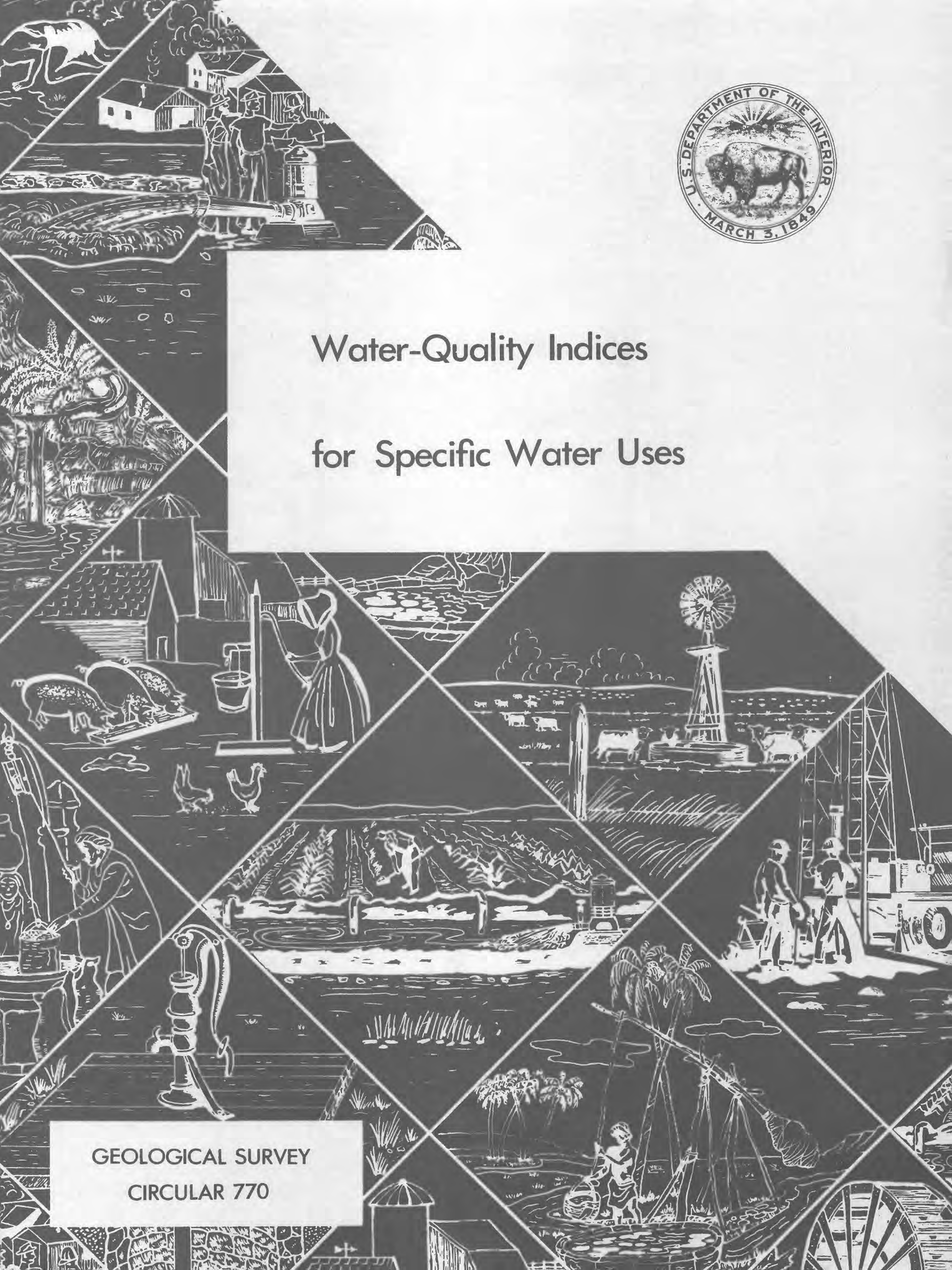

Water-Quality Indices for Specific Water Uses

GEOLOGICAL SURVEY

CIRCULAR 770

Water-Quality Indices for Specific Water Uses

By J. D. Stoner

GEOLOGICAL SURVEY CIRCULAR 770

1978

United States Department of the Interior

CECIL D. ANDRUS, *Secretary*

Geological Survey

H. William Menard, *Director*

Free on application to Branch of Distribution, U.S. Geological Survey, 1200 South Eads Street, Arlington, VA 22202

CONTENTS

ILLUSTRATION

TABLES

Water-Quality Indices for Specific Water Uses

By JERRY D. STONER

ABSTRACT

Water-quality indices were developed to assess waters for two specific uses—public water supply and irrigation.The assessment for a specific water use is based on the availability of (1) a set of limits for each water quality property selected, (2) a rationale for selection, and (3) information that permits one to appraise the relationship of the concentration of the selected property to the suitability of the specific water use. The selected properties are divided into two classes: Type-I properties, those normally considered toxic at low concentrations, and type-II properties, those which affect aesthetic conditions or which at high concentrations can be considered toxic or would otherwise render the water unfit for its intended use.

In the method used, type-I properties affect the index only when their recommended limits are exceeded. The type-II properties affect the value of the index over the complete range, from optimum or ideal concentrations to concentrations exceeding their respective recommended limits. The index value is the summation of the type-I and type-II effects. The range of the index is such that the value 100 represents a perfect water, zero a water that has the aggregate effect of the properties at their recommended limits, and a negative value a water unfit for the use intended without further treatment.

The index is designed to (1) provide numbers so that various waters can be compared directly with one another, (2) allow for comparison of water-quality changes with time, (3) indicate waters of both "good" and "bad" quality, and (4) provide values which managers and other nontechnical personnel can use more easily to characterize water quality. The method developed can be applied to water-quality indices for specific uses that are very broad or very narrow in scope.

