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MODELING THE SPATIAL DISTRIBUTION OF COLIFORMS IN
GRAND TRAVERSE BAY

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Abstract. A steady state mathematical model for the total coliform distribution in Grand Traverse Bay has been developed using continuity equations and experimental data describing die-away kinetics. Advective and dispersive transport phenomena were approximated using square-law assumptions and field dye tracer techniques. The predictive capability of the model was verified by comparing model calculations with observations during quasi-steady periods in 1963, 1964 and 1971. The utility of the model was demonstrated with two examples showing coliform distributions resulting from alternate waste disposal schemes. (Key words: Coliform bacteria; mathematical modeling; Grand Traverse Bay).

INTRODUCTION

The lower section of the west arm of Grand Traverse Bay has experienced elevated total coliform bacteria levels during a period between 1960 and 1970. This deterioration of water quality is the result of industrial, municipal and storm sewer discharges into the Bay. The University of Michigan Sea Grant Project has established an extensive data collection and mathematical modeling program covering a wide range of water quality variables. This paper reports on the development, verification and application of a model capable of predicting the steady state spatial distribution of total coliform bacteria in the Bay. The ultimate goal of the project is the development of a methodology which can be used by water resource planning agencies to minimize the impact of pollutants on the aquatic environment.

Between the years 1956 and 1965 Traverse City obtained its water supplies from a submerged pipe extending 1400 ft (425.6 m) into the west arm of the Bay, as shown in Fig. 1. The water treatment plant personnel made daily measurements of total coliform bacteria determined by the most probable number (MPN) procedure during this period. These data illustrate distinct seasonal periodicities as well as a long-term growth of the maximum levels as shown in Fig. 2. During this same period several river and beach surveys were conducted which identified the distribution of the MPN of total coliform along the southern shore of the west arm. Figure 3 shows the average of three such surveys conducted during early August 1964. Also shown are the location of two industrial waste discharges operative during this time. The observed seasonal transients and shoreline distributions are the result of such industrial discharges, wastes from summer tourist activity, the Boardman River loading and several storm sewer discharges. A major goal of the Sea Grant modeling and field studies is to quantitatively establish the impact of each of these waste sources separately, thus permitting a rational evaluation of alternate planning and water quality control policies.

A previous paper by Canale et al. (1972) has explored the usefulness of statistical models as a means of dealing with the transient behavior of total coliform levels in the Bay. These authors stressed the advantages of deterministic models based on continuity laws and presented data which defined the temperature dependence of the die-away rate of total coliform in the Bay. It

