MODEL OF COLIFORM BACTERIA IN GRAND TRAVERSE BAY

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Statistical and preliminary deterministic models for total coliform bacteria in Grand Traverse Bay, Mich., have been developed previously. This work was reported in an earlier paper by Canale et al. This paper presented historical water quality data that clearly demonstrated seasonal as well as long-term changes in the bacterial quality of the waters in the west arm of the bay. These transient characteristics were studied with statistical techniques such as autoregression and multiple regression analysis. In addition to time variations, the data also portray a consistent spatial distribution of total coliform as observed at several beach sites on the southern shore of the west arm of the bay. The kinetic behavior of the death of total coliform bacteria in the bay was delineated by a correlation of experimental data collected by a number of different workers. The die-away of coliform in the bay was approximated by using first-order kinetic expressions, with the reaction rate coefficient being relatively independent of illumination, pre-chlorination, and season of the year. The reaction rate coefficient was found to be dependent on incubation temperature, with lower temperatures favoring prolonged survival. Knowledge of the annual temperature cycle in the bay waters was used to calculate the reaction rate coefficient as a function of the time of year.

The observed seasonal changes in total coliform bacteria, where summer peaks are approximately 50 times greater than winter values, are also the consequence of time-variable coliform inputs to the bay. The sources of coliform include the Boardman River, direct industrial waste discharges, storm sewer discharges, septic tank outfalls, groundwater seepage, private and commercial watercraft, waterfowl, swimmers and bathers, and circulation from the outer bay. A rational plan to control coliform density in the bay must be based on quantitative knowledge of the individual impact of each of these sources.

The goal of this paper is to develop and demonstrate verification of a simple and easily applied model for total coliform bacteria in Grand Traverse Bay. Field data collected over a number of years under various loading intensities will be compared to model predictions. After verification, the model will be used to predict the coliform levels resulting from individual coliform sources. Further, the model will be used to project the improvements expected under alternate enforcement schemes.

**Proposed Model**

Meier and Gannon have reported that except for near-shore regions, the west arm of the bay is relatively free of total coliform gradients. This suggests that a deterministic model of the coliform in the bay may be based on sectioning the region into two zones, as illustrated in Figure 1, where each zone is considered homogeneous in the vertical direction. An analysis of the spatial and transient behavior of total coliforms in either zone depends on a knowledge of the behavior in the neighboring zone, because each segment is coupled to the other through convective and dispersive transport. Although such an analysis is not difficult, an attempt was made to uncouple the zones by considering that a fraction of the loading is short-circuited directly to the offshore zone. This approach seems reasonable, because circulation patterns reported by Green for the west bay indicate the presence of rather...
high surface velocities in a direction perpendicular to the shore. This characteristic of the flow is the result of a deep-water channel that extends northerly from the southern shore of the bay. Southwest winds of 15 mph (24.2 km/hr) can cause surface velocities up to 0.3 mph (0.483 km/hr), which are capable of rapidly transporting contaminants originating near the shoreline to the outer bay. The un-coupled model is illustrated in Figure 2. The fraction of the loading short-circuit ed to the outer bay, $f$, cannot be determined directly. However, the value of $f$ depends on the magnitude of the advection and dispersion in a direction normal to the shore and can be estimated by analysis of observed coliform distributions.

The offshore section of the model is considered to be a completely mixed body of water. The time scale is such that the transient behavior of the model is representative of the observed weekly average values of total coliform. The continuity equation for total coliforms in this section can be written as

$$\frac{dc}{dt} = -\left[\frac{1}{\tau} + K(t)\right]c + \frac{W(t)}{V}$$  \hspace{1cm} (1)

where

- $c =$ weekly average total coliform density,
- $\tau =$ average residence time of a fluid element in the section,
- $K =$ time-variable temperature-dependent first-order reaction rate coefficient,
- $V =$ section volume, and
- $W(t) =$ the time-variable coliform loading caused by all sources. The residence time is calculated by dividing the section volume by the total flow into the section. The major components of the total flow are (a) Boardman River, (b) direct industrial discharges, and (c) circulation from the upper bay. These flows can be estimated from data obtained during surveys by the Michigan Water Resources Commission and the circulation models developed by Green. The resulting flows and section volume have been used to calculate an average residence time of 0.43 days. This figure has been used in subsequent calculations, which follow.