INTRODUCTION

At the present time an increased emphasis has been placed upon the development of water-quality indices. Much of the effort in developing quality indices is directed toward quantifying such terms as "good" and "bad," and the values between these extremes. In this context, a water-quality index is a grading system for comparison of various waters.

A water-quality index is also the summation of the individual effects of the several properties used to develop the index. This attribute of an index allows direct comparison of the overall quality of different waters even though the concentration ranges of the individual constituents may be very different. These two attributes, the quantification of "good" and "bad" and the summation of individual effects, allow the user to examine waters and view them in terms of ranked order—for example; bad, poor, good, better, best. The water-quality index is also a method of providing water-quality information that can be more readily used by planners, managers, and other nontechnical people. In general, managers and planners will have technical staffs to analyze the raw data. However, the technical analyses must still be presented to the managers and planners in a form they can understand and use. The water-quality index is a useful tool in bridging this information gap.

The water-quality index can be a good tool for presenting water-quality data. It can be used in trend analyses, graphical displays, and in tabular presentations. It is an excellent format for summarizing overall water-quality conditions over space and time.

This report presents a new concept in the development of water-quality indices. Application of the method to a wide range of use categories and waters should show its utility and test the validity of the concept. The method should not be construed to be an official U.S. Geological Survey technique.

EARLIER INDICES

A general water-quality index not directed toward any specific water use was developed and reported by Brown, McClleland, Deininges, and Tozer (1970). They concluded that a single numerical expression reflecting the composite influence of significant properties of water quality is feasible. Various investigators have developed water-quality indices for specific uses. Amongst the oldest is the classification scheme for irrigation waters by Wilcox (1955). More recently, Harkins (1974) developed an index specifically for use in trend analysis, and Walski and Parker (1974) developed an index to be applied to recreational use.

DEVELOPMENT OF THE INDEX

Classification of waters according to specific uses has become increasingly important. Applying a general water-quality index to specific-use waters may lead to conclusions that are not entirely valid, primarily because the importance and influence of water-quality properties vary for different uses. As an example, water temperature is relatively unimportant in water used for irrigation but is of vital importance in waters used for the maintenance of aquatic life. With the method to be described, a water-quality index for any water use, broad or narrow in scope, can be developed if certain information can be provided. The minimum information needs are (1) a set of limits for each water-quality property to be considered, (2) a rationale for establishment of the limits, and (3) some information on, or appraisal of, the relation of various concentrations of each property to the specific water use for which the index is being developed.

Two broad water-use categories, public water supply and irrigation, were analyzed to develop the method. The National Academy of Sciences and National Academy of Engineering report, "Water Quality Criteria 1972" (1972), provided the necessary information for the development of the water-use indices.

The water-quality properties, rank order, weighting factors, and mathematical expressions used in this report are the author's subjective choices based upon his experience and the National Academy of Sciences report, and as such, they will probably not be accepted by all readers. All developers of indices face the problem of subjectiveness. The DELPHI method, as used by Brown, McClleland, Deininges, and Tozer (1970) could be applied to the procedure developed in this report to reduce subjectiveness.

CRITERIA

Two criteria were adopted to develop a base from which a specific-use index could be generated. The first criterion was that the number generated as the index value from one water must be directly comparable to the index number generated from a different water. The second criterion was that the number generated should represent the "fitness" of the water for the specific-use category under consideration. These criteria differ from the criteria of other indices in that most indices developed to date have been concerned with judging waters in terms of general overall quality—that is, how "good" the waters are—irrespective of their intended use.

BOUNDARY CONDITIONS

In order to meet the established criteria, the QF's (quality function), which are the mathematical functions representing individual water-quality properties making up the WQI (water-quality index), and the WQI itself assign to an "ideal" water the arbitrary value of 100. Because of the method of computation, the boundary conditions for the individual properties were applied to the respective QF's. The QF's and WQI for a water at the recommended concentration limits were arbitrarily set at zero. In this way, when the QF's or WQI (which is the sum of the individual effects), are somewhere in the range of 0 to 100, the "goodness" of the water for a specific use can be judged. The QF of an individual property whose value has exceeded the limit becomes negative. The more the limit is exceeded, the larger the negative number becomes. No limit is placed upon the value that a negative number can become. If the sum of the individual effects is negative, then the WQI becomes negative. Thus, if the value of a property normally not considered toxic at commonly found concentrations reaches a toxic concentration, or if a concentration renders the water unfit for use, the value will make the WQI negative.

MATHEMATICAL FUNCTIONS

Mathematical functions instead of graphical descriptions were chosen to describe the effect of the water-quality properties upon the index.

Mathematical expressions provide a simpler and faster computation scheme than graphical interpretation and can be easily adapted to computer processing. Because there was no evidence to indicate that a complicated function would be any more valid than a simple function, the simplest functions that would describe the apparent effects of the properties were used. The linear function $a+bx$, the parabolic function $a+bx^2$, and the parabolic function $a+bx+cx^2$ were the only functions used. Though other simple mathematical functions such as $a + b$ logx were reviewed, they were not used because the linear and parabolic forms adequately satisfied the developmental criteria. Other mathematical forms should not be precluded in the development of indices, particularly if they are more suitable to the criteria that have been established for the index under development. The application of a mathematical function to the effect of a water-quality property is shown in figure 1. In this example, the parabolic form, $a+bx^2$, was chosen. When the concentration of a property is ideal, the curve is at its maximum, $QF=100$, and when the concentration of the property is at its recommended limit, $QF=0$. Given these two points on the curve, it is a simple process to determine the constants a and b in the equation $a+bx^2$.

