drinking water standards of the World Health Organization and the U. S.

	Concentrations In Milligrams Per Liter						
	WHO International (1958)			WHO European (1961)		U.S.P.H.S. (1962)	
	Permissible Limit	Excessive Limit	Maximum Allowable	Recommended Limit	Tolerance Limit	Recommended Limit	Maximum Allowable
Alkyl benzene sulfonate	--	--	--	--	--	0.5	--
Ammonia (NIL)	--	--	--	0.5	--	--	--
Arsenic	--	--	0.2	--	0.2	0.01	0.05
Barium	--	--	--	--	--	--	1.0
Cadmium	--	--	--	--	0.05	--	0.01
Calcium	75	200	--	--	--	--	--
Carbon chloroform extract	--	--	--	--	--	0.2	--
Chloride	200	600	--	350	--	250	--
Chromium (hexavalent)	--	--	0.05	--	0.05	--	0.05
Copper	1.0	1.5	--	3.0*	--	1.0	--
Cyanide	--	--	0.01	--	0.01	0.01	0.2
Fluoride	--	--	--	1.5	--	0.8-1.7#	1.6-3.4#
Iron	0.3	1.0	--	0.1	--	0.3	--
Lead	--	--	0.1	--	0.1	--	0.05
Magnesium	50	150	--	125**	--	--	--
Magnesium + Sodium sulfate	500	1000	--	--	--	--	--
Manganese	0.1	0.5	--	0.1	--	0.05	--
Nitrate (as NO_3)	--	--	--	50	--	45	--
Oxygen, dissolved (minimum)	--	--	--	5.0	--	--	--
Phenolic compounds (as phenols)	0.001	0.002	--	0.001	--	0.001	--
Selenium	--	--	0.05	--	0.05	--	0.01
Silver	--	--	--	--	--	--	0.05
Sulfate	200	400	--	250	--	250	--
Total solids	500	1500	--	--	--	500	--
Zinc	5.0	15	--	5.0	--	5.0	--

* After 16 hours contact with new pipes; but water entering a distribution system should have less than 0.05 mg/l of copper.

** If there are 250 mg/l of sulfate present, magnesium should not exceed 30 mg/l.

\# Recommended limits and maximum allowable concentrations vary inversely with mean annual temperature.

through the various unit processes of water treatment and finally water distribution. Table 4.02 gives some insight into the source quality which would be permissible with various levels of water treatment.

Although this list does cover some important parameters, it should not be taken as a set of criteria for source water because of the absence of some important water quality parameters and because of the variation in treatment processes in removing different contaminants. It has been presented, however, because it will permit a quick initial classification of waters as to their desirability for domestic supply.

Section 4.05. Water Quality Requirements for Industrial Use

Industry uses water as a buoyant transporting medium, cleansing agent, coolant, and as a source of steam for heating and power production. Often the quality required for these purposes is significantly higher than that required for human consumption. The availability of this water of high quality is often an important parameter in site selection by an industry with high quality requirements as shown in references 4.03 - 4.06.

The needs of a particular industry as to both quantity and quality of water varies with the competition for water, the efficiency of the plant process with regard to water utilization, the recycling of water, the location of the plant site and the ratio of the cost of the water to the cost of the product. For economic reasons and for reasons of quality control and operation responsibility, industries with high water use usually develop their own supply and treatment facilities.

Volumetrically, the largest use of water in industry is for cooling purposes. In such use, problems may result from corrosion, scaling, and the growth of slimes if quality is not controlled. A partial list of generally acceptable standards for cooling water is as follows:

Characteristic	Amount
Temperature	Appropriate
Turbidity	< 50 units
Hardness	< 50 mg/l
Iron and Manganese	< 0.5 mg/l
pH	6.5 - 7.5

Table 4.02. Standards for raw water sources of domestic water supply*

Constituent	Excellent source of water supply, requiring disinfection only, as treatment	Good source of water supply, requiring usual treatment such as filtration and disinfection	Poor source of water supply, requiring special or auxiliary treatment and disinfection
BOD (5-day) mg/l			
Monthly average:	0.75-1.5	1.5-2.5	Over 2.5
Maximum day, or sample:	1.0 -3.0	3.0-4.0	Over 4.0
Coliform MPN per 100 ml			
Monthly average:	50-100	50-5,000	Over 5,000
Maximum day, or sample:	Less than 5% over 100	Less than 20% over 5,000	Less than 5% over 20,000
Dissolved Oxygen			
mg/l average:	4.0-7.5	4.0-6.5	4.0
% saturation:	75% or better	60% or better	---
pH			
Average:	6.0-8.5	5.0-9.0	3.8-10.5
Chlorides, max. mg/l	50 or less	50-250	Over 250
Fluorides, mg/l	Less than 1.5	1.5-3.0	Over 3.0
Phenolic compounds, max.mg/l	None	0.005	Over 0.005
Color, units	0-20	20-150	Over 150
Turbidity, units	0-10	10-250	Over 250

*Data obtained from reference 1.01.

Cooling water is usually drawn from surface or ground-water sources although treated municipal wastewater has proven economical in some parts of the United States.

Section 4.06. Water Quality Requirements for Agricultural Use

Farmstead Water Supplies. Farmstead water is that water used by the human farm population for drinking, food preparation, bathing, and laundry. It also includes water used for the washing and hydrocooling of fruits and vegetables, and water used in the production of milk. The quality of water desired for farmstead use is generally that required for public water supplies.

Irrigation Water. It is not feasible to set rigid quality standards for irrigation waters because of such varied and complex factors as soil porosity, soil chemistry, climatic conditions, the ratio of rainwater to irrigation water, artificial and natural drainage, relative tolerance of different plants, and interferences between and among constituents in the water. Examples of the latter are the antagonist influence of calcium - sodium, boron - nitrates, and selenium - sulfates.

Some general guidelines have been established which indicate the relative usability of a water for irrigation and generally indicate the waters for which more detailed study would be necessary. The most important quality parameters are discussed below.

The effect of salinity is one of the more important water quality considerations for agricultural waters. Since only pure water is lost to the atmosphere during the evapotranspiration process, the salt concentration of the soil can increase rapidly during the drying process. An increase of salt concentration in the moisture of the root zone has an adverse effect on plant growth. The salinity level is easily measured by determination of the electrical conductivity (EC). EC measures the ability of the solution to conduct electricity and can be correlated with the actual salt concentration.

High sodium concentrations in irrigation waters affects the soil structure, infiltration, and permeability rates. Since good drainage is essential for management of salinity in irrigation and for reclamation of saline lands, good soil structure and permeability must be maintained. A high percentage of exchangeable sodium in a soil containing swelling-type clays results in a dispersed condition unfavorable for water movement and plant growth.

The most reliable index of the sodium hazard, or the tendency of an irrigation water to form exchangeable sodium in the soil is the sodium-adsorption-ratio (SAR) which is calculated and defined by the formula:

$$\mathrm{SAR} = \frac{\mathrm{Na}^{+}}{\sqrt{\dfrac{\mathrm{Ca}^{++} + \mathrm{Mg}^{++}}{2}}} \qquad (4\text{-}1)$$

The concentrations of the elements are expressed as milliequivalents per liter (me/l)*. Having calculated SAR by equation 4-1 and knowing the electrical conductivity, irrigation waters can be classified with respect to both the salinity (Cl) and the sodium (Na) hazards by using fig. 4.01 and table 4.03. Water in the Cl-Sl area of the diagram can be used on almost all soils without detrimental effects. With increasing salinity, less exchangeable sodium can be tolerated and more leaching will be required to prevent salinity damage. A thorough description of the SAR and its use is contained in reference 4.02.

In addition to the effect from total salinity, individual ions may have varying effects on plant growth. These ions include both common and trace elements occurring naturally in irrigation water and those introduced by man's activities. Some of the more important ions which need to be considered for irrigation waters are: aluminum, arsenic, beryllium, boron, cadmium, chrominum, cobalt, copper, iron, fluoride, lead, lithium, manganese, molybdenum, nickel, selenium, tin, tungsten, titanium, banadium, and zinc.

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*

$\mathrm{Na}^{+}(\mathrm{me/l}) = .04350\ \mathrm{Na}^{+}(\mathrm{mg/l})$

$\mathrm{Ca}^{++}(\mathrm{me/l}) = .04990\ \mathrm{Ca}^{++}(\mathrm{mg/l})$

$\mathrm{Mg}^{++}(\mathrm{me/l}) = .08224\ \mathrm{Mg}^{++}(\mathrm{mg/l})$

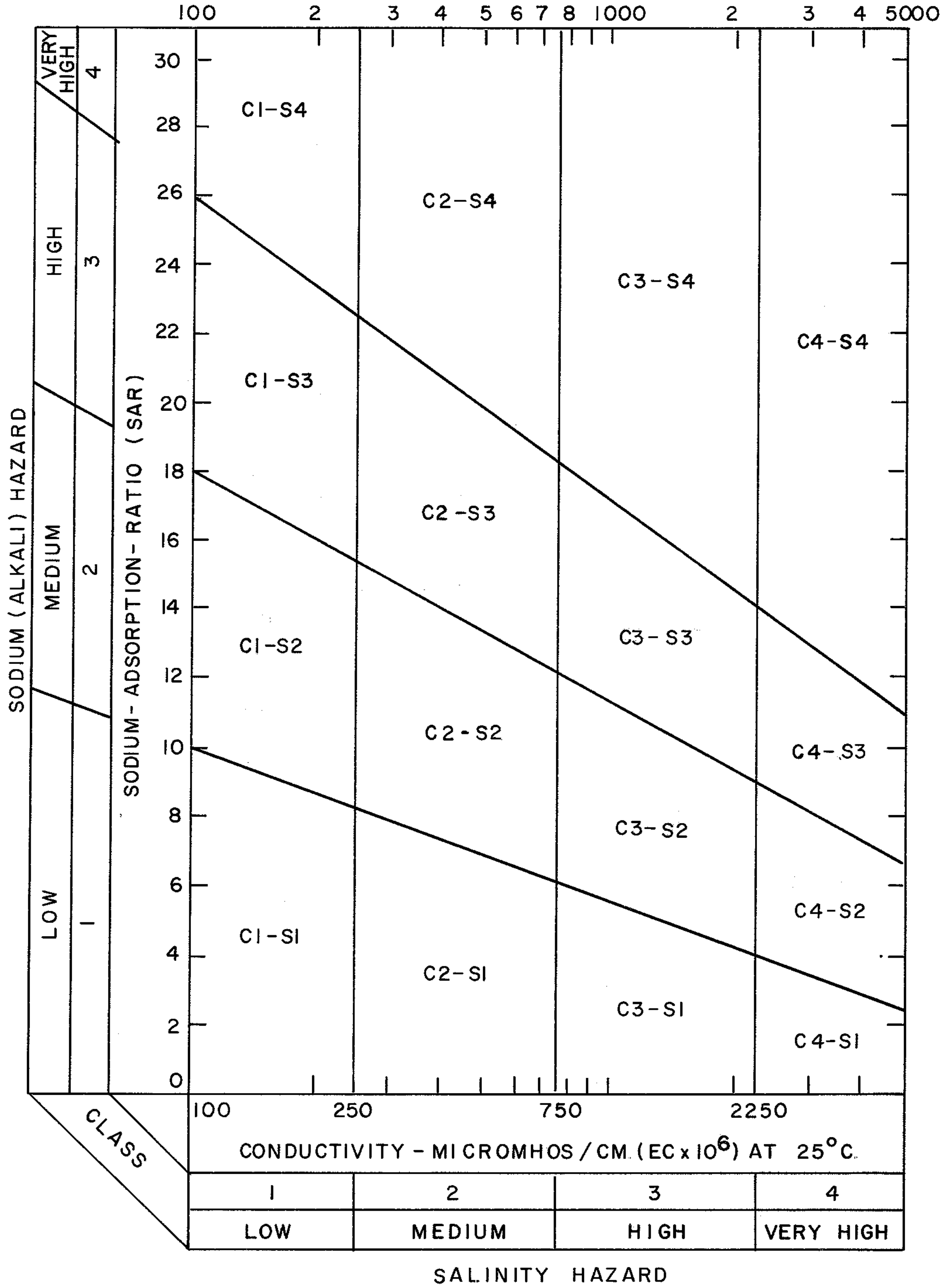

Fig. 4.01. Diagram for the classifications of irrigation waters*

*From reference 4.02.

Table 4.03. Classification of irrigation waters*

Low Salinity Water (C1) can be used for irrigation with most crops on most soils with little likelihood that soil salinity will develop. Some leaching is required, but this occurs under normal irrigation practices except in soils of extremely low permeability.

Medium Salinity Water (C2) can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control.

High Salinity Water (C3) cannot be used on soils with restricted drainage. Even with adequate drainage, special management for salinity control may be required and plants with good salt tolerance should be selected.

Very High Salinity Water (C4) is not suitable for irrigation under ordinary conditions, but may be used occasionally under very special circumstances. The soils must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching, and very salt-tolerant crops should be selected.

Low Sodium Water (S1) can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium. However, sodium-sensitive crops such as stonefruit trees and avocados may accumulate injurious concentrations of sodium.

Medium Sodium Water (S2) will present an appreciable sodium hazard in fine-textured soils having high cation exchange capacity, especially under low leaching conditions, unless gypsum is present in the soil. This water may be used on coarse-textured crops or organic soils with good permeability.

High Sodium Water (S3) may produce harmful levels of exchangeable sodium in most soils and will require special soil management--good drainage, high leaching, and organic matter additions. Gypsiferous soils may not develop harmful levels of exchangeable sodium from such waters. Chemical amendments may be required for replacement of exchangeable sodium, except that amendments may not be feasible with waters of very high salinity.

Very High Sodium Water (S4) is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity, where the solution of calcium from the soil or use of gypsum or other amendments may make the use of these water feasible.

*From reference 4.02

Other quality parameters of importance are alkalinity, acidity, chlorides, bicarbonates, pesticides, temperature, suspended solids, radionuclids, and biodegradable organics. All of these factors need to be weighed carefully in evaluating the suitability of water for irrigating a particular crop. A reference on irrigation water quality (reference 4.03) should be consulted for more information.

Livestock Watering. There is surprisingly little data on the effect of water quality on livestock, but generally they thrive best on water meeting human drinking water standards. The intake of highly mineralized water by animals can cause physiological disturbances of varying degrees of severity. In some cases, particular ions such as nitrates, flourides, selenium salts, and molybdenum may be harmful. Certain algae and protozoa have also been proven toxic to livestock.

Section 4.07. Water Quality Requirements for Aquatic Life

The basic purpose of water quality criteria for aquatic life is to restore or maintain environmental conditions that are essential to the survival, growth, reproduction, and general well-being of the important aquatic organisms. These criteria are ordinarily determined without the aid of economic considerations.

Generally, a number of major problems arise in establishing water quality criteria for an aquatic community because of the inability to quantify the effects of the pertinent parameters and reduce them to a conceptual model that describes the nature of the biological community which will develop under a given set of conditions. But extensive research should be considered when unusually high concentrations of such parameters as alkalinity, acidity, heavy metals, cyanides, oil, solids, turbidity or insecticides are known to exist.

Section 4.08. Water Quality Requirements for Recreational Use

For an aquatic system to be acceptable for swimming and bathing, it must be aesthetically enjoyable (i.e., free from obnoxious floating or suspended substances, objectionable color and foul odors), it must contain no substances that are toxic upon ingestion or irritating to the skin or sense organs, and it must be reasonably free of pathogenic bacteria.

Stream standards generally do not cover the first two terms as related to swimming and bathing except in qualitative terms. In the United States, numerous standards exist for bacteriological quality based on the coliform count in the water. Generally, the standards range downward from 1,000 coliform bacteria per 100 ml to as low as 50 per 100 ml. Such standards are not based on demonstrated transmittal of disease, but have been established because in these ranges the standards are economically reasonable and no problems appear. The use of an aquatic system for boating and aesthetic enjoyment is generally not so demanding as the requirements for swimming or the propagation of fish and aquatic life although these three water uses are usually closely linked.

Chapter 5

Causes of Water Quality Degradation

CHAPTER 5. CAUSES OF WATER QUALITY DEGRADATION

Section 5.01. Natural Water Quality

Since all water found in nature has been contaminated to some degree, our quest for "pure" or "clean" water becomes a relative task depending on our definition of the terms involved. The concern for environmental degradation must concentrate on the pollutional loadings in excess of those loadings from a baseline or natural condition.

As water vapor passes over land, it picks up contaminants characteristic of the land such as pollen, dust, insecticides, and the air pollution from industrial urban areas. As shown in table 5.01, rain is not the pristine water some believe it to be, but contains impurities found in the atmosphere due to both man and nature.

Table 5.01. Rainfall constituent concentrations in Cincinnati, Ohio, U.S.A.*

Constituent	Storm Ranges	Storm Average
pH	3.9 - 6.1	4.8
Suspended Solids (mg/l)	0.5 - 58.0	13.0
Volatile Suspended Solids (mg/l)	0.5 - 12.0	3.8
Chemical Oxygen Demand (mg/l)	4.6 - 59.0	16.0
Nitrogen (mg/l)	0.5 - 2.8	1.3
Inorganic N (mg/l)	0.12 - 2.3	0.69
Hydrolyzable PO_4 (mg/l)	0.0 - 0.9	0.24
Organic Chlorine (mg/l)	0.08 - 0.41	0.28

* Data obtained from reference 5.01.

After rainwater falls to the ground, it is either transported over the surface or through the ground as it seeks to again reach the sea. That which passes over the surface may erode away material by either mechanical force or chemical contamination. It may also be subject to the addition of organic material such as leaves, branches, pollen and animal residues. The water which enters the ground may dissolve or leach away underlying strata and as a result, increase the level of contaminants which are present in dissolved or ionic form.

That the early settlers in the United States found natural waters which were lacking in desirability because of their poor quality is evidenced by the names they gave to water sources and cities. Several examples are names such as: Red River, Bitter Springs, Salt Fork, Salt Lake, Sulfur Springs, Muddy Boggy, Hot Springs, Chalk River, Black River, and Mineral Wells.

The point to be made is that poor-quality water can exist under natural conditions where the additional problems of environmental modification and environmental pollution do not exist. These poor-quality conditions may be in the form of total salinity, specific ion concentrations, overabundant nutrients, oxygen depleting organic material, high temperature, or chemicals and organisms toxic to fish and wildlife.

It is extremely important that basic data on water quality be collected at the earliest possible date in order that the data may serve as baseline data to evaluate future changes in quality. This is particularly so in areas not yet affected by man and his modern civilization where the data will represent the level of "natural" water quality.

Section 5.02. Environmental Modification

Prior to the last century, man had only the power of his own back and that of the animals he could harness to aid him in locally modifying and combating nature for his sustenance, safety, and pleasure. For the most part, his activities were insignificant when compared to the overall size of the natural system he was modifying. In fact, his fight with the natural elements for a livelihood made him think of nature and natural conditions as an opponent to be attacked. In the last century, however, man has learned to harness machines and energy to such an extent that he can overpower nature and drastically alter his environment in a number of ways. Many of these changes relate directly or indirectly to the quantity and quality of our water resource.

Probably the first major change was the mechanization in farming which permitted larger areas of land to be cleared and tilled. This generally led to a change in runoff patterns and an increased sediment load in the streams. These factors, in turn, affected the fresh water, sediment, and nutrient inflow to bays and estuaries.

Similarly, the use of dams and reservoirs can greatly alter the flow and quality of streams and rivers. The current trend is toward the "total" management of our surface water resource. This is usually accomplished by a series of dams, reservoirs, locks, floodways, etc., which provide for the multiple use of the water resource for municipal and industrial water supply, hydropower, irrigation, navigation, flood control, and recreation purposes.

Other environmental modifications of significant magnitude are the dredging of deep ship channels through shallow bays and rivers, the filling of productive marshland and the filling of natural water passageways with spoil banks, flood control levees or other structures.

The effects of an environmental modification may not prove to be detrimental to the aquatic system in the long run, but many will make drastic changes in the aquatic community by making the environment less desirable to present species and more desirable to their competitors and parasites. In addition, established patterns of salinity distribution, temperature distribution, and sediment deposition may be altered.

These comments on environmental modification are not intended to be an argument against the progress that is possible in water resource development; instead they are intended to make the water resource planner aware that there may be long-term effects from any water resource development.

Section 5.03. Environmental Pollution

Introduction. One of the prices that man has paid for increased agricultural yield, the increased standard of living through industrialization and the advantages of urban living has been the degradation of his air and water resources. Many bodies of water throughout the world which were pleasant, productive aquatic systems in the not-to-distant past are now foul, unsightly, dangerous byproducts of our advanced civilization. Any material may be harmful to an aquatic system if discharged in sufficient quantity, so the list of present or potential pollutants is infinite. However, the materials which appear as pollutants as a result of human life, and agriculture and industrial practices are generally classified as either domestic, agricultural, or industrial wastes.

Domestic Wastes. Ordinarily, domestic waste is interpreted as the wastes of urban living which are deposited in a watercourse. Such waste material includes human sanitary wastewater containing excreta, food washings and cooking wastes, and bath and laundry wastes. Also included would be the waste materials from small commercial and industrial establishments whose waste is small enough in volume or of such similarity to the sanitary wastewater that they should not be considered separately as industrial waste. The runoff from rainfall in the urban area should also be included, as it may contain relatively large concentrations of oil and grease, nutrients, pesticides, heavy metals, and settleable solids.

The quantity and quality of the domestic wastes from an area depend greatly on the standard of living and the basic sanitation practices of the population, but the four prime quality concerns are pathogenic organisms, oxygen demand, nutrients, and solids. Table 5.02 shows typical characteristics of domestic sewage in the United States.

Water has been shown to be the carrier of a number of human disease organisms such as typhoid, paratyphoid, amoebic and bacillary dysentery, cholera, and schistosomiasis. Coliforms which are present in large quantities in the human gastrointestinal tract are evaluated as an indicator organism and their presence in a water source should serve as a warning that pathogenic organisms may be present. In a developing area, the pathogen problem is the first problem which should be solved.

Table 5.02. Typical characteristics of domestic sewage in the United States*

Constituents	Weak	Medium	Strong
Physical Characteristics			
Total solids (mg/l)**	450	800	1200
Total volatile solids (mg/l)	250	425	800
Suspended solids (mg/l)	100	200	375
Volatile suspended solids (mg/l)	75	130	200
Chemical Characterisitcs			
pH - (units)	6.5	7.5	8.0
Total nitrogen (mg/l)	15	40	60
Organic nitrogen (mg/l)	10	25	40
Ammonia nitrogen (mg/l)	-	0.5	1.0
Nitrate nitrogen (mg/l)	-	0.5	1.0
Total phosphate - PO_4 (mg/l)	5	15	30
Biological Characteristics			
Total coliform $(\frac{MPN}{100\ ml})$	1×10^6	30×10^6	100×10^6
Biochemical oxygen demand (mg/l) (5-day at $20^\circ C$)	100	200	450

* Data obtained from reference 5.02.

** Quite variable depending on natural water quality of region.

Domestic wastes decay easily and quickly and thus they require considerable oxygen to accomplish this oxidation. The required oxygen is obtained from the dissolved oxygen in the water and the resulting depletion of this oxygen can cause an anaerobic condition.

Nutrients, particularly nitrogen and phosphorus, are of major importance to an aquatic system in that they are the primary food for plant growth in the stream. Eutrophication or overenrichment of lakes and reservoirs has become a major problem in many important aquatic systems in the United States.

Urban storm runoff, at one time, was thought to be relatively clean water, but recent research (reference 5.01 and 5.02) has shown otherwise. The rainfall on a city picks up substantial contamination from dust and air pollution before it reaches the ground. Once on the ground it picks up such materials as vegetation and vegetation debris, dirt, solvents, unburned gasoline, organic matter from dogs, cats and wild animals, street washings, fertilizers, and pesticides. In fact, the total pollution capacity may exceed that of the rest of the domestic sewage load for the period of the runoff.

Table 5.03 demonstrates specific measurements of physical, chemical, and biological parameters of urban storm runoff. This table indicates that the mean coliform count of these waters is significantly higher than that allowed for bathing waters in the United States. Table 5.04 shows the comparison of the annual urban runoff load to the annual domestic waste load (less urban runoff) for the same city.

Agricultural Wastes. The wastes from agriculture may be a significant cause for water quality degradation in many aquatic systems. The source of these wastes may be categorized as animal wastes, processing wastes, and agricultural chemicals.

Animal wastes are similar in quality constituents to human wastes, but the practice of using high-density animal feed lots causes greatly concentrated loadings.

A major problem in agricultural areas is the runoff from farm lands using excess quantities of fertilizers. The runoff can transport concentrations of nitrogen and phosphorus into streams and lakes causing overenrichment of the aquatic system.