The die-away of total coliform can be assumed to be first-order, because bacterial nutrients in the bay are low. Canale et al. have shown that the reaction rate coefficient varies linearly with temperature, as described in Equation 2:

$$K(T) = 0.2 + 0.0223T$$  \hspace{1cm} (2)

where $T$ is in degrees Celsius and $K$ has the units day$^{-1}$. Equation 2, together with measurements of the annual temperature cycle, permits the calculation of $K$ at any time during the year. Figure 3 shows the
FIGURE 2.—Uncoupled two-zone model.

annual variation of $K$ in the lower west arm of Grand Traverse Bay based on daily temperature observations during 1958 and 1959.

Equation 1 is linear and has the general solution

$$c(t) = e^{-\alpha(t)} \int \frac{W(t)}{V} e^{\alpha(t)} dt + c_0 e^{-\alpha(t)}$$  \hspace{1cm} (3)

where

$$\alpha(t) = \int \left[ \frac{1}{T} + K(t) \right] dt$$

and $W(t)$ are arbitrary but integrable functions of time. This solution can be used to obtain the time variation of $c$ provided that the system parameters and forcing functions are known. It has also been convenient to use CSMP (Continuous System Modeling Program) for the numerical integration of Equation 3.

The near-shore section can be approximated as a one-dimensional strip with a net flow in the eastward direction parallel to the shoreline. Longitudinal dispersion superimposed on the net flow accounts for mixing because of the turbulent nature of the flow. The magnitude of the dispersion coefficient, $E_x$, reflects the degree of the lack of complete knowledge of the flow pattern. The continuity equation for total coliforms in this section can be written as

$$\frac{\partial c}{\partial t} = E_x \frac{\partial c}{\partial x} - U_x \frac{\partial c}{\partial x} - K(T)c$$  \hspace{1cm} (4)

where

$x = \text{distance downstream from a source in a direction parallel to the shoreline}$, and $U_x = \text{velocity}$. Available field data are not sufficient to verify both the transient and spatial behavior of coliform in this strip. Therefore, quasi-steady-state verification is sought by using spatial distributions obtained by time-averaging data collected during periods of relatively constant temperature and loading conditions. For this case, Equation 4 has a well-known solution that gives the distribution of $c$ resulting from a single point source,

$$\frac{c}{c_0} = \exp (jx)$$  \hspace{1cm} (5)

in which

$$j = \frac{U}{2E} \left[ 1 \pm \sqrt{1 + \frac{4KE}{U^2}} \right]$$
and

\[ W = Q \sqrt{1 + \frac{4KE}{U^2}} \]

Equation 4 is linear; thus, multiple-source distributions are obtained by using the principle of superposition. Because the kinetics, advective transport, and loading have been estimated independently, only the dispersion coefficient and \( f \) are to be determined. The values of these coefficients are obtained by comparing the solution given by Equation 5 with field observations.

**Verification**

During 1963 a survey of coliform discharges into the bay and the Boardman River was conducted by the Michigan Water Resources Commission. The survey included measurements of the quantity and coliform density of several fruit-processing wastes. During this same period, several river and beach surveys were conducted by the municipal employees associated with the Traverse City Waste Treatment Plant. In addition, a record is available showing daily variations in the coliform density and turbidity in waters drawn at the Water Treatment Plant (see Figure 1 for intake pipe location).

The loading required to produce the response recorded at the municipal water intake pipe can be calculated by using Equation 1, because estimates of the residence time, volume, and kinetics are available. This calculated loading \( W_{\text{calc}} \) is computed from observed values of the coliform concentration \( c_{\text{obs}} \) with the equation

\[
\frac{W_{\text{calc}}(t_i)}{V} = \frac{d}{dt} \left[ c_{\text{obs}}(t_i) \right] + \left\{ \frac{1}{\tau} + K[T(t_i)] \right\} c_{\text{obs}}(t_i)
\]

\((i = 1, N)\) (6)

and a suitable method for estimating the time derivative of \( c_{\text{obs}} \). The ratio of the calculated loading \( W_{\text{calc}}(t_i) \) to all known loadings is an estimate of the value of \( f \). Figure 4 shows a comparison of \( W_{\text{calc}}(t_i) \) and 3 percent of all known loading from industrial, municipal, and stream sources. The loading associated with circulation flows from the outer bay is considered insignificant. Except for the fall period, the known and calculated loading seem con-
consistent when a constant value of \( f \) equal to 0.03 is used. Differences between the calculated and observed loading could be the result of either a time-variable \( f \) or waste loadings from unknown sources. Although either factor may be of some im-

FIGURE 4.—Calculated and measured coliform loading during 1963.

FIGURE 5.—Model-predicted response of outer section during 1963.
FIGURE 6.—Beach coliform observations and model predictions during July 1963.

portance, the level of fruit-packing activity in the area generally parallels the deviation between calculated and known loading. Thus the unknown loading as shown in Figure 4 is probably the result of secondary late summer packing operations.

