# EXPRESSION FOR DRINKING WATER SUPPLY STANDARDS

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**ABSTRACT:** Various authorities and regulating agencies have set standards for deciding the suitability of a water for drinking purposes. These standards prescribe the permissible concentrations of quality variables. When some variables exceed the permissible levels, a decision for permitting further use of the water supply has to be based on the importance of those variables with exceeded concentrations. It is proposed that standards for a drinking water supply should be set through a single number representing the integrated effect of all the variables, keeping due regard to the importance of each variable. Such an integrated water quality index (WQI) would help in decision making. Models and curves have been presented to evolve a WQI for drinking water supplies. It is suggested that water with a WQI lower than 90 should not be permitted. The acceptable quality therefore, should be in the 90–100 range of the WQI.

## INTRODUCTION

A water supply intended for the public should have the essential requirements of being wholesome and palatable. To exercise a check on such public water supplies, standards promulgated by various authorities such as the United States Environmental Protection Agency and W.H.O., have been set. These standards limit the concentrations of various constituents in the water. Such concentrations are provided to give guidance on the physical, chemical, and bacteriological quality of the water supplied and ensure its wholesomeness and palatability. In well managed water treatment plants, regular monitoring of the raw water, as well as the treated water, is performed to check on treatment and quality just before it's supplied to the public.

In some situations, the treated water does not satisfy the standards in respect to some water quality properties. The decision to supply such water to the public should depend on the exceeded concentrations as well as the importance of the property, as far as its contributions to the health of the consumers. As an example, whether or not the chloride, the total dissolved solids (TDS) concentration, or the concentration of coliform organisms has exceeded the set limit should be viewed before a decision is made. If it is chlorides or TDS that are in excess, another factor that would influence the decision is to what extent they exceed the permissible concentration. Often it is a group of variables having different importance, in regard to their effects on the health of the public that exceed their permissible levels. Sometimes a water supply is rejected if the concentration of some variable exceeds its permissible limits, regardless of the type of variable. Making decisions regarding acceptability of water would be easy if the overall effect in the water quality deviation could be expressed in an integrated manner, giving due regard to both the importance of each constituent as well as the magnitude of its exceeded concentration.

Therefore, it is considered appropriate to set upper and lower levels of standards for drinking water through a simple number. This number would show the overall integrated effect of all the water quality variables and their respective concentrations, as well as the related implications of drinking such water. The integrated number, or index, should be so evaluated that the effect of variables with different importance to drinking water quality are appropriately taken care of. For example, since there can be little compromise on the permissible concentration of coliforms, the integrated index formulation should, therefore, be sensitive enough to lower the integrated index value significantly when the coliforms rise to an unacceptable concentration level. Similarly, if the chlorides rise above their permissible level, it would be a minor threat to human health; thus the integrated index should show only a slight drop with the rising concentrations of chlorides. Presentation of drinking water standards through such an integrated water quality index (WQI) has been attempted herein.

## INTEGRATED WATER QUALITY INDEX

To fulfill the stated objective: (1) The integrated water quality index (WQI) should change with changes in the values of each of the water quality variables; (2) the change should be greater due to a variable which produces the more important quality impact; (3) the index should approach a very low value when some critical variable (whose concentration beyond the permissible level cannot be compromised) exceeds the permissible limit; and (4) the index should remain unchanged when a variable's concentration changes within its permissible level.

Brown, et al. (1,2) at the National Sanitation Foundation presented a model for an index which varied from 0–100. To evaluate the integrated index, they took an *arithmatic mean of the weighted quality index for* each variable. Because they used the arithmatic mean, their index was not significantly sensitive to changes in the values of the variables. Another model they developed was of the multiplicative type, where the geometric mean of the variables was taken such that,

$$\mathrm{WQI}(M) = \prod_{i=1}^{n} q_i^{w_i} \quad \text{.......} \quad (1)$$

in which, $\mathrm{WQI}(M)$ = the multiplicative water quality index; $q_i$ = the quality of the $i$th variable (which varied from 0–100 and was obtainable from curves presented for the variables); and $w_i$ = the unit weight of the $i$th variable, which varied from 0–1. Walski and Parker (6) also took the geometric mean and used a sensitivity function ranging from 0–1.0 in place of the variable's quality. Their model incorporated this sensitivity function for which values were calculated from curves and models they presented. They confined their study to the recreational use of water, and due to the difficulty of assigning proper weightings to each of the variables, their model may not significantly reflect the importance of each