The problems caused by pesticides may be either acute or chronic. When pesticide concentrations of sufficiently high levels are allowed to enter the aquatic system, acute toxicity may occur and immediately harm various aquatic organisms. Of greater danger are the long-term or chronic effects of continued exposure to low-level pesticides which affect both the aquatic community and man himself. For the most part, these long-term effects are unknown.

Table 5.03. Constituent concentrations in urban storm runoff at Cincinnati, Ohio, U.S.A. (July 1962 through September 1963 exclusive of January and February)*

PHYSICAL AND CHEMICAL

Parameter		Range	Mean
		(Units)	
Turbidity		30 - 1,000	170
Color		10 - 380	81
pH		5.3 - 8.7	7.5
		(mg/l)	
Alkalinity		10 - 210	59
Hardness (as $CaCO_3$)	Ca	24 - 200	63
	Mg	2 - 46	15
	Total	29 - 240	78
Chloride		3 - 35	12
Suspended Solids		5 - 1,200	210
Volatile Suspended Solids		1 - 290	53
Chemical Oxygen Demand		20 - 610	99
Biochemical Oxygen Demand (5-day at 20°C)		2 - 84	19
Nitrogen (as N)	NO_2	0.02 - 0.2	0.05
	NO_3	0.1 - 1.5	0.4
	NH_3	0.1 - 1.9	0.6
	Org.	0.2 - 4.8	1.7
PO_4 (total soluble as PO_4)		0.07 - 4.3	0.8

BACTERIOLOGICAL

	Counts Exceeded in Designated Percent of Samples (Colonies per 100 ml)		
	90%	50%	10%
Coliforms	2,900	58,000	460,000
Fecal Coliforms	500	10,900	76,000
Fecal Streptococci	4,900	20,500	110,000

* Data obtained from reference 5.02.

Table 5.04. Comparison of annual urban storm runoff loads and annual sewage loads for Cincinnati, Ohio, U.S.A.*

Constituent	Storm Runoff (kg/yr/hectare)	Sanitary Sewage (raw) (kg/yr/hectare)	% $\frac{\text{Storm}}{\text{Sanitary}}$
Suspended Solids	820	610	130
Volatile Suspended Solids	180	400	45
Chemical Oxygen Demand	270	1080	25
Biochemical Oxygen Demand (5-day at 20°C)	37	610	6
PO_4	2.8	30	9
Total Nitrogen as N	10.0	91	11

* Data obtained from reference 5.02.

Industrial Wastes As a result of manufacturing, most industries produce some kind of liquid-borne waste. These may be detrimental to the quality of the water in many ways, namely: toxicity, oxygen demands, sludge deposits, surface films and thermal effects.

Whenever a water resource project is contemplated, the planner should acquaint himself with the processes of the major industries in the basin to evaluate the nature and magnitude of their industrial waste problem. In general, the manufacture of a specific product by different manufacturers will result in similar liquid waste materials. There are publications available (references 4.03, 4.04, 4.05, and 4.06) which give general characteristics of industrial wastes and the average quantity of water per unit of plant output. Such information is valuable for initial planning and preliminary evaluation of water quality but should not be substituted for detailed evaluation of the specific industries as a part of detailed project planning.

An effect generally unique with industries is the toxicity of their waste. This includes spent metal plating liquids containing heavy metals and cyanides, chemicals from chemical processing plants, mine drainage, and organic materials such as strong phenolics, pharmaceuticals, petrochemical wastes, and pesticides.

Certain industries cause damage by physical rather than chemical means. Damage may be caused by wastes from lumbering and mining operations which contribute large amounts of silt, sawdust, and other insoluble products. Thermal power plant operations may raise temperature levels excessively or hydropower operations may lower them excessively. Petroleum operations may discharge films and dyeing operations might drastically color receiving streams.

Taste and odor may be another effect of industrial waste discharges. Often the undesirable tastes are increased by chlorination of the water as a part of later treatment.

Inorganic chemicals may be discharged in excessive quantities by a number of industrial processes. Salt water from oil production and sulphur production can be particularly degrading. Even sludges from water treatment may significantly increase the inorganic level in the stream. Also, there are a number of industries that discharge sodium, potassium, calcium, magnesium, and iron.

Radioactive wastes are a relatively new contaminant group to the aquatic system. Such wastes may be discharged by power reactors, isotope production, radioisotope use, uranium mining, and uranium smelting.

Chapter 6

Water Quality Calculations

CHAPTER 6. WATER QUALITY CALCULATIONS

Section 6.01. Reservoir Quality

The presence of a reservoir in a stream affects the quality of the outflow as compared to the inflow by virtue of the storage and mixing which takes place in the reservoir. The effect of such an impoundment may be easily evaluated for conservative parameters if the waters of the reservoir are sufficiently mixed that an assumption of complete mixing within an analysis time period does not lead to appreciable error.

The simplest technique requires the assumption that the reservoir outflow during a given time period is of constant quality and equal to the quality of the reservoir storage at the end of the computational time period. It is then assumed that the inflow for the time period occurs independently of the outflow and the reservoir quality is determined by a quality mass balance at the end of the time period.

The equation for calculating the quality of the reservoir storage at the end of a given time period (e.g., month) is as follows:

$$QR_2 = [QR_1 (S_1) + QI (I)] / (S_1 + I - E + P) \qquad (6\text{-}1)$$

where:

QR_2 = reservoir quality at the end of the period

QR_1 = reservoir quality at the start of the period

S_1 = reservoir storage at the start of the period

QI = inflow quality during the period

I = inflow volume during the period

E = evaporation volume from reservoir during the period

P = precipitation volume falling on the reservoir surface during the period

The reservoir storage and the inflow, outflow, evaporation, and precipitation volumes must be in a consistent set of units. The reservoir and inflow quality are in concentration units (e.g., mg/l). The discharge quality is assumed equal to the QR_2 value. The analysis is then repeated for successive periods using the end-of-period values from one calculation for the start-of-period values for the next computation. The Hydrologic Engineering Center has developed a computer program that uses the above procedure. The program, "Reservoir Yield," has been included as Appendix 1 in Volume 8 of this report.

An improved technique uses an iterative method to average inflow and outflow quality at the start and end of the time period. The quality of the inflow water into the reservoir is known at both the start and end of the time period and the outflow quality is known at the beginning of the period. The outflow quality at the end of the period is unknown; however, since this is the same as the end-of-period quality of the reservoir for which a solution is being sought, the quality equation can be written as follows:

$$QR_2 = [QR_1 (S_1) + .5(I)(QI_1 + QI_2) - .5(O)(QO_1 + QO_2)] / (S_1 + I - O - E + P) \qquad (6\text{-}2)$$

where:

QI_1 = inflow quality at the start of the period
QI_2 = inflow quality at the end of the period
O = outflow volume during the period
QO_1 = outflow quality at the start of the period
QO_2 = outflow quality at the end of the period

The other terms are the same as defined for equation 6-1.

This technique requires the initial (first iteration in each period) assumption that the outflow quality at the end of the period is the same as at the beginning. After QR_2 has been evaluated once, it can be substituted for QO_2 and a more accurate value of QR_2 determined. The new value for QR_2 may be again substituted for as many successive cycles as are necessary to obtain the desired accuracy.

The analysis is then repeated for successive periods using the end-of-period values from one calculation for the start-of-period values for the next computation.

Equations 6-1 and 6-2 are useful for routing of conservative parameters through fully mixed reservoirs. More complex procedures are available (reference 6.01) for the analysis of either stratified reservoirs or the routing of nonconservative parameters. A detailed description of a procedure for thermal analysis of a stratified impoundment is attached as Appendix 1. The science of simulating reservoir water quality conditions is rapidly developing. Technical journals should be reviewed regularly to keep informed on the state-of-the-art.

Section 6.02. Stream Quality

Conservative Materials. One of the responsibilities of personnel in the water quality management field is the prediction of stream quality profiles. The simplest analysis is for the discharge of conservative (i.e., nondecaying) materials to a stream.

For example, let it be assumed that an idealized stream such as the one shown in fig. 6.01 has an initial flow and quality of Q_1 and $QUAL_1$ and tributary inflows, Q_2 and Q_3, of quality, $QUAL_2$ and $QUAL_3$. The qualities at points A and B may be evaluated by the equations:

$$QUAL_A = \frac{Q_1 (QUAL_1) + Q_2 (QUAL_2)}{Q_1 + Q_2} \qquad (6-3)$$

$$QUAL_B = \frac{Q_1 (QUAL_1) + Q_2 (QUAL_2) + Q_3 (QUAL_3)}{Q_1 + Q_2 + Q_3} \qquad (6-4)$$

A general equation to calculate the resultant quality, $QUAL_X$, from "N" tributaries can be written as follows:

$$QUAL_X = \frac{\sum_{i=1}^{N} Q_i (QUAL_i)}{\sum_{i=1}^{N} Q_i} \qquad (6-5)$$

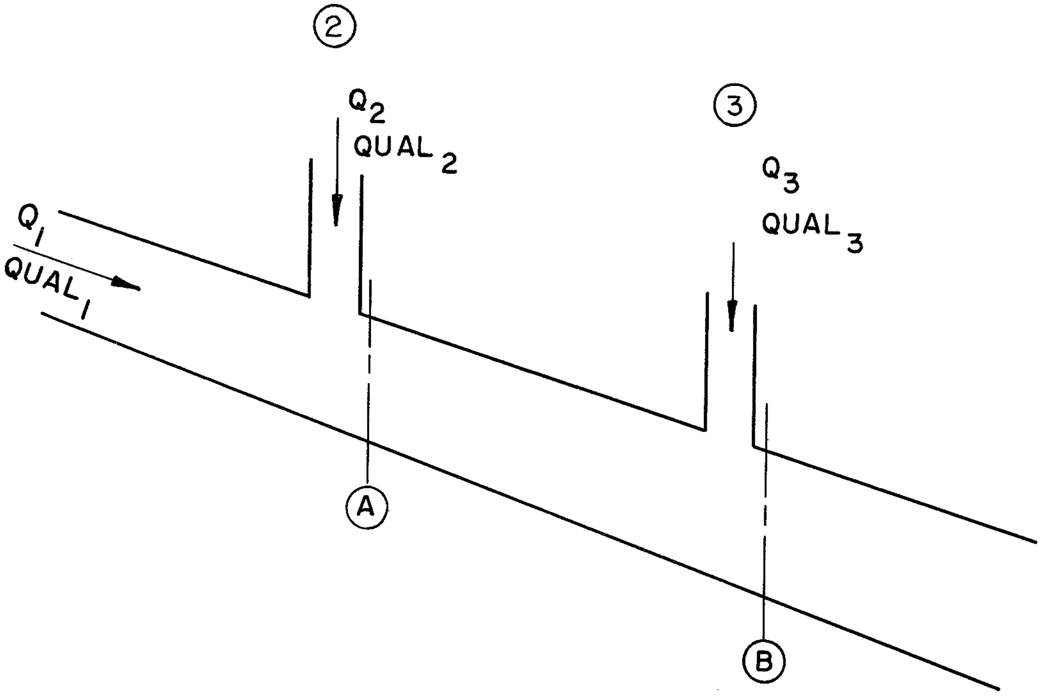

Fig. 6.01. Conservative waste discharge analysis

Nonconservative Materials. Nonconservative materials are those whose concentration in the stream changes as a result of physical removal, or chemical or biochemical change. The most common are organic materials which are oxidized in the stream by biochemical means and radioisotopes which are undergoing natural decay. The primary difficulty in determining the quality profiles for nonconservative materials is that it is extremely difficult to evaluate the decay function for many materials. However, biochemical oxygen demand (BOD) and dissolved oxygen (DO) are two nonconservative parameters of considerable interest, and procedures have been developed for estimating their concentrations as a function of time. The BOD in mg/l expresses the quantity of oxygen required by the bacteria during time t for the oxidation of organic material in the wastewater. Laboratory test results for field samples are usually reported as 5-day BOD at 20°C. The sample initially has a potential to consume a given quantity of oxygen. This potential is known as the ultimate first stage BOD, L_o. The unsatisfied oxygen demand on the fifth day, L , is calculated by the following equation:

$$L = L_o - BOD_5 \tag{6-6}$$

The relationship between L and L_o at time t is given by the following equation:

$$L = L_o e^{-k_1 t} \tag{6-7}$$

where k_1 is the deoxygenation rate coefficient.
By combining equations 6-6 and 6-7:

$$L_o = BOD_5/(1 - e^{-k_1 t}) \tag{6-8}$$

Given a laboratory measurement of the 5-day BOD and the deoxygenation rate coefficient, k_1, the ultimate oxygen demand, L_o, can be calculated using equation 6-8. The relationship between L_o, L , and BOD_5 is shown graphically in fig. 6.02.

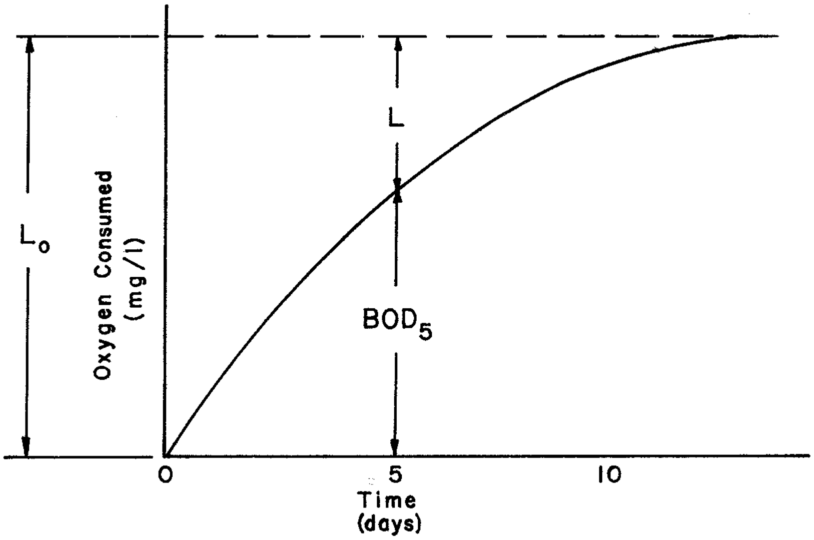

Fig. 6.02. Biochemical oxygen demand curve

The following example demonstrates the use of equation 6-8:

A sewage sample measured in the laboratory has a 5-day BOD of 143 mg/1. Assuming k_1 is equal to .25/day, the ultimate first stage BOD (L_o) can be calculated as follows:

$$L_o = BOD_5/(1 - e^{-k_1 t}) = 143/(1 - e^{-.25(5)}) = 143/(1 - .287) = 200 \text{ mg/1}$$

The DO profile for a specific river reach can be calculated using the Streeter-Phelps equation (reference 6.02), which expresses the rate of change of the oxygen deficit (saturation value of DO minus the actual value of DO) as the algebraic sum of the deoxygenation and reaeration terms as follows:

$$\frac{dD}{dt} = k_1 L - k_2 D \qquad (6\text{-}9)$$

where:

D = oxygen deficit in mg/1
= $DO_{sat} - DO_{actual}$

k_1 = deoxygenation rate coefficient
= f (temperature)

L = unsatisfied oxygen demand in mg/1 at time t
= $L_o e^{-k_1 t}$

L_o = ultimate first stage BOD in mg/1

k_2 = reaeration rate coefficient
= f (temperature, depth, velocity, channel characteristics)

t = time in days

Use of equation 6-9 requires the assumptions of: (1) complete mixing in the stream cross section, (2) continuous uniform discharge of the waste loading, and (3) aerobic conditions throughout the river reach.

Integration of equation 6-9 gives an equation for D_t at time t using boundary conditions of $D_t = D_o$ at time $t = 0$.

$$D_t = \frac{k_1 L_o}{k_2 - k_1} (e^{-k_1 t} - e^{-k_2 t}) + (D_o) e^{-k_2 t} \qquad (6\text{-}10)$$

Evaluation of k_1 and k_2 is difficult, but the following approximate values are usually sufficient:

Type of Waste	$k_{1_{20^\circ C}}$ limits (days^{-1})*	
Slowly degradable waste	.10	.20
Domestic waste	.20	.25
Readily degradable waste	.25	.50

Stream Type	$k_{2_{20^\circ C}}$ limits (days^{-1})**	
Small ponds and backwater	.12	.23
Sluggish streams and large lakes	.23	.34
Large streams of low velocity	.34	.46
Large streams of normal velocity	.46	.69
Swift streams	.69	1.15
Rapids and waterfalls	1.15	greater

The k_1 and k_2 coefficients are responsive to temperature and should be adjusted to the stream temperature T (°C) by the following equations:

$$k_{1_T} = k_{1_{20^\circ C}} \theta_1^{(T-20)} \qquad (6\text{-}11)$$

$$k_{2_T} = k_{2_{20^\circ C}} \theta_2^{(T-20)} \qquad (6\text{-}12)$$

where:

θ	range	most frequently used
θ_1	1.047 - 1.14	1.047
θ_2	1.0 - 1.15	1.016

*Reference 6.03

**These values of $k_{2_{20^\circ C}}$ from reference 2.03 are given for rough approximation only. More refined values can be calculated by methods discussed in references 6.04, 6.05 and 6.06.

θ_1 is temperature dependent, with the higher values being associated with higher temperatures.

By equating to zero the derivative of equation 6-10, with respect to t, the resulting equations for calculating the distance x_c (or the associated time, t_c), between the point of pollution and the point of maximum oxygen deficit are as follows:

$$t_c = \frac{\log_e \left[\left(\frac{k_1 L_o}{k_2 - k_1} - D_o \right) k_2 / \frac{(k_1^2 L_o)}{k_2 - k_1} \right]}{(k_2 - k_1)} \qquad (6\text{-}13)$$

and

$$x_c = \bar{V} t_c = \frac{Q}{A} t_c \qquad (6\text{-}14)$$

where:

$\bar{V}$ = mean velocity

Q = discharge

A = cross sectional area

The units of t_c are days and the variables $\bar{V}$, Q, and A can be in any consistent set of units. Substituting t_c into equation 6-10 the resulting equation for D_c is:

$$D_c = \frac{k_1 L_o}{k_2} e^{-k_1 t_c} \qquad (6\text{-}15)$$

The oxygen relations are represented graphically in fig. 6.03.

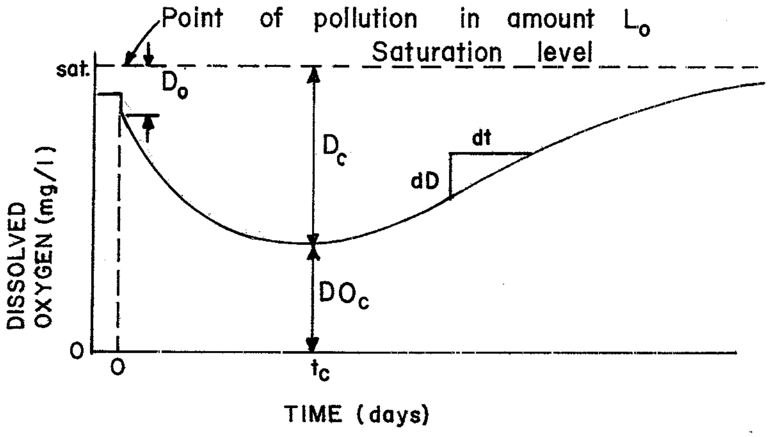

Fig. 6.03. Dissolved oxygen sag curve

The following example demonstrates the use of equations 6-11 through 6-15.

A city discharges 10 cms. of sewage into a stream in which the minimum rate of flow is 300 cms. The velocity of flow in the stream is about 3 km. per hour. The temperature of the sewage and stream is 25°C. The ultimate BOD (L_o) of the sewage is 200 mg/l and of the stream is 0.5 mg/l. The sewage contains no dissolved oxygen, but the stream is 85 percent saturated with oxygen just upstream of the point of discharge. At 20°C, k_1 is estimated to be 0.25/day and k_2 is estimated to be 0.5/day. The DO saturation concentration of the stream is 8.38 mg/l at 25°C (see table 2.01).

Assuming t is equal to zero at the location of the pollution source, the minimum dissolved oxygen concentration and its location downstream from the pollution source can be determined as follows:

$$(L_o)_{mixed} = [(L_o)_{effluent}\ (Q)_{effluent} + (L_o)_{stream}\ (Q)_{stream}]/(Q)_{mixed}$$

$$(L_o)_{mixed} = [(200)(10) + (.5)(300)]/(300 + 10) = 6.94 \text{ mg/l}$$

$$(DO)_{stream} = .85\ (DO_{sat}\ @\ 25°C) = .85\ (8.38) = 7.12 \text{ mg/l}$$

$$(DO)_{mixed} = [(DO)_{effluent}\ (Q)_{effluent} + (DO)_{stream}\ (Q)_{stream}]/(Q)_{mixed}$$

$$(DO)_{mixed} = [(0)(10) + (7.12)(300)]/(300 + 10) = 6.89 \text{ mg/l}$$

$$D_o = DO_{sat} - DO_{mixed} = 8.38 - 6.89 = 1.49 \text{ mg/l}$$

Assume $\theta_1 = 1.047$ and $\theta_2 = 1.016$

from equations 6-11 and 6-12:

$$(k_1)_{25°C} = .25\ (1.047)^{25-20} = .31$$

$$(k_2)_{25°C} = .50\ (1.016)^{25-20} = .54$$

from equation 6-13:

$$t_c = \log_e \left[\left(\frac{.31 \times 6.94}{.54 - .31} - 1.49\right)(.54)/\left(\frac{.31^2 \times 6.94}{.54 - .31}\right)\right]/(.54 - .31)$$

$$t_c = \log_e (1.464)/.23 = 1.65 \text{ days}$$

from equation 6-14:

$$x_c = (3\text{km/hr})(1.65 \text{ days})(24 \text{ hr/day}) = 119 \text{ km}$$

from equation 6-15:

$$D_c = \frac{.31(6.94)}{.54} e^{-.31(1.65)} = 2.39 \text{ mg/l}$$

$$(DO)_c = (DO)_{sat} - D_c = 8.38 - 2.39 = 5.99 \text{ mg/l}$$

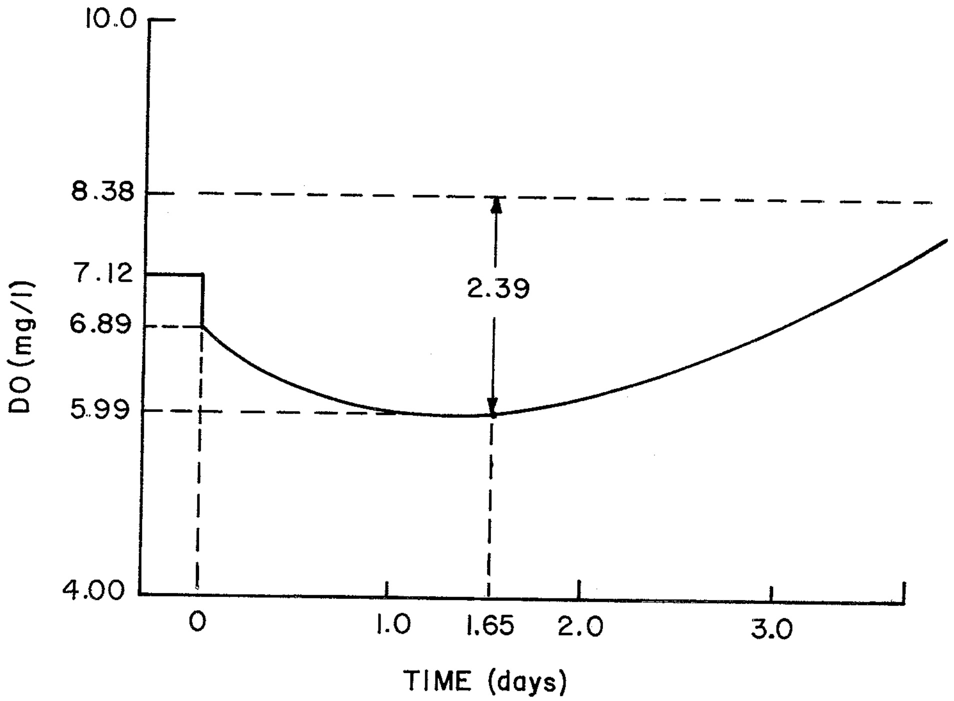

Fig. 6.04. Stream profile

DO Fluctuation. More accurate analyses take into account the diurnal DO fluctuations due to photosynthesis which normally cause the DO to be highest in the daytime and lowest at night. To discuss the diurnal dissolved oxygen pattern, a hypothetical waste discharge into a stream will be assumed.

The dissolved oxygen in the stream is not removed instantly from the water upon the admixture of sewage, but rather begins to diminish slowly. As the population of oxygen-consuming organisms builds up, the DO deficit in the water increases. As this occurs, any equilibrium which may have existed with the atmosphere is destroyed, and the rate of reaeration through the surface increases.

