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Big Eddies And Mixing Processes In The Great Lakes

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BIG EDDIES AND MIXING PROCESSES IN THE GREAT LAKES

By

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Project 16050 DIL
Program Element 1BA023

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ABSTRACT

Physical factors involved in the disposal of effluents in the Great Lakes were studied. The experimental work was carried out at the Baie du Doré research station on Lake Huron in the summer seasons of 1967 and 1968. Data evaluation and parallel theoretical work continued into 1970.

Some direct measurements of lake turbulence intensity were obtained and the structure of big eddies studied in a variety of ways. Some information was obtained on the interrelationship of short internal waves and turbulence. The turbulence intensity level could be shown to be proportional to effective diffusivity.

Further studies were carried out of mean concentration and fluctuation distributions in dye plumes. A comprehensive review article on lake dispersion was prepared. This also contained proposals for specific pollution prediction models, as well as tentative estimates of quantitative parameters required in the use of those models.

Coastal flow processes became recognized as being of especial importance in pollution problems in virtue of the observed "coastal entrapment" of pollutants discharged near shore. Theoretical models of the coastal boundary layer were therefore studied, leading to the discovery of "coastal jets."

This report was submitted in fulfillment of Project Number 16050 DIL, by the University of Waterloo, Waterloo, Ontario, Canada, under the sponsorship of the Environmental Protection Agency. Work was completed as of August 31, 1970.

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SECTION I

CONCLUSIONS

A number of different results arose from this project. Some fundamental insight was gained in regard to such diverse dynamical problems as large scale circulation in the Great Lakes and the relationship of internal waves to turbulence. Quantitative data characteristic of turbulent diffusion were collected, both on the distribution of mean concentration and on concentration fluctuations. The results of the project were summarized for potential practical use and pollution prediction models were proposed.

SECTION II

RECOMMENDATIONS

The results of this project add up to only a beginning of an understanding of coastal dispersal processes. In order to provide reliable methods of pollution prediction, much further work will be required on coastal dynamics, transport and diffusion in the coastal zone and on mass-exchange episodes. Major and sustained efforts in these areas should prove very rewarding.

SECTION III

INTRODUCTION

The broad objective of the research supported by this grant was the elucidation of the physical factors involved in the mixing of pollutants with the water masses of the Great Lakes. Specifically, according to the initial application, stress was to be laid on the role played by relatively large eddies in diffusion processes. Some of these large eddies called "Langmuir circulations" were known to have a helical structure and to give rise to "windrows" on the surface. However, the precise physical mechanism of Langmuir circulations and their exact dynamical role in the structure of the surface or "mixed" layer of the sea (or of large lakes) was and is unknown. In the course of the project attention gradually shifted also to <u>transport</u> (as distinct from mixing or diffusion) of pollutants in the coastal zone, the dynamical structure of which proved to be quite complex. Large-scale mass exchange episodes between coastal zone and main lake mass, in particular, became recognized as potentially critical controlling influences in coastal pollution.

Research on mixing processes and coastal dynamics in the Great Lakes has been pursued by the principal investigator and his associates since 1962 and is continuing. Grant 16050 DIL was awarded for the support of this work in 1967 and continued for another year in 1968, then was extended without additional funds into 1970. The <u>experimental</u> work supported by the grant was performed at the Baie du Doré research station on Lake Huron in the 1967 and 1968 seasons. A detailed summary of the experimental results of these two seasons was given respectively in the following two interim reports:

> Dispersal processes in Lake Huron, by G. T. Csanady, I. S. F. Jones, and B. C. Kenney, Department of Mechanical Engineering, University of Waterloo, May 1968, 80 pp. (contains 1967 season data).

> Dynamics and Diffusion in the Great Lakes, by G. T. Csanady, B. Pade, G. M. Bragg, M. Mekinda, and A. M. Hale, Department of Mechanical Engineering, University of Waterloo, November 1969, 142 pp. (contains 1968 season data).