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variable. Since any variable would have different significance to the many uses of the water the sensitivity-function values corresponding to the same variable value differed for different water uses. Therefore, based on an approach which included the importance of each variable in the sensitivity-function value, Bhargava (3) evaluated a simplified and rational model for working out the WQI. This model is expressed as

$$WQI = \left[\prod_{i=1}^{n} f_i\right]^{1/n} \quad (2)$$

in which, $f_i$ = the sensitivity function value of the $i$th variable, which included the effect of the concentration and weight of the $i$th variable in the use, and varied from 0–1; and $n$ = the number of variables considered. Curves based on the requirements of the WQI and involving the weighting effect of each variable on the various uses of water were plotted; and the WQI computed thus, were used for the classification of river waters for different beneficial uses (3). The effect on the WQI, due to changes in the concentration of a single variable, were depicted through curves to illustrate the effect of different weightings of a variable for the different uses (3).

## CRITERIA FOR EVOLVING SENSITIVITY FUNCTION VALUES FOR DRINKING WATER SUPPLY STANDARDS

For evolving the sensitivity function values for the different values of each variable used in defining the standards for drinking water supplies, all the variables are divided into groups. These groups are based on the importance related to the health of the people, and the degree of flexibility in allowing the concentrations to exceed the set standards.

The first group includes the concentration of coliform organisms to represent the bacterial quality of drinking water. This variable has a direct implication on the health of the consumer, and cannot be allowed in excess of the standards set by the various authorities. The sensitivity function for this variable should, therefore, fall rapidly to a level such that the WQI is significantly lowered to unacceptable levels, i.e., when the concentration of the coliforms exceed the permissible level and become dangerous.

The second group of variables include toxicants, heavy metals, etc., some or all of which have a cumulative toxic effect on the consumer. Their permissible concentrations are based on the physiological effects associated with symptoms related to concentrated levels of these variables. For such variables, a slight deviation from the permissible levels may be allowed, and it is thought that a deviation of any one variable alone to the extent of about 2 times the permissible level, should lower the WQI to an unacceptable level.

The third group of variables include the materials that cause physical effects, such as odor, color, turbidity, and other aesthetic qualities which are important factors in the public's acceptance and confidence in a public water system (4,5). Their concentrations relate to the palatability of the water and an excess of these variables would be disliked but would not be dangerous. Their implementation would not drive the public to obtain drinking water from potentially lower quality, higher risk sources. However, a little flexibility in their concentrations may be permissible and therefore, the sensitive function for these variables should gradually fall off when their concentration exceeds the permissible levels. It is also thought that a deviation of any one variable alone, to the extent of about 3 times the permissible level, should lower the WQI to an unacceptable level in the stated circumstances.

The fourth group of variables includes the inorganic and organic nontoxic substances such as chloride, sulfates, foaming agents, iron, manganese, zinc, copper, total dissolved solids (TDS), etc. Their values ex-