As the population of microorganisms grows still larger, its rate of growth begins to increase. Very soon a population is achieved where the demand for oxygen may exceed the amount which can be supplied through the surface film. The concentration of free DO now begins to drop sharply and may go to zero.

If the system does exhaust the oxygen supply and if sufficient food for the microorganisms remains, anaeorbic conditions will be established. Oxygen, of course, continues to enter at a maximum rate through the surface, but is immediately used up. The overall rate of oxidation of the waste or food material, however, will not increase significantly because surface aeration can supply but a small portion of the oxygen needed and the anaerobic decay occurs at a slower rate.

If there is no replenishment of the food supply, the large population of fungi and bacteria eventually uses up most of the available food, and begins to starve. Growth now begins to slow down, and the population eventually drops back to its original low level. Meanwhile, time has passed as the mass of water flows downstream. An abundance of fundamental plant nutrients such as nitrate and phosphate have been released to the water as a result of microbial respiration. Algae begin to grow and may increase rapidly to tremendous numbers. The algae begin to release great quantities of oxygen during the daylight hours. At first this oxygen is exhausted each night by respiration of the algae and other microorganisms, but soon persists around the clock until the algae have exhausted their food supply and decrease to a normal population for an unpolluted stream.

With the free DO from the algae, the more efficient aerobic type of respiration can again be employed by the microorganisms. This hastens the oxidation or stabilization process, and leaves behind a minimum residue of well mineralized material to accumulate on the bottom.

The symbiotic relationship described above was discussed as if each element was a step to be completed prior to progression to the next step and independent of all other steps. In nature, the entire symbiosis is occurring simultaneously and each element of the relationship is dependent on all other elements.

Chapter 7

Water Quality Surveys

CHAPTER 7. WATER QUALITY SURVEYS

Section 7.01. Types of Stream Surveys

Water quality data is as necessary for water quality planning or management as flow data is for hydrologic engineering design. Thus, a given water resource must be tested, measured, and evaluated to determine its suitability for use and to determine the nature and extent of changes in the water that have occurred through use. The commonly used method for performing this work is referred to as a water quality survey. Water quality surveys may range from a program of monthly samples analyzed with a portable field kit to a program of continuous electronic monitors, supported by a sophisticated laboratory, and by automated data storage and retrieval systems. The survey level to be initiated in any given area is a function of economics, facilities, personnel, quality parameters of importance in the system, and present and future uses of the water resource.

Some water quality surveys consist of gathering basic data on streams unaffected by man, while other surveys are used to locate specific sources of pollution.

Stream surveys in support of enforcement actions are conducted after contamination has occurred, and satisfactory pollution abatement measures have not been undertaken. These surveys usually include an investigation into the quantity and characteristics of the specific pollutants and the adverse effects produced in the receiving waters.

There are also long-term surveys to maintain surveillance of water quality conditions. This type of survey is used to evaluate "trends" in the data and hopefully avoid pollution from conventional water pollutants as well as from some of the new synthetic organic compounds and other trace materials which may create a problem.

Surveys which provide for projection and forecasting (comprehensive planning) of stream quality conditions should gather information regarding the following:

a. Natural water quality,

b. Present water use and the qualitative and quantitative requirements of various water users, _c_. The growth and development of the area (industrial expansion, recreational needs, economic resources, etc.),

_d_. Projection of present water quality, pollution hazards, and water availability to anticipated future requirements, and

_e_. Projection of water storage requirements for water quality management.

Section 7.02. Preliminary Planning

Preliminary planning involves assembling all available information such as maps and reports on the stream under consideration, a detailed definition of the problem and objectives of the study, and a tentative plan of study.

This tentative plan will be used for guidance in the subsequent field reconnaissance and should include:

_a_. Locations and concentrations of known sources of waste,

_b_. Locations of areas of water use and a list of legitimate water uses,

_c_. Maps and descriptions of the stream channel and the location of important tributaries and unique features such as dams and diversions.

_d_. Locations of existing sampling stations and additional sites where quality data are needed,

_e_. Sampling frequency and number of samples at each station,

_f_. Types of laboratory determinations to be made,

_g_. Locations of existing stream gaging stations and additional points where streamflow data are needed.

_h_. Listing of hydrological data needed and possible means of procurement.

_i_. Lists of special supplies and equipment needed,

_j_. Estimates of personnel requirements, and

_k_. Estimates of approximate cost of field operations.

A field inspection should follow the preliminary planning when possible. This step is often neglected, but a small advance party of experienced field men can obtain information and make preparations that will save time and money and avoid confusion and possible error when the subsequent major field study begins.

Section 7.03. Field Operations

The survey team then proceeds to the aquatic resource for a visual observation of the entire system by wading, walking the bank, surveying by boat and, in some cases, by aerial reconnaissance. Points of waste discharge and dispersion patterns, visual evidences of pollution and mixing of tributaries, streamflow characteristics, approximate channel widths and depths, locations of prospective sampling stations, and water uses should be noted. Bottom composition of biological organisms serves as an index of the degree of pollution, bottom samples indicate the extent of sludge deposits, and algae indicates the overenrichment of nutrients and the probable significance of photosynthesis.

It is necessary to evaluate stream velocity as a function of depth at each gage site and to determine channel cross sections throughout the length of the system. The travel time may be determined by making a dye release in the stream (reference 7.01) and monitoring the time of travel to each reach for a specific magnitude of flow.

The selection of sampling stations warrants special attention. Normally such stations are established above waste discharges and at the mouth of tributary streams. Sufficient additional points should be established to permit the verification of analytical models developed to predict quality profiles. Establishment of sampling points at flow gaging stations is always wise.

Samples should be collected for preliminary analysis in order to determine what laboratory methods should be used and what special parameters should be routinely evaluated. Guidance on the selection of sampling locations, the sampling frequency and on the pertinent parameters for laboratory analysis can be found in reference 7.01. Concurrent with the field operation the preliminary plan should be reevaluated as initial experiences dictate necessary revisions.

Section 7.04. Sample Analyses

In the United States, the most widely recognized publication for the examination of the quality of water is Standard Methods for the Examination of Water, Sewage, and Industrial Wastes (reference 2.02). This publication outlines in great detail the standard analytical tests to be used for the analysis of water and wastewaters and should be referenced for further information on laboratory techniques.

Often it is necessary to make field measurements, and this necessity is generally dictated by one or more of the following considerations:

a. The sample is unstable in chemical composition, so that changes may occur during transfer to the laboratory, or

b. Costly laboratory operations can be eliminated as the result of information obtained on the site, or

c. Transportation of samples to central laboratories for analysis is impractical.

It is believed that one or more of these conditions will often exist in collecting data in developing countries and thus, some emphasis should be placed on field techniques. It should be remembered, however, that since laboratory determinations are uniformly easier, faster, and more accurate than the same tests performed under field conditions, samples should be transferred to the laboratory for analysis whenever possible.

An important consideration when purchasing portable field equipment is rugged construction; yet it should be small and light enough to be carried by one man. Sturdy cases should be designed to hold all the pieces of equipment securely in place during travel. Delicate instruments such as photometers and balances are not ordinarily suitable for field use. Chemical methods for field use are necessarily restricted. In general, long tedious procedures involving extreme accuracy in measurements of reagents should be avoided. Visual comparators, test papers, and spot tests are generally preferred.

Some specific tests of importance which are often run in the field are:

a. Dissolved Oxygen. Samples having high oxygen demand cannot be transferred to the laboratory without seriously changing the dissolved oxygen (DO) concentration. In addition, preliminary surveys of DO levels are helpful in locating critical areas of oxygen depletion.

b. pH. Small portable electrometric instruments for measuring pH are now available and are ideally suited to field use. When such instruments are not available, the older color indicators will generally give satisfactory results.

c. Alkalinity and Hardness. In certain pollutional situations, alkalinity and hardness may be conveniently determined in the field.

d. Conductivity. A field test often overlooked is conductivity. Studies have shown a definite correlation between electrical conductivity (EC) and such parameters as total dissolved solids (TDS), alkalinity and chlorides. Conductivity measurements are especially useful in brackish and estuarine waters. Reliable portable instruments are available for this determination.

e. Others. Other parameters that can be evaluated in the field are stream geometry, stream velocity (current meter and dye studies), and temperature. Some parameters such as carbon dioxide, chlorine, chromate, copper, fluoride, hydrogen sulfide, iron, manganese, sulfate, and silica can be evaluated by colorimetric tests.

Chapter 8

Water Quality Management

CHAPTER 8. WATER QUALITY MANAGEMENT

Section 8.01. Prevention of Contamination

When the water quality in an aquatic system is below desirable or acceptable levels, various techniques are available to improve the water quality. An obvious but sometimes overlooked solution is to prevent the contaminant material from being discharged into the aquatic system.

For example, where a sediment problem exists because of farming practices which permit unnecessary erosion, modified farm practices may significantly reduce the sediment load. Similarly, lower application rates or different application methods for fertilizers or pesticides may be necessary to improve water quality.

There are cases in the home and industry where nontoxic materials may be substituted for toxic ones, chemical use may be minimized, chemicals may be recovered for further use, and waste materials may be disposed of by other means.

Section 8.02. Waste Treatment

When water quality degradation is caused by domestic and industrial wastes, significant quality improvement may be achieved by waste treatment. To achieve this treatment, a variety of physical, chemical, and biological unit operations fit together into an almost infinite number of combinations to transform a polluted inflow into an effluent of desired quality. Table 8.01 is a summary of most of these unit operations.

Table 8.01. Unit operations for waste treatment

Physical	Chemical	Biological
Screening	Neutralizing	Anaerobic Digestion
Mixing	Precipitating	Aerobic Digestion
Settling	Coagulating	Septic Tanks
Skimming	Ion Exchange	Digesters
Cooling	Solvent Extraction	Trickling Filters
Heating	Adsorption	Activated Sludge
Distillation	Oxidation	Extended Aeration
Freezing		Oxidation Ponds
Filtration		

Systems for the treatment of domestic wastes have been categorized into primary, secondary, and tertiary treatment. Primary treatment normally consists of screening, sedimentation and disinfection of the inflow accompanied by some form of treatment for the residual sludge. This level of treatment usually solves the major public health problem of the transmission of water-borne diseases, but only removes 35 to 50 percent of suspended materials and organic material.

Secondary treatment is usually comprised of one or more stages of aerobic biological treatment followed by sedimentation. In this process part of the organic material is decomposed into inorganic chemicals (carbon dioxide, water, nitrates, phosphates, etc.) and the remainder is incorporated into a biological floc which may be removed by settling. Such systems may achieve a removal of as much as 95 percent of the suspended matter and organic material. Some 50 to 60 percent of the nitrogen and phosphates of the original waste stream is also removed in the process

Tertiary or advanced treatment is applied to those systems designed to improve secondary effluents. The sophistication of the tertiary treatment may range from systems for organic material, nitrogen, and phosphorus removal to systems for complete water reclamation such as ion exchange or distillation.

Section 8.03. Use of Reservoirs for Water Quality Management

Introduction. Reservoirs may serve several purposes in the management of water quality. If used properly, substantial benefits can be achieved; on the other hand, unwise use of reservoirs may cause increased quality degradation. Benefits may accrue as a result of detention mixing or selective withdrawal of water in a reservoir or the blending of waters from several reservoirs.

Reservoirs as Detention Basins. Reservoir mixing is a continual process where low inflows of poor quality are stored and mixed with higher inflows of better quality. Generally this is accomplished in large reservoirs where annual or even multiple-year flows are retained, but the concept extends even to small reservoirs in which weekly or even daily quality changes occur due to variability of loadings from waste discharges.

The use of a reservoir as a mixing devise should be considered whenever the inorganic water quality is unacceptable during some periods but where the average quality falls within the acceptance level. Lake Texoma on the Red River in the United States is an example of a reservoir which drastically modifies the quality pattern. Although monthly inflow quality has equaled 1950 mg/l chloride concentration, the outflow quality has not exceeded 520 mg/l.

Many materials which enter a reservoir are removed by settling. This applies not only to incoming settleable solids but also to colloidal and dissolved materials which become of settleable size by chemical precipitation or by synthesis into biological organisms. Reservoirs are often used to prevent such settleable material from entering navigable rivers and estuaries where settleable materials would interfere with desired uses. Two notable examples of reservoirs used as sediment traps in the United States are the Eufaula and Keystone Reservoirs which prevent sediment from reaching the Arkansas River navigational systems. However, reservoirs that receive substantial sediment will have a short useful life. Planning should include evaluation of the ultimate fate and possible replacement of such reservoirs.

Reservoirs as Stratified Systems. Reservoirs become stratified if density variations caused by temperature or dissolved solids is sufficiently pronounced to prevent complete mixing. This stratification may be helpful or harmful depending on the outlet works, inflow water quality, and the operating procedure of the reservoir.

Temperature stratification can be beneficial if the water which enters the reservoir during the cooler months can be stored and released during the warmer months. The cooler water released during the warm months can be valuable as a cooling water source, can provide for higher oxygen transfer or slower organic waste oxidation, and can make the water more aesthetically acceptable for water supply and recreational purposes.

Dissolved oxygen stratification usually occurs in density stratified lakes, particularly during the warmer months. The phenomenon occurs because oxygen which has been introduced into the epilimnion by surface reoxygenation does not transfer through the metalimnion into the hypolimnion at a rate high enough to satisfy the oxygen demand by dissolved and suspended materials and by benthal organisms. Thus, the cool bottom waters which are sometimes desirable may be undesirable from a dissolved oxygen standpoint unless energy dissipation structures are constructed to transfer substantial oxygen into reservoir effluent waters. Mechanical reservoir mixing to equalize temperature and transfer oxygen to lower reservoir levels is being extensively studied in the United States (reference 8.01) and shows promise as a tool for managing reservoir water quality.

Reservoirs as Flow Management Devices. Reservoirs may improve water quality by merely permitting the management of flow. This management may include maintenance of minimum flows, blending selective releases from one or more reservoirs to maintain a given stream quality, and the exclusion of a flow from a system by diversion.

Minimum flow is often maintained in a stream for navigation, recreation, fish and wildlife, and water rights purposes. Such flows may also aid in maintaining acceptable water quality.

There is general agreement that water may be stored and selectively released to help reduce natural water quality problems where source control is not possible and also that water should not be stored and released solely to improve water quality where similar improvement may be achieved by treatment. The use of a water resource to dilute treatable waste materials is regarded as the misuse of a valuable resource.

Selective release of water from one or more reservoirs may help improve quality at one or more downstream locations. Such releases may be one of the governing factors in establishing reservoir management rules. The water to be released may either be good quality water that will improve the river quality or poor quality water that is to be discharged when it will do a minimum of harm (e.g., during high flow).

Section 8.04. Water Quality Legislation

Water Quality Standards. It has been found by experience that good water quality is not maintained in the absence of legislative control. There are many reasons for the failure of individuals, cities, and industries to act collectively for the maintenance of good quality waters.

One of the reasons for this failure is that there is a disagreement as to what quality of water should be maintained in an aquatic system. Part of this disagreement is caused by a lack of scientific information on the effect of contaminants on all phases of the food chain of aquatic communities. A second part is a disagreement as to whether an aquatic community should be maintained. In other words, do economic or other considerations justify the use of an aquatic system as a sewer for domestic and industrial wastes?

Assuming that the latter philosophy does not hold, it becomes necessary to determine what quality shall be maintained and to develop a mechanism to see that such standards are enforced. Standards serve as a guideline for the level of treatment necessary to maintain acceptable quality for beneficial uses and to help provide a more wholesome environment for both the present and future.

One of two philosophies is usually followed when establishing water quality standards. Either receiving water standards are established to protect the aquatic system, or standards are established to regulate effluents into the system.

Receiving Water Standards. Receiving water standards establish quality parameter thresholds or levels for the aquatic system. This gives those entities causing pollution the joint responsibility of maintaining the receiving water quality at predetermined levels. Receiving water standards are preferred by many because it establishes equitable use zones in the receiving water, generally allows for the assimilative capacity of the receiving water to be utilized, and places the responsibility for determining appropriate discharge levels with the polluter.

This type of standard produces enforcement problems because of the difficulty of locating the responsible polluter in complex systems. Equity problems occur when new industries come in or when similar industries are located on different parts of the aquatic system and perhaps required to have different levels of treatment.

Receiving water standards are opposed by many who feel that they are a "license to pollute" up to the level established by the standards and that each industry or municipality should treat their waste to the limit of existing technology.

Effluent Standards. In setting effluent standards, the water quality agency assumes the responsibility of determining what level of waste discharge may be permitted to achieve the desired quality in the aquatic system. These standards may require the maximum level of treatment feasible and may establish equitable levels for various industrial groups or may consider each aquatic system and industry as a special case. If used properly, effluent standards require a higher level of competency on the part of the personnel in the regulating agency.

Compliance with Standards. There has been considerable debate in the United States over the past few years as to the best way to achieve compliance with water quality standards. The path chosen to date has been to enforce the regulations by persuasion where possible and by more forceful levels of action when and where necessary.

When water quality management is merely a police-type enforcement, pollution fines can be viewed as an overhead expense. If on the other hand, the polluters were charged an effluent tax based on the quality and quantity of their effluent, there would be an economic advantage to the polluter for achieving a reduction in the volume and an improvement in the quality of the effluent.

Several other taxing schemes with different philosophies such as tax rebates to industries with good pollution control records and grants for treatment control facilities have also been suggested.

United States Legislation. Four congressional acts and five amendments, together with recent presidential executive orders, constitute the existing status of water quality legislation for surface waters of the United States.

The 1899 River and Harbors Act was enacted to control man-made obstructions in navigable waterways. Recent court interpretations of the Act and the changing national attitudes toward pollution abatement recently led to executive orders requiring a government permit to discharge any material into a navigable waterway or a tributary of a navigable waterway.

The 1912 Public Health Service Act gave specific authority to the U. S. Public Health Service to conduct investigations of stream and lake pollution.

In 1948 the Federal Water Pollution Control Act was passed and became the basis of water quality legislation for the United States. Eight years later this Act was rewritten to expand Federal government responsibility and authority to combat the growing national pollution problem. Amendments to the Act were passed in 1961, 1965, 1966, 1970 and 1972.

The 1961 amendment transferred the responsibility for the Federal Water Pollution Control Program from the Public Health Service to the Secretary of the Department of Health, Education and Welfare. Also, it increased the scope of Federal enforcement by changing the investigative responsibility from intrastate waters to all navigable waters.

Due to the legislation of 1965 and 1966, the Federal Water Pollution Control Administration (FWPCA) was established and was given enforcement responsibility for the basic Act. The FWPCA was given funds to help support the construction of waste treatment plants.

In 1970 the Administration name was changed to Federal Water Quality Administration, and stricter regulations were provided to control both oil pollution and pollution due to Federal activities.

The 1972 amendment is by far the most extensive piece of water quality legislation ever adopted in the United States. The amendment is designed to "restore and maintain the chemical, physical and biological integrity of the Nation's waters." It requires the use of (1) the "best practicable treatment" by July 1977, (2) the "best available treatment" by July 1983 and (3) the elimination of pollutant discharges by 1985. Federal leadership and financial assistance is provided for assurance of continuous progress towards these goals.

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Appendix 1

Reservoir Temperature Stratification

RESERVOIR TEMPERATURE STRATIFICATION

TABLE OF CONTENTS

RESERVOIR TEMPERATURE STRATIFICATION

THE HYDROLOGIC ENGINEERING CENTER
GENERALIZED COMPUTER PROGRAM
723-X6-L7410

I. INTRODUCTION

1. ORIGIN OF PROGRAM

This program is a modification of program 723-X2-L2810 which was prepared for the Sacramento District, Corps of Engineers, by The Hydrologic Engineering Center. The input requirements have been modified to include several new options. Up-to-date information and copies of source statement cards can be obtained from the Center upon request by Government and cooperating agencies.

2. PROGRAM PURPOSE

This program is intended for application to design and planning problems involving consideration of multi-level intake structures. The program will simulate the vertical distribution of water temperature within a reservoir and estimate the mean monthly release temperature through each level of intake. The results of the program are useful in determining the required number of intake levels and their vertical location.[1] An alternative use of the program involves studying project and preproject conditions for evaluation of the thermal portion of the project's environmental impact.

3. PROGRAM CAPABILITY

The program simulates the vertical distribution of water temperature within a reservoir on a monthly basis from data on initial conditions and on inflow, outflow, evaporation, precipitation, radiation, and average air temperature. Outflow requirements can be specified as any combination of releases through specific outlets and in terms of maximum and minimum allowable outflow temperatures. Model coefficients can be determined automatically from observed temperature profiles, in which case a printout plot of the observed and computed profiles is shown. Input may be in either English or Metric units and the output will be in corresponding units. A provision is included to output release quantities and temperatures on tape and to accept inflow quantities and temperatures from tape so that studies for tandem reservoirs can be made in a single computer run.

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[1] An Approach to Reservoir Temperature Analysis, The Hydrologic Engineering Center Technical Paper No. 21, L. R. Beard and R. G. Willey, April 1970.

4. SUPPORTING PROGRAMS AND PLANNED EXPANSION

It is anticipated that this program will be expanded to include quality parameters other than temperature, and that a separate program will be developed to analyze the variation of temperature and other quality parameters with distance downstream of a reservoir. It is requested that any user who finds an inadequacy or desirable addition or modification notify The Hydrologic Engineering Center.

II. PROGRAM DESCRIPTION

5. THEORETICAL ASSUMPTIONS

a. One dimensional model - The present state of the art of reservoir hydrodynamics and the current availability of meteorological data suggests the use of a relatively straightforward method to analyze reservoir temperature profiles. It is assumed in the temperature model that the reservoir can be divided into conceptual horizontal layers that are isothermal throughout the volume of the layer. This assumption is necessary for development of a one dimensional model. It is probably sufficiently accurate in most situtations; but cases do exist where sloping isothermal lines are observed. The latter situation generally occurs at reservoirs having a high ratio of mean monthly inflow to storage capacity.

b. Other assumptions - Assumptions which are an inherent part of the calculations are discussed in addendum 1.

6. AREAS OF APPLICATION

a. Existing reservoirs - Because of recently established stream temperature standards, there is a need for methods to analyze the capability of existing reservoir systems to meet operational temperature limits. If recent thermal data have been collected in the reservoir for one or more years, the model can be calibrated with the observed data and then used to simulate historic thermal conditions that existed prior to the collection of the thermal data.

b. Proposed reservoirs - When a thermal analysis is required at a proposed reservoir, thermal data from nearby existing reservoirs are used for model calibration. The thermal conditions in the proposed reservoir can then be evaluated using the regional calibration coefficients.

7. METHODOLOGY

The reservoir is divided into horizontal layers of uniform thickness equal to any integral number of feet or meters. The choice of layer thickness involves a trade-off between the degree of profile definition desired, and the cost of both data preparation and computer time.