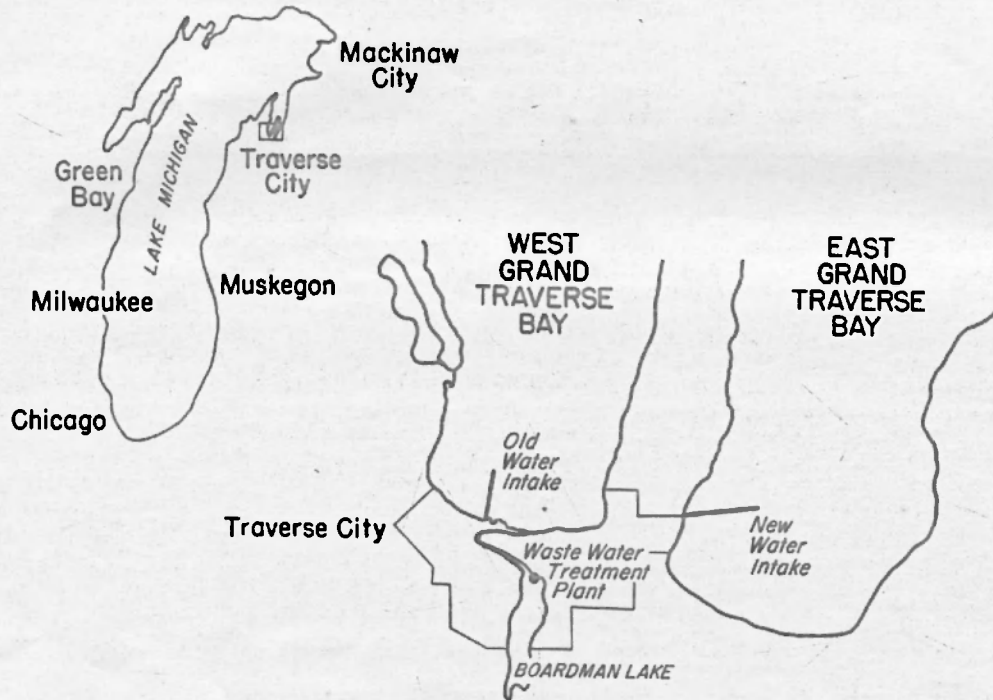


FIG. 1. Traverse City area and location of municipal water intake pipe.

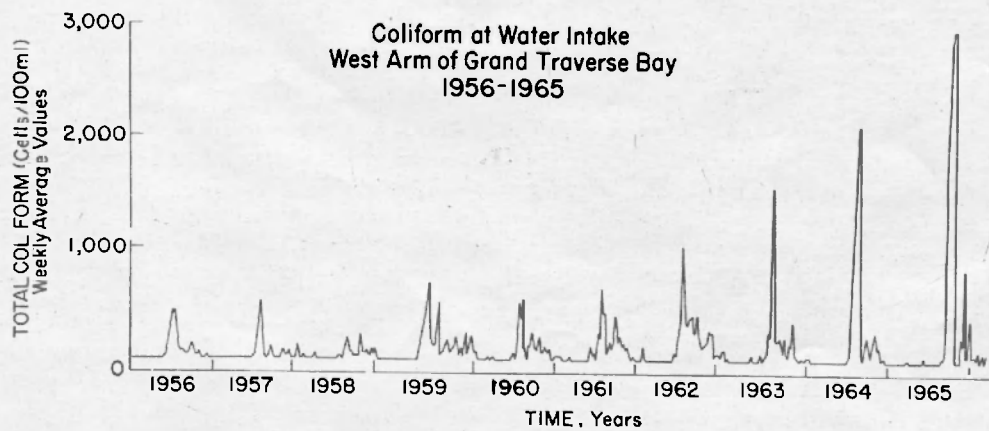


FIG. 2. Weekly average total coliform at water intake pipe between 1956 and 1965.

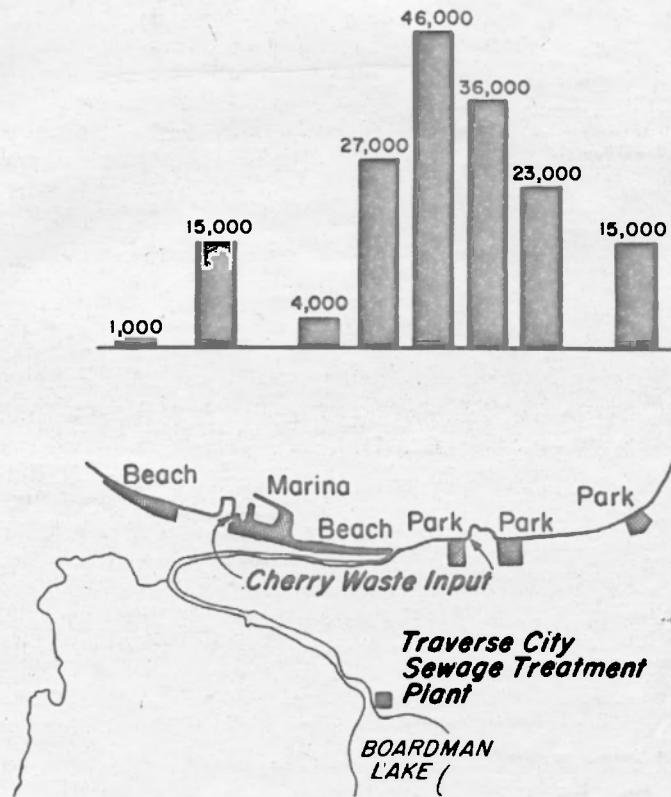


FIG. 3. Average total coliform (cells/100ml) at Traverse City beaches, 13-17 August 1964.