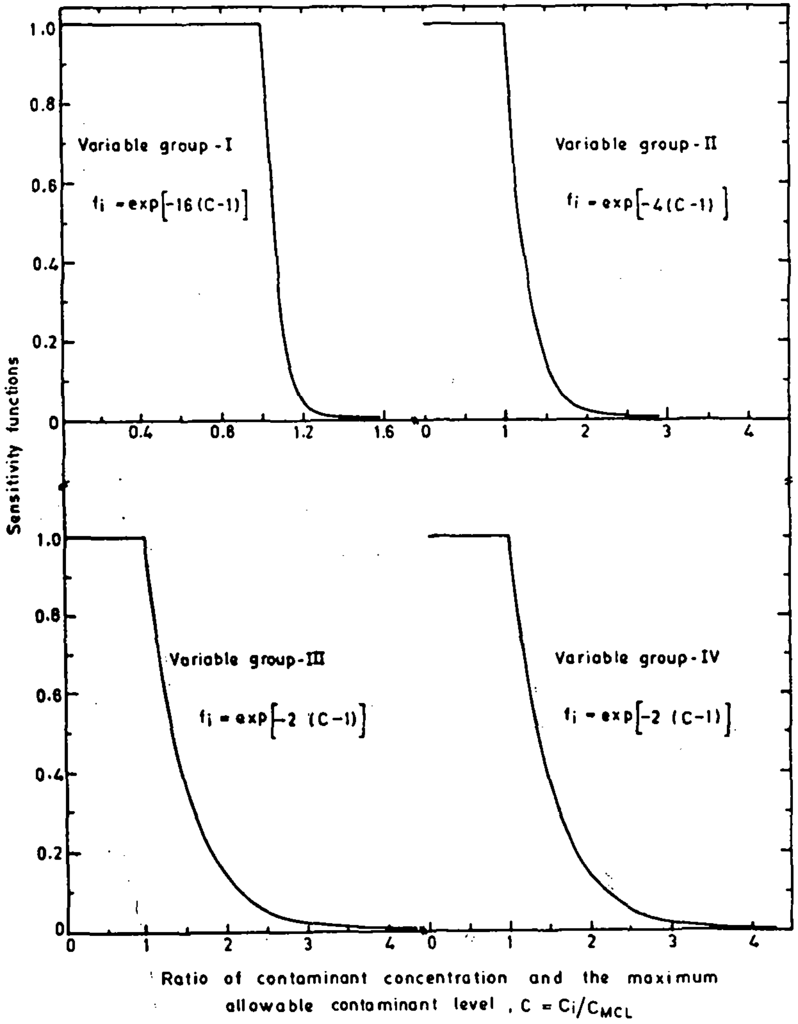

**FIG. 1.—Sensitivity Functions for Different Ratios of Variable Concentration to Its Permissible Concentration**

ceeding the permissible levels is not at all dangerous. States may establish higher or lower levels as appropriate to their particular circumstances depending upon local conditions, such as unavailability of alternate raw water source or other compelling factors, provided that public health and welfare are adequately protected. However, at considerably higher concentrations, these contaminants may also be associated with adverse health implications, and therefore, when their concentrations rise to levels where the water becomes unacceptable to most people, the sensitivity function should fall to low value rendering the WQI to reach a very small value. In these circumstances, it is thought that a deviation of any one variable alone to the extent of about 3 times the permissible level should lower the WQI to an unacceptable level.

Based on the previous governing principles, models are evolved for evaluating the sensitivity function values for the variables in the previously mentioned groupings. The newer U.S. EPA water quality standards (4,5) in accordance with these groupings, have been used.

C represents the ratio of the contaminant concentration, $C_i$, and the maximum allowable contaminant level, $C_{MCL}$ (as per the United States Environmental Protection Agency Drinking Water Regulations). $C = C_i/C_{MCL}$ is thus a unitless number. $C = 1.0$ for $C_i$ less than $C_{MCL}$. The models for sensitivity function, $f_i$, in a functional form relating to C, and the C and $C_i$ values at different $f_i$ values are plotted in Fig. 1, and presented for each of the four groups of variables (contaminants) in Table 1.

**TABLE 1.—Plotted Variables From Fig. 1**

| Variables (contaminants) (1) | Model for sensitivity function (2) | $C_{MCL}$ (as per U.S. EPA) (3) | C Values from Plots of Models for $f_i$ (Fig. 1), Corresponding to $f_i$ Values of: | | | | |
|---|---|---|---|---|---|---|---|
| | | | | $f_i$ Values | | | |
| | | | C: (4) | 1.0 (5) | 0.135 (6) | 0.018 (7) | 0.0025 (8) |
| Group I: Coliform organisms, e.g., coliform bacteria | $f_i = \exp[-16(C-1)]$ | 1 coliform bacteria per 100 ml (Membrane Filter Technique) | $C_i$ (Number per 100 ml) | 0–1<br>1 | 1.125<br>1.125 | 1.250<br>1.250 | 1.375<br>1.375 |
| Group II: Heavy metals, other toxicants, etc., e.g., chromium, lead, silver | $f_i = \exp[-4(C-1)]$ | 0.05 mg/L each | $C_i$ (mg/L) | 0–1<br>0.05 | 1.5<br>0.075 | 2.0<br>0.10 | 2.5<br>0.125 |
| Group III: Physical variables, e.g., turbidity color | $f_i = \exp[-2(C-1)]$ | 1 TU<br>15 color units | $C_i$ (TU)<br>$C_i$ (CU) | 0–1<br>1.0<br>15 | 2.0<br>2<br>30 | 3.0<br>3<br>45 | 4.0<br>4<br>60 |
| Group IV: Organic and inorganic nontoxic substances, e.g., chloride, sulfate TDS | $f_i = \exp[-2(C-1)]$ | 250 mg/L each<br>500 mg/L | $C_i$ (mg/L)<br>$C_i$ (mg/L) | 0–1<br>250<br>500 | 2.0<br>500<br>1,000 | 3.0<br>750<br>1,500 | 4.0<br>1,000<br>2,000 |

## EVOLVING WQI VALUES FOR GIVEN WATER QUALITY

Once the quality of a given water supply has been monitored for its various variables, $f_i$, the sensitivity function for each of the $n$ variables can be worked out or estimated from Fig. 1. The WQI can then be easily estimated from the model given by Eq. 2. In the newer U.S. EPA standards the total number of water quality variables ($n$) are 35.