Usually a layer of thickness between 1 and 5 feet is satisfactory. It is necessary to specify the reservoir storage capacity at the top of each layer and at the bottom of each level of outlets. Although water released from a particular outlet actually comes from both above and below the outlet invert, releases as computed in this model are made from the water immediately above the intake invert elevation of each outlet. It is considered that this approximation will have minor effect on computation accuracy, because water ordinarily blended from higher and lower levels would have approximately the same temperature as the water at the invert level.

a. Atmospheric energy exchange - The exchange of energy between the reservoir and the atmosphere is assumed to affect only the top several meters of water, except for diffusion within the reservoir, which is computed separately. The exchange is considered to affect water temperatures linearly, with maximum effect at the surface and zero effect at the selected depth of energy penetration. Three atmospheric factors are considered in the energy exchange computation. These are solar radiation, evaporation, and a combination of conduction and long-wave radiation expressed as a function of the difference between air temperature and water temperature. All three exchanges are computed before stability and diffusion computations are made. In doing this, the exchange that is a function of air temperature is based on the water surface temperature at the start of the computation interval. Equations for these exchanges are described in addendum 1.

b. Thermal stability and ice formation - Water is mixed from the surface downward until no lower levels contain warmer water than exists at higher levels. This computation is constrained to temperatures above 4°C, corresponding to the maximum density of water. If water is cooled below this temperature, the temperature of each layer from the surface downward is allowed to go negative until an amount of energy equal to that required to form ice has been extracted from that layer.

c. Vertical diffusion - A rather simple diffusion computation has been found to work reasonably well where observed temperature profiles have been reconstituted. It is assumed that incomplete mixing of adjacent layers occurs over a 10-meter range, starting from the bottom and proceeding upward through the reservoir one layer at a time. The degree of mixing is controlled by a calibration coefficient. Paragraph 7i and addendum 1 describe model calibration and vertical diffusion respectively.

d. Inflow energy - It is recognized that there is some mixing as the inflow water descends into the reservoir to seek its temperature level. The model contains a provision for mixing a constant percentage of inflow with each layer as the inflow water descends through the warmer reservoir layers. The inflow temperature is consequently modified upward, and the inflow ultimately reaches a reservoir level at a temperature somewhat warmer than the original inflow temperature.

e. Computational interval - In some cases, inflow during a period as long as a month can exceed the total reservoir content. When this happens, computation on a monthly interval becomes very unstable. In order to preserve computational stability, it is possible to specify that the computation be divided into any number of parts and that only a fraction of the water and energy transfers be computed in each part. Thus the partial computations would be repeated the specified number of times before the quantities for the entire computational interval are printed out.

f. Selection of intake levels - Where there is latitude in selection of outlets for releasing water of a required temperature, two methods of operation are available. Method 1 selects the two intakes closest together that can blend water of the required temperature. With this method, a maximum choice of temperatures is available for subsequent months. Method 2 blends water from the highest and lowest available intakes. This operation generally provides a mixture of water having high and low dissolved oxygen content.

g. Target release temperature - When selecting the best release temperature from a target temperature range, the model has the capability of examining future target temperature criteria for any number of desired months. The model calculates the release temperature that would change the average reservoir temperature from its existing value to the average value of the temperature criteria for the specified number of future months.

h. Reservoir system input-output - A provision is included to output release quantities and temperatures on tape and to accept inflow quantities and temperatures from tape so that studies for tandem reservoirs can be made in a single computer run. If the temperature of the release water changes before it enters the downstream reservoir, the program must be modified as explained in the Programmers Manual.

i. Model calibration - Model calibration coefficients can be derived automatically on the basis of minimizing the sum of squares of errors in temperature between computed and observed profiles. Observed profiles must extend from the surface downward to any depth for which data are obtained. Any number of observed profiles can be used for a single model calibration. Errors are measured between computed and observed temperatures for each level and each profile. Computed temperatures are interpolated for the date of the observed profile by linear interpolation between end-of-month temperatures at the depth corresponding to the depth of the observed temperature. The program uses a gradient optimization technique[2] in which the coefficients are specified arbitrarily and are changed by the computer in accordance with the resulting effect of minimizing the standard error of computed temperatures. It is not necessary to calibrate the model for all coefficients. Fixed values for any of the coefficients can be prespecified, and the computer will optimize only the remaining coefficients. In order to facilitate evaluation of the calibration, a plot of the computed and observed

---

[2] Optimization Techniques for Hydrologic Engineering, The Hydrologic Engineering Center Technical Paper No. 2, Leo R. Beard, April 1966.

profiles is printed out. The proper selection of model calibration coefficients is an important element in any temperature study using this program. The HEC has developed calibration at numerous reservoirs in various regions of the United States. The information is available to the user on request. It is asked that program users notify the Center of their results on model calibration so that this information can be shared with other users.

j. Calculation procedure - A detailed description of the calculation procedure, including the required equations, is given in addendum 1. A functional flow chart for the program is shown in figure 1.

III. PROGRAM USAGE

8. EQUIPMENT REQUIREMENTS

a. Computer storage and speed - The program requires a FORTRAN IV compiler and a computer of at least the GE-400 series (32K) capacity. The use of higher speed computers (UNIVAC 1108, CDC 6600, etc.) is much more efficient for calibrating the model when 2 or more years of thermal profile data are used. However, the program runs sufficiently fast for long-term records (30 or more years) once the calibration coefficients have been determined. A list of approximate execution times and storage requirements for various types of computers is shown in table 1.

TABLE 1

Computer	Program Storage (in words)	Program Execution Time (per year of record)
	Model Calibration	
CDC-7600	14K	30 sec
CDC-6600	14K	3 min
UNIVAC-1108	12K	6 min
IBM 360/50	---	30 min
GE-425	11K	60 min
	Calibrated Model	
CDC-6600	14K	5 sec
UNIVAC-1108	12K	9 sec
CDC-3300	---	1 min
GE-425	11K	3 min

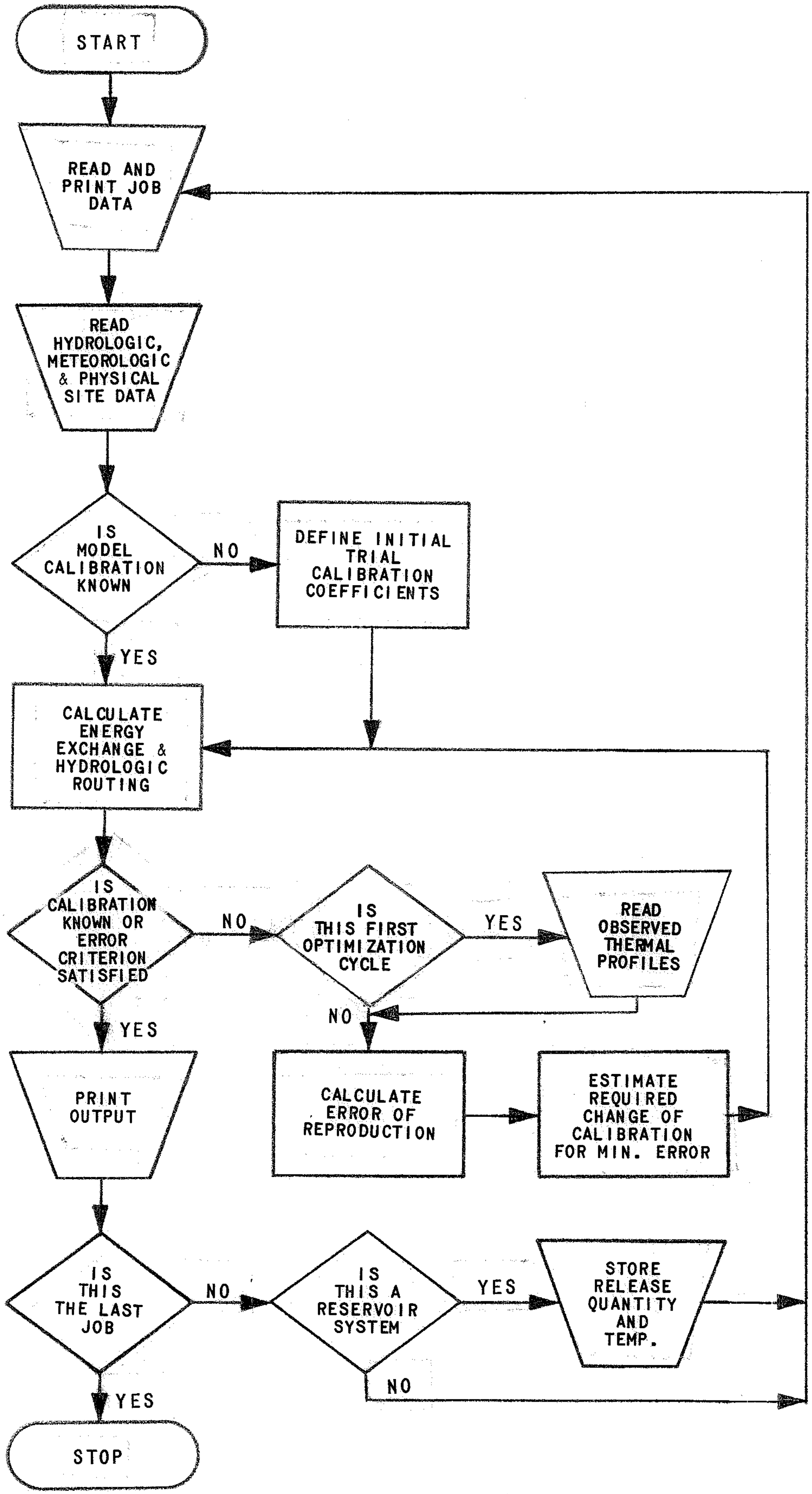


FIGURE 1. FUNCTIONAL FLOW CHART

b. I-O equipment - Cards are used for input, printer for output and units 92, 93, and 94 for temporary binary storage.

9. INPUT PREPARATION

Input data requirements are described in addendum 3 and examples are shown on pages 10-25. Consistent unit systems are "Metric and °C" or "English and °F". Required input is summarized as follows:

1. Inflow quantity and temperature for each month
2. Lake evaporation and precipitation for each month
3. Total monthly outflow quantity
4. Monthly discharge through each intake level or downstream temperature criteria
5. Average air temperature for each month
6. Solar radiation (obtained from figure 2 or table 2 for known latitude)
7. Reservoir physical data (i.e., storage-elevation data, intake configuration, etc.)
8. Thermal depth profiles or estimated calibration coefficients

10. PROGRAM OUTPUT

The output includes a printout of most input data, the calibration coefficients (given or derived), results of the optimization subroutine (if model is being calibrated), plots of observed and calculated temperature profiles (if model is being calibrated), end-of-month calculated temperature profiles, end-of-month storage, monthly average outflow temperature and quantity through each level of outlets and flow-weighted average temperature for all outlets.

11. EXAMPLE PROBLEMS

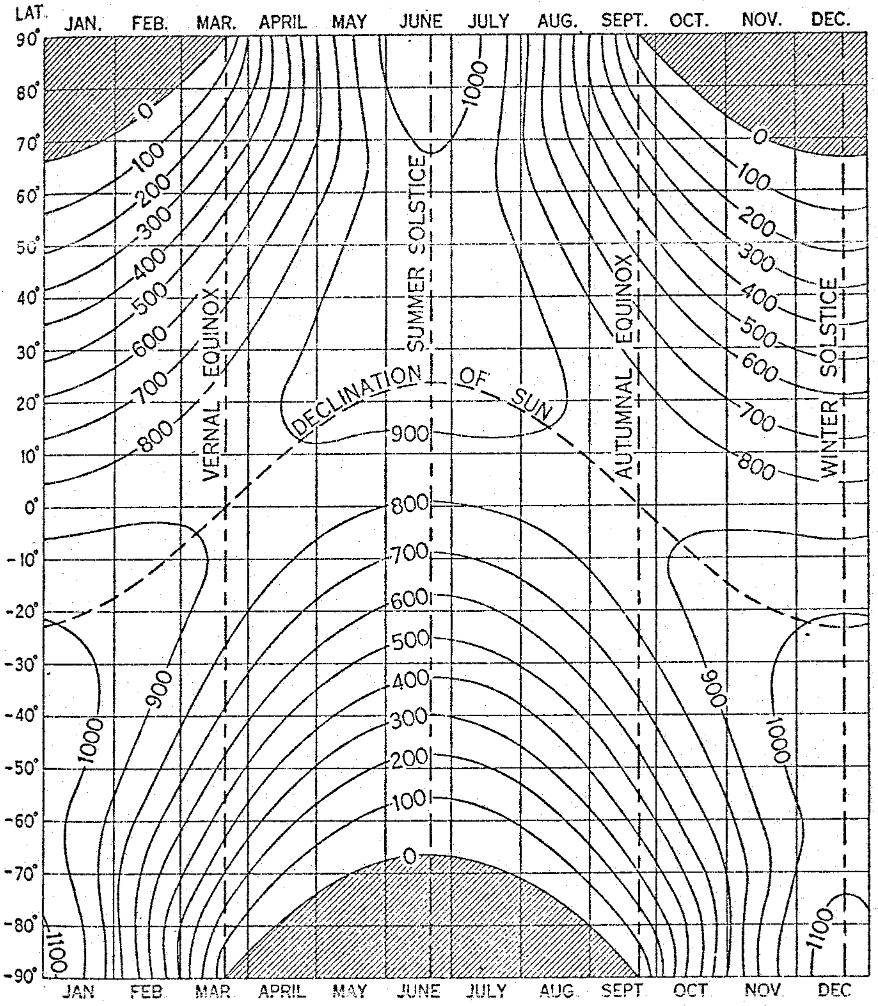
a. Example 1. Model Calibration - This example is intended to illustrate the use of the program for developing calibration coefficients from observed temperature profiles.

Detroit Reservoir, located on the North Santiam River in Oregon, has the physical characteristics shown in table 3.

FIGURE 2

CHART OF THE TOTAL DAILY SOLAR RADIATION AT THE TOP OF THE ATMOSPHERE

The solid curves represent total daily solar radiation on a horizontal surface at the top of the atmosphere, measured in cal. cm.$^{-2}$ Shaded areas represent regions of continuous darkness.



The above data was obtained from the Smithsonian Meteorological Tables, by Robert J. List, 6th revised edition, 1949.

TABLE 2

TOTAL DAILY SOLAR RADIATION AT THE TOP OF THE ATMOSPHERE

Values are in cal. cm.$^{-2}$ and apply to a horizontal surface

	Longitude of the sun															
	0°	22½°	45°	67½°	90°	112½°	135°	157½°	180°	202½°	225°	247½°	270°	292½°	315°	337½°
	Approximate date															
	Mar. 21	Apr. 13	May 6	May 29	June 22	July 15	Aug. 8	Aug. 31	Sept. 23	Oct. 16	Nov. 8	Nov. 30	Dec. 22	Jan. 13	Feb. 4	Feb 26
Latitude	cal. cm.$^{-2}$															
90°		423	772	999	1077	994	765	418								
80	155	423	760	984	1060	980	754	418	153	7						7
70	307	525	749	939	1012	934	742	519	303	129	24				24	131
60	447	635	809	934	979	929	801	629	442	273	146	72	49	73	146	276
50	575	732	867	958	989	954	859	725	568	414	286	204	176	205	289	419
40	686	807	910	972	991	967	901	798	677	545	429	348	317	350	434	553
30	775	865	929	967	975	960	921	856	765	663	564	492	466	494	568	670
20	841	894	923	935	935	930	916	884	831	760	685	627	605	630	691	769
10	882	897	893	881	873	877	886	887	871	835	789	748	733	752	795	845
0	895	873	837	804	790	800	830	863	885	886	870	851	843	855	878	896
—10	882	824	760	707	687	704	753	814	871	910	927	931	933	936	936	921
—20	841	750	660	593	567	590	654	741	831	907	959	988	999	993	968	918
—30	775	654	543	465	436	463	538	646	765	877	964	1020	1041	1025	973	888
—40	686	538	413	329	297	328	409	533	677	819	944	1027	1059	1032	953	828
—50	575	408	276	193	165	192	274	404	568	743	901	1014	1056	1018	909	752
—60	447	269	140	68	47	68	139	266	442	644	840	987	1046	992	847	652
—70	307	127	23				23	126	303	532	778	993	1081	998	785	539
—80	155	7						7	153	429	790	1041	1132	1046	796	434
—90										429	801	1056	1149	1062	809	434

The above data was obtained from the Smithsonian Meteorological Tables, prepared by Robert J. List, 6th revised edition, 1949.

TABLE 3

Parameter	Magnitude
length at full pool	10 miles
maximum width at full pool	1.5 miles
surface area at full pool	3,500 acres
capacity at full pool	455,000 acre-feet

Detroit Dam is a gravity structure 386 feet high. The dam has four levels for possible withdrawal (spillway, power plant penstock, and two lower sluices).

The project weather station collects the required meteorological input data of air temperature, rain, and evaporation. Inflow temperature measurements are available for 75% of the inflow volume and reservoir temperature profiles are measured daily near the dam. The remaining 25% of the inflow was assumed to have a temperature equal to the average (flow-weighted) measured inflow temperature. Often inflow temperature data is available for only a small portion of the hydrologic record, but can be extended in time by graphically correlating it with air temperature.

Example input is shown on page 12 and is explained in addendum 3. A part of the example output is shown on page 15 and the output variables are defined in addendum 2. In examining the output, the top half of page 15 should be checked to insure that the correct input data has been used. The bottom half of page 15 and the top half of page 16 is output from the optimization subroutine. The changes made to each variable in the attempt to minimize the least-square error in the reproduction of observed temperature profiles are indicated. The last two lines in this set of output read as follows:

```
CRITERION FOR VARIABLE 1      1.6679      1.6677      1.6676
VAR 1 ADJ FROM      .83  TO  .81
```

These lines indicate that variable 1 (the air temperture coefficient) has been changed from .83 to .81 and that the least-square error on this trial (the final trial) was 1.6679 temperature units. The other two least-square error values pertain to the magnitude of the error function at points used to measure the slope and change in slope of the error function. This printout option is controlled by the variable IDGST on the "B" card. The next set of output defines the "optimized" set of calibration coefficients. If the last change in each variable was a small percentage of the variable's magnitude, then these values can be used as optimum values. If the percentage change is large, the job should be rerun using the final values from this first run as the initial estimate of the calibration coefficients for the second run.

Each end-of-month calculated temperature profile is printed out by layers followed by a plot of any observed profiles for the next month. The plot includes a calculated profile which has been interpolated to the date of the observed profile. Before any confidence is place in the model calibration, the plots should show a comparison between calculated and observed values that is satisfactory to the user. The numerical value that describes the degree of reproducibility is the least-square error discussed above. The summary printout which follows the temperature profile output for all 12 months includes some input data which should be checked against the recorded data as well as a printout of calculated end-of-month storage, calculated discharge temperature through each outlet and the flow-weighted average temperature through all outlets.

GENERAL PURPOSE DATA FORM
(8 COLUMN FIELDS)

PROGRAM 723-X6-L7410
DATE
REQUESTED BY RGW
PREPARED BY
CHECKED BY
PAGE 1 OF 3

	1	2	3	4	5	6	7	8	9	10
A			DETRØIT RESERVØIR							
A		TEMPERATURE STRATIFICATIØN STUDY								
A	PERIØD ØF RECØRD,			JAN 1965 - 1967						
B	3	1965	12	1	1	48	8	4	4	1
B	0	1	1	0	0	4	0	3		
D	367000	1.983472	1.983472	494973	114700	-2	-2	-2	-2	-2
D	65	40	.504167	-1	0					
E	-.7	-.1	-.04	-.6	-.2					
F	-2	-2	-2	-2						
G	31	28	31	30	31	30	31	31	30	31
G	30	31								
H	45	125	197	402	607	967	1482	1997	2600	4200
H	6100	8200	10341	14000	17500	21000	25100	29238	35200	40800
H	47000	53700	61546	68500	77200	86200	96500	108027	119000	131000
H	144500	158300	172224	188000	204000	220000	237000	254593	272000	292000
H	314000	336500	360245	386000	410000	438000	466000	494973		
I	40	40	40	40	40	40	41	42	42	42
I	41	41	41	41	41	41	40	40	41	41
I	41	41	41	41	41	41	41	41	41	40
I	40	40	40	40	40	40	40	40	40	40
I	40	40	40	40	-1	-1	-1	-1		
J	2000	27000	76000	364000						
M	38	41	46	49	51	59	68	66	60	56
M	47	37								
N	.30	1.10	2.78	2.54	3.15	4.04	5.51	4.35	4.53	2.77
N	1.02	.48								
Ø	21.22	5.64	1.76	5.70	3.97	.64	.28	2.32	.36	4.81
Ø	10.99	11.85								
P	5883	4682	935	906	1875	1231	957	1022	1758	2147
P	3243	1428								

SPK Form 321
1 Jul 66

(Previous editions are obsolete)

Input for Example 1

GENERAL PURPOSE DATA FORM

(8 COLUMN FIELDS)

PROGRAM 723-X6-L7410

DATE

REQUESTED BY RGW

PREPARED BY

CHECKED BY

PAGE 2 OF 3

1	2	3	4	5	6	7	8	9	10
S 300	420	600	800	920	980	960	850	680	490
S 340	260								
T 2	0	0	0	0	0	0	0	0	0
T 0	0								
T 2746	2312	0	0	0	19	0	0	0	0
T 0	0								
T 3135	2370	935	906	1827	1213	957	1022	1758	2147
T 3243	1428								
T 0	0	0	0	48	0	0	0	0	0
T 0	0								
U 5563	3118	1827	2722	2087	1361	879	683	615	669
U 1442	1139								
V 39	38	39	41	46	50	52	55	50	47
V 43	38								
W 11	201	301	405	501	601	701	801	902	1002
W 1101	1201								
X 10	348035	0	39	68.63	39	93.63	38	118.63	39
168.63	39	193.63	38	218.63	39	243.63	40	268.63	41
293.63	40								
X 8	266538	0	38	12.80	39	112.80	39	137.80	40
162.80	39	212.80	39	237.80	41	262.80	40		
X 8	327163	0	40	136.16	40	161.16	41	186.16	39
211.16	40	236.16	40	261.16	41	286.16	40		
X 12	427231	0	44	43.92	44	68.92	43	118.92	43
143.92	42	168.92	41	193.92	41	218.92	40	243.92	40
268.92	41	293.92	41	318.92	40				
X 11	440297	0	52	22.60	51	47.60	50	72.60	48
97.60	45	122.60	43	147.60	42	172.60	41	197.60	41
222.60	40	322.60	40						

SPK Form 321
1 Jul 66

(Previous editions are obsolete)

Input for Example 1

GENERAL PURPOSE DATA FORM

(8 COLUMN FIELDS)

PROGRAM 723-X6-L7410
DATE
REQUESTED BY RGW
PREPARED BY
CHECKED BY
PAGE 3 OF 3

1	2	3	4	5	6	7	8	9	10
X 11	447043	0	62	24.50	56	49.50	52	74.50	50
99.50	47	124.50	44	149.50	44	174.50	43	199.50	43
224.50	41	324.50	41						
X 13	440652	0	70	22.70	62	47.70	58	72.70	54
97.70	51	122.70	48	147.70	45	172.70	44	197.70	44
222.70	42	272.70	42	297.70	41	322.70	41		
X 14	417274	0	64	15.90	65	40.90	61	65.90	57
90.90	55	115.90	51	140.90	47	165.90	45	190.90	44
215.90	42	240.90	43	265.90	43	290.90	42	315.90	42
X 10	347085	0	63	18.29	59	43.29	59	68.29	59
93.29	56	118.29	55	143.29	46	168.29	46	193.29	43
293.29	43								
X 12	257828	0	59	9.30	56	34.30	56	59.30	55
84.30	55	109.30	53	134.30	48	159.30	43	184.30	43
209.30	44	234.30	43	259.30	43				
X 8	154606	0	49	7.80	48	57.80	48	82.80	47
107.80	44	157.80	44	182.80	43	207.80	43		

The M, N, O, P, T, U, V, W and X cards for years 1966 and 1967 are not shown

A									
A									
A									
A									
A									

SPK Form 321
1 Jul 66

(Previous editions are obsolete)

Input for Example 1

```
                 DETRUIT RESERVOIR
            TEMPERATURE STRATIFICATION STUDY
         PERIOD OF RECORD,   JAN 1965 - 1967

THE OUTPUT UNITS ON INFLOW AND OUTFLOW ARE IN CFS, EVAP AND PRECIP IN INCHES, STORAGE IN AF, AND TEMPERATURE IN DEGREES F

     NYR      IYR     NPER     IPER    MSTRT    NLAYR    LAYER    NOUTL    NMINQ    IDERV    METRC    IDGST      NIC      NIT     NOTL    INTER
       3     1965       12        1        1       48        8        4        4        1        0        1        1        0        0        4
    MRFL      NMO
       0        3

    STORA     CISA     COSA    STRMX    STRMN      TIN     TAIR     EVAP     PRCP     QMIN     TMAX     TMIN    CSOUT     SOLR      DEP
   367000    1.983    1.983   494973   114700       -2       -2    -2.00    -2.00       -2       65       40     .504       -1    32.81

      AIR-TEMP COEF      INFLO MIXING COEF       DIFFUSION COEF       EVAP HEAT COEF       INSOLATION COEF
        -.700                 -.100                 -.040                 -.600                 -.200
        .700                  .100                  .040                  .600                  .200

QOMIN=        -2.0      -2.0      -2.0      -2.0

STCAP=          45       125       197       402       607       967      1482      1997      2600      4200
              6100      8200     10341     14000     17500     21000     25100     29238     35200     40800
             47300     53700     61546     68500     77200     86200     96500    108027    119000    131000
            144500    158300    172224    188000    204000    220000    237000    254593    272000    292000
            314000    336500    360245    386000    410000    438000    466000    494973

TSTRT=        40.0      40.0      40.0      40.0      40.0      40.0      41.0      42.0      42.0      42.0
              41.0      41.0      41.0      41.0      41.0      41.0      40.0      40.0      41.0      41.0
              41.0      41.0      41.0      41.0      41.0      41.0      41.0      41.0      41.0      40.0
              40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0
              40.0      40.0      40.0      40.0      -1.0      -1.0      -1.0      -1.0

STOUT=        2000     27000     76000    364000

CRITERION FOR VARIABLE 1      1.6855      1.6881      1.6892
VAR  1 ADJ FROM    .70 TO   1.00

CRITERION FOR VARIABLE 2      1.6948      1.6951      1.6951

CRITERION FOR VARIABLE 3      1.6948      1.6956      1.6966
VAR  3 ADJ FROM    .04 TO    .04

CRITERION FOR VARIABLE 4      1.6929      1.6947      1.6962
VAR  4 ADJ FROM    .50 TO    .69

CRITERION FOR VARIABLE 5      1.6818      1.6816      1.6815
VAR  5 ADJ FROM    .20 TO    .20

CRITERION FOR VARIABLE 1      1.6815      1.6806      1.6798
VAR  1 ADJ FROM   1.00 TO    .93

CRITERION FOR VARIABLE 2      1.6758      1.6760      1.6762
VAR  2 ADJ FROM    .10 TO    .10

CRITERION FOR VARIABLE 3      1.6757      1.6767      1.6779
VAR  3 ADJ FROM    .04 TO    .04

CRITERION FOR VARIABLE 4      1.6747      1.6743      1.6738
VAR  4 ADJ FROM    .69 TO    .67
```