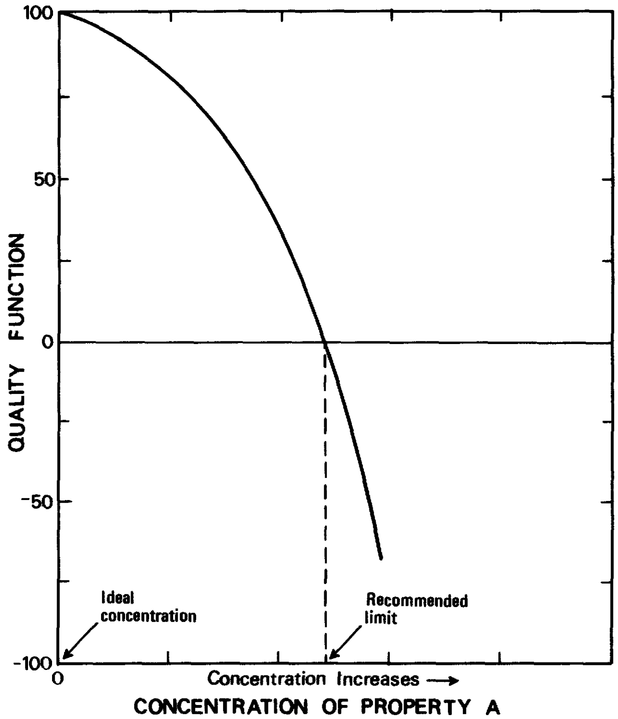

FIGURE 1.—Plot of the function $QF=a+bX^2$ for property A, where a and b are constants derived from the recommended limits and ideal concentration, x is the concentration of property A and QF is the quality function.

TYPES OF PROPERTIES

Properties were selected on the premise that the water-quality index would be applied to raw waters. A study of the selected water-quality properties showed that they could be divided into two groups based on the way in which each group affected the specific water use.

TYPE-I PROPERTIES

The first group, or type-I properties, are those normally considered toxic at low concentrations. Examples are: lead at 0.05 mg/L (milligrams per liter); chlordane at 0.003 mg/L and radium 226 at 20 pCi/L (picocuries per liter). The information available indicated that it would not be practical to assign a mathematical statement to describe the effect of concentration levels on the QF with a reasonable degree of validity. That is, it would be difficult to compare the fitness of a water with 0.001 mg/L chlordane to one with 0.002 mg/L chlordane. Another characteristic of type-I properties is that a significant health hazard is indicated when any one property exceeds the prescribed limits. If or when information becomes available relating the effects of various subtoxic concentrations of a type-I property, it would then be treated as a type-II property.

The computation scheme adopted for the type-I properties is essentially a go or no-go system. It is assumed that if the concentration is equal to or less than the limiting concentration, there will be no effect upon the WQI, whereas if the concentration is greater than the limit, there will be a significant impact. If a positive value of the WQI represents a "fit" water, then the effect of a type-I property exceeding the limiting concentration on the WQI should be such that the WQI can not be greater than zero. If more than one type-I property exceeds the limit, then the water will become increasingly unfit for use; therefore, the individual effects are allowed to become additive. Type-I properties are assigned the following values: a zero if the concentration is less than or equal to the limiting concentration and −100 (minus) if the recommended limiting concentration is exceeded. Therefore, if the value of at least one type-I property exceeds the limiting concentration, the value of the WQI can never be greater than zero. The following expression describes the effect upon the WQI of the type-I properties.

$$\sum_{j=1}^{n} (T)_j \tag{1}$$

where $(T)_j$ is the value of the jth type-I property.

TYPE-II PROPERTIES

Type-II properties are those that affect aesthetic conditions such as color, taste and odor, or those that could make the water unfit for use, or produce deleterious health effects when their concentrations become significantly high. Some examples of type-II properties for a public water supply index are color, chloride, sulfate, and fluoride. The available information indicates that it is possible to apply mathematical functions to the effects of the properties on the water use with a reasonable degree of validity.

Type-II properties are assigned simple mathematical functions to describe their effects upon water use. In order to have the sum of the QF's of the selected type-II properties approach a WQI value of 100 as the respective concentrations approach their ideal values, the QF's needed to be adjusted. Brown, McClleland, Deininges, and Tozer, like other investigators, (1970) have determined that the type-II properties are not equally important. Before the QF's can be adjusted, it is necessary to rank, in terms of their relative importance, the selected type-II properties. The QF adjustment factor is the RF (ranking factor). The boundary condition of the ranking factors is that their sum must equal one. That is:

$$\sum_{i=1}^{m} (RF)_i = 1.00 \tag{2}$$

where $(RF)_i$ is the ranking factor of the ith type-II property.

The following computation scheme was used to determine values for the RF's. If properties A through E are in order of rank, then:

$$(RF)_A + (RF)_B + (RF)_C + (RF)_D + (RF)_E = 1.00 \tag{3}$$

The respective RF's can be determined if the RF values of B through E can be assigned some value or function in terms of A, the highest ranking property. This technique can be used when properties are in groups of equal weight; that is, when more than one property is assigned the same weight with respect to the most significant property or properties. All that is required is a simple substitution into equation 3 as follows:

$$a(RF)_A + b(RF)_B + \text{---------------} \; e(RF)_E = 1.00$$

where a, b, ------, e are the numbers of properties in each group.

A simple function relating concentration values to the QF is then determined. The RF multiplied by the respective QF is the contribution of any given type-II property to the WQI, and the sum of the type-II effects is the contribution of the type-II properties to the WQI.

$$\sum_{i=1}^{n} (QF)_i (RF)_i \tag{4}$$

INDEX

The specific use water-quality index is the sum of the effects of the type-I and type-II properties.

$$WQI(A) = \sum_{i=1}^{n} (QF)_i (RF)_i + \sum_{j=1}^{z} (T)_j \tag{5}$$

Where: $WQI\ (A)$ is the water-quality index for specific use A,
n is the number of type-II properties,
z is the number of type-I properties,
$(QF)_i$ is the ith type-II quality function,
$(RF)_i$ is the ith type-II ranking factor and
$(T)_j$ is the value of the jth type-I property.