It is seen from Fig. 1 and the various models used for their plots, that the WQI of a water would equal 100 when all its variables have values less than or equal to their respective permissible levels set by any authority. If however, one, or a group of variables exceed their concentration(s) beyond the permissible levels, the WQI would work out to be less than 100. The WQI would be slightly less then 100 if the variables that exceed their concentrations from the permissible level, belong to the nondangerous types. It is also easily seen that if the variables of the dangerous types would exceed their concentrations beyond the permissible levels, the WQI would be reduced more significantly. Four models (appearing in Column 2 of Table 1), evaluating the sensitivity function values for substitution in Eq. 2 (with $n = 35$) for the WQI estimation, show that the WQI value would drop slightly below 90 when the concentration of one variable belonging to group I deviates to 1.25 times its permissible limit; or of any one variable belonging to group II deviates to 2.0 times it permissible limit; or of any one variable belonging to group III or IV, deviates to 3.0 times its permissible limit. It is notable that the WQI drops to 90 with only one variable of any one group deviating. In view of the criteria outlined while grouping the variables on the basis of permissible flexibility in their deviations, it is justified to allow a WQI range of 90–100 for a public water system. For obvious reasons, therefore, a treated water having a WQI value lower than 90 should not be supplied to the public. This index 90 ensures that not a single variable has deviated to an extent to cause any health hazard to the consumer. This range of 90–100 as the permissible limit of the WQI is, however, an arbitrary judgment. Depending on economy, facilities available for water treatment, quality of available raw water source, etc., one can set his own range of the permissible WQI.

The variation effect of a variable belonging to any of the four groups on the WQI can also be observed. To show this point, assume that the WQI of a water supply is 100, i.e., all the variables are within their permissible limits. Now suppose, one variable of any one group varies in concentration beyond the permissible level. The WQI will change, and the new WQI for the different values of the single varying variable can be worked out from the expression

$$WQI' = WQI\left(\frac{f_i'}{f_i}\right)^{1/n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

in which, WQI′ = the changed WQI due to change in the concentration of one variable of any one group; $f_i'$ = the sensitivity function for the changed concentration ($C_i'$) of the variable and is determinable from the models and plots presented in Fig. 1; WQI = the value when all variables were within permissible limits and equals 100; $f_i$ = the sensitivity function of the variable when its concentration ($C_i$) is within the permissible limits and equals 1.0; and $n$ = the number of variables involved. Thus