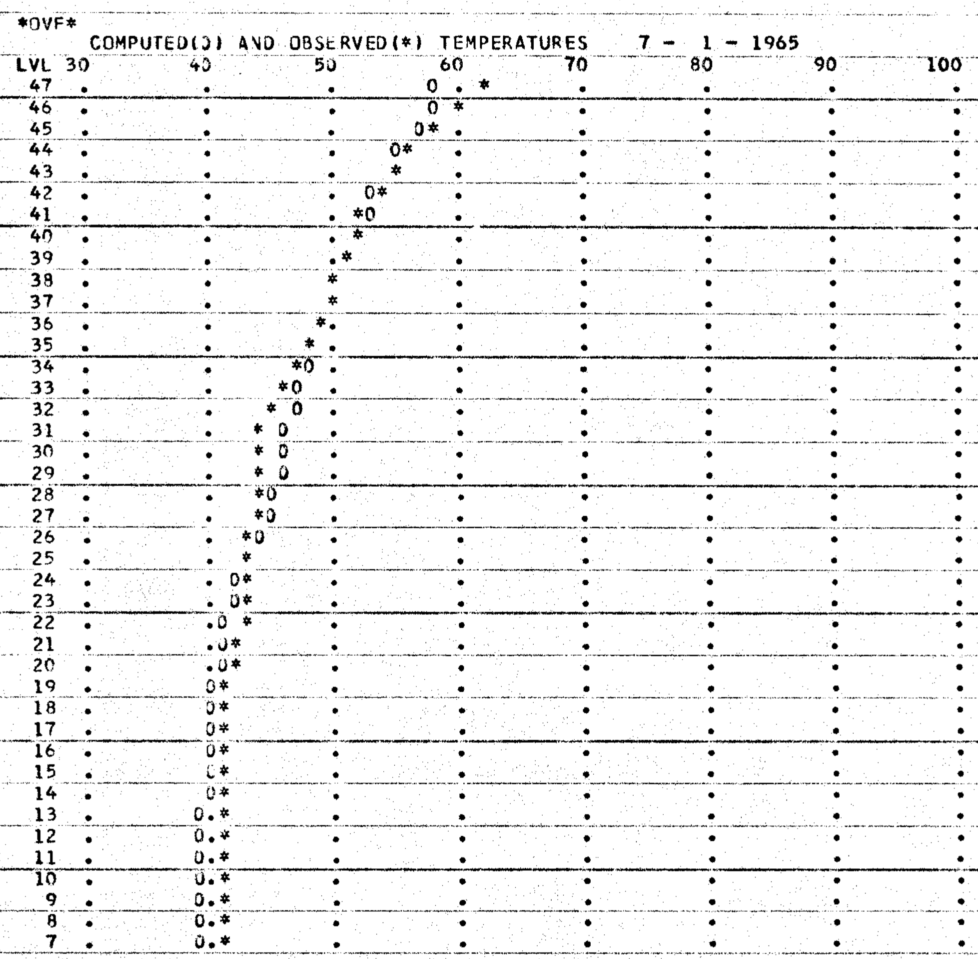
Printout for Example 1

```
CRITERION FOR VARIABLE 5        1.6737      1.6739      1.6728

CRITERION FOR VARIABLE 1        1.6737      1.6730      1.6735
VAR  1 ADJ FROM     .93 TO    .92

CRITERION FOR VARIABLE 2        1.6730      1.6730      1.6734

CRITERION FOR VARIABLE 3        1.6730      1.6734      1.6741
VAR  3 ADJ FROM     .04 TO    .04

CRITERION FOR VARIABLE 4        1.6726      1.6726      1.6738
VAR  4 ADJ FROM     .67 TO    .67

CRITERION FOR VARIABLE 5        1.6726      1.6724      1.6716
VAR  5 ADJ FROM     .20 TO    .19

CRITERION FOR VARIABLE 1        1.6717      1.6713      1.6709
VAR  1 ADJ FROM     .92 TO    .83

CRITERION FOR VARIABLE 2        1.6717      1.6720      1.6722
VAR  2 ADJ FROM     .10 TO    .12

CRITERION FOR VARIABLE 3        1.6710      1.6713      1.6717
VAR  3 ADJ FROM     .04 TO    .04

CRITERION FOR VARIABLE 4        1.6709      1.6701      1.6693
VAR  4 ADJ FROM     .67 TO    .63

CRITERION FOR VARIABLE 5        1.6689      1.6679      1.6683
VAR  5 ADJ FROM     .19 TO    .19

CRITERION FOR VARIABLE 1        1.6679      1.6677      1.6676
VAR  1 ADJ FROM     .83 TO    .81

DERIVED VARIABLES

     AIR TEMP COEF    INFLO MIXING COEF       DIFFUSION COEF       EVAP HEAT COEF       INSOLATION COEF
        .811                .116                  .045                  .634                 .188

                                                     RESERVOIR TEMPERATURES
YEAR  PER       1       2      3      4      5      6      7      8      9     10     11     12     13     14     15     16     17     18     19     20
1965    1    39.3    39.3   39.3   39.3   39.3   39.3   39.3   39.3   39.3   39.3   39.3   39.3   39.3   39.3   39.3   39.3   39.3   39.3   39.4   39.6
             39.6    39.6   39.7   39.7   39.7   39.7   39.7   39.8   39.8   39.8   39.8   39.8   39.8   39.8   39.8   39.8   39.8   39.8   39.8   39.8
             39.8    39.8   39.8
```

Plotted profiles for Feb. 1965 through Jun. 1965 are not shown.

End-of-month calculated temperature profiles for Feb. 1965 through Jun. 1965 are not shown.

Printout for Example 1



```
 *OVF*
      COMPUTED(0) AND OBSERVED(*) TEMPERATURES    7 -  1 - 1965
 LVL 30        40        50        60        70        80        90        100
  47  .         .         .       0 . *       .         .         .         .
  46  .         .         .       0 *         .         .         .         .
  45  .         .         .      0* .         .         .         .         .
  44  .         .         .    0*   .         .         .         .         .
  43  .         .         .    *    .         .         .         .         .
  42  .         .         .  0*     .         .         .         .         .
  41  .         .         . *0      .         .         .         .         .
  40  .         .         . *       .         .         .         .         .
  39  .         .         .*        .         .         .         .         .
  38  .         .         *         .         .         .         .         .
  37  .         .         *         .         .         .         .         .
  36  .         .        *.         .         .         .         .         .
  35  .         .       * .         .         .         .         .         .
  34  .         .      *0 .         .         .         .         .         .
  33  .         .     *0  .         .         .         .         .         .
  32  .         .    * 0  .         .         .         .         .         .
  31  .         .   * 0   .         .         .         .         .         .
  30  .         .   * 0   .         .         .         .         .         .
  29  .         .   * 0   .         .         .         .         .         .
  28  .         .   *0    .         .         .         .         .         .
  27  .         .   *0    .         .         .         .         .         .
  26  .         .  *0     .         .         .         .         .         .
  25  .         .  *      .         .         .         .         .         .
  24  .         . 0*      .         .         .         .         .         .
  23  .         . 0*      .         .         .         .         .         .
  22  .         .0 *      .         .         .         .         .         .
  21  .         .0*       .         .         .         .         .         .
  20  .         .0*       .         .         .         .         .         .
  19  .         0*        .         .         .         .         .         .
  18  .         0*        .         .         .         .         .         .
  17  .         0*        .         .         .         .         .         .
  16  .         0*        .         .         .         .         .         .
  15  .         0*        .         .         .         .         .         .
  14  .         0*        .         .         .         .         .         .
  13  .        0.*        .         .         .         .         .         .
  12  .        0.*        .         .         .         .         .         .
  11  .        0.*        .         .         .         .         .         .
  10  .        0.*        .         .         .         .         .         .
   9  .        0.*        .         .         .         .         .         .
   8  .        0.*        .         .         .         .         .         .
   7  .        0.*        .         .         .         .         .         .
```

Printout for Example 1

Plotted profiles for Aug. 1965 through Dec. 1965 are not shown.

End-of-month calculated temperature profiles for Jul. 1965 through Nov. 1965 are not shown.

```
*OVN*
                                                     RESERVOIR TEMPERATURES
YEAR  PER    1     2     3     4     5     6     7     8     9    10    11    12    13    14    15    16    17    18    19    20
1965   12  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.7  39.8  39.8  40.1  40.2  40.4  40.5  40.8
           40.9  41.1  41.2  41.2  41.3  41.3  41.3  41.3  41.3  41.3  41.3

                                                   FLOWS AND TEMPERATURES FOR 1965
              YEAR         1         2         3         4         5         6         7         8         9        10        11        12
INFLO       1842.1    5563.0    3118.0    1827.0    2722.0    2087.0    1361.0     879.0     683.0     615.0     669.0    1442.0    1139.0
 EVAP          2.7        .3       1.1       2.8       2.5       3.2       4.0       5.5       4.3       4.5       2.8       1.0        .5
 PRCP          5.8      21.2       5.6       1.8       5.7       4.0        .6        .3       2.3        .4       4.8      11.0      11.9
OUTFL       2172.3    5383.0    4682.0     935.0     906.0    1875.0    1232.0     957.0    1022.0    1758.0    2147.0    3243.0    1428.0
REQDQ       2172.3    5383.0    4682.0     935.0     906.0    1875.0    1231.0     957.0    1022.0    1758.0    2147.0    3243.0    1428.0
STMX                  494973    494973    494973    494973    494973    494973    494973    494973    494973    494973    494973    494973
STOR                  352498    266679    321292    430199    443474    450158    443837    422400    353344    262933    157428    141292
STMN                  114700    114700    114700    114700    114700    114700    114700    114700    114700    114700    114700    114700

TA            51.5      38.0      41.0      46.0      49.0      51.0      59.0      68.0      66.0      60.0      56.0      47.0      37.0
TMPIN         42.2      39.0      38.0      39.0      41.0      46.0      50.0      52.0      55.0      50.0      47.0      43.0      38.0
TMPMX         65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0
TPOUT         43.9      39.5      39.2      39.6      40.0      41.3      42.9      44.9      47.4      51.7      54.3      50.4      43.4
TMPMN         40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0
RELEASES THRU OUTLET  1
 QOMN                    2.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
QOUTL                    2.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
TOUTL                   39.3       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
RELEASES THRU OUTLET  2
 QOMN                 2746.0    2312.0       0.0       0.0       0.0      19.0       0.0       0.0       0.0       0.0       0.0       0.0
QOUTL                 2746.0    2312.0       0.0       0.0       0.0      19.0       0.0       0.0       0.0       0.0       0.0       0.0
TOUTL                   39.4      39.0       0.0       0.0       0.0      39.8       0.0       0.0       0.0       0.0       0.0       0.0
RELEASES THRU OUTLET  3
 QOMN                 3135.0    2370.0     935.0     906.0    1827.0    1213.0     957.0    1022.0    1758.0    2147.0    3243.0    1428.0
QOUTL                 3135.0    2370.0     935.0     906.0    1827.0    1213.0     957.0    1022.0    1758.0    2147.0    3243.0    1428.0
TOUTL                   39.6      39.3      39.6      40.0      41.2      43.0      44.9      47.4      51.7      54.3      50.4      43.4
RELEASES THRU OUTLET  4
 QOMN                    0.0       0.0       0.0       0.0      48.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
QOUTL                    0.0       0.0       0.0       0.0      48.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
TOUTL                    0.0       0.0       0.0       0.0      48.0       0.0       0.0       0.0       0.0       0.0       0.0       0.0
```

Results for calender years 1966 and 1967 are not shown.

Printout for Example 1

b. Example 2. Analysis of a Proposed Reservoir - This example illustrates application of the program for situations where estimates of the calibration coefficients have been obtained by regional analysis. Detroit Reservoir is analyzed assuming thermal profiles do not exist but that the model calibration coefficients are known. Refer to example 1 for physical characteristics of the dam and reservoir.

Example input is shown on page 20 and is explained in addendum 3. Example output is shown on page 22 and the variables are defined in addendum 2. Examination of the output should include checking the top half of page 22 and the summary of "flows and temperatures" at the end of each year to insure that the program obtained correct input data. The remainder of the output includes the end-of-month calculated temperature profiles and reservoir storage, discharge temperature and quantity through each outlet and flow-weighted average temperature through all outlets.

Examination of the output shows that the release temperature was below the temperature criteria in January through March for the first two years. The January profiles for the first two years show that the warmest water in the reservoir can not satisfy the criteria, but the February and March temperature criteria might be met by using two penstock intake levels at elevations above the existing level.

In many cases, for analysis of a proposed reservoir, the releases are not specified for particular outlet levels and the program makes the decision as to which levels are used to meet the downstream temperature criteria. In such cases, the program uses the NMINQ(B-9) value equal to zero and therefore no F card or T cards would be required.

GENERAL PURPOSE DATA FORM

(8 COLUMN FIELDS)

PROGRAM 723-X6-L7410

DATE

REQUESTED BY RGW

PREPARED BY

CHECKED BY

PAGE 1 OF 2

	1	2	3	4	5	6	7	8	9	10
A			DETRØIT RESERVØIR							
A		TEMPERATURE STRATIFICATIØN STUDY								
A		PERIØD ØF RECØRD, JAN 1965 - DEC 1967								
B	3	1965	12	1	1	48	8	4	4	0
B	0	0	1	0	0	4	0	3		
D	367000	1.983472	1.983472	494973	114700	-2	-2	-2	-2	-2
D	65	40	.504167	-1	0					
E	.816	.114	.043	.637	.193					
F	-2	-2	-2	-2						
G	31	28	31	30	31	30	31	31	30	31
G	30	31								
H	45	125	197	402	607	967	1482	1997	2600	4200
H	6100	8200	10341	14000	17500	21000	25100	29238	35200	40800
H	47000	53700	61546	68500	77200	86200	96500	108027	119000	131000
H	144500	158300	172224	188000	204000	220000	237000	254593	272000	292000
H	314000	336500	360245	386000	410000	438000	466000	494973		
I	40	40	40	40	40	40	41	42	42	42
I	41	41	41	41	41	41	40	40	41	41
I	41	41	41	41	41	41	41	41	41	40
I	40	40	40	40	40	40	40	40	40	40
I	40	40	40	40	-1	-1	-1	-1		
J	2000	27000	76000	364000						
M	38	41	46	49	51	59	68	66	60	56
M	47	37								
N	.30	1.10	2.78	2.54	3.15	4.04	5.51	4.35	4.53	2.77
N	1.02	.48								
Ø	21.22	5.64	1.76	5.70	3.97	.64	.28	2.32	.36	4.81
Ø	10.99	11.85								
P	5883	4682	935	906	1875	1231	957	1022	1758	2147
P	3243	1428								

SPK Form 321
1 Jul 66

(Previous editions are obsolete)

Input for Example 2

GENERAL PURPOSE DATA FORM

(8 COLUMN FIELDS)

PROGRAM 723-X6-L7410
DATE
REQUESTED BY RGW
PREPARED BY
CHECKED BY
PAGE 2 OF 2

1	2	3	4	5	6	7	8	9	10
S 300	420	600	800	920	980	960	850	680	490
S 340	260								
T 2	0	0	0	0	0	0	0	0	0
T 0	0								
T 2746	2312	0	0	0	19	0	0	0	0
T 0	0								
T 3135	2370	935	906	1827	1213	957	1022	1758	2147
T 3243	1428								
T 0	0	0	0	48	0	0	0	0	0
T 0	0								
U 5563	3118	1827	2722	2087	1361	879	683	615	669
U 1442	1139								
V 39	38	39	41	46	50	52	55	50	47
V 43	38								

The M, N, Ø, P, T, U, and V cards for years 1966 and 1967 are not shown

1	2	3	4	5	6	7	8	9	10
A									
A									
A									
A									
A									

SPK Form 321
1 Jul 66

(Previous editions are obsolete)

Input for Example 2

```
            DETROIT RESERVOIR
       TEMPERATURE STRATIFICATION STUDY
   PERIOD OF RECORD,  JAN 1965 - DEC 1967

 THE OUTPUT UNITS ON INFLOW AND OUTFLOW ARE IN CFS, EVAP AND PRECIP IN INCHES, STORAGE IN AF, AND TEMPERATURE IN DEGREES F

     NYR     IYR    NPER    IPER   MSTRT   NLAYR   LAYER   NOUTL   NMINQ   IDERV   METRC   IDGST    NIC     NIT    NOTL   INTER
       3    1965      12       1       1      48       8       4       4       0       0       1       1       0       0       4
    MREL     NMO
       0       3

     STORA       CISA        COSA   STRMX    STRMN       TIN     TAIR     EVAP     PRCP     QMIN     TMAX     TMIN    CSOUT    SOLR      DEP
   367000.      1.983       1.983 494973. 114700.        -2.      -2.    -2.00    -2.00      -2.      65.      40.     .504     -1.    32.81

       AIR TEMP COEF    INFLO MIXING COEF       DIFFUSION COEF       EVAP HEAT COEF      INSOLATION COEF
            .811               .116                  .045                 .634                .188

   QOMIN=     -2.0      -2.0      -2.0      -2.0

   STCAP=      45.      125.      197.      402.      607.      967.     1482.     1997.     2600.     4200.
             6100.     8200.    10341.    14000.    17500.    21000.    25100.    29238.    35200.    40800.
            47000.    53700.    61546.    68500.    77200.    86200.    96500.   108027.   119000.   131000.
           144500.   158300.   172224.   188000.   204000.   220000.   237000.   254593.   272000.   292000.
           314000.   336500.   360245.   386000.   410000.   438000.   466000.   494973.

   TSTRT=     40.0      40.0      40.0      40.0      40.0      40.0      41.0      42.0      42.0      42.0
              41.0      41.0      41.0      41.0      41.0      41.0      40.0      40.0      41.0      41.0
              41.0      41.0      41.0      41.0      41.0      41.0      41.0      41.0      41.0      40.0
              40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0
              40.0      40.0      40.0      40.0      -1.0      -1.0      -1.0      -1.0

   STOUT=    2000.    27000.    76000.   364000.

                                                         RESERVOIR TEMPERATURES
   YEAR  PER     1     2     3     4     5     6     7     8     9    10    11    12    13    14    15    16    17    18    19    20
   1965    1  39.3  39.3  39.3  39.3  39.3  39.3  39.3  39.3  39.3  39.3  39.3  39.3  39.3  39.3  39.3  39.3  39.3  39.3  39.4  39.6
              39.6  39.6  39.7  39.7  39.7  39.7  39.7  39.8  39.8  39.8  39.8  39.8  39.8  39.8  39.8  39.8  39.8  39.8  39.8  39.8
              39.8  39.8  39.8
   1965    2  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0
              39.2  39.3  39.4  39.4  39.4  39.5  39.5  39.6  39.7  39.7  39.8  39.9  40.1  40.3  40.4  40.6  40.8  41.1  41.4
   1965    3  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.1  39.1  39.1  39.1  39.2  39.2  39.2
              39.3  39.4  39.4  39.5  39.6  39.8  39.9  40.0  40.0  40.1  40.2  40.3  40.4  40.6  40.9  41.3  41.8  42.2  42.8  43.7
              44.6  44.9
   1965    4  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.1  39.1  39.1  39.1  39.1  39.1  39.1  39.2  39.2  39.2  39.3  39.3  39.4
              39.5  39.6  39.7  39.8  40.0  40.4  40.5  40.7  40.9  41.1  41.3  41.5  41.7  41.9  42.1  42.3  42.5  42.7  43.1  43.5
              44.2  44.9  45.7  46.6  47.7  48.4
   1965    5  39.0  39.0  39.1  39.1  39.1  39.1  39.1  39.1  39.1  39.1  39.2  39.2  39.2  39.3  39.3  39.4  39.4  39.5  39.6  39.8
              39.9  40.2  40.4  40.7  41.2  42.4  42.6  42.9  43.1  43.4  43.7  44.1  44.5  44.9  45.4  45.8  46.2  46.7  47.0  47.4
              47.8  48.4  49.1  49.7  50.4  51.3  51.8
   1965    6  39.1  39.1  39.1  39.1  39.1  39.2  39.2  39.2  39.2  39.3  39.3  39.4  39.4  39.5  39.6  39.7  39.9  40.1  40.3  40.6
              40.9  41.3  41.8  42.3  43.1  44.4  44.8  45.1  45.5  45.8  46.2  46.7  47.1  47.6  48.2  48.8  49.5  50.3  51.0  51.8
              52.4  53.3  54.3  55.2  56.4  57.4  58.0
   1965    7  39.1  39.2  39.2  39.3  39.3  39.3  39.4  39.4  39.5  39.5  39.6  39.7  39.8  40.0  40.1  40.3  40.6  40.9  41.2  41.6
              42.1  42.6  43.3  44.0  44.9  46.5  47.0  47.5  48.0  48.5  49.1  49.7  50.3  51.0  51.8  52.6  53.5  54.4  55.4  56.3
              57.4  58.6  59.8  61.1  63.0  64.5  65.2
   1965    8  39.3  39.4  39.4  39.5  39.5  39.6  39.7  39.8  39.9  40.0  40.1  40.2  40.4  40.6  40.9  41.2  41.5  41.9  42.4  43.0
              43.6  44.3  45.2  46.1  47.4  49.7  50.2  50.9  51.6  52.2  52.9  53.6  54.2  55.0  55.8  56.7  57.5  58.3  59.0  59.8
```

Printout for Example 2

```
              60.7  61.6  62.4  63.2  64.1  64.4
   1965    9  39.5  39.7  39.8  39.9  39.9  40.1  40.2  40.3  40.5  40.6  40.8  41.0  41.3  41.5  41.9  42.3  42.8  43.4  44.1  44.9
              45.8  46.9  48.1  49.4  51.4  54.7  55.2  55.6  55.9  56.3  56.7  57.1  57.4  57.7  58.1  58.3  58.6  58.7  58.9  58.9
              59.0  59.0  59.0
   1965   10  39.9  40.2  40.3  40.4  40.6  40.7  40.9  41.1  41.3  41.5  41.8  42.1  42.4  42.8  43.3  43.9  44.6  45.3  46.1  47.0
              48.0  49.1  50.2  51.4  53.1  55.5  55.8  55.9  55.9  56.0  56.0  56.0  56.0  56.0  56.0  56.0  56.0  56.0  56.0
   1965   11  40.5  40.9  41.1  41.3  41.4  41.6  41.9  42.1  42.4  42.7  43.0  43.3  43.6  44.0  44.4  44.7  45.1  45.4  45.5  45.7
              45.8  46.1  46.4  46.7  47.4  49.6  49.7  49.7  49.8  49.8  49.8  49.8
   1965   12  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.6  39.7  39.7  39.8  39.8  40.1  40.2  40.4  40.5  40.8
              40.9  41.1  41.2  41.3  41.3  41.3  41.3  41.3  41.3  41.3  41.3

                                                          FLOWS AND TEMPERATURES FOR 1965
              YEAR         1         2         3         4         5         6         7         8         9        10        11        12
   INFLO    1842.1    5563.0    3118.0    1827.0    2722.0    2087.0    1361.0     879.0     683.0     615.0     669.0    1442.0    1139.0
    EVAP       2.7        .3       1.1       2.8       2.5       3.1       4.0       5.5       4.4       4.5       2.8       1.0        .5
    PRCP       5.8      21.2       5.6       1.8       5.7       4.0        .6        .3       2.3        .4       4.8      11.0      11.8
   OUTFL    2172.3    5883.0    4682.0     935.0     906.0    1875.0    1232.0     957.0    1022.0    1758.0    2147.0    3243.0    1428.0
   REQDQ    2172.3    5883.0    4682.0     935.0     906.0    1875.0    1231.0     957.0    1022.0    1758.0    2147.0    3243.0    1428.0
   STMX              494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.
   STOR              352498.   266679.   321292.   430199.   443474.   450158.   443837.   422400.   353344.   262933.   157428.   141292.
   STMN              114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.

   TA         51.5      38.0      41.0      46.0      49.0      51.0      59.0      68.0      66.0      60.0      56.0      47.0      37.0
   TMPIN      42.2      39.0      38.0      39.0      41.0      46.0      50.0      52.0      55.0      50.0      47.0      43.0      38.0
   TMPMX      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0
   TPOUT      43.9      39.5      39.2      39.6      40.0      41.3      42.9      45.0      47.5      51.7      54.3      50.5      43.4
   TMPMN      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0
   RELEASES THRU OUTLET  1
    QOMN                 2.0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0
   QOUTL                 2.0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0
   TOUTL                39.3        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0
   RELEASES THRU OUTLET  2
    QOMN              2746.0    2312.0        .0        .0        .0      19.0        .0        .0        .0        .0        .0        .0
   QOUTL              2746.0    2312.0        .0        .0        .0      19.0        .0        .0        .0        .0        .0        .0
   TOUTL                39.4      39.0        .0        .0        .0      39.8        .0        .0        .0        .0        .0        .0
   RELEASES THRU OUTLET  3
    QOMN              3135.0    2370.0     935.0     906.0    1827.0    1213.0     957.0    1022.0    1758.0    2147.0    3243.0    1428.0
   QOUTL              3135.0    2370.0     935.0     906.0    1827.0    1213.0     957.0    1022.0    1758.0    2147.0    3243.0    1428.0
   TOUTL                39.6      39.3      39.6      40.0      41.2      43.0      45.0      47.5      51.7      54.3      50.5      43.4
   RELEASES THRU OUTLET  4
    QOMN                  .0        .0        .0        .0      48.0        .0        .0        .0        .0        .0        .0        .0
   QOUTL                  .0        .0        .0        .0      48.0        .0        .0        .0        .0        .0        .0        .0
   TOUTL                  .0        .0        .0        .0      48.0        .0        .0        .0        .0        .0        .0        .0

                                                      RESERVOIR TEMPERATURES
   YEAR  PER     1     2     3     4     5     6     7     8     9    10    11    12    13    14    15    16    17    18    19    20
   1966    1  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0
              39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  36.0
   1966    2  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0
              39.0  39.0  39.0  39.0  39.1  39.2  39.2  39.4  39.6  39.9  40.2  40.7  41.0
   1966    3  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.1  39.1
              39.1  39.1  39.2  39.2  39.3  39.4  39.4  39.5  39.5  39.5  39.6  39.6  39.7  39.9  40.1  40.5  40.9  41.2  41.9  42.6
              43.2
   1966    4  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.0  39.1  39.1  39.1  39.1  39.2  39.2  39.3
              39.4  39.5  39.7  39.9  40.4  41.3  41.5  41.6  41.7  41.8  41.9  42.0  42.1  42.2  42.3  42.5  42.9  43.3  43.9  44.6
              45.3  46.3  47.5  48.6
   1966    5  39.0  39.0  39.0  39.0  39.0  39.0  39.1  39.1  39.1  39.1  39.1  39.1  39.1  39.2  39.2  39.3  39.4  39.5  39.7  39.9
              40.1  40.5  40.9  41.4  42.2  44.2  44.4  44.7  44.9  45.1  45.3  45.6  45.7  45.9  46.2  46.5  47.0  47.6  48.2  49.2
              49.9  51.2  52.7  54.4  54.9
   1966    6  39.0  39.1  39.1  39.1  39.1  39.1  39.1  39.2  39.2  39.2  39.3  39.4  39.4  39.5  39.7  39.8  40.0  40.3  40.6  41.0
```