When a type-II property exceeds its recommended limit sufficiently to render the water unfit for its intended use, that is, the value of the respective QF times RF is −100 or a larger negative number, the WQI has a negative number. One can argue that once a property reaches a concentration that renders the water unfit, any further increase does not make the water any more unfit. This is probably true; for example, a water with 20,000 mg/L chloride is probably no more unfit for drinking than a water containing 10,000 mg/L chloride. The WQI is, however, designed in part to provide managers and planners with information they can use in making decisions. In general, the greater the negative number the greater the need for treatment.

In practice, computation is simplified if the respective QF's and RF's are combined into single functions. The computation scheme is also easily adaptable to most of the programmable calculators available today.

EXAMPLES OF SPECIFIC INDICES

The method which was used to develop the indices for two specific water-use categories was tested to determine its' applicability. It was found in addition that preliminary application of the developed WQI's to available data indicate that the choices of ranking factors, quality functions, and the ranking of parameters seem to be reasonable estimates. The discussion of the public water-supply index is the most comprehensive, and only those points or computation schemes in the irrigation index that differ markedly from the public water-supply index are discussed in detail.

PUBLIC WATER SUPPLY INDEX

The water-quality constituents included in the public water-supply index WQI(P) were selected on the basis of their (1) hazard to human health, (2) significant aesthetic effects, (3) significant economic effects and (or) (4) ability to render the water undesirable to a majority of consumers.

TYPE-I PROPERTIES

The public water supply type-I properties are those that are generally accepted to be toxic at small concentrations. They include the trace metals, pesticides, and the hazardous radionuclides. The selected type-I properties and their respective recommended limits are given in table 1.

TYPE-II PROPERTIES

The following discussion describes briefly the rationale for selection, the recommended limits, and the type of curve applied for the type-II properties given in table 2.

TABLE 1.—*Type-I properties selected for public water supply index*

[All properties expressed in mg/L except the last four radionuclides which are expressed in pCi/L]

Property	Recommended limit
Arsenic	0.1
Barium	1.0
Cadmium	.01
Chromium	.05
Lead	.05
Mercury	.002
Selenium	.01
Cyanide	.2
Aldrin	.001
Chlordane	.003
DDT	.05
Dieldrin	.0005
Endrin	.0001
Heptachlor	.0001
Heptachlor-epoxide	.0001
Lindane	.005
Methoxychlor	1.0
Toxaphene	.005
Organophosphorus-carbamate	.1
2, 4-D	.02
Silvex	.03
2, 4, 5-T	.002
Radium-226	20
Iodine-131	100
Strontium-90	200
Strontium-89	2,000

TABLE 2.—*Type II properties selected for public water supply index*

Property	Concentration	
	Limit	Ideal
Ammonia-nitrogen	0.5 mg/L	0.0 mg/L
Chloride	250 mg/L	0.0 mg/L
Color	75 Pt-Co units	0 Pt-Co units
Copper	1.0 mg/L	0.0 mg/L
Fecal coliform bacteria	2,000 cells/100 mL	0 cells/100 mL
Fluoride	R = 1	R = 0.1
Iron	0.3 mg/L	0.0 mg/L
MBAS	0.5 mg/L	0.0 mg/L
Nitrite-nitrogen	1.0 mg/L	0.0 mg/L
pH	5.0, 9.0	7.0
Phenols	1.0 μg/L	0.0 μg/L
Sulfate	250 mg/L	0 mg/L
Zinc	5.0 mg/L	0.0 mg/L

Ammonia.—Ammonia was selected because of its effect on the efficiency of chlorination (an economic reason) and because it is an indicator of pollution (health hazard). The recommended limit for ammonia is 0.5 mg/L and the ideal concentration is assumed to be 0.0 mg/L. Ammonia concentrations are expressed in terms of milligrams per liter ammonia as nitrogen (NH_4-N). The linear equation determined for ammonia that is based upon the recommended limits is

$$QF(NH_4\text{-}N) = 100\text{-}200\ (\text{mg/L } NH_4\text{-}N).$$

Chloride.—Chloride was selected because of its effect on taste and because it accelerates corrosion of distribution systems. In addition, high concentrations of chloride can cause water to be unfit for human consumption. The recommended limit is 250 mg/L and the ideal concentration is taken to be 0.0 mg/L. In general, the utility of a water for public supply decreases as the chloride concentration increases. The rate at which the utility decreases is unknown; therefore the linear form was chosen because it is the simplest expression that would express this relationship. The equation determined for chloride is

$$QF(\text{Cl}) = 100 - 0.4(mg/L\ \text{Cl}).$$

Color.—Color was selected because increased color can make waters esthetically undesirable; also, increased color reduces the efficiency of ion exchange resins used in water treatment facilities to remove metals. The recommended limit for color is 75 Pt-Co (platinum-cobalt) units, and the assumed ideal is 0 Pt-Co units. Esthetic acceptance of color in drinking water is very difficult to quantify. The author believes that the undesirability of a water due to color increases at a rate faster than that expressed by the linear equation; therefore the parabolic form was used. The equation for color determined from the recommended limits is

$$QF(color) = 100 - 0.0178(\text{Pt-Co } units)^2.$$

Copper.—Copper was selected because it affects taste, it may accelerate corrosion, and in large doses it may cause vomiting and (or) liver damage. The recommended concentration limit of copper for public water supplies is 1.0 mg/L. Copper is essential to human health, and if the only source of this element were drinking water, the ideal concentration would not be 0.0 mg/L; however, copper is normally consumed in adequate quantities in foodstuffs; therefore, in order to simplify the computation, the ideal concentration is taken to be 0.0 mg/L. The parabolic form of the equation was chosen for copper because it reflects the rapid degradation of drinking water due to taste by copper concentrations greater than 1.0 mg/L. The equation developed for copper was