$$WQI' = 100\left(\frac{f_i'}{1}\right)^{1/n} \quad \ldots\ldots (4)$$

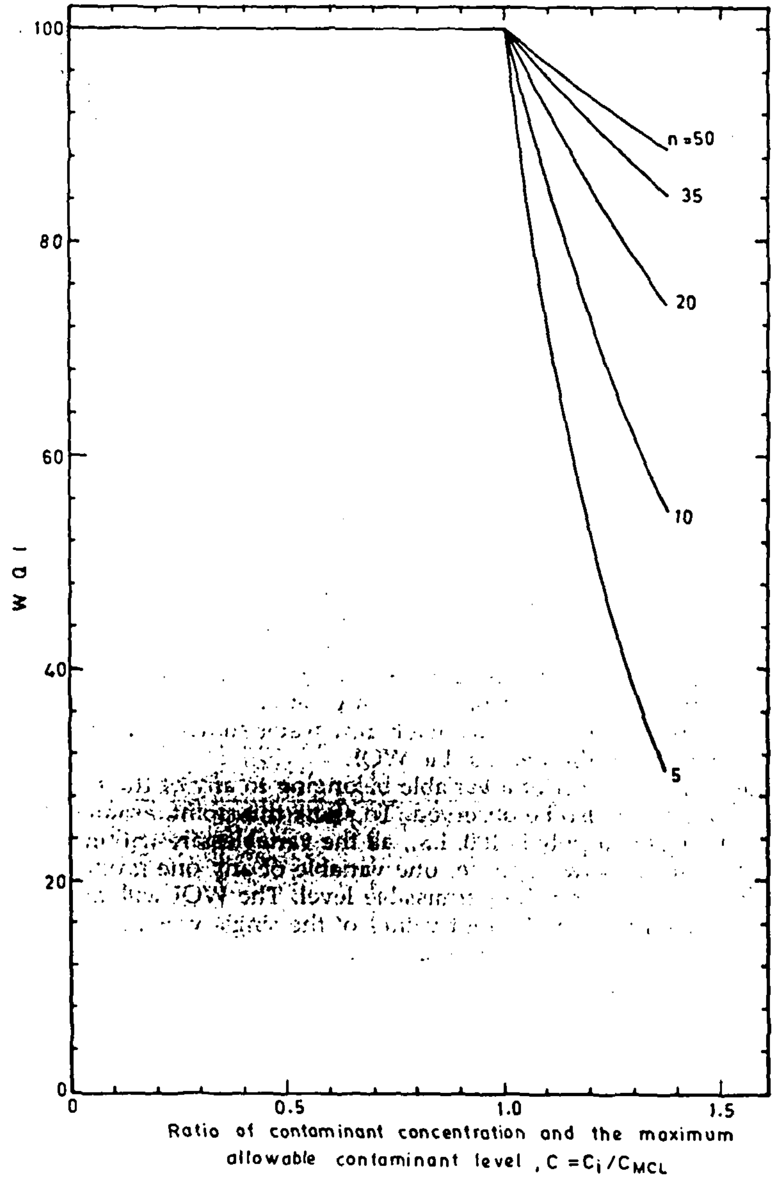

FIG. 2.—Variation of WQI with $C$ at Various $n$ Values (Variables of Group I)

For each of the four groups of the variables, the new WQI′ values for different changed concentrations ($C_i'$ values) of any one variable belonging to any one group, are worked out from Eq. 4, and plotted in Figs. 2–4 as variation plots of the WQI with respect to changes in concentration of one variable beyond the permissible limits, for the various $n$ values. When $m$ variables change, the variation power factor in Eq. 4 would change to $(m/n)$. When a public water supply has been monitored for contaminants, its WQI can also be evaluated directly from the curves presented in Figs. 2–4 by using C values of the deviated variables taking one variable at a time. Plots of C versus $n$ at the different WQI

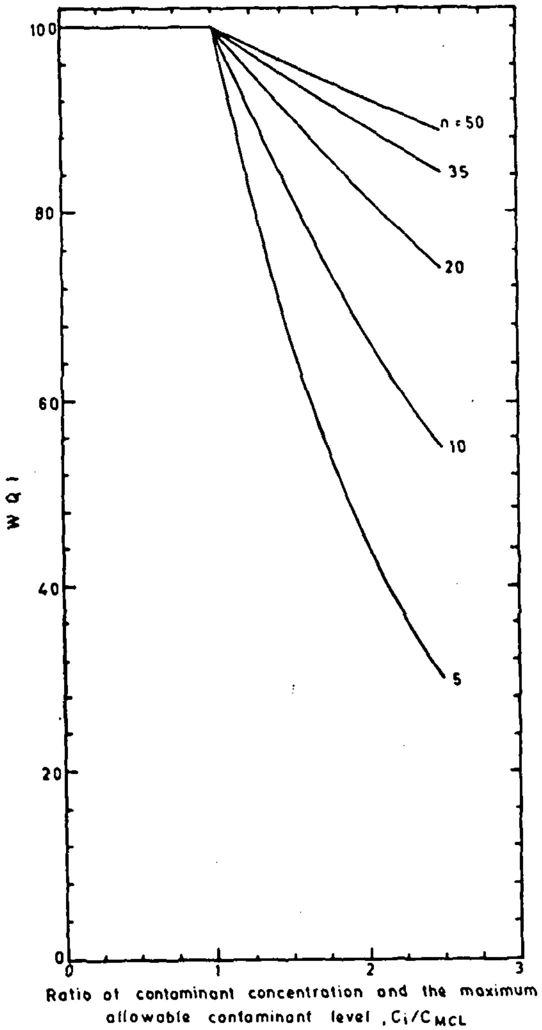

FIG. 3.—Variation of WQI with C at Various $n$ Values (Variables of Group II)