Printout for Example 2

```
              41.4  41.9  42.5  43.1  43.9  45.2  45.6  46.0  46.4  46.7  47.1  47.6  48.0  48.5  49.1  49.7  50.4  50.9  51.6  52.4
              53.4  54.3  55.5  56.9  58.5  59.1
   1966    7  39.1  39.2  39.2  39.2  39.3  39.3  39.4  39.4  39.5  39.6  39.7  39.8  40.0  40.1  40.4  40.6  40.9  41.4  41.8  42.2
              42.8  43.4  44.0  44.8  45.8  47.2  47.7  48.3  48.7  49.2  49.8  50.4  51.0  51.6  52.4  53.2  53.9  54.8  55.6  56.5
              57.5  58.5  59.5  60.8  62.2  62.7
   1966    8  39.3  39.4  39.5  39.5  39.6  39.7  39.8  39.9  40.0  40.1  40.3  40.5  40.7  40.9  41.2  41.6  42.0  42.5  43.1  43.6
              44.3  45.1  45.9  46.8  48.1  50.0  50.6  51.3  51.9  52.4  53.0  53.7  54.3  55.0  55.7  56.4  57.1  57.9  58.9  59.8
              60.6  61.5  62.7  63.7  64.1
   1966    9  39.6  39.8  39.9  40.0  40.1  40.2  40.4  40.5  40.7  40.9  41.1  41.4  41.7  42.0  42.4  42.9  43.4  44.1  44.8  45.6
              46.5  47.5  48.6  49.8  51.7  54.2  54.8  55.3  55.7  56.1  56.4  56.9  57.3  57.8  58.3  58.8  59.4  59.9  60.4  60.7
              61.2  61.5  61.7
   1966   10  40.1  40.4  40.6  40.7  40.8  41.0  41.2  41.4  41.7  41.9  42.2  42.5  42.9  43.3  43.8  44.4  45.0  45.7  46.5  47.3
              48.1  49.0  49.9  50.8  51.8  54.0  54.2  54.3  54.3  54.3  54.4  54.4  54.4  54.4  54.4  54.4  54.4  54.4  54.4
   1966   11  40.8  41.2  41.4  41.6  41.7  42.0  42.2  42.4  42.7  42.9  43.1  43.4  43.5  43.7  43.7  43.8  43.8  43.9  44.1  44.3
              44.5  44.9  45.7  48.2  48.2  48.3  48.3  48.4  48.4  48.4  48.4
   1966   12  40.4  40.4  40.4  40.4  40.4  40.4  40.4  40.4  40.4  40.4  40.4  40.4  40.4  40.4  40.4  40.4  40.4  40.4  40.4  40.4
              40.4  40.5  40.5  40.6  41.4  42.0  42.1  42.2  42.3  42.4  42.4

                                                   FLOWS AND TEMPERATURES FOR 1966
              YEAR         1         2         3         4         5         6         7         8         9        10        11        12
 INFLO      2063.8    2959.0    1368.0    3375.0    3973.0    2931.0    1457.0     877.0     615.0     551.0     769.0    2517.0    3374.0
  EVAP         2.6        .6        .5       2.0       3.0       3.9       3.5       4.4       5.1       3.8       3.0        .8        .5
  PRCP         6.7      17.1       6.3      11.9       3.0       2.1       2.4       1.9        .2       1.7       6.5      14.4      13.5
 OUTFL      2074.9    2948.0     966.0    1144.0    2705.0    2777.0    1007.0     902.0     947.0    1426.0    2085.0    4523.0    3469.0
 REQDQ      2074.9    2948.0     966.0    1144.0    2705.0    2777.0    1007.0     902.0     947.0    1426.0    2085.0    4523.0    3469.0
 STMX                494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.
 STOR                144298.   167449.   306377.   381809.   390825.   417337.   415056.   393417.   340793.   260668.   143565.   139565.
 STMN                114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.

 TA           51.6      38.0      40.0      43.0      50.0      56.0      59.0      64.0      66.0      63.0      53.0      46.0      41.0
 TMPIN        41.9      38.0      38.0      39.0      41.0      44.0      48.0      52.0      52.0      51.0      45.0      42.0      40.0
 TMPMX        65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0
 TPOUT        44.3      39.3      39.1      39.3      40.1      42.2      44.1      45.6      47.9      51.3      53.5      47.7      42.3
 TMPMN        40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0
 RELEASES THRU OUTLET  1
  QOMN                    .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0
 QOUTL                    .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0
 TOUTL                    .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0
 RELEASES THRU OUTLET  2
  QOMN                 408.0        .0        .0      49.0        .0        .0      28.0      18.0      32.0        .0    1051.0     327.0
 QOUTL                 408.0        .0        .0      49.0        .0        .0      28.0      18.0      32.0        .0    1051.0     327.0
 TOUTL                  39.0        .0        .0      39.1        .0        .0      40.9      42.0      43.4        .0      44.9      40.8
 RELEASES THRU OUTLET  3
  QOMN                2540.0     966.0    1144.0    2642.0    2777.0    1007.0     874.0     929.0    1394.0    2085.0    3472.0    3142.0
 QOUTL                2540.0     966.0    1144.0    2642.0    2777.0    1007.0     874.0     929.0    1394.0    2085.0    3472.0    3142.0
 TOUTL                  39.4      39.1      39.3      40.0      42.2      44.1      45.7      48.0      51.5      53.5      48.6      42.5
 RELEASES THRU OUTLET  4
  QOMN                    .0        .0        .0      14.0        .0        .0        .0        .0        .0        .0        .0        .0
 QOUTL                    .0        .0        .0      14.0        .0        .0        .0        .0        .0        .0        .0        .0
 TOUTL                    .0        .0        .0      47.3        .0        .0        .0        .0        .0        .0        .0        .0

                                                   RESERVOIR TEMPERATURES
 YEAR    PER     1     2     3     4     5     6     7     8     9    10    11    12    13    14    15    16    17    18    19    20
 1967      1  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2
              40.2  40.2  40.2  40.2  40.3  40.4  40.4  40.5  40.6  40.8  41.0  41.1  41.3  41.5  41.8  42.0  42.1
 1967      2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.2  40.3  40.3  40.3  40.3
              40.3  40.3  40.4  40.4  40.5  40.7  40.7  40.8  40.9  41.1  41.2  41.5  41.7  41.9  42.2  42.6  42.9  43.0
 1967      3  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1
              40.1  40.1  40.2  40.2  40.2  40.3  40.3  40.4  40.5  40.6  40.8  41.0  41.2  41.4  41.8  42.1  42.4  42.8  43.4  43.8
 1967      4  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.2  40.2  40.2  40.2
```

Printout for Example 2

```
              40.3  40.3  40.4  40.5  40.7  41.0  41.2  41.3  41.5  41.6  41.8  42.0  42.2  42.3  42.6  42.9  43.4  43.9  44.3  44.9
              45.5  45.8
    1967   5  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.1  40.2  40.2  40.2  40.2  40.2  40.3  40.3  40.4  40.5
              40.7  40.8  41.0  41.3  41.8  42.6  42.9  43.2  43.6  43.9  44.2  44.6  45.0  45.4  45.8  46.2  46.5  46.9  47.4  48.1
              48.9  49.7  50.9  52.3  53.6
    1967   6  40.1  40.1  40.1  40.1  40.1  40.1  40.2  40.2  40.2  40.2  40.2  40.3  40.3  40.4  40.4  40.5  40.6  40.8  41.0  41.2
              41.5  41.9  42.4  42.9  43.8  45.3  45.7  46.1  46.5  46.9  47.4  47.9  48.5  49.1  49.8  50.5  51.3  52.1  52.7  53.4
              54.4  55.6  56.7  58.1  59.9  61.0
    1967   7  40.1  40.2  40.2  40.2  40.2  40.3  40.3  40.3  40.4  40.4  40.5  40.5  40.6  40.8  40.9  41.1  41.3  41.6  42.0  42.4
              42.9  43.5  44.2  45.0  46.2  48.2  48.7  49.4  49.9  50.5  51.1  51.9  52.5  53.4  54.3  55.3  56.3  57.4  58.5  59.4
              60.5  61.5  62.7  64.1  65.4
    1967   8  40.2  40.3  40.4  40.4  40.4  40.5  40.6  40.6  40.7  40.8  40.9  41.1  41.3  41.5  41.8  42.1  42.6  43.2  43.8  44.4
              45.2  46.1  47.1  48.3  49.9  52.4  53.1  53.8  54.5  55.2  55.9  56.7  57.5  58.3  59.2  60.1  61.0  62.2  63.4  64.6
              65.6  66.8  68.1  68.7
    1967   9  40.5  40.6  40.7  40.8  40.8  40.9  41.1  41.2  41.4  41.6  41.8  42.0  42.3  42.7  43.1  43.6  44.3  45.0  45.8  46.8
              47.8  49.0  50.4  51.8  54.0  57.0  57.7  58.2  58.7  59.1  59.6  60.1  60.6  61.1  61.6  62.0  62.4  62.8  63.1  63.4
              63.6  63.7
    1967  10  40.9  41.1  41.3  41.4  41.5  41.7  41.9  42.1  42.4  42.7  43.0  43.3  43.7  44.1  44.7  45.2  45.9  46.6  47.3  48.0
              48.7  49.3  49.9  50.4  51.2  53.8  54.3  54.7  54.9  55.0  55.1  55.1  55.2  55.2  55.2  55.2  55.2  55.2  55.2  55.2
              55.2
    1967  11  41.5  41.9  42.2  42.3  42.5  42.7  43.0  43.3  43.6  43.9  44.2  44.5  44.8  45.2  45.5  45.8  46.0  46.3  46.6  46.8
              47.1  47.4  47.8  48.7  49.9  49.9  49.9  49.9  49.9  49.9  50.0
    1967  12  39.5  39.5  39.5  39.5  39.5  39.5  39.5  39.5  39.5  39.5  39.5  39.5  39.5  39.5  39.5  39.5  39.5  39.5  39.6  39.7
              39.8  39.8  39.9  40.0  40.2  40.6  40.7  40.7  40.7  40.7  40.7  40.7  40.7

                                               FLOWS AND TEMPERATURES FOR 1967
             YEAR         1         2         3         4         5         6         7         8         9        10        11        12
  INFLO    1845.8    4024.0    2267.0    1872.0    1470.0    2646.0    1825.0     841.0     615.0     560.0    1815.0    1728.0    2486.0
   EVAP       2.8        .2        .6        .7       1.5       4.0       4.0       6.0       6.8       5.8       2.1        .8        .5
   PRCP       6.1      18.0       4.5       7.3       5.3       2.3       1.1        .0        .1       2.1      14.9       6.5      11.7
  OUTFL    1829.3    2717.0    2018.0    1009.0     910.0    1336.0    1429.0    1136.0    1172.0    1458.0    2173.0    4364.0    2230.0
  REQDQ    1829.3    2717.0    2018.0    1009.0     910.0    1336.0    1429.0    1136.0    1171.0    1459.0    2173.0    4364.0    2230.0
  STMX              494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.   494973.
  STOR              222855.   237362.   291619.   325807.   405892.   428601.   408698.   372769.   318432.   299364.   143518.   160868.
  STMN              114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.   114700.

  TA         52.7      41.0      42.0      42.0      44.0      55.0      63.0      69.0      73.0      67.0      53.0      47.0      37.0
  TMPIN      43.4      40.0      40.0      39.0      41.0      45.0      50.0      56.0      55.0      52.0      46.0      44.0      39.0
  TMPMX      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0      65.0
  TPOUT      45.8      40.4      40.5      40.3      40.6      41.6      43.6      46.5      49.3      53.9      53.0      50.1      42.8
  TMPMN      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0      40.0
  RELEASES THRU OUTLET  1
   QOMN                  .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0
  QOUTL                  .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0
  TOUTL                  .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0        .0
  RELEASES THRU OUTLET  2
   QOMN                  .0        .0        .0        .0        .0        .0        .0      61.0      19.0        .0     664.0        .0
  QOUTL                  .0        .0        .0        .0        .0        .0        .0      61.0      19.0        .0     664.0        .0
  TOUTL                  .0        .0        .0        .0        .0        .0        .0      42.5      44.2        .0      47.0        .0
  RELEASES THRU OUTLET  3
   QOMN              2717.0    2018.0    1009.0     910.0    1336.0    1429.0    1111.0    1098.0    1430.0    2173.0    3700.0    2230.0
  QOUTL              2717.0    2018.0    1009.0     910.0    1336.0    1429.0    1111.0    1098.0    1434.5    2173.0    3700.0    2230.0
  TOUTL                40.4      40.5      40.3      40.6      41.6      43.6      46.1      49.5      54.0      53.0      50.7      42.8
  RELEASES THRU OUTLET  4
   QOMN                  .0        .0        .0        .0        .0        .0      25.0      13.0       9.0        .0        .0        .0
  QOUTL                  .0        .0        .0        .0        .0        .0      25.0      13.0       4.5        .0        .0        .0
  TOUTL                  .0        .0        .0        .0        .0        .0      61.5      67.0      65.0        .0        .0        .0
```

Printout for Example 2

ADDENDUM 1

Calculation Procedure

A thermal analysis of a reservoir is made by calculating an energy balance. The energy balance accounts for all significant energy exchanges into and out of the reservoir. Figure A1-1 illustrates the driving forces which are considered in the energy balance. The arrowhead indicates whether a particular force can transfer energy into or out of the reservoir. Conduction can transfer energy in either direction dependent on the sign of the temperature gradient between air temperature and surface water temperature. Figure A1-1 also illustrates that vertical diffusion transfers energy between the horizontal isothermal layers of the reservoir. Assuming the initial state of a reservoir is adequately defined, the following procedure is used to conduct a thermal analysis of an existing or proposed reservoir:

a. Calculate the transfer of energy by conduction between the water and the atmosphere by the following equation:

$$E_1 = \Sigma F C_1 (T_A - TW_L) S_L \tag{1}$$

where the summation is over all layers within the selected depth of energy penetration, and:

E_1 = Energy transferred to the water within the selected depth of energy penetration in acre-feet-degrees F (or thousand cubic meters-degrees C)

F = A factor which decreases linearly with depth from 1 at the surface to 0 at the bottom to properly account for the change in energy transfer with depth

C_1 = A calibration coefficient between 0 and 1

T_A = Monthly average air temperature in degrees F (or degrees C)

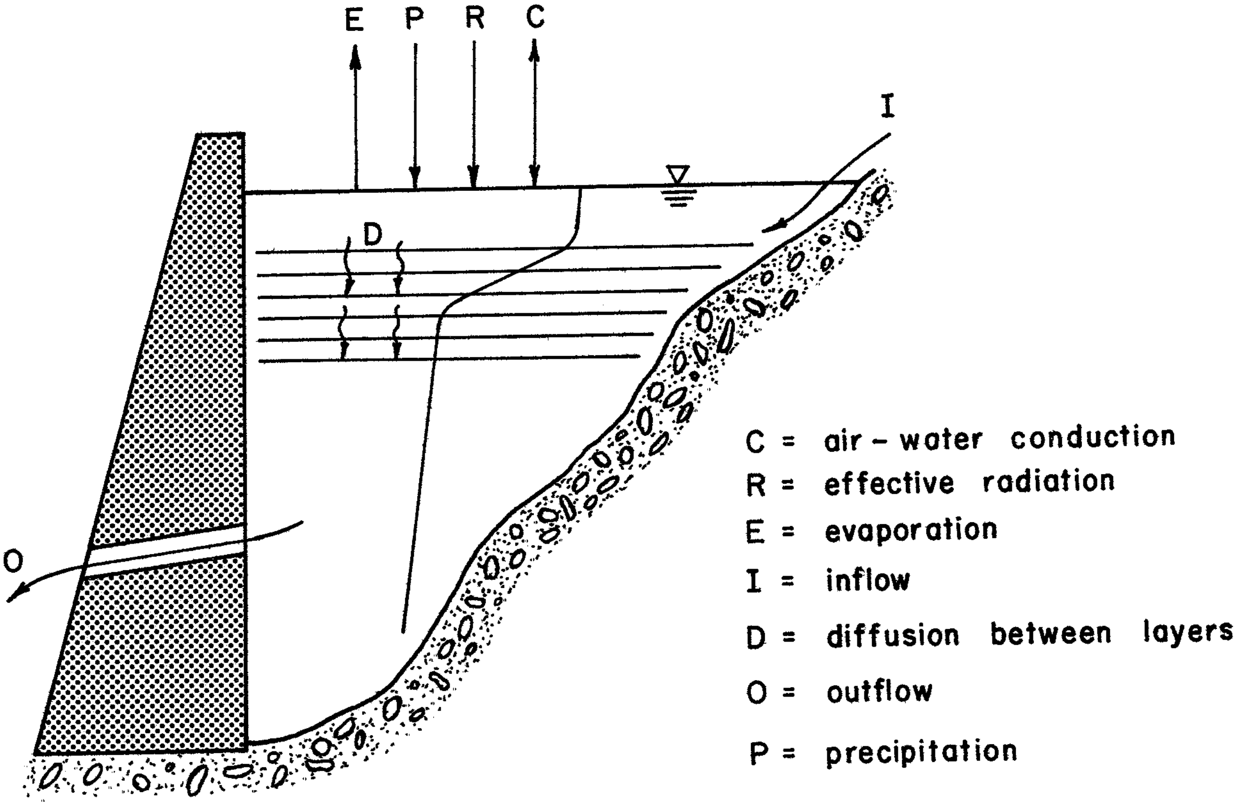
TW_L = Water temperature of layer L in degrees F (or degrees C)

S_L = Storage in layer L in acre-feet (or thousand cubic meters)

b. Calculate the energy transferred to water from solar radiation by the following equation:

$$E_2 = KC_2 (R)(A)(ND) \tag{2}$$

where the energy transfer is assumed to decrease linearly from a maximum at the surface to zero at the bottom of the selected depth and:



air - water conduction - can cool or warm the water to some limited depth (approx. 30 - 50 feet).

effective radiation - warms the water to some limited depth (approx. 30 - 50 feet).

evaporation - cools the water to some limited depth (approx. 30 - 50 feet).

inflow - cools the water in each layer above the layer where it concludes its descent.

diffusion - heat transfer to the next lower layer. Tends to make the reservoir isothermal.

Figure A1-1. Energy Budget

E_2 = Energy transferred to the water within the selected depth of energy penetration in acre-feet-degrees F (or thousand cubic meters-degrees C)

K = A conversion constant = .0036 for English units (or .002 for metric units)

C_2 = A calibration coefficient between 0 and 1

R = Solar radiation in calories per sq. cm. per day (figure 2 of main document)

A = Reservoir surface area in acres (or thousand square meters)

ND = Number of days in the month

c. Calculate the energy removed from the water by gross lake evaporation by the following equation:

$$E_3 = C_3 (H_E)(V_E) \qquad (3)$$

where the energy transfer is assumed to decrease linearly from a maximum at the surface to zero at the bottom of the selected depth and:

E_3 = Energy removed from the water within the selected depth of energy penetration in acre-feet-degrees F (or thousand cubic meters-degrees C)

C_3 = A calibration coefficient between 0 and 1

H_E = Latent heat of vaporization plus approximate heat to warm water = 1062 BTU per pound (or 590 calories per gram)

V_E = Volume of water evaporated in acre-feet (or thousand cubic meters)

d. The coefficients in equations 1, 2, and 3 (along with the three coefficients in equations 4, 5, and 7) can be determined from recorded data. The energy calculated with equations 1, 2, and 3 is transferred in the order discussed, to (or from) the top several layers of reservoir water as a function of depth, decreasing linearly from a maximum at the top layer to a value of zero at the selected depth of energy penetration.

e. Rainfall on the water surface is added to the reservoir volume at the average temperature of the top layer, and evaporation volume is subtracted from the top layer.

f. Any thermally unstable layers are thoroughly mixed from the surface downward until no lower levels contain warmer water than exists at higher levels. This computation is constrained to temperatures above 4°C, corresponding to the maximum density of water. If water is cooled below this temperature, the temperature of each layer from the surface downward is allowed to go negative until an amount of energy equal to that required to form ice has been extracted from that layer.

g. If the reservoir inflow is cooler than the surface temperature, it will descend and partially mix with the upper layers. The temperature of each layer and the temperature of the inflow that results from the exchange of energy between the inflow and the reservoir volume at each level is calculated by use of the following equations:

$$T'_L = T_L + C_4\ (T_{avg} - T_L) \tag{4}$$

$$T'_I = T_I + C_4\ (T_{avg} - T_I) \tag{5}$$

where: T'_L = Temperature at layer L in degrees F (or degrees C) after inflow energy transfer

T_L = Temperature at layer L in degrees F (or degrees C) prior to inflow energy transfer

C_4 = A calibration coefficient between 0 and 1

T_{avg} = Average (weighted by volume) of inflow temperature and temperature of layer L in degrees F (degrees C)

T'_I = Temperature of inflow in degrees F (or degrees C) after inflow energy transfer

T_I = Temperature of inflow in degrees F (or degrees C) prior to inflow energy transfer

T_{avg} = Average (weighted by volume) of inflow temperature and temperature of layer L in degrees F (degrees C)

The calculations involving equations 4 and 5 must be repeated for each layer. The inflow is thus warmed slightly as it descends to a level where the temperature equals the modified inflow temperature, but never descends below water which has a temperature of maximum water density (4°C). It is then added to the reservoir, and all water in higher layers is raised. A thermal stability check is made and any unstable layers are thoroughly mixed.

h. The temperature changes resulting from the vertical diffusion of energy can be calculated by the following equations:

$$T_{av} = \frac{\Sigma T_L V_L}{\Sigma\ V_L} \tag{6}$$

$$T'_L = T_L + C_5\ (T_{av} - T_L) \tag{7}$$

where the summation is for all layers L over a 10-meter range and:

T_{av} = Average temperature of all layers within a 10-meter range

T_L = Temperature at layer L in degrees F (or degrees C) prior to diffusion of energy

V_L = Volume in layer L in acre-feet (or thousand cubic meters)

T'_L = Temperature at layer L in degrees F (or degrees C) after diffusion of energy

C_5 = A calibration coefficient between 0 and 1

This calculation involving equations 6 and 7 must be repeated for each set of layers 10 meters thick, starting at the bottom of the reservoir and proceeding upward a layer at a time. This process is repeated once per computation interval. If the computation interval is less than 6 times per month, the process is repeated 6 times per computational interval to insure adequate opportunity for diffusion of energy. It should be recognized that energy transfers computed for long intervals leave the reservoir in an unreal condition and that his diffusion computation is a practical means of overcoming this and accounting for diffusion.

i. The releases assigned to specific outlets are made by withdrawing the required quantity from the storage available immediately above the outlet invert level, accounting for the total released quantity and energy.

j. The temperature limits which apply to the remaining required release are calculated as follows:

$$T'_{max} = (T_{max}Q_T - Q_1T_1)/(Q_T - Q_1) \quad (8)$$

$$T'_{min} = (T_{min}Q_T - Q_1T_1)/(Q_T - Q_1) \quad (9)$$

where: T'_{max} = Maximum desirable release temperature for remaining (after specific outlet releases) required release in degrees F (or degrees C)

T_{max} = Maximum desirable release temperature for total release in degrees F (or degrees C)

Q_T = Total required release in acre-feet (or thousand cubic meters)

Q_1 = Release required through specific outlets in acre-feet (or thousand cubic meters)

T_1 = Temperature of water released through specific outlets in degrees F (or degrees C)

T'_{min} = Minimum desirable release temperature for remaining (after specific outlet releases) required release in degrees F (or degrees C)

T_{min} = Minimum desirable release temperature for total release in degrees F (or degrees C)

k. The target temperature of the remaining required release is calculated by the following equation:

$$T = \left[E - T_N(V-Q)\right]/Q \qquad (10)$$

where: T = Target temperature of the remaining release in degrees F (or degrees C)

E = Reservoir energy above the lowest usable outlet in acre-feet-degrees F (or thousand cubic meters-degrees C)

T_N = The average of the "N" succeeding months' maximum and minimum temperature requirements in degrees F (or degrees C)

N = The number of future months of target temperature criteria used to determine a best release temperature

V = Reservoir volume remaining above the lowest usable outlet in acre-feet (or thousand cubic meters)

Q = Remaining release required during the current month in acre-feet (or thousand cubic meters)

Equation 10 is used to determine the discharge temperature of the remaining release (Q) such that the average temperature of the water remaining above the lowest usable outlet is changed to equal the average temperature of the selected number of succeeding months' maximum and minimum temperature requirements. If the target temperature calculated with equation 10 is outside the desirable range calculated with equations 8 and 9, the closest temperature limit is adopted as the target temperature.

l. Water is released to meet the target temperature calculated in step k by one of 2 operational release methods. Method 1 calculates the energy that could be released through the two nearest usable outlets that are above and below where the target temperature exists. With this method, maximum choice of temperatures is available for subsequent months. Method 2 selects the highest and lowest usable outlets, which leaves the temperature of the lake more uniform. Using either method, the quantity of water released through the two outlets is mixed so as to match the target temperature.