was found that the die-away could be approximated with first order kinetic expressions with the rate coefficient linearly related to temperature.

$$K(T) = .2 + .0223T \text{ (day}^{-1}\text{)} \tag{1}$$

Eq. 1 has an intercept value of K equal to $.2 \text{ day}^{-1}$ at T equal to zero and a slope equal to $.0223 \text{ day}^{-1}\text{C}^{-1}$ when T is in degree C. These workers suggested the use of Eq. 1 in a two-segment model of the lower west arm of the Bay. The first zone consisted of a shoreline strip representative of the beach region, the second an outer section representative of the vicinity of the water intake pipe. Canale (1972) has extended the above work using preliminary models for water circulation. The usefulness of this simple model was demonstrated by determining the impact of storm sewer discharges and other inputs in the shoreline strip. The present work has combined some results of a preliminary numerical model for Bay circulation with a multiple segmentation scheme for the lower part of the west arm.

MODEL DEVELOPMENT

Material balance models for the steady state spatial distribution of total coliform density require knowledge of the advective and dispersive transport processes, growth or death kinetics and the location of all coliform sources. Eq. 2 is a mathematical statement of the law of continuity for total coliform in a three-dimensional system.

$$\frac{\partial c}{\partial t} + \nabla \cdot (Uc) = \nabla \cdot (E\nabla c) + r_c \quad (2)$$

where c is the concentration of total coliform, U is the velocity, E is the dispersion coefficient and r_c is the reaction rate of coliform. The direct solution of Eq. 2 for natural systems is usually not possible. Therefore in practice, it is necessary to use numerical approximations which are equivalent to considering a continuous body of water as a series of finite interconnected segments. Thomann (1972) has shown that for steady state conditions, Eq. 2 can be reduced to the following for the case of first order kinetics:

$$V_k \frac{dc_k}{dt} = 0 = \sum_j [-Q_{kj} (\alpha_{kj} c_k + \beta_{kj} c_j) + E'_{kj} (c_j - c_k)] - V_k K_k c_k + W_k \quad (3)$$

where:

c_k = concentration of total coliform in segment k ,

c_j = concentration of total coliform in segment j ,

V_k = volume of segment k ,

Q_{kj} = net flow from segment k to segment j ,

α_{kj} = finite difference weighting factor,

$\beta_{kj} = 1 - \alpha_{kj}$,

$E'_{kj} =$ dispersion mixing coefficient between segments k and $j = E_{kj} A_{kj} / L_{kj}$,

K_k = first order reaction coefficient in segment k given by Eq. 1,

E_{kj} = dispersion coefficient between segments k and j ,

A_{kj} = cross-sectional area between segments k and j ,

L_{kj} = average characteristic lengths of segments k and j and

W_k = coliform load in segment k .

The basis for the multisegment coliform model rests on the assumptions that the circulation in the region of interest is steady in time and is homogeneous with respect to depth. As of this date, there are few data from either field measurements or numerical hydrodynamic models which directly substantiate these assumptions. Three empirical observations seem to vitiate the steady state hypotheses:

1. The wind stresses which are responsible for the bulk of the net mass transport in the Bay are not stationary in a statistical sense with respect to either time or space; however, Baker (personal communication)¹ has shown that the preponderance of winds over the Bay have a westerly component, while the dominant directions are southwesterly and north northwesterly.

¹Baker, D. G. Department of Meteorology, University of Michigan, Ann Arbor, Michigan.