$$QF(\text{Cu}) = 100 - 100(mg/L\ \text{Cu})^2.$$

Fecal Coliform Bacteria.—Fecal coliform bacteria were chosen because they are a more specific indicator of warm-blooded animal contamination than total coliform bacteria and they are one of the major pollution indicators in use today. The recommended limit for fecal coliform bacteria is 2,000 cells/100 mL (cells per 100 milliliter) and the ideal concentration is assumed to be 0.0 cells/100 mL. Although the absolute relationship between fecal coliform bacteria and health risk from disease has not been established, it intuitively seemed that the risk factor should probably be expressed in the parabolic equation. For example, the risk of becoming ill from drinking water with a fecal coliform bacteria count of 6,000 cells/100 mL is probably more than twice that resulting from drinking water with a fecal coliform bacteria count of 3,000 cells/100 mL. The equation determined for fecal coliform bacteria is

$$QF(fecal\text{-}coli) = 100 - 0.000025(cells\ 100/mL)^2.$$

Fluoride.—As concentration of fluoride increases the physiological effects increase. Lower concentrations cause mottling of teeth, chipping of teeth, and skeletal defects; extremely high concentrations cause illness and even death. The recommended maximum concentration of fluoride in drinking water is based on the air temperature National Academy of Sciences and National Academy of Engineering (1972) (table 3). A certain amount of fluoride in water does help to prevent dental cavities; therefore, the ideal concentration is set at one-tenth the recommended maximum concentration rather than zero. The fluoride value used in the equation describing its effect is the ratio R: $R = X_a/X_m$ where X_a is the fluoride concentration in mg/L and X_m is the specific temperature recommended concentration in mg/L. This approach allows using a single expression wherein air temperature is not a vari-

TABLE 3.—*Recommended maximum fluoride concentrations*
[From National Academy of Sciences and National Academy of Engineering, 1972]

Annual average maximum daily air temperatures (°F)	(°C)	Maximum fluoride concentration (mg/L)
80–91	26.5–32.8	1.4
72–79	21.9–26.4	1.6
65–71	18.1–21.8	1.8
59–64	14.7–18.0	2.0
55–58	12.5–14.6	2.2
50–54	9.7–12.4	2.4

able. Because the ideal value of R is not zero, a parabolic equation is used to reflect the two-sided relationship of fluoride concentrations. The equation determined for fluoride is

$$QF(\mathrm{F})=98.8+24.7(R)+123(R)^2.$$

Iron.—Iron affects taste, stains clothes and plumbing fixtures, and forms deposits in distribution systems. It was for these reasons, primarily aesthetic and economic, that iron was selected. The recommended limit for iron is 0.3 mg/L, and the ideal concentration is assumed to be 0.0 mg/L. The linear form was chosen because it was the simplest equation that would describe the utility decreasing as the concentration increased. The equation determined for iron is

$$QF(\mathrm{Fe})=100-33.3(mg/L\ \mathrm{Fe}).$$

Methylene blue active substances.—MBAS (methylene blue active substances) were chosen because of their tendency to produce undesirable aesthetic effects, to produce dispersion of insoluble or sorbed substances, to foam, to interfere with the removal of substances by the coagulation, sedimentation, and (or) filtration processes. The recommended limit for MBAS is 0.5 mg/L, and the ideal concentration is taken to be 0.0 mg/L. The linear form was selected for the same reason it was selected for iron. The equation determined for MBAS is

$$QF(MBAS)=100-200(mg/L\ MBAS).$$

Nitrite-nitrogen.—NO_2-N (nitrite-nitrogen) was selected because of its toxicity, particularly because it causes methemoglobinemia in infants. The recommended limit for NO_2 (nitrite) is 1.0 mg/L expressed as N (nitrogen), and the ideal concentration is assumed to be 0.0 mg/L NO_2-N. As with fecal-coliform bacteria, the parabolic form was chosen because it allows a much faster decrease in the QF than does the linear form. The equation determined for NO_2-N is

$$QF(\mathrm{NO_2—N})=100-100(mg/L\ \mathrm{NO_2—N})^2.$$

pH.—pH was selected because it affects water-treatment processes and can contribute to the corrosion of distribution lines and household plumbing fixtures. This corrosion can add such constituents as iron, copper, lead, zinc and cadmium to the water supply. The recommended limits for pH are 5.0 and 9.0, and for simplicity the ideal value is taken as 7.0. The parabolic form was chosen because it is one of the simplest two-sided forms. The equation determined for pH is

$$QF(pH)=-1{,}125+350(pH)-25(pH)^2.$$

Phenols.—Phenolic compounds were selected because of their effect on odor. Even though their recommended limit is quite small, they are considered a type-II property because exceeding the recommended limit does not necessarily cause a health hazard or preclude use of the water. The recommended limit for phenols is 1.0 μg/L(microgram per liter), and the ideal concentration is taken to be 0.0 μg/L. The linear form was selected for the same reason it was selected for iron. The equation determined for phenols is

$$QF(phenols)=100-100(\mu g/L\ phenols).$$

Sulfate.—The selection of sulfate (SO_4) was based on its taste and laxative effects. The recommended limit for sulfate is 250 mg/L, and the ideal concentration is assumed to be 0.0 mg/L. The linear form was selected for the same reason it was selected for iron. The equation determined for sulfate is