If it becomes necessary to use other outlets also, lower and higher outlets are used as required. If it is found that this process does not satisfy the target temperature, the release will be withdrawn only from the one outlet which will produce water with a temperature closest to the target temperature.

m. The end-of-month storage and the temperature of the water in each layer is determined by redistributing the reservoir water to fill all the "empty spaces" resulting from the release. A thermal stability check is made and any unstable layers are thoroughly mixed.

n. The above computation procedure is repeated for each month.

ADDENDUM 2

DEFINITION OF OUTPUT VARIABLES

CISA - Coefficient to convert inflow for 1 day to storage units per day, preceded by minus sign if inflow is in volume units

COSA - Coefficient to convert outflow for 1 day to storage units per day, preceded by minus sign if outflow is in volume units

CSOUT - Coefficient to convert storage units to cfs-days (or cms-days)

DEP - Depth of energy penetration in feet (or meters)

EVAP - Evaporation during period in inches (or millimeters)

IDERV - Calls for derivation of coefficients, when positive

IDGST - Calls for diagnostic printout, when positive

INFLOW - Inflow during period in cfs (or cms)

INTER - Number of computational intervals per month

IPER - Number of first period in year

IYR - Calendar year during which operation study starts

LAYER - Depth of layer in feet (or meters)

METRC - Positive value indicates use of metric system

MREL - Index to specify the operational method of release

MSTRT - Month number at which computation is to start during first year

NIC - Number of local inflow locations to be read from cards

NIT - Number of inflow locations to be read from tape

NLAYR - Total number of layers in reservoir

NMINQ - Number of outlet levels through which minimum flows are required

NMO - Number of future months of target temperature criteria used to calculate best release temperature

NOTL - Number of separate outflow distribution channels

NOUTL - Total number of outlet levels

NPER - Number of periods in year

NYR - Number of years of study

OUTFL - Actual outflow during period in cfs (or cms)

PER - Calender month number

PRCP - Precipitation during period in inches (or millimeters)

QMIN - Required outflow, average for year

QOMIN - Average required release through each outlet for period

QOMN - Required release through each outlet for period

QOUTL - Actual outflow through each outlet for period in cfs (or cms)

REQDQ - Input value of required outflow during period

SOLR - Average solar radiation in calories per day for year
STCAP - Storage capacity in acre-feet (or thousand cubic meters) at top of each layer
STMN - Minimum permissible storage at end of period in storage units
STMX - Maximum permissible storage at end of period in storage units
STOR - Storage at end of period in storage units
STORA - Initial storage in acre-feet (or thousand cubic meters)
STOUT - Storage capacity at invert of each outlet in storage units
STRMN - Minimum permissible storage constant for year in storage units
STRMX - Maximum permissible storage constant for year in storage units
TA - Average air temperature for period in degrees F (or °C)
TAIR - Average air temperature if same for all periods in °F (or °C)
TIN - Average inflow temperature if same for all periods in °F (or °C)
TMAX - Maximum permissible release temperature if same for all periods in degrees F (or °C)
TMIN - Minimum permissible release temperature if same for all periods in degrees F (or °C)
TMPIN - Average inflow temperature for period in degrees F (or °C)
TMPMN - Minimum permissible release temperature for period in degrees F (or °C)
TMPMX - Maximum permissible release temperature for period in degrees F (or °C)
TPOUT - Release temperature for period in degrees F (or °C)
TOUTL - Temperature of QOUTL
TSTRT - Starting temperature profile in degrees F (or °C)

ADDENDUM 3
INPUT REQUIREMENTS

1. Card Format

Input is entered in ten 8-column fields per card, except that the first column of each card is retained for card identification. Thus, the first item of data on each card occupies columns 2-8. If they are right justified in their field, whole numbers can be punched without decimal points. All integer numbers (identified by variable names starting with letters I through N) must be punched without decimal points. Where the value of a variable is zero, the field may be left blank. The first title card of each job must have an A in column 1 in order to identify the start of the job. In certain cases where a job is aborted, the computer can waste cards until it finds the start of the next job.

2. Multiple Jobs

When several jobs are to be computed during the same run (stacked jobs), the data cards for the last job only are to be followed by five blank cards. If only a single job is to be run, five blank cards must follow the data cards for that run. An A in column 1 of the first of the five blank cards is required.

3. Card Contents

A Three title cards are required at the beginning of each job. Alphabetical characters and numbers may be used in any of the fields of all three cards. The contents of the cards will be printed at the beginning of the program output. An A in column 1 of the first card is required.

B Job specification

Field	Variable	Value	Description
1	NYR	+	Number of years of data
2	IYR	+	Calendar year during which operation study starts
3	NPER	+	Number of periods per year (not to exceed 12)
4	IPER	+	Number of first period in year; e.g., 1 if using calendar year or 10 if using water year
5	MSTRT	+	Month number of first period of computation for first year (ordinarily same as IPER, B-4)

B Job specification (continued)

Field	Variable	Value	Description
6	NLAYR	+	Number of layers in reservoir (not to exceed 100)
7	LAYER	+	Depth of layers in feet (or meters)
8	NOUTL	+	Number of levels of outlets (not to exceed 9)
9	NMINQ	0	All outlet releases are varied to meet target temperature criteria
		+	Number of outlets through which required releases will be specified
10	IDERV	0	All five model calibration coefficients are known
		1	Positive integer indicates 1 or more coefficients are to be derived from observed temperature profiles
11	METRC	0	English system of units are used (temperature values must be in °F)
		1	Metric system of units are used (temperature values must be in °C)
12	IDGST	0	Suppresses diagnostic printout from optimization routine
		1	Calls for diagnostic printout from optimization routine
13	NIC	0	No local inflow in a tandem reservoir system
		+	Number of tributaries having inflow data to be read from cards
14	NIT	0	Run is for a single reservoir calculation or the upstream reservoir in a tandem system
		+	Number of tributaries having inflow and temperature data to be read from tape output calculated at an upstream reservoir for input to a downstream reservoir in a tandem reservoir system

B Job specification (continued)

Field	Variable	Value	Description
15	NOTL	0	Used for a single reservoir calculation
		+	Number of separate outflow distribution channels which deliver discharge to a downstream reservoir in a tandem reservoir system
16	INTER	0	Program uses four computational intervals per month
		+	Number of computational intervals per month
17	MREL	0	Uses the method of release which searches for the first usable outlet above and the first usable outlet below the layer which contains the desired release temperature
		1	Uses the method of release which draws water from the highest and lowest usable outlet
18	NMO	0	Program uses 3 future months of target temperature criteria to calculate a best release temperature for any given month
		+	Number of future months of target temperature criteria used to calculate a best release temperature for any given month

C Outlet distribution channels (NOTL, B-15,cards); omit if NOTL (B-15) is zero

Field	Variable	Value	Description
1	NOUL	+	Number of outlets releasing to distribution channel I
2	KOUTL(I,K)	+	Outlet number K (numbered from bottom upward) which releases to distribution channel I (NOUL, C-1, items)

D Job data

Field	Variable	Value	Description
1	STORA	+	Initial reservoir storage in acre-feet (or thousand cubic meters)

D Job data (continued)

Field	Variable	Value	Description
2	CISA	+	Coefficient to convert inflow rate to storage units per day
		-	Coefficient to convert inflow volume to storage units

Some examples are as follows:

Storage units	Inflow units	CISA
acre-feet	cfs	1.983472
acre-feet	acre-feet	-1.00
acre-feet	day-second-feet	-1.983472
thousand m^3	cms	86.4
thousand m^3	m^3	-10^{-3}

Field	Variable	Value	Description
3	COSA	+	Coefficient to convert outflow rate to storage units per day
		-	Coefficient to convert outflow volume to storage units

Some examples are as follows:

Storage units	Outflow units	COSA
acre-feet	cfs	1.983472
acre-feet	acre-feet	-1.00
acre-feet	day-second-feet	-1.983472
thousand m^3	cms	86.4
thousand m^3	m^3	-10^{-3}

Field	Variable	Value	Description
4	STRMX	+	Maximum permissible storage in acre-feet (or thousand cubic meters)
		-1	Monthly maximum permissible storage will be read on K card in first year only
		-2	Monthly maximum permissible storage will be read on K card for each year

D Job data (continued)

Field	Variable	Value	Description
5	STRMN	+	Minimum permissible storage in acre-feet (or thousand cubic meters)
		-1	Monthly minimum permissible storage will be read on L card in first year only
		-2	Monthly minimum permissible storage will be read on L card for each year
6	TIN	+	Average annual inflow temperature in degrees F (or C). If NIC(B-13) is greater than 1, a positive TIN is the same for all tributaries
		-1	Monthly inflow temperature will be read on V card in first year only
		-2	Monthly inflow temperature will be read on V card for each year
7	TAIR	+	Average annual air temperature in degrees F (or C)
		-1	Monthly average air temperature will be read on M card in first year only
		-2	Monthly average air temperature will be read on M card for each year
8	EVAP	+	Lake evaporation for year in inches (or millimeters)
		-1	Monthly lake evaporation will be read on N card in first year only
		-2	Monthly lake evaporation will be read on N card for each year
9	PRCP	+	Precipitation for year in inches (or millimeters)
		-1	Monthly precipitation will be read on O card in first year only
		-2	Monthly precipitation will be read on O card for each year

D Job data (continued)

Field	Variable	Value	Description
10	QMIN	+	Average annual outflow in units corresponding to COSA (D-3)
		-1	Monthly outflow will be read on P card in first year only
		-2	Monthly outflow will be read on P card for each year
11	TMAX	+	Average annual maximum permissible outflow temperature in degrees F (or C)
		-1	Monthly maximum permissible outflow temperature will be read on Q card in first year only
		-2	Monthly maximum permissible outflow temperature will be read on Q card for each year
12	TMIN	+	Average annual minimum permissible outflow temperature in degrees F (or C)
		-1	Monthly minimum permissible outflow temperature will be read on R card in first year only
		-2	Monthly minimum permissible outflow temperature will be read on R card for each year
13	CSOUT	+	Coefficient to convert storage units to cfs-days (or cms-days) for output

Some examples are as follows:

Storage units	CSOUT
acre-feet	.504167
thousand m^3	.011574

D Job data (continued)

Field	Variable	Value	Description
14	SOLR	+	Average annual solar radiation in calories per sq. cm. per day
		-1	Monthly solar radiation will be read on S card in first year only
		-2	Monthly solar radiation will be read on S card for each year
15	DEP	+	Depth of penetration of solar radiation, conduction, and evaporation energy in feet (or meters). The depth used for application should be the same as that used for calibration
		0	Uses programmed value of 32.81 feet (or 10 meters) for depth of energy penetration

E Coefficients

Field	Variable	Value	Description
1	VAR(1)	+	Air Temperature Coefficient--Index[†] of energy transferred by conduction due to the difference between the air and water surface temperature
		negative value between 0 and -1	Initial estimate of index[†] to be used for calibrating the air temperature coefficient
		-1	Uses programmed initial index[†] for calibrating the air temperature coefficient
2	VAR(2)	+	Inflow Mixing Coefficient--Index[†] of energy transferred to the inflow due to the difference between the modified inflow temperature and the temperature of each reservoir layer. The transfer affects each layer as the inflow descends through the reservoir.

[†] Index equals zero if no energy is transferred and equals one if sufficient energy is transferred to reach equilibrium.

E Coefficients (continued)

Field	Variable	Value	Description
		negative value between 0 and -1	Initial estimate of index[†] to be used for calibrating the inflow mixing coefficient
		-1	Uses programmed initial index[†] for calibrating the inflow mixing coefficient
3	VAR(3)	+	Vertical Diffusion Coefficient--Index[†] of energy transferred between adjacent layers (downward) due to the difference in temperature between layers
		negative value between 0 and -1	Initial estimate of index[†] to be used for calibrating the vertical diffusion coefficient
		-1	Uses programmed initial index[†] for calibrating the vertical diffusion coefficient
4	VAR(4)	+	Evaporation Coefficient--Index[†] of energy lost from the reservoir water surface due to evaporation. The remaining energy required for the heat of vaporization is obtained by cooling the air.
		negative value between 0 and -1	Initial estimate of index[†] to be used for calibrating the evaporation coefficient
		-1	Uses programmed initial index[†] for calibrating the evaporation coefficient
5	VAR(5)	+	Insolation Coefficient--Index[†] of energy transferred to the reservoir due to solar radiation. The solar radiation energy that is not effective in warming the reservoir has been "lost" due to absorption and reflection within the atmosphere and reflection at the water surface

[†] Index equals zero if no energy is transferred and equals one if sufficient energy is transferred to reach equilibrium.

E Coefficients (continued)

Field	Variable	Value	Description
		negative value between 0 and -1	Initial estimate of index† to be used for calibrating the insolation coefficient
		-1	Uses programmed initial index† for calibrating the insolation coefficient

F Required outlet releases (NOUTL, B-8, items); omit if NMINQ (B-9) is zero

Variable	Value	Description
QOMIN(K)	+	Required release from each successive outlet K in order of elevation (from bottom upward) with units corresponding to COSA
	-1	Monthly required release for each outlet K will be read on T cards in first year only
	-2	Monthly required release for each outlet K will be read on T cards for each year
	-3	Monthly release will be varied to meet target temperature criteria and does not require T cards for outlet K

G Period lengths (NPER, B-3, items)

Variable	Value	Description
NDAYS(I)	+	Number of days in each successive period I

H Storage capacity (NLAYR, B-6, items)

Variable	Value	Description
STCAP(L)	+	Storage capacity in acre-feet (or thousand cubic meters) at top of each successive layer L (from bottom to top)

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† Index equals zero if no energy is transferred and equals one if sufficient energy is transferred to reach equilibrium.

I Initial reservoir temperature (NLAYR, B-6, items)

Variable	Value	Description
TSTRT(L)	+	Average temperature in degrees F (or C) for each successive layer L at start of computation (from bottom to top).
	-1	Designates layers without any water.

J Location of outlets (NOUTL, B-8, items)

Variable	Value	Description
STOUT(K)	+	Storage capacity in acre-feet (or thousand cubic meters) at lowest point that can discharge through outlet K (from bottom to top)

K Maximum storage (NPER, B-3, items); Omit if STRMX (D-4) is positive. Supply for first year only if STRMX (D-4) is -1 and for every year if index is -2.

Variable	Value	Description
STMX(I)	+	Maximum permissible storage in acre-feet (or thousand cubic meters) at end of each successive period I

L Minimum storage (NPER, B-3, items); omit if STRMN (D-5) is positive. Supply for first year only if STRMN (D-5) is -1 and for every year if index is -2.

Variable	Value	Description
STMN(I)	+	Minimum permissible storage in acre-feet (or thousand cubic meters) at end of each successive period I

M Average air temperature (NPER, B-3, items); Omit if TAIR (D-7) is positive. Supply for first year only if TAIR (D-7) is -1 and for every year if index is -2.

Variable	Value	Description
TA(I)	+	Average air temperature for each successive period I in degrees F (or C)

N Evaporation (NPER, B-3, items); Omit if EVAP(D-8) is positive. Supply for first year only if EVAP(D-8) is -1 and for every year if index is -2.

Variable	Value	Description
EVP(I)	+	Lake evaporation in inches (or millimeters) for each successive period I

O Precipitation (NPER, B-3, items); Omit if PRCP(D-9) is positive. Supply for first year only if PRCP(D-9) is -1 and for every year if index is -2.

Variable	Value	Description
PCP(I)	+	Precipitation in inches (or millimeters) for each successive period I

P Required outflow (NPER, B-3, items); Omit if QMIN(D-10) is positive. Supply for first year only if QMIN(D-10) is -1 and for every year if index is -2.

Variable	Value	Description
QMN(I)	+	Required total release for each successive period I in units corresponding to COSA(D-3)

Q Maximum outflow temperatures (NPER, B-3, items); Omit is TMAX(D-11) is positive. Supply for first year only if TMAX(D-11) is -1 and for every year if index is -2.

Variable	Value	Description
TMX(I)	+	Maximum permissible temperature of outflow for each successive period I in degrees F (or C)

R Minimum outflow temperatures (NPER, B-3, items); Omit if TMIN(D-12) is positive. Supply for first year only if TMIN(D-12) is -1 and for every year if index is -2.

Variable	Value	Description
TMN(I)	+	Minimum permissible temperatue of outflow for each successive period I in degrees F (or C)

S Solar radiation (NPER, B-3, items); Omit if SOLR(D-14) is positive. Supply for first year only if SOLR(D-14) is -1 and for every year if index is -2.

S (Continued)

Variable	Value	Description
SOL(I)	+	Average solar radiation for period I in calories per sq. cm. per day (from figure 2 or table 2 in main document)

T Required outlet releases (NPER, B-3, items) (NMINQ, B-9, pairs of cards); Omit for outlets having a QOMN value (F card) that is positive or -3. Supply first year only for outlets having a QOMN value (F card) of -1 and for every year if index is -2.

Variable	Value	Description
QOMN(I,K)	+	Required release in period I through specific outlet K, numbered by elevation (from bottom upward), with units corresponding to COSA(D-3). Only supplied for outlets where QOMIN (F card) is -1 or -2 (bottom to top)

U Inflow (NPER, B-3, values) (NIC, B-13, pairs of cards); Use local inflow for a downstream reservoir in a tandem reservoir system.

Variable	Value	Description
QI(I)	+	Average inflow for each successive period I in units corresponding to CISA(D-2)

V Inflow temperatures (NPER, B-3, items) (NIC, B-13, pairs of cards); Use local inflow temperature for a downstream reservoir in a tandem reservoir system. Omit if TIN(D-6) is positive. Supply for first year only if TIN(D-6) is -1 and for every year if index is -2.

Variable	Value	Description
TI(I)	+	Average temperature of inflow for each successive period I in degrees F (or C)

W Observed temperature profile dates (card required every year); omit if IDERV(B-10) is zero.

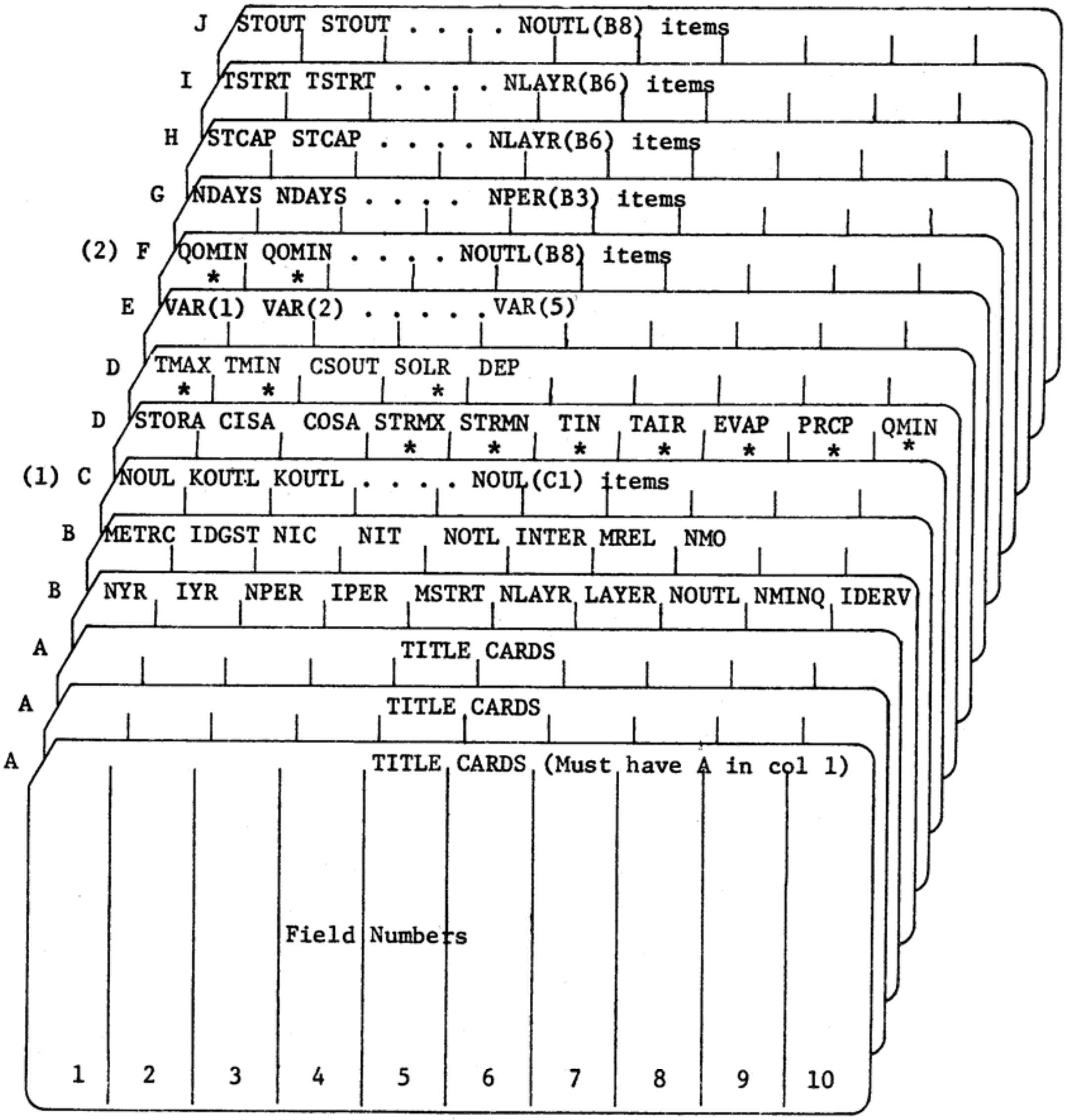
Field	Variable	Value	Description
1	NPFL	+	Number of observed profiles during year
2	IDAY(K)	+	Date of each successive profile (NPFL, W-1, items); calendar month number followed by two digits for day of month, no decimal points

X Observed temperature profile, repeat for each value of IDAY (W card); omit if IDERV(B-10) is zero. Data should contain sufficient depth-temperature pairs to allow accurate interpolation between points for profile definition.