2. Johnson and Monahan (1971) have observed that the Bay interacts sharply with Lake Michigan and is in fact forced to oscillate at frequencies which have been found to correspond to normal modes of Lake Michigan.

3. During the summer months, Arnold (personal communication)² has found that the Bay has a well-developed thermal stratification characterized by a well-defined thermocline at depths ranging from approximately 10 to 15 m; thus, the assumption of homogeneity of water properties within each cell of the model is to some extent faulty.

Although such criticisms of the steady state assumptions exist, it is possible to at least partially rationalize the use of an essentially phenomenological steady state circulation model for the lower west arm of the Bay. Although the Bay does not have a stationary state of circulation, there are two physical facts which indicate that the surface waters tend to drift eastward. Firstly, Arnold (1972) has observed that the outflow of the Boardman River, characterized by high nutrient levels, appears to move along the eastern side of the Bay. Secondly, the winds over the Bay generally possess a westerly component which will tend to move the surface layer of water eastward. The most frequent winds are from the southwest; thus, it has been assumed that the surface layer in the middle of the Bay has a net northeastward drift. Likewise it is expected that a net southeastward drift will result from northwest winds. The water moving out of the region will be replenished by upwelling and/or boundary currents in the shore zones. Thus under southwest winds, it is expected that a slow counter clockwise surface circulation will occur in the region covered by the model. Assuming a square law for the wind stress at the water surface, τ_w ,

$$\tau_w = \frac{\rho_{air}}{2} C_D \bar{U}_{10}^2 \tag{4}$$

where C_D is the drag coefficient, \bar{U}_{10} is the mean velocity measured at 10 m above the surface and ρ_{air} is the air density. The scale of the water velocity at the surface, U_τ , is obtained from the stress:

$$|U_\tau| = \sqrt{\frac{\tau_w}{\rho_{air}}} = \left[\frac{C_D}{2} \right]^{1/2} \bar{U}_{10} \tag{5}$$

Subsequent calculations assume a mean velocity, $\bar{U}_{10} = 1.5$ m/sec, and $C_D = 2 \times 10^{-3}$ which is consistent with values obtained by Davidson (1970)³ on Lake Michigan. Using these values for \bar{U}_{10} and C_D , typical value for $U_\tau = 4.7$ cm./sec is found. If it is assumed that the wind drift, U_w , below the surface is described by:

$$U_w = |U_\tau| \cos \left(\frac{Z}{d} \frac{\pi}{2} \right) \tag{6}$$

where Z is the depth and d is the depth of the epilimnion, the net wind drift can be estimated by taking the integral of the wind drift velocity.

$$\frac{1}{d} \int_{Z=0}^d U_w dZ = \frac{|U_\tau|}{d} \int_{Z=0}^d \cos \left(\frac{Z}{d} \frac{\pi}{2} \right) dZ = \frac{2}{\pi} |U_\tau| = 3.0 \text{ cm./sec} \tag{7}$$

²Arnold, D. F. Great Lakes Research Division, University of Michigan, Ann Arbor, Michigan.

³Davidson, K. L. 1970. An investigation of the influence of water waves on the adjacent airflow. Department of Meteorology and Oceanography, University of Michigan, Ann Arbor, Michigan.

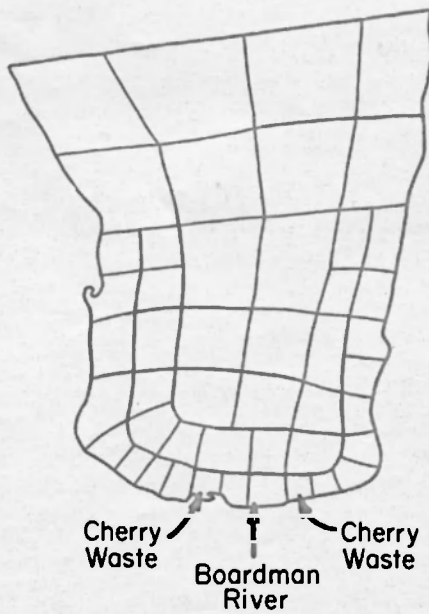


FIG. 4. Forty-eight segment model for the west arm of Grand Traverse Bay.

comparison of the model predictions and the MPN distribution observed during a four-day quasi-steady period between 13 and 17 August 1964. The calculated distribution agrees well with measured values again in this case, where the overall level of contamination is an order of magnitude greater than that observed during 1963, with the difference due to greater inputs from both the Boardman River and industrial sources.