Equation 1 can also be integrated using known loadings to forecast values of coliform density. The effective input to this section is assumed to equal the surveyed loading times \( f \). Figure 5 shows such a forecast obtained with this loading and numerical integration using a fourth-order Runge-Kutta algorithm.

Equation 5 can be fitted to a quasi-steady-state coliform distribution observed during July 22 to July 24, 1963, by adjusting the value of the dispersion coefficient. The major loads come from two cherry waste discharges and the Boardman River. In each case it is assumed that the loads are point sources and 3 percent of the load is short-circuited directly to the outer segment. The kinetics are given by Equation 2 and the net circulation velocity is 0.327 mpd (0.61 cm/sec). The magnitude of the dispersion coefficient is then the single unknown parameter, which determines the final shape of the distribution as well as the initial dilution of the waste streams. Figure 6 compares available beach coliform data with the fit obtained by using a dispersion coefficient of 0.12 sq mi/day (36 sq m/sec). Although reasonable values of the fraction of short-circuiting and the dispersion coefficient permit a satisfactory fit of the available data, the proposed model cannot yet be presumed valid. Additional data must be examined, preferably under different loading or temperature conditions, before verification is achieved.

The temporal and spatial distribution of
total coliform in the bay and the Boardman River during 1964 has also been characterized by means of numerous surveys and routine monitoring by the water and wastewater treatment plant personnel. The validity of the structure of the model as
well as the consistency of the empirically determined coefficients $E$ and $f$ can be further evaluated using these data. This evaluation is made by computing predictions of the temporal and spatial distribution of total coliforms during 1964 using known loadings and kinetic behavior along with the coefficients $E$ and $f$ found by fitting 1963 data. The resulting predictions are then compared with actual data obtained in 1964. A favorable fit would suggest a consistency among the mechanisms affecting the distribution. Figure 7 compares loadings calculated according to Equation 6 with 3 percent of measured loadings. Again, with the exception of the fall period, the measured loading seems to account for the observed values of $c$. Figure 8 shows predicted values of total coliforms using known industrial and Boardman River loading and unknown fall loading, and compares these calculated values with values recorded at the municipal intake during 1964. Figure 9 shows a comparison of model predictions and the observed coliforms at the beach sites during a quasi-steady period between Aug. 13 and 17, 1964. The predictions were obtained by using a dispersion coefficient of 0.12 sq mi/day (12 sq m/sec) and loadings equal to $(1-f)$ times known loadings.

During 1970 and 1971, Meier and Gannon collected data on the distribution of total coliforms in the Traverse City area and on the sources of coliforms for the bay. Figure 10 shows the average levels of total coliforms recorded at the beach sites on the southern shore of the west arm of the bay.
bay during a period between July 11 and 16, 1970. Also shown is a predicted distribution based on a single point source at the mouth of the Boardman River. The model predictions were computed by using the same parameter values used to fit 1963 data and predict similar distributions in 1964. The Boardman River loading accounts for the measured coliform density during this period of July before the cherry-processing season.

**Discussion**

The proposed model structure and coefficient values have been tested with data collected over a period of 7 yr. During the 7 yr, the extent of the coliform loading and the subsequent response have varied over several orders of magnitude. In addition to these long-term changes, distinct seasonal differences in coliform distribution have been predicted adequately by the model. In each case it has been possible to explain the observed data with a simple model based on continuity equations. Only two coefficients were obtained by data-fit techniques, and once determined from the distribution in 1963, were not further adjusted to improve the fit of data obtained in subsequent years.

However, several empirical observations counter the assumptions of the model. Meier and Gannon have measured the die-away of total and fecal coliforms in the bay following the inoculation of closed containers with fresh wastewater. The decay following an aftergrowth was found to be dependent on the light intensity, with
much slower depletion in the dark bottles. The use of Equation 1 with vertical mixing results in death rates intermediate between dark values and full sunlight values, and thus results are representative of daily average light conditions. A more sophisticated analysis will be needed if problems arise that require knowledge of the total coliform distribution within time periods of less than 1 day, or in regions where the assumption of homogeneity with depth is violated.

A longitudinal dispersion coefficient of 0.12 sq mi/day (36 sq m/sec) has consistently produced satisfactory fits of measured data however, the value of the dispersion coefficient in Grand Traverse Bay has been studied by Green by direct measurement. The dispersion coefficient was calculated from the distribution of a fluorescent dye following the release of a concentrated point source. A range of values was found for the dispersion coefficient by using finite difference representations of governing continuity equations. Values of the dispersion coefficient obtained in this manner were approximately one order of magnitude below values found by fitting Equation 5 to the coliform distribution. However, the agreement between these values and the empirically determined value of 0.12 sq mi/day (36 sq m/sec) is considered satisfactory, because the length scales of the segmentation and precision of information on the advective transport are vastly different in each case.