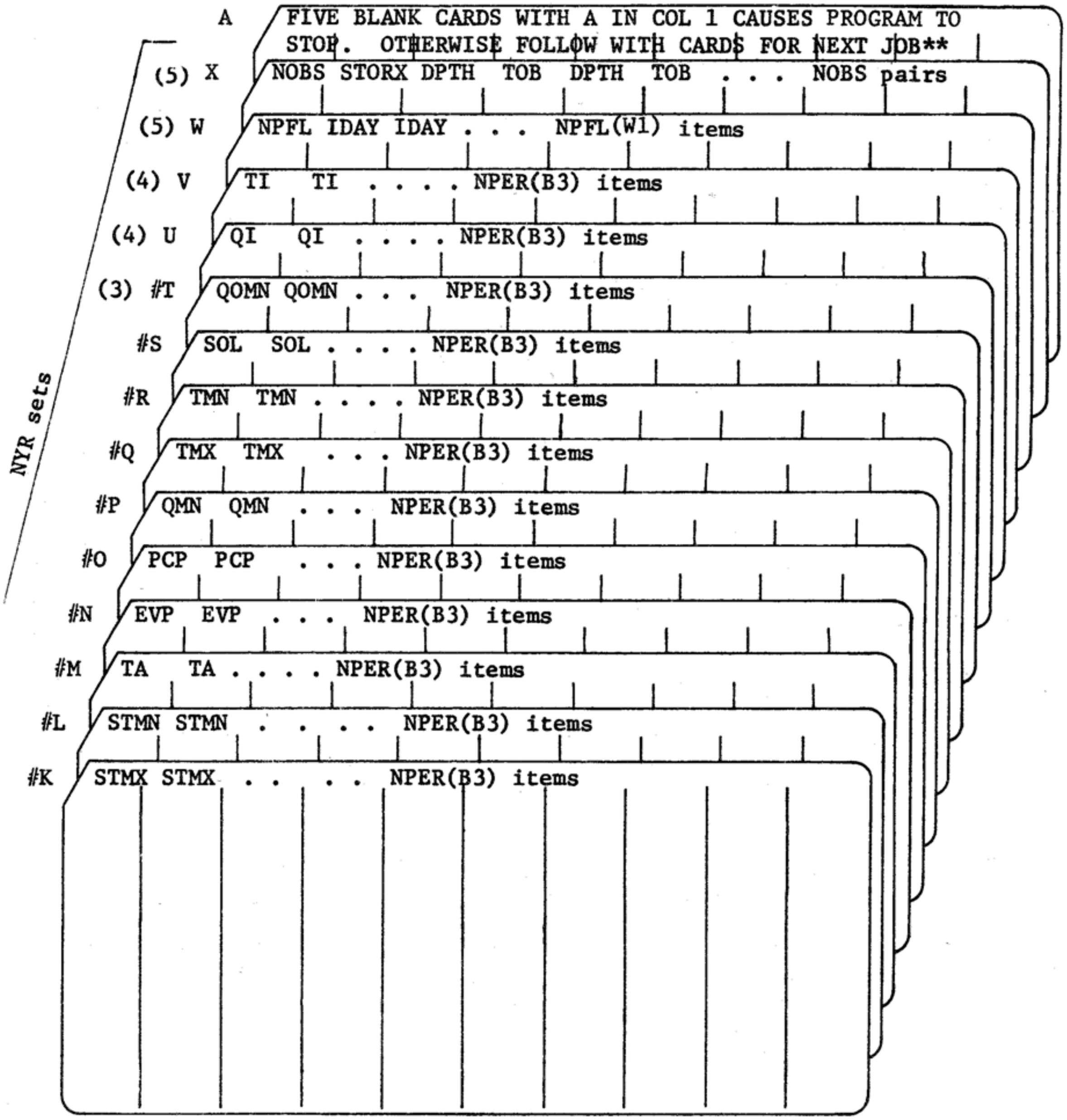
Field	Variable	Value	Description
1	NOBS	+	Number of given points on profile
2	STORX	+	Storage at time of profile
3	DPTH(1)	0	Indicates TOB(1), X-4, value is the water surface temperature
4	TOB(1)	+	Observed surface temperature in degrees F (or C)
5	DPTH(2)	+	Depth below surface to TOB(2), X-6, in feet (or meters)
6	TOB(2)	+	Observed temperature at DPTH(2), X-5, in degrees F (or C)
7, etc			Repeat for increasing depths until NOBS (X-1) pairs are read

A Five blank cards with A in column 1 of first card will cause computer to stop

4. SUMMARY OF INPUT CARDS



Notes:
(1) Repeat NOTL (B15) times
(2) Omit if NMINQ (B9) is zero
* -1 for any of these items will call for monthly data that is the same for all years. -2 will call for different monthly data every year.



Notes: (3) Omit if NMINQ(B9) is equal to zero, otherwise repeat a number of times equal to the number of QOMIN values (F card) that are equal to -1 or -2.

(4) Use local inflows and local inflow temperatures for a downstream reservoir in a tandem reservoir system. Repeat NIC(B13) times.

(5) Omit if IDERV(B10) is less than or equal to zero. Repeat the X card for each value of IDAY (W card).

\# Supplied in first year if corresponding index marked with * is -1 and supplied every year in same order if index is -2.

**NEXT JOB CAN BE NEXT RESERVOIR OF TANDEM RESERVOIR SYSTEM

Appendix 2

Glossary of Water Quality Terms

APPENDIX 2. GLOSSARY OF WATER QUALITY TERMS*

Absolute Humidity	The actual weight of water vapor contained in a unit volume of the atmosphere.
Acclimation	The process of adjusting to a change in environment.
Acre-Foot	A unit for measuring the volume of water--is equal to the quantity of water required to cover 1 acre to a depth of 1 foot and is equal to 43,560 cubic feet or 325,851 gallons.
Aerobe	Oxygen-requiring organism.
Aerobic Respiration	A biochemical reaction in which materials combine with oxygen to produce energy. Synonymous with biological oxidation.
Algae	Photosynthetic unicellular microscopic plant.
Algicide	A chemical highly toxic to algae. Algicides are often applied to water to control nuisance algal blooms.
Alkali	Soluble salts, principally of sodium, potassium, magnesium, and calcium.
Alkalinity	A term used to represent the content of carbonates, bicarbonates, hydroxides, and occasionally borates, silicates, and phosphates in water. It is expressed in mg/l of calcium carbonate.
Amino Acid	An organic compound containing both amino (NH_2) and carboxyl (COOH) groups.
Anadromous Fish	Fish that spend a part of their life in the sea or lakes, but ascent rivers at regular intervals to spawn (e.g., sturgeon, shad, salmon, trout, and striped bass).
Anaerobe	An organism that grows in the absence of molecular oxygen.
Aneometers	Instruments used in measuring wind velocity.
Area-Capacity Curve	A graph showing the relation between the surface area of the water in a reservoir, the corresponding volume, and elevation.

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*This glossary contains some of the pertinent definitions from "Glossary of Selected Hydrologic Terms," P.A. Richard and R. McQuisten, University of Wyoming, May 1966 (revised September 1968). Verbal permission to reprint these definitions was obtained from P.A. Richard.

Assimilation	The absorption and utilization of a nutrient by an organism.
Bacteria	Aerobic: Bacteria which require free (elementary) oxygen for their growth. Anaerobic: Bacteria which grow in the absence of free oxygen and derive oxygen from breaking down complex substances.
Benthos	Collective term for organisms living in the bottom material of oceans, lakes and streams.
Bio-Assay	A test using a species of fish adaptable to laboratory conditions which consists essentially of preparing various concentrations of a waste with selected dilution and observing the reaction of the test fish over a definite time period. The fish which are used are normally fathead minnows or bluegill sunfish. The dilution water is normally water from the receiving stream into which the waste will be discharged.
Biochemical Oxygen Demand (BOD)	The quantity of oxygen utilized in the biochemical oxidation of organic matter in a specified time, at a specified temperature. It is not related to the oxygen requirements in chemical combustion, being determined entirely by the availability of the material as a biological food and by the amount of oxygen utilized by the microorganisms during oxidation.
Biodegradable	A substance that is capable of being readily decomposed by biological means, especially by bacterial action.
Bloom	A readily visible concentrated growth or aggregation of plankton (plant and animal).
cfs-day	**The volume of water represented by a flow of 1 cubic foot per second for 24 hours. It equals 86,400 cubic feet, 1.983471 acre-feet, or 646,317 gallons. May be abbreviated sfd.**
cfsm (cu. ft./sec./sq. mi.)	**The average number of cubic feet of water per second flowing from each square mile of area drained by a stream, assuming that the runoff is distributed uniformly in time and area. Sometimes abbreviated as csm.**

Chemical Oxygen Demand (COD)	The amount of oxygen required for the chemical oxidation of organics in a liquid.
Chlorine Demand	The difference between the amount of chlorine added to water, sewage, or industrial wastes and the amount of residual chlorine remaining at the end of a specified contact period. The demand for any given water varies with the amount of chlorine applied, time of contact, and temperature.
Chlorine Residual	Chlorine concentration in excess of the chlorine demand.
Chlorophyll	A green light-trapping pigment essential as an electron donor in photosynthesis.
Climate	The sum total of the meteorological phenomena that characterizes average and extreme conditions of the atmosphere over a long period of time at any one place or region of the earth's surface. The collective state of the atmosphere at a given place or over a given area within a specified period of time.
Coagulant	A material, which, when added to sewage or water, will combine with certain substances ordinarily present and form a precipitate comprising floc particles more or less gelatinous in character having the capacity to remove colloids from sewage or water.
Coagulation	Formation of a clot or gelatinous mass.
Coliform Organism	A nonpathogenic group of organisms which are used as a test to determine the presence or absence of fecal contamination.
Conservation Storage	Storage of water for later release for useful purposes such as municipal water supply, power, or irrigation in contrast with storage used for flood control.
Conservative	A conservative constituent is one for which the concentration is directly related to the extent of dilution, i.e., the substance is not decomposed, altered chemically, or removed physically as a result of natural processes.

Correlation	The process of establishing a relation between a dependent variable and one or more related independent variables. Correlation is simple if there is only one independent variable; multiple, if there is more than one independent variable.
Cubic Feet per Second (cfs)	A unit expressing rates of discharge. One cubic foot per second is equal to the discharge through a rectangular cross section, 1 foot wide and one foot deep, flowing at an average velocity of one foot per second. Also called second feet.
CUSEC	An abbreviation for cubic feet per second, common in the British Commonwealth countries.
Daily or Diurnal Temperature Range	The difference between the highest and lowest temperatures recorded on a particular day.
Deficit, Saturation	(1) The difference between the quantity of a substance in solution and the quantity of such substance required to create a saturated condition, at a given temperature, usually expressed in terms of percentage of the difference to that required for saturation. (2) The difference, expressed in percentage, between the quantity of dissolved oxygen in a stream and the quantity of oxygen required to create a condition of saturation therein, under given conditions.
Demand, Benthal	The demand upon dissolved oxygen of water overlying benthal deposits under natural stream conditions resulting from the upward diffusion of decomposition products of the deposits into the overlying water.
Denitrification	A biological process in which gaseous nitrogen is produced from nitrite and nitrate.
Density Current	A flow of water maintained by gravity through a large body of water, such as a reservoir or lake, and retaining its unmixed identity because of a difference in density.
Detritus	The heavier mineral debris (usually in bedload form) moved by natural watercourses.

Dew Point	The temperature to which air with a given quantity of water vapor must be cooled to cause condensation of the vapor therein.
Disinfection	The killing of the larger portion (but not necessarily all) of the harmful and objectional microorganisms in, or on, a medium by means of chemicals, heat, ultraviolet light, etc.
Dissolved Oxygen (DO)	The amount of free (not chemically combined) oxygen in water. Usually expressed in mg/1.
Dry-Adiabatic Lapse Rate	The decrease in temperature per 1,000 feet of rise in elevation in the unsaturated lower layers of the atmosphere. Usually used as 5.4°F per 1,000 feet (or 1°C per 100 meters).
Ecology	The study of the interrelationship of organisms among themselves and their environment.
Effluent	(1) Liquid which flows from a containing space. (2) Sewage, water, or other liquid, partially or completely treated, or in its natural state, as the case may be, flowing from a reservoir, basin, or treatment plant, or part thereof.
Epilimnion	The upper layer of a thermally stratified body of water that extends from the surface to the metalimnion and has nearly uniform temperature. See metalimnion.
Estuary	Commonly an arm of the sea at the lower end of a river. Estuaries are often enclosed by land except at channel entrance points. The estuary is commonly subjected to tidal influence.
Eutrophication	The process of overfertilization of a body of water by nutrients which produce more organic matter than the self-purification processes can overcome.
Evaporation	The process by which water is changed from the liquid or the solid state into the vapor state.
Evaporation Pan	A pan used to hold water during observations for the determination of the quantity of evaporation at a given location. Such pans are of varying sizes and shapes.

Evaporation Rate	The quantity of water, expressed in terms of depth of liquid water, which is evaporated from a given surface per unit of time. It is usually expressed in inches depth per day, month, or year.
Evapotranspiration	The volume of water evaporated and transpired from soil and plant surfaces per unit land area.
Facultative Aerobe	An organism that, although fundamentally an anaerobe, can grow in the presence of free oxygen.
Fauna	The animals peculiar to a specific environment.
Fetch	(1) The distance which waves have traveled in open water, from their point of origin to the point where they break. (2) The distance of the water or the homogeneous type surface over which the wind blows without appreciable change in direction.
Flora	The plants peculiar to a specific environment.
Fungi	Thallophytic plants that lack chlorophyll and are filamentous in structure; molds.
Hardness	Existence of magnesium and calcium compounds in water which will normally cause scaling problems in pipelines through the formation of calcium carbonate.
Herbicide	Chemical or a mixture of chemicals intended to control or destroy any vegetation.
Hydrographic Survey	An instrumental survey to measure and determine characteristics of streams and other bodies of water within an area, including such things as location, areal extent, and depth of water in lakes or the ocean; the width, depth, and course of streams; position and elevation of high water marks; location and depth of wells, etc.
Hydrologic Budget	An accounting of the inflow to, outflow from, and storage in, a hydrologic unit, such as a drainage basin, aquifer soil zone, lake, reservoir, or irrigation project.
Hydrologic Cycle	The complete cycle of phenomena through which water passes, commencing as atmospheric water vapor, passing into liquid and solid form as precipitation, then along or into the ground surface, and finally again returning to the form of atmospheric water vapor by means of evaporation and transpiration. Also called Water Cycle.

Hypolimnion	The lower level of a thermally stratified body of water which extends from the metalimnion to the bottom and which is essentially removed from surface influence. See metalimnion.
Immediate Oxygen Demand (IOD)	The presence of reducing agents such as sulfites, sulfides, or ferrous iron, which cause an immediate demand on the dissolved oxygen in a stream.
Influent	Sewage, water, or other liquid, raw or partly treated, flowing into a reservoir, basin, or treatment plant, or part thereof.
Ionization	The process of the formation of ions by the splitting of molecules of electrolytes in solution.
Lapse Rate	A vertical temperature gradient (i.e., the rate of change of temperature with elevation in the free atmosphere).
Latent Heat of Vaporization	The amount of heat absorbed by a unit mass of substance, without change in temperature, while passing from the liquid to the vapor state.
Leaching	(1) The removal of soluble constituents from soils or other material by water. (2) The removal of salts and alkali from soils by abundant irrigation combined with drainage. (3) The disposal of a liquid through a nonwatertight artificial structure, conduit, or porous material by downward or lateral drainage, or both, into the surrounding permeable soil.
Limnology	That branch of hydrology pertaining to the study of lakes.
Liter	Metric unit of volume containing 1,000 milliliters (ml).
Marsh	A meadow-like area overgrown with aquatic plants.
Median Lethal Dose (LD_{50})	The dose that is lethal to 50 percent of a group of test organisms for a specified period. The dose material may be ingested or injected.
Median Tolerance Limit (TL_m)	The concentration of the test material at which 50 percent of the test organisms are able to survive for a specified period of exposure.

Metabolism	The chemical and physical processes continuously taking place in living organisms and cells, comprising those processes by which assimilated nutrient is built up into protoplasm (anabolism), and those by which protoplasm is used and broken down into simpler substances, with the release of energy (catabolism).
Metalimnion	That layer, in a body of water, having thermal stratification for which the temperature difference is largest per unit of depth. This layer separates the epilimnion from the hypolimnion. See Epilimnion and Hypolimnion.
Microorganism	Form of life of microscopic dimensions.
Nitrate Reduction	The reduction of nitrates to nitrites or ammonia.
Nitrification	The transformation of ammonia nitrogen to nitrates.
Nonconservative	A nonconservative constituent is one that may be subject to chemical, biological, or physical processes that tend to alter it or remove it from solution or suspension.
Nutrient	A substance that can be used as a food.
Organic Compound	A compound of carbon, as distinguished from a non-carbon-containing compound, designated inorganic.
Oxidation	The process of combining with oxygen, or the loss of electrons or hydrogen.
Oxidation Pond	A large shallow body of water in which waste is discharged. Reaeration is accomplished through surface agitation by wind action and as a result of activity of algae utilizing the carbon dioxide and adding oxygen back to the system. This system requires substantially high dilution so that the time involved normally is in days rather than hours. This system sometimes is referred to as an aerated lagoon when surface aerators are installed.
Oxygen Sag Curve	A curve that represents the profile of dissolved oxygen content along the course of a stream, resulting from deoxygenation associated with biochemical oxidation of organic matter, and reoxygenation through the absorption of atmospheric oxygen and through biological photosynthesis.

Oxygen Saturation Capacity	The maximum quantity of dissolved oxygen that a liquid exposed to the atmosphere can contain at a given temperature and pressure.
Parasite	An organism that derives its nourishment from a living plant or animal.
Parts per Million (ppm)	Concentration units used to measure how many parts of a specific water quality parameter are present in a million parts of water sampled. Synonymous to mg/l when density of liquid equals 1.
Pathogenic	Capable of producing disease.
pH (Hydrogen Ion Concentration)	Measure of acidity or alkalinity of water. Distilled water, which is neutral, has a pH value of 7; values above 7 indicate the presence of alkalies, while those below 7 indicate acids. Also, pH equals the negative logarithm of the hydrogen-ion, $[H^+]$, concentration.
Photosynthesis	The process in which chlorophyll and the energy of light are used by plants to synthesize carbohydrates from carbon dioxide and water.
Plankton	Collective term for the passively floating or drifting flora and fauna of a body of water; consists largely of microscopic organisms.
Pollution	The addition of sewage, industrial wastes, or other harmful or objectionable material to water.
Potable	Water which is safe for human consumption.
Precipitation	As used in hydrology, precipitation is the quantity of water, in liquid or solid state to fall from the atmosphere upon a land or water surface. It is the common process by which atmospheric water becomes surface and subsurface water. Precipitation includes rainfall, snow, hail, and sleet.
Protein	One of a class of complex organic nitrogenous compounds composed of an extremely large number of amino acids joined through peptide linkages.
Protozoa	Unicellular organisms belonging to the animal kingdom.

Putrefaction	Decompositon of proteins by microorganisms, producing disagreeable odors.
Quality, Water	A term used to describe the chemical, physical, and biological characteristics of water in respect to its suitability for a particular purpose. The same water may be of good quality for one purpose or use, and bad for another, depending upon its characteristics and the requirements for the particular use.
Rainfall	The quantity of water that falls as a liquid from the atmosphere upon a land or water surface.
Reaeration	The absorption of oxygen by a liquid.
Reach	(1) The length of channel uniform with respect to discharge, depth, area, and slope. (2) The length of a channel for which a single gage affords a satisfactory measure of the stage and discharge. (3) The length of a river between two gaging stations. (4) More generally, any length of a river.
Reduction	A chemical process involving the removal of oxygen, the additon of hydrogen, or the gain of electrons.
Relative Humidity	The ratio of the actual quantity of water vapor present to the quantity of water vapor required for saturation at the same temperature and pressure.
Reoxygenation	The replenishment of oxygen in a stream from (1) dilution water entering the stream, (2) biological reoxygenation through the activities of certain oxygen-producing plants, and (3) atmospheric reaeration.
Reregulating Reservoir	A reservoir for reducing diurnal fluctuations resulting from the operation of an upstream reservoir.
Reservoir	A pond, lake, tank, basin, or other space, either natural in its origin, or created in whole or in part by the building of engineering structures, which is used for storage, regulation, and management of water.
Salinity	The relative concentration of salts, usually sodium chloride, in a given water. It is usually expressed in terms of the number of mg/l of chloride.

Saturated-Adiabatic Lapse Rate	The decrease in temperature per 1,000 feet of rise in elevation in the saturated lower layers of the atmosphere. Usually used as 3°F per 1,000 feet (.5°C per 100 meters).
Second-Foot	An abbreviated expression for cubic feet per second (cfs).
Second-Foot-Day	The discharge during a 24-hour period when the rate of flow is 1 cubic foot per second. It is equal to 86,400 cubic feet, or 1.9835 acre-feet. Abbreviated sfd.
Sediment	Sand, silt, and clay material that is being transported or has been transported by moving water.
Sediment Discharge	The rate at which dry weight of sediment passes a section of a stream or is the quantity of sediment, as measured by dry weight, or by volume, that is discharged in a given time.
Seiche	An oscillation of the water surface of a lake or other large body of water due to unequal atmospheric pressure, wind, or other cause, which sets the surface in vibration.
Self-Purification	The natural processes of water purification whereby the bacterial content is reduced, the BOD is largely satisfied, the organic content is stabilized, and the dissolved oxygen returned to the equilibrium level.
Sludge	Flocculent forms of microorganisms in a waste treatment system. Bottom sediments from waste streams.
Solids, Dissolved	Solids which are present in solution.
Solids, Settleable	Suspended solids which will subside in quiescent water, sewage, or other liquid in a reasonable period. Such period is commonly, though arbitrarily, taken as 2 hours. Also called Settling Solids.
Solids, Suspended	The solids that are in suspension in water, sewage, or other liquids and are largely removable by filter paper.

Solids, Total	The solids in water, sewage, or other liquids; it includes the suspended solids (largely removable by filter paper), and the dissolved solids (those which pass through filter paper).
Solids, Volatile	Organic fraction of the total solids.
Specific Heat	The ratio of the amount of heat required to raise the temperature of a given weight of a given substance 1°F, to that required to raise the temperature of the same weight of water from 62°F to 63°F.
Specific Humidity	The mass of water vapor per unit mass of moist air.
Standard Methods	Methods of analysis of water, sewage, and sludge approved by a Joint Committee of the American Public Health Association, American Water Works Association, and Water Pollution Control Federation.
Standards, U.S. Public Health Service Drinking Water	Standards prescribed by the U.S. Public Health Service for the quality of drinking water supplied to interstate carriers.
Stream	A body of flowing water. The term is usually applied to a body of water flowing in a natural surface channel, but is also applied to a body of water flowing in a well-defined, open or closed conduit, a jet of water issuing from any opening, such as a nozzle, a fissure in rock, etc.
Swamp	A flat wet area usually covered by standing water and having a heavy growth of aquatic plants.
Thermal Stratification (of a lake)	A layered condition that develops in lakes where the layers are defined as follows: The upper layer of the lake, known as the epilimnion, in which the water temperature is virtually uniform; a stratum next below, known as the metalimnion, in which there is a marked drop in temperature per unit of depth; and the lowermost region or stratum, known as the hypolimnion, in which the temperature from its upper limit to the bottom is nearly uniform.
Thermocline	The plane within the metalimnion having the largest temperature difference per unit of depth.
Thermograph	Instrument used to record temperature.

Total Storage	The volume of a reservoir below the maximum controllable level including dead storage.
Toxic	Chemical compounds or ions that are harmful to aquatic life.
Tributary	A surface stream which contributes its water to another larger stream or body of water.
Usable Storage	The volume normally available for release from a reservoir below the elevation of the maximum controllable level.
Vapor Blanket	The layer of air which overlays a body of water, and has, due to its proximity to the water, a higher content of water vapor than the surrounding atmosphere.
Vaporization	The process by which water changes from the liquid to the gaseous state.
Virus	An obligate intracellular parasitic microorganism smaller than bacteria. Most can pass through filters that retain bacteria.
Water Analysis	The determination of the physical, chemical, and biological characteristics of water. Such analyses involve usually four different kinds of examination: bacteria, chemical, microscopic and physical.
Water Quality	A term used to describe the chemical, physical, and biological characteristics of water in respect to its suitability for a particular purpose. The same water may be of good quality for one purpose or use, and bad for another, depending upon its characteristics and the requirements for the particular use.
Water Year	The 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 1959, is called the "1959 water year."

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