$$QF(\mathrm{SO_4})=100-0.4(mg/L\ \mathrm{SO_4}).$$

Zinc.—Zinc was selected because of its effect on taste at higher concentrations. Zinc is essential in human metabolism, and the activities of insulin and several body enzymes are dependent upon it. The recommended limit for the maximum concentration of zinc in public water supplies is 5.0 mg/L. Even though zinc is essential, the ideal concentration is set at 0.0 mg/L because adequate quantities are normally consumed in foodstuffs. The linear form was used because it expresses more closely the fact that quite high concentrations, 50 mg/L according to Hinman (1938), can be tolerated for protracted periods without harm. The equation determined for zinc is

$$QF(\text{Zn}) = 100 - 20(\text{mg}/L\ \text{Zn}).$$

The 13 water-quality constituents chosen as type-II properties for public water supplies were judged not to be of equal importance in their contribution to the water-quality index. For this reason, an attempt was made to rank them based upon the following order of importance—toxicity, health hazard, aesthetic effect, and economic effect. It was not practical to determine an exact ranking order for the 13 type-II properties; however, it was reasonable to separate them into groups that could be ranked. Each property within a group has the same weight as any other property in that same group. The groups were designated *A* through *E*; group *A* was the most significant. The following values were assigned to the groups: $A=1.00$; $B=0.667A$; $C=0.50A$; $D=0.40A$ and $E=0.33A$. The method described on page 4 of this report was then used to determine the RF for each of the groups. The groups, RF's, and the equations for calculating the individual type-II property effects are given in table 4.

APPLICATION OF INDEX

Several analyses were selected to show how the public water supply index could be used to judge various waters. The information for the selected analyses is given in table 5. The information is provided here to show the effect of the individual type-II properties on the water-quality index. Normally, the water-quality index would be the only value given. No information was available for the radio-chemical type-I properties, and it was assumed that they did not exceed their respective limits. Data were available for most of the other type-I properties, and they did not exceed their respective limits. If type-I property data were missing, it was also assumed that the values did not exceed their respective limits. Some of the conclusions that can be drawn from table 5 are:

1. Of the first three sources, the Little Wehiva River is the most suitable and the Cedar Bayou is the least suitable.
2. All of the first three sources could be used for public water supplies.
3. The Cedar Bayou, although adequate, should be examined further to determine the reason for its relatively low score. In this example, the properties to be examined are color, phenols, and fecal coliform.
4. The adequacy of Buffalo Bayou is dependent upon water discharge. The water is generally unfit for use without further treatment.
5. The Buffalo Bayou at low-water discharge is extremely hazardous to use as a public water supply.

IRRIGATION INDEX

The water-quality index for irrigation waters was based on the recommended limits prescribed

TABLE 4.—*Type-II property effects for the public water supply index*

Group	Property	Ranking factor	Water quality index equation
A	Ammonia-nitrogen	0.134	$13.4 - 26.8\ (\text{mg/L } NH_4\text{-N})$
	Nitrite-nitrogen	.134	$13.4 - 13.4\ (\text{mg/L } NO_2\text{-N})^2$
	Fecal coliform bacteria	.134	$13.4 - 0.0000034\ (\text{cells/100 mL})^2$
B	pH	0.089	$-100 + 31.1(\text{pH}) - 2.22(\text{pH})^2$
	Fluoride	.089	$8.79 + 2.20(R) - 10.95(R)^2$
C	Chloride	0.067	$6.7 - 0.0268\ (\text{mg/L Cl})$
	Sulfate	.067	$6.7 - 0.0268\ (\text{mg/L } SO_4)$
D	Phenols	0.053	$5.3 - 5.3\ (\mu\text{g/L Phenols})$
	MBAS	.053	$5.3 - 10.6\ (\text{mg/L MBAS})$
E	Copper	0.045	$4.5 - 4.5\ (\text{mg/L Cu})^2$
	Iron	.045	$4.5 - 15.0\ (\text{mg/L Fe})$
	Zinc	.045	$4.5 - 0.9\ (\text{mg/L Zn})$
	Color	.045	$4.5 - 0.0008\ (\text{Pt-Co units})^2$

TABLE 5.—*Public water supply indices and individual property effects for selected waters*

Parameter	Units	(1) Conc.	(1) WQI(i)	(2) Conc.	(2) WQI(i)	(3) Conc.	(3) WQI(i)	(4) Conc.	(4) WQI(i)	(5) Conc.	(5) WQI(i)	(6) Conc.	(6) WQI(i)	(7) Conc.	(7) WQI(i)
Ammonia-nitrogen	mg/L	0.13	9.92	0.11	10.45	0.05	12.06	0.29	5.63	5.5	−134	1.9	−37.52	1.0	−13.40
Nitrite-nitrogen	mg/L	.02	13.39	.01	13.40	.00	13.40	.00	13.40	.18	12.97	.20	12.86	.07	13.33
Fecal-coliform	cells/ 100 mL	2200	−3.06	190	13.28	400	12.86	110	13.36	50000	−8486	2000	.00	5380	−85.01
pH	units	6.4	8.11	7.8	7.52	7.0	8.92	7.1	8.90	7.5	8.38	7.1	8.90	7.1	8.90
Fluoride	[1]	0	8.79	.22	8.74	.13	8.89	.05	8.87	.17	8.85	[2].17	8.85	.10	8.90
Chloride	mg/L	20	6.16	170	2.14	17	6.24	18	6.22	86	4.40	[2]60	5.09	35	5.76
Sulfate	mg/L	14	6.32	100	4.02	9.6	6.44	8.0	6.49	23	6.08	[2]20	6.12	12	6.38
Phenols	μg/L	1.0	.00	.0	5.30	1.0	.00	.0	5.30	.0	5.30	.0	5.30	.0	5.30
MBAS	mg/L	.00	5.30	.00	5.30	.29	2.23	.00	5.30	.56	−.64	.00	5.30	.05	4.77
Copper	mg/L	.007	4.46	.005	4.46	.010	4.46	.006	4.46	.004	4.45	.011	4.46	.007	4.46
Iron	mg/L	.150	2.25	.390	−1.35	.050	3.75	.280	.30	.120	2.70	.120	2.70	.220	1.20
Zinc	mg/L	.020	4.48	.030	4.47	.010	4.49	.030	4.47	.040	4.46	.820	3.76	.230	4.29
Color	Pt-Co	130	−9.02	30	3.78	30	3.78	180	−21.42	30	3.78	50	2.50	130	−9.02
Index		57.1		81.5		87.5		61.3		−8560		28.3		−44.1	