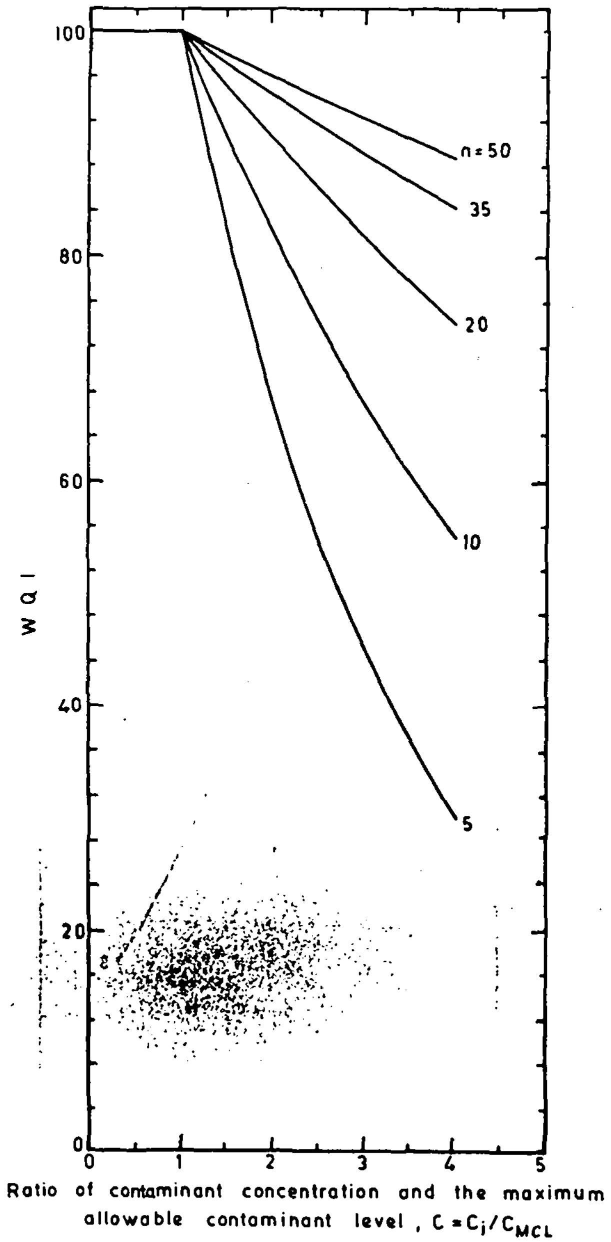

FIG. 4.—Variation of WQI with $C$ at Various $n$ Values (Variables of Group III and IV)

values for groups I–IV have also been shown in Figs. 5(*a–c*). These plots clearly indicate that WQI drops to around 90, as pointed out before, when the concentration of one variable from Group I, Group II, or Group III or IV deviates to 1.25, 2, or 3 times the permissible value, respectively. Plots of Figs. 5(*a–c*) are used to correlate $n$, WQI, and $C$ values through the following models:

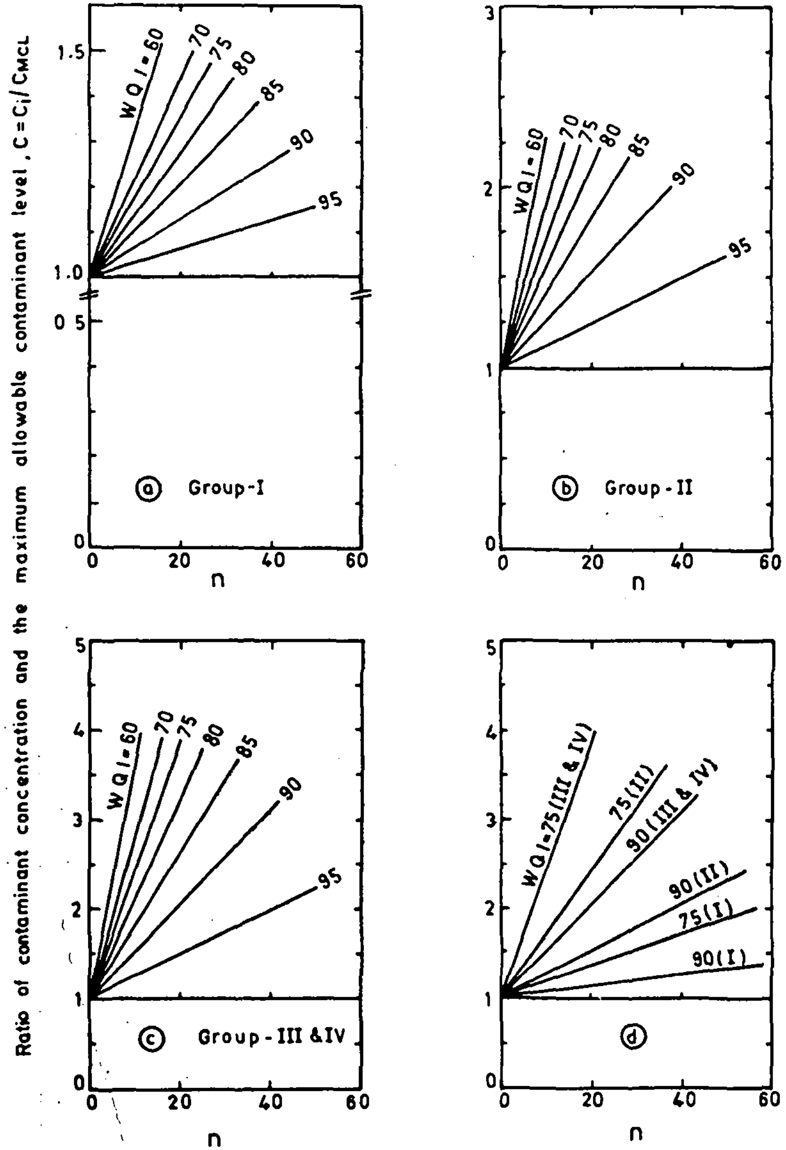

FIG. 5.—Variation Plots of $C$ as Function of $n$

Group I: $n = (C - 1)(1.056)^{WQI}$ .............................. (5)

Group II: $n = (C - 1)(1.035)^{WQI}$ .............................. (6)

Group III & IV: $n = (c - 1)(1.025)^{WQI}$ ......................... (7)

Fig. 5(*d*) presents variation plots of C as a function of *n* at WQI values of 90 and 75 for all the four groups. This provides a ready comparison of permitted deviation in the value of any one variable belonging to any one group and shows the number of parameters, $C_i$, which one must analyze to make the water quality acceptable. From Figs. 2–4 improvements in WQI due to treatment processes such as sedimentation/filtration for turbidity improvements or disinfection for coliforms inactivation, can also be estimated.

### EXAMPLE OF DELHI WATER SYSTEM

India's capital, Delhi, has water treatment plants, one each at Wazirabad and Okhla situated, respectively, at the upstream and downstream side of the Delhi stretch of the Yamuna river. The raw water quality of the river at both these locations is indicated in Table 2. In Table 2, "nil" indicates that the $C_i$ value is less than the detection limit of the analytical procedure. Since at both these locations the water is subjected to a complete conventional treatment [at Okhla, heavy prechlorination is also practiced due to the high BOD (about 6–8 mg/L) of the river water at this point], the coliform organisms and turbidity are reduced to less than 1/100 ml, and 1 TU, respectively. Therefore, from Wazirabad treatment plant, all the quality variables are within their permissible limits (U.S. EPA standards) and, therefore, the WQI stands at 100. At Okhla, the treated water would have all of its quality variables (23 in number) except manganese within their permissible limits (U.S. EPA standards). Since the concentration of manganese, a variable belonging to Group IV (which is presumably not reduced significantly during the conventional water treatment), is 2 times the permissible limit (i.e., $C = 2$) and is the only variable that deviates from its permissible limit, the WQI value of this water would be lowered to 91 as can be apparent from the use of plots (at $C = 2$, and $n = 23$) presented in Figs. 4 and 5. The 91 as WQI shows that the water is permissible for supply to the public. Since the raw water quality in term s of BOD is not good at Okhla, the public is suspicious about the water system from that plant. This has given rise to controversies several times although no epidemic could be attributed to it. The WQI shows it. However, at both treatment plants at Delhi, it should be ensured that filtration and disinfection units are operating efficiently enough to reduce the coliforms and turbidity to permissible levels.

**TABLE 2.—Raw Water Quality of Yamuna River at Wazirabad and Okhla in Delhi**

| Group number (1) | Contaminant(s) (2) | Concentration ($C_i$) Delhi (3) | Concentration ($C_i$) Okhla (4) | Unit (5) |
|---|---|---|---|---|
| I | Coliform Bacteria | +12,000 | +93,000 | Number/100 ml |
| II | Arsenic | nil | nil | Milligrams per liter |
| | Barium | nil | nil | Milligrams per liter |
| | Cadmium | nil | nil | Milligrams per liter |
| | Chromium | nil | nil | Milligrams per liter |
| | Fluoride | 0.2 | 0.3 | Milligrams per liter |
| | Lead | nil | nil | Milligrams per liter |
| | Mercury | nil | nil | Milligrams per liter |
| | Nitrate-N | nil | 0.8 | Milligrams per liter |
| | Selenium | nil | nil | Milligrams per liter |
| | Silver | nil | nil | Milligrams per liter |
| III | Turbidity | 20 | 30 | TU |
| | Color | 5 | 15 | Color units |
| | Odor | — | — | Threshold odor number |
| | pH | 8.1 | 7.9–8.2 | |
| IV | Chloride | 12–30 | 40–70 | Milligrams per liter |
| | Copper | 0.009 | 0.015 | Milligrams per liter |
| | Detergents as ABS | 0.02–0.1 | 0.15–0.2 | Milligrams per liter |
| | Iron | 0.05–0.1 | 0.1–0.13 | Milligrams per liter |
| | Manganese | 0.02–0.05 | 0.05–0.12 | Milligrams per liter |
| | Sulfate | 30–40 | 45–60 | Milligrams per liter |
| | Total dissolved solids | 200–250 | 315–380 | Milligrams per liter |
| | Zinc | 0.03–0.05 | 0.02 | Milligrams per liter |