Grant funds were also used to support evaluation and assessment of the experimental data and parallel relevant theoretical work. As a result, a number of publications arose from the work supported; these are listed in a later section. Particular attention is drawn to a major review article entitled "Dispersal of Effluents in the Great Lakes" (Water Research, 1970) which gives a comprehensive summary of findings up to early 1970.

The research actually performed relates to three more or less distinctly identifiable topics: (a) lake turbulence, (b) diffusion, and (c) coastal currents. An attempt follows to give an overview of the work in these three categories, very briefly summarizing what are thought to be the main scientific or engineering results. For greater detail, reference should be made to the two previous reports, containing all the experimental data, and to the publications in the literature.

SECTION IV

LAKE TURBULENCE

In analogy with well known results in the atmospheric diffusion of pollutants, it was expected that turbulence intensity in the surface layer of the lakes would exert a controlling influence on the spreading of any effluents. However, no suitable instrument was available to make turbulence measurements in such a way as to include contribution of the big eddies, known to be important for diffusion. Jones (1968 report) developed a light directional vane, which measured at least lateral (≡ perpendicular to the mean current, in the horizontal plane) turbulence intensity. Bragg and Mekinda (1969 report) have further developed this instrument.

Turbulence intensity data collected with the aid of the directional vane showed considerable day-to-day variations (Jones, 1968 report) and also large changes in the vertical (Mekinda, 1969 report). In addition, it became clear that internal waves contribute to the observed velocity fluctuations and that it may be very difficult experimentally to separate "turbulence" from "internal waves" (Csanady and Mekinda, 1969 report). Observed velocity spectra were complex and suggested that internal waves feed energy to turbulent motions, establishing several "equilibrium ranges" in the spectrum.

Another light on this problem was thrown by Hale (1969 report) who has carried out visualization studies of water movements with the aid of an underwater movie camera and fluorescent dye. His results illustrated the "breaking" of internal waves, presumably leading to the formation of turbulence.

The series of windrow observations carried out in 1968 (Csanady and Pade, 1969 report) may also be classed as "direct" turbulence observations, emphasizing the large eddies. The windrow problem had proved elusive: surface cooling was thought to be certainly the cause of more or less well-defined large helical vortices on some occasions, certainly not on others. One possible problem was that surface streaks due to causes other than Langmuir circulations could have been labeled "windrows." The objective identification technique evolved for the 1968 experiments (drift bottles caught by a long net spun across the current) showed irregularities in windrow spacings similar to those observed by others and again demonstrated that surface cooling is not essential for the appearance of windrows. The irregularity and ubiquitousness of windrows finally led to the conclusion that Langmuir circulations are more or less "ordinary" manifestations of big eddies in turbulent flow, which are not completely irregular also in such other situations as jets or boundary layers.

SECTION V

DIFFUSION

Directly linked to the lake turbulence measurements were the diffusion experiments carried out by Kenney and Jones in the 1967 season (1968 report). These experiments added to the previously existing body of evidence on dye plume diffusion, and also tentatively demonstrated a more or less direct proportionality between lateral turbulence intensity and effective turbulent diffusivity. This has provided an explanation for the relatively large day-to-day variations of previously observed diffusivities--"good" or "bad" days for pollutant dispersion apparently occur according to whether turbulent eddies are vigorous or not. This connection between turbulence and diffusion was to be expected, but the great day-to-day variability of both could not have been foreseen.

Another diffusion study was conducted in cooperation with C. R. Murthy of the Canada Centre for Inland Waters, also at the Baie du Doré research station in 1968. The results of this work extended earlier evidence on the distribution of mean concentration in a dye plume and also on the fluctuations of concentration. From a practical point of view, it is important to note that the root mean square fluctuation is comparable to the mean concentration in a plume, so that actual peak concentration readings may be two or three times higher than the maximum (centreline) mean concentration at a given plume cross section. The results of this work were reported in the Journal of Physical Oceanography (January 1972, the first issue of that new journal).