NOTE: (1) Cedar Bayou near Crosby, Texas, Nov. 8, 1972.
(2) Chocolate Bayou near Alvin, Texas, May 16, 1973.
(3) Little Wehiva River near Altamonte Springs, Florida, May 17, 1973.
(4) Buffalo Bayou at Piney Point, Texas, Nov. 15, 1972 discharge 400 cubic feet per second.
(5) Buffalo Bayou at Piney Point, Texas, Mar. 12, 1973 discharge 59 cubic feet per second.
(6) Buffalo Bayou at Piney Point, Texas, May 14, 1973 discharge 155 cubic feet per second.
(7) Buffalo Bayou at Piney Point, Texas, discharge weighted average of (4) through (6).

[1] Value shown for concentration is the ratio (R).
[2] Concentration estimated from available data.

for continuous use of water on all soil types (National Academy of Sciences and National Academy of Engineering, 1972).

TYPE-I PROPERTIES

The constituents that were selected as type-I properties were those that are generally considered to be extremely phytotoxic at very low concentrations. The properties given in table 6 are either trace metals, molybdenum and selenium, that are extremely phytotoxic, or are organic herbicides.

TABLE 6.—*Recommended limits of type-I properties for irrigation index*

Property	Recommended limit
Molybdenum	0.01 mg/L
Selenium	.02 mg/L
Delepon	.2 μg/L
TCA (trichloracetic acid)	.2 μg/L
2, 4-D	.1 μg/L

TYPE-II PROPERTIES

Of the constituents selected for type-II properties (table 7), only the SAR (sodium absorption ratio) and the specific conductance are presented here in greater detail. Fecal coliform bacteria were selected for their indication of potential hazard to livestock and human health, and the elemental constituents were chosen for their phytotoxicity.

SAR.—The SAR was chosen because it is a measure of the degree to which irrigation water tends to enter into cation-exchange reactions in soil. High values of the SAR imply that sodium may be replacing absorbed calcium and magnesium in the soil; this replacement is damaging to soil structure (Wilcox, 1955; Hem, 1970). The SAR is computed as follows:

$$SAR = \frac{(Na^+)}{\left[\frac{(Ca^{+2})+(Mg^{+2})}{2}\right]^{1/2}} \quad (6)$$

where the ion concentrations are expressed as meq/L (milliequivalents per liter). Because the SAR is related to the sodium to calcium-magnesium ratio it can be large even though the concentrations of sodium, calcium, and magnesium are relatively small.

Specific conductance.—The specific conductance was selected as a measure of salinity or dissolved solids. Specific conductance is expressed in micromhos per centimeter at 25°C.

The type-II properties selected for the irrigation index, their group ranking, concentration limits, and the equations for calculating their respective contribution to the WQI are given in table 7.

APPLICATION OF INDEX

The irrigation indices determined for selected western waters, where irrigation is a significant practice, are shown in table 8. Because of the number of minor elements included in the index, it is difficult to find analyses that include the complete suite of properties. It was necessary to estimate two or three concentration values for most of the available analyses. Missing data were estimated by two methods. If data were available from other analyses at the same station, these data were used. If no data were available from the selected station, data from stations upstream or downstream or both were used. If data were not available to make a reasonable estimation, the station was not used. The error in estimation was probably not large enough to significantly affect the value determined for the index. The data for Silver Tip Creek were included to show the effect of high SAR, specific conductivity, and boron values. Even if the missing concentration data were available and were at the ideal concentration, the index would still be negative. The data in table 8 are presented to show the application of the irrigation index.

CONCLUSIONS

Water-quality indices for specific water-use categories can be developed and used to advantage. The water-use category can be very broad in scope, such as those in this report, or quite narrow in scope. For example use categories can be restricted to items such as a single fish species of commercial importance, an important cash crop such as pecans, or a single industry that requires a specific water quality for its processes. Whether the use category is broad or narrow, information must be available on the effect on that use of the concentrations of the significant water-quality constituents. If it is, a useful water-quality index can be developed.

TABLE 7.—*Type-II properties for irrigation index*

Group	Property	Concentration [1] Limit	Concentration [1] Ideal	Water quality index equation
A	SAR	10	0	$11.1 - 0.111\ (SAR)^2$
	Specific conductance	750	0	$11.1 - 0.00002\ (micromhos)^2$
	Fecal coliform	1,000	0	$11.1 - 0.000011\ (cells/100\ mL)^2$
B	Arsenic	0.1	0.0	7.4 - 74.0 (mg/L As)
	Boron	1.0	.0	$7.4 - 7.4\ (mg/L\ B)^2$
	Cadmium	.01	.0	$7.4 - 74{,}000\ (mg/L\ Cd)^2$
C	Aluminum	5.0	0.0	$5.55 - 0.222\ /mg/L\ Al)^2$
	Beryllium	.1	.0	$5.55 - 555\ (mg/L\ Be)^2$
	Chromium	.1	.0	$5.55 - 555\ (mg/L\ Al)^2$
	Cobalt	.05	.0	5.55 - 111 (mg/L Co)
	Manganese	.2	.0	5.55 - 27.75 (mg/L Mn)
	Vanadium	.1	.0	5.55 - 55.5 (mg/L V)
D	Copper	.2	.0	$2.80 - 70.0\ (mg/L\ Cu)^2$
	Fluoride	1.0	.0	$2.80 - 2.80\ (mg/L\ F)^2$
	Nickel	.2	.0	$2.80 - 70.0\ (mg/L\ Ni)^2$
	Zinc	2.0	.0	$2.80 - 0.7\ (mg/L\ Zn)^2$

[1] Concentration units are shown in column 5.