Gannon (1970) has also collected samples to obtain the distribution of bacteria in the Traverse City area and on the sources of bacteria to the Bay. Data describing the bacteriological quality of Lake St. Clair, the Detroit River and Lake Erie were reported by Gannon (1971). These studies recognized the limited value of total coliform determinations as a measure of the bacteriological acceptability of water and, therefore, sought to enumerate specific disease causing organisms as well. The work evaluated the relationships among total coliform, fecal coliform, fecal

streptococcus, *Staphylococcus* and *Salmonella* at beach and water intake locations. A detailed description of sampling techniques, laboratory procedures and data analysis can be found in the report by Gannon (1970). Figure 7 compares model-predicted total coliform profiles and the field observations of

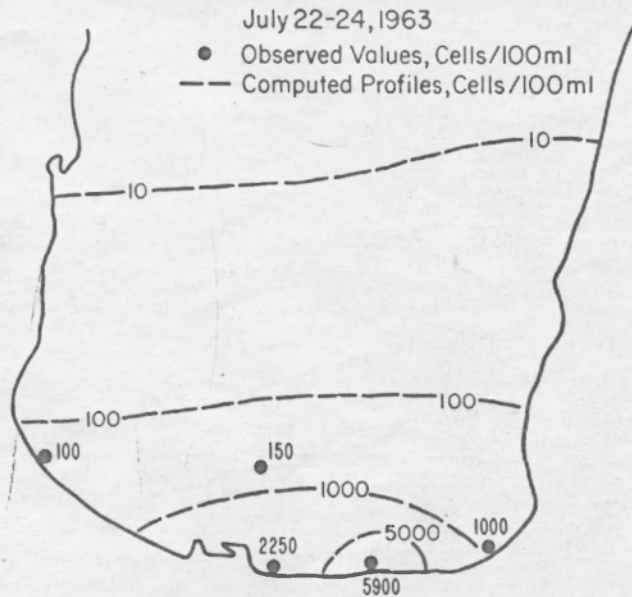


FIG. 5. Comparison of computed profiles with observed total coliform, 1963.

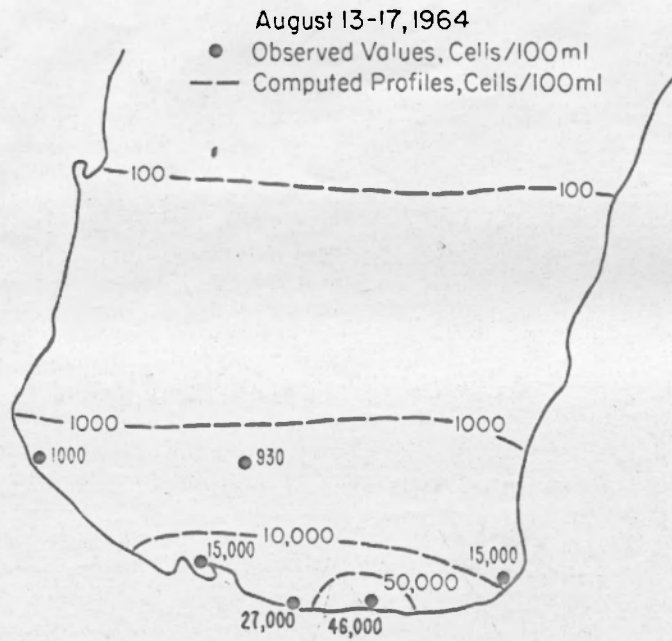


FIG. 6. Comparison of computed profiles with observed total coliform, 1964.