### PRACTICAL APPLICATIONS

The integrated water quality index (WQI) for drinking water supplies can be conveniently used for deciding the suitability of the water supply for the public. Once the quality of the treated water is monitored, the WQI can be worked out for an index and an administrative decision can be made permitting the consumption of a treated water. Such a decision is expected to prove more rational. Only one standard (namely, WQI, not to be exceed 90) may be enough instead of laying out permissible levels for a very large number of quality variables, because even if the concentration of one variable rises to a high level, the WQI would not reach near 90.

### SUMMARY

A water supply to the public is monitored for its various quality variables to examine if any exceed concentration beyond the range of standards set by the various regulating agencies. In most situations, some variables do exceed their permissible levels. In these cases, the decision to allow such water for public use would depend on the importance of the variable involved, as well as the magnitude of its exceeded concentration, in respect to its effects on the health of consumers. Such a decision would be easy if the effect of all the variables can be expressed through an integrated number which takes account of the importance as well as the concentration of each variable. An approach has been presented to evolve such an integrated water quality index (WQI) for drinking water supplies. It has been suggested that public drinking water supplies should have a WQI larger than 90.

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## APPENDIX II.—NOTATION

*The following symbols are used in this paper:*

$C$ = ratio of contaminant concentration ($C_i$) and maximum allowable contaminant level ($C_{MCL}$);
$C_i$ = concentration of contaminant;
$C_i'$ = changed contaminant concentration;
$C_{MCL}$ = maximum allowable contaminant level as per U.S. EPA drinking water regulations;
$f_i$ = sensitivity function of $i$th variable;
$f_i'$ = changed sensitivity function of $i$th variable;
$n$ = number of water quality variables under consideration;
$q_i$ = quality of $i$th variable;
$w_i$ = unit weight of $i$th variable;
WQI = water quality index;
WQI$'$ = changed WQI; and
WQI($M$) = multiplicative WQI.

# CALCIUM SULFATE SOLUBILITY IN ORGANIC-LADEN WASTEWATER

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**ABSTRACT:** Calcium sulfate solubility product and ion pair dissociation constant were measured in clean water, and these results were employed in tests with a pretreated coal conversion process wastewater to assess the tendency for organic matter in the wastewater to function as a complexing agent for calcium. It was demonstrated that wastewater organic matter interacted with calcium to form a calcium-organic complex. The extent of this interaction in wastewater was as significant as that for formation of the $CaSO_4^0$ ion pair in assessing solubility of $CaSO_4$. It was shown that the organic matter complexed with calcium to an extent comparable to humic acid, and that the complexing strength was similar to that predicted for citrate when compared on an equivalent COD or TOC basis. The results of this study are important for evaluating $CaSO_4$ scale-forming reactions if wastewater is to be reused as makeup water to an evaporative cooling tower.

## INTRODUCTION

The purposes of this investigation were to: (1) Determine the solubility of calcium sulfate in clean water and in organic-laden coal conversion process wastewater; and (2) to examine the effect of organic constituents in wastewater and in synthetic process wastewater on calcium sulfate solubility. The study entailed both laboratory experiments and chemical equilibria modeling. The work performed in this study was part of a project to evaluate several issues associated with water reuse strategies for the production of substitute fuels from coal. Calcium sulfate solubility was of interest because this compound may typically limit the cycles of concentration which may be achieved in an evaporative cooling tower. This is important, as reuse of wastewater as cooling tower makeup water has been consistently identified as the most significant means of reducing source water requirements for coal conversion facilities (5,9,29,30). The methodology employed in this investigation is applicable to study of calcium sulfate solubility in other industrial wastewater reuse applications.

## CALCIUM SULFATE

**Solubility.**—Calcium sulfate may precipitate in three forms: gypsum ($CaSO_4 \cdot 2H_2O$), anhydrite ($CaSO_4$) and hemihydrate ($CaSO_4 \cdot 1/2H_2O$). Gypsum and anhydrite are the dominant forms in the temperature range of natural waters and recirculating waters in cooling towers. The solu-

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