TABLE 8.—*Irrigation indices and individual property effects for selected waters*

[All properties expressed in mg/L except Specific conductivity which is expressed in umho/cm and Fecal coliform which is expressed in cells/100 mL]

Property	(1) Conc.	(1) WQI(i)	(2) Conc.	(2) WQI(i)	(3) Conc.	(3) WQI(i)	(4) Conc.	(4) WQI(i)	(5) Conc.	(5) WQI(i)
SAR	0.0	11.10	4.0	9.32	0.8	11.03	0.1	11.10	15	−13.88
Specific conductance	451	7.03	1750	−50.15	117	10.83	22	11.09	6340	−792.81
Fecal coliform	200	10.66	140	10.88	[2]48	11.07	0	11.10	--	--
Arsenic	.001	7.33	.000	7.40	.000	7.40	.002	7.25	--	--
Boron	.020	7.40	.260	6.90	.050	7.38	.000	7.40	3.100	−63.7
Cadmium	.000	7.40	.000	7.40	.001	7.33	.001	7.33	--	--
Aluminum	.000	5.55	[1].000	5.55	[1].000	5.55	.010	5.55	--	--
Beryllium	[1].000	5.55	.000	5.55	.000	5.55	.000	5.55	--	--
Chromium	.000	5.55	.000	5.55	.000	5.55	.000	5.55	--	--
Cobalt	.00	5.55	[1].000	5.55	[1].000	5.55	.000	5.55	--	--
Manganese	.020	5.00	.010	5.27	.020	5.00	.010	5.27	.020	5.00
Vanadium	.002	5.44	[1].000	5.55	.005	5.27	.000	5.55	--	--
Copper	.001	2.80	.020	2.77	.003	2.80	.001	2.80	--	--
Fluoride	.1	2.77	.5	2.10	.5	2.10	.1	2.77	1.6	−4.37
Nickel	.000	2.80	.005	2.80	[1].000	2.80	.003	2.80	--	--
Zinc	[1].020	2.80	.020	2.80	.020	2.80	.010	2.80	--	--
Index	94.7		35.2		98.0		99.5		(−873)	

NOTE: (1) Castle Creek above Deerfield Reservoir, near Hill City, South Dakota, Dec. 18, 1972.
(2) Powder River at Moorhead, Montana, Apr. 4, 1972.
(3) Big Jacks Creek near Bruneau, Idaho, June 15, 1972.
(4) Little Boulder Creek above Baker Lake, near Clayton, Idaho, Aug. 29, 1972.
(5) Silver Tip Creek near Belfry, Montana, Aug. 8, 1972.

[1] Estimated value.
[2] Immediate coliform value.

Most of the analytical data presently available do not contain the complete suite of properties required for application to one or more of the indices. Indices can be calculated using an incomplete suite of properties; however, the uncertainty of the index value increases with the number of missing properties. Comparing index values computed from data sets having missing properties is risky at best. The comparability of two waters where different properties are missing—for instance, fecal coliform bacteria for one water and fluoride for the other—is also risky. If one must use indices computed from incomplete suites of data, these indices should be computed from identical data sets so that they at least are directly comparable. In addition, care must be taken to inform the user of the index of the added uncertainty caused by the missing data. If at all possible, the missing properties should be estimated from available data; or if the index values are to be used in management decisions, the missing data should be collected.

Certain items are not provided by the index, and any attempt to use it as a guide for these is likely to lead to erroneous conclusions. These items are:

1. The index does not provide information on the concentration and distribution of the individual water-quality properties.
2. The index represents the net effect of all the properties involved; it does not provide information on which properties have positive and which have negative effects on the index.
3. The comparison of two index numbers will not provide information as to whether one water is more amenable to treatment than the other; it will indicate only the relative use hazards in the two waters.
4. A positive index number will only indicate that on the whole the water is fit for a particular use; it will not indicate whether a given property is marginal.

The index was designed to:

1. Provide directly comparable numbers such that various waters can be judged for use in specific categories.
2. Allow for comparison of water quality changes over time.
3. Provide information that managers and other nontechnical personnel can use easily.
4. Indicate waters of "good" and "bad" water quality for specific-use categories.

REFERENCES

Brown, R. M., McClleland, N. I., Deininges, R. A., and Tozer, R., 1970, A water quality index—do we dare?: Madison, Wisconsin Univ., National symposium on data and instrumentation for water-quality management, Proceedings, p. 363–383.

Harkins, R. D., 1974, An objective water quality index: Water Pollution Control Federation Jour., v. 46, no. 3, p. 588–591.

Hem, J. D., 1970, Study and interpretation of the chemical characteristics of natural water: U.S. Geological Survey Water-Supply Paper 1473, 363 p.

Hinman, J. J., Jr., 1938, Desirable characteristics of a municipal water supply: Am. Water Works Assoc. Jour., v. 39, no. 39(3), p. 484–494.

National Academy of Sciences and National Academy of Engineering, 1972, Water quality criteria 1972: U.S. Environmental Protection Agency, EPA R3–73–033, 594 p.

Walski, T. M., and Parker, F. L., 1974, A consumers water quality index: Am. Soc. Civil Engineers Proc., Jour. Environ. Eng. Div., v. 100, no. EE3, p. 593–611.

Wilcox, L. V., 1955, Classification and use of irrigation waters: U.S. Dept. Agriculture, Circ. 969, 19 p.