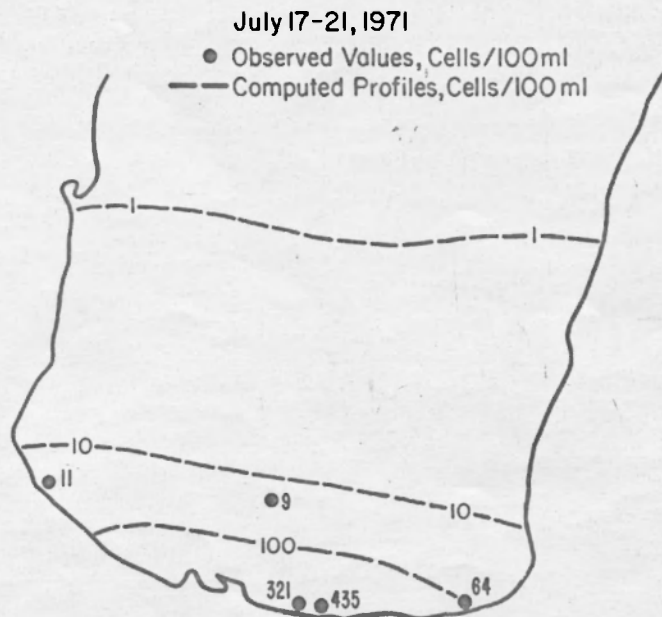


FIG. 7. Comparison of computed profiles with observed total coliform, 1971.

Gannon (1970) between 17 and 21 July 1971. Approximately 30% of the total coliform loading during this period of above average rainfall resulted from direct storm sewer discharges. It is observed that the model predictions compare favorably with measurements and that overall levels of bacterial contamination are one order of magnitude below conditions recorded during 1963 and two orders of magnitude below 1964 observations. The improvements in water quality have resulted from reductions in the amount of fruit processing wastes which enter the Bay. Such reductions have been the result of 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.

APPLICATION

Canale (1972) has used a simple two-segment model for total coliform and has demonstrated its application in a number of cases of interest to local officials in Traverse City. These applications included determining the impact of 1) storm sewer discharges, 2) individual waste sources, 3) residential and industrial development and 4) water craft storage tank spills. Each of these uses of the simple model can be easily extended to the multicell case. In addition, it is possible to examine alternate waste disposal schemes and new watershed developments using the 48 segment model. As an example, Fig. 8 shows the predicted results of removing 90% of the fruit processing wastes present during 1964 along with the simultaneous introduction of two new fruit processing plants in the Cedar Creek drainage basin on the west side of the Bay. Figure 9 demonstrates the hypothetical effect of disposing

1964 coliform loadings through an outfall extending northerly 1500 ft (456 m) from the southern shore of the Bay.