A considerable proportion of the principal investigator's time budgeted under this grant was taken up by preparing the comprehensive review for Water Research, already referred to in the Introduction. Apart from a coherent picture of mixing processes in the Great Lakes, also some specific pollution prediction models were proposed in this article, valid hopefully for sewage outfalls and other pollution sources.

SECTION VI

COASTAL CURRENTS

Some large-scale diffusion experiments in 1966 and 1967 (not supported by Grant 16050 DIL) have indicated the crucial importance of larger scale coastal flow processes in the dispersal of pollutants. Specifically, it was recognized that effluents discharged at the shore tend to remain trapped in the coastal zone for periods of several days, to be removed during large-scale mass-exchange episodes associated with coastal current reversal. The dynamics of coastal currents, and in particular their frequency of reversal thus becomes deeply implicated in the disposal of effluents in the Great Lakes.

Nearshore currents, their direction in relation to winds, and particularly their reversals of direction have been studied experimentally by Jones (1968 report). The preliminary result was (confirmed by much subsequent work not supported under this grant) that currents were mostly shore-parallel and retained one direction or the other for periods of the order of 100 hours, or the typical period of weather cycles.

With partial support from this grant, a considerable amount of effort was also devoted to theoretical studies of coastal currents. This led to the discovery of baroclinic "coastal jets," which are concentrated bands of current within 10 km. or so from the shores. The direction of these currents is determined by major wind-stress impulses (storms, in other words) and they are accompanied by thermocline upwellings or downwellings, one or the other according to the direction of the current. A current reversal brings about large thermocline movements and results in the mass-exchange episode already alluded to. The results of these theoretical studies were reported by the principal investigator in a series of articles in the open literature from 1967 to the present. Support from Grant 16050 DIL was involved in some of these; they are listed in the next section.

SECTION VII

PUBLICATIONS IN THE LITERATURE AT LEAST PARTIALLY SUPPORTED BY GRANT 16050 DIL

1. Csanady, G. T., "Wind-Driven Summer Circulation in the Great Lakes," J. Geophys. Res., 73, pp. 2579-2589 (1968).

2. Csanady, G. T., "Simple Analytical Models of Wind-Driven Circulation in the Great Lakes," Proc. 11th Conf. on Great Lakes Res., Int. Assoc. for Great Lakes Res., Toronto, pp. 371-384 (1968).

3. Jones, I. S. F., "Surface Layer Currents in Lake Huron," Proc. 11th Conf. on Great Lakes Res., Int. Assoc. for Great Lakes Res., Toronto, pp. 406-411 (1968).

4. Csanady, G. T., "Dispersal of Effluents in the Great Lakes," Water Research, 4, pp. 79-114 (1970).

5. Csanady, G. T., and M. Mekinda, "Rapid Fluctuations of Current Direction in Lake Huron," Proc. 13th Conf. on Great Lakes Res., Int. Assoc. for Great Lakes Res., pp. 397-412 (1970).

6. Hale, A. M., "Dye Injection in the Vicinity of the Thermocline," Proc. 13th Conf. on Great Lakes Res., Int. Assoc. for Great Lakes Res., pp. 419-429 (1970).

7. Murthy, C. R., and G. T. Csanady, "Experimental Studies of Relative Diffusion in Lake Huron," J. Phys. Oceanogr., 1, pp. 17-24 (1971).

8. Kenney, B. C., and I. S. F. Jones, "Relative Diffusion as Related to Quasi-periodic Current Structures," J. Phys. Oceanogr., 1, pp. 224-232 (1971).

9. Csanady, G. T., "Baroclinic Boundary Currents and Edge Waves in Basins with Sloping Shores," J. Phys. Oceanogr., 1, pp. 92-104 (1971).

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17a. Descriptors

*Turbulence, *Water circulation, Movement, Turbulent boundary layers, Lakes, *Great Lakes, Hydraulics, *Diffusion, *Currents (Water), Eddies, Mixing, Waves (Water), Wind Tide, Mathematical model, Transport

17b. Identifiers

Lake coastal currents, Nearshore currents, coastal jets, Windrows, Helical vortex

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