Johnson and Monahan have shown that circulation within the bay is strongly influenced by the oscillation of Lake Michigan. Green's numerical hydrodynamic models for the bay with Lake Michigan forcing functions, along with empirical findings, suggest that truly steady-state conditions are never achieved in the bay. However, Canale and Green have developed a phenomenological model of circulation for the bay that supports the two-segment approach proposed here.

The analysis of coliform data between 1963 and 1971 has not suggested a need to include sources from groundwater, bay sediments, or aftergrowth. Thus, it is concluded that these sources were an insignificant fraction of the total input during the survey periods. However, the University of Michigan Sea Grant project plans field studies to evaluate specifically the magnitude of sources other than the Boardman River, industrial wastes, and storm sewer overflows during the summer of 1972.

**Application**

The availability of a verified model permits an analysis of alternate planning and
control policies on the bacterial quality of the bay waters as well as the probable impact of individual existing or new sources of contamination. For example, the role of storm sewer discharges as a factor in determining the levels of bacterial pollution in the bay is of current concern to Traverse City officials. Also, planners are considering opening the Hospital Creek drainage area for additional residential and industrial expansion. The probable impact on the bay of different levels of development under various treatment schemes should be a key factor in determining the ultimate recommendations concerning future expansion in this area. A final application of the model concerns the control of wastes released directly from small private watercraft.
Meier and Gannon have examined the levels of total coliform at Traverse City beaches during 1971. Their work included a survey of the Boardman River loading as well as surveillance of several storm sewers that discharge directly into the bay. The estimated total loading from these sources during July and early August is presented in Figure 11. Figure 12 shows coliform levels in samples obtained from the old municipal water intake during this period and compares these observations with model predictions. The rainfall during July and August 1971 was 1.5 times the long-term average for the area. Thus, although storm sewer discharges do contribute a significant fraction of the total pollution level, the overall levels are well below state recommendations for raw water supplies and total body contact recreational use. Figure 13 shows the observed contamination of beaches by boat spills of coliforms.

FIGURE 15.—Seasonal temperature effect on equivalent loads to outer section.

FIGURE 16.—Contamination of beaches by boat spills of coliforms.
tamination of Traverse City beaches, and estimates the individual contributions of the Boardman River and the individual storm sewers. Little improvement in the bacterial quality would be expected from collection and treatment of the storm sewer runoff.

It is seen that the degree of contamination during 1971 is several orders of magnitude lower than that recorded in 1963 and 1964. The improvements are the consequence of reducing the concentration of cherry-processing wastes that enter the bay. Such reductions have resulted from routing these wastes to the municipal treatment plant, which was made possible by the cooperation of the fruit-processing industry with state and local water quality control officials.

The effect of residential and industrial development in the Hospital Creek drainage basin is illustrated in Figures 14 and 15. Figure 14 shows the pollution resulting from the uncontrolled discharge of 1,000 population equivalents. The model projections account for the natural cyclic per capita production of total coliforms, as noted by Velz, as well as additional loading increases resulting from tourists during the summer season. Figure 15 shows the impact of two equivalent triangular industrial loadings released at different periods within a year. Although some advantage is obtained by releasing during the summer, when die-away rates are at a maximum, the recreational use of the local waters during this period would obviously prohibit such a practice.

Barbaro et al. have shown that the recreational use of water in marina and beach areas can significantly influence the bacterial quality of lakes. Although the discharge of holdings from boats into Grand Traverse Bay is prohibited by Michigan state law, it is of interest to examine the result of such discharges from accidental spills or violations of state regulations. Figure 16 shows the expected steady-state contamination at Traverse City beaches resulting from the release of holding tank wastes from six boats per day during late August. The predictions testify to the importance of the legislation that requires that boats with toilets be equipped with holding tanks for storage of wastes and that marinas have facilities for pump-out and disposal of holdings. Any relaxation of such control could prove disastrous to the maintenance of water quality in Grand Traverse Bay for total body contact recreational use.

SUMMARY AND CONCLUSIONS

A predictive model for total coliform bacteria has been developed by using continuity equations with a simple fluid transport model and temperature-dependent first-order kinetics. The resulting linear equations can be solved easily and evaluated without the use of a computer. The model has been verified over a wide range of loadings during a period of several years with data obtained during numerous field surveys. The model has been applied to a number of problems of interest to local planners and other officials concerned with the control of water quality in Grand Traverse Bay.

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