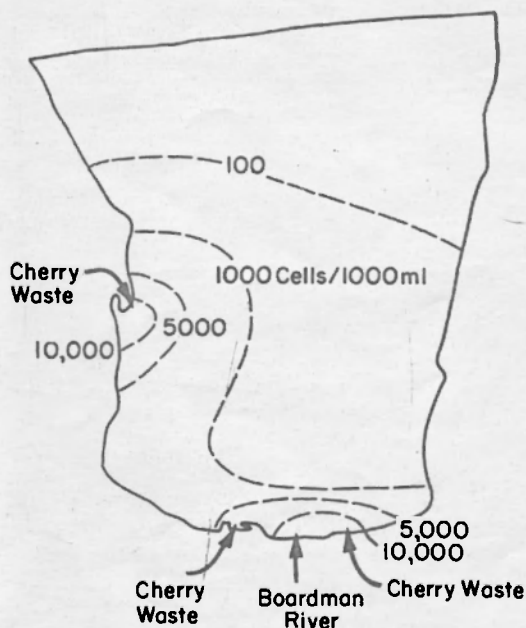
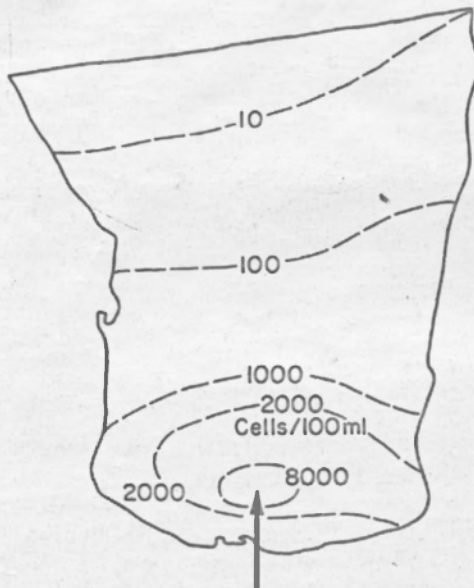


FIG. 8. Calculated distribution of total coliform with 90% treatment of 1964 fruit processing wastes and introduction of two new plants at Cedar Lake.

SUMMARY AND CONCLUSIONS

A steady state mathematical model for total coliform distribution in Grand Traverse Bay has been developed using continuity equations and experimental data describing die-away kinetics. Advective and dispersive transport phenomena were approximated using square law assumptions and field dye tracer techniques. The predictive capability of the model was verified by comparing model calculations with observations during quasi-steady periods in 1963, 1964 and 1971. The utility of the model was demonstrated with two examples showing coliform distributions resulting from alternate waste disposal schemes.



Boardman River and Cherry Waste

Currently comprehensive single- and multi-level numerical hydrodynamic models of the entire Grand Traverse Bay circulation are being developed. The results of these models will be incorporated into more realistic time-dependent models for bacterial contamination, as well as biological production.

FIG. 9. Calculated distribution of total coliform from 1964 loadings with all discharge through 1500 ft (456 m) outfall pipe.

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REFERENCES

- ARNOLD, D. E. 1972. In situ primary production measurements and associated parameters in Grand Traverse Bay, Lake Michigan. This proceedings.
- CANALE, R. P. 1972. Field verification and application of a model for total coliform bacteria in Grand Traverse Bay. *J. Water Poll. Control. Fed.*, in press.
- _____ and S. NACHIAPPAN. 1972. Steady state modeling program—Application manual. Sea Grant Tech. Rpt. No. 27, MICHU-SG-72-207, Sea Grant Prog., Univ. Michigan, Ann Arbor, Michigan.
- _____, R. L. PATTERSON, J. J. GANNON and W. F. POWERS. 1972. Water quality models for total coliform bacteria in Grand Traverse Bay. *J. Water Poll. Control Fed.*, in press.
- GANNON, J. J. 1970. Health aspects of Great Lakes water as related to water supply and recreational uses. Sea Grant Tech. Rpt. No. 1, Sea Grant Prog., Univ. of Michigan, Ann Arbor, Michigan.
- _____. 1971. Some observations regarding bacteriological relationships in Lake St. Clair, Detroit River and northwestern Lake Erie areas. Abstracts Proc. 14th Conf. Great Lakes Res., Internat. Assoc. Great Lakes Res., 139.
- JOHNSON, R. G. and E. C. MONAHAN. 1971. Current meter observations of the circulation in Grand Traverse Bay and Lake Michigan: Mooring methods and initial results. Sea Grant Tech. Rpt. No. 8, Sea Grant Prog., Univ. Michigan, Ann Arbor, Michigan.
- KENNY, B. C. and I. S. F. JONES. 1971. *J. Phys. Oceanog.*, 1:224-232.
- THOMAN, R. V. 1972. Systems analysis and water quality management. Environmental Research and Applications, Inc., New York.