

# Summary of Accomplishments

E. J. Aubert

Great Lakes Environmental Research Laboratory  
National Oceanic and Atmospheric Administration  
U.S. Department of Commerce

and

T. L. Richards

Atmospheric Environment Service  
Canada Department of the Environment

## 1. Introduction

The International Field Year for the Great Lakes was a joint United States-Canadian experimental and theoretical research program dealing with hydrology, meteorology, and limnology of Lake Ontario and its basin under the aegis of UNESCO's International Hydrologic Decade. Central objectives were to improve our understanding of the physical, chemical, and biological processes of the lake and its basin, and to provide a scientific basis for improved Great Lakes management pertaining to water quality, water quantity, and environmentally sensitive operations. These management activities include municipal, industrial, and rural water supply; protection of water and ecosystem quality; fisheries resource management; water related recreation; commercial navigation; control of water levels and flows; hydropower; shore use and erosion control; and warnings of hazardous and destructive conditions.

The major emphasis in IFYGL was on experimental studies, and many accomplishments relate to more precise estimates of known effects with respect to various processes. Of itself, a major accomplishment was the development of the IFYGL archives, where data are available for detailed analyses: testing of hypotheses; development, testing, and evaluation of numerical models; and engineering applications.

In summarizing and synthesizing the IFYGL accomplishments one is ultimately concerned with more precise numerical models to predict and to simulate Lake Ontario's processes and its ecosystem under natural conditions and with anthropogenic changes. At the early stages of IFYGL (1972) the numerical modeling capability was in its infancy or in some instances had not even been born. It was generally recognized that knowledge was lacking concerning important physical, chemical, and biological processes, and that a better understanding of the physical, chemical, and biological dynamics was required to develop improved numerical models. Advances in numerical modeling of water quality, water quantity, and physical phenomena can be cited among IFYGL major accomplishments.

This summary chapter follows the organization of the preceding chapters of this book. Each program is summarized in terms of its major objectives, the measurement program, and significant accomplishments. Major accomplishments, as viewed by the authors, of the total IFYGL program and a few critical research needs are identified in the final section.

## 2. Meteorology Program

A comprehensive interdisciplinary study such as

IFYGL required a broad meteorology program, not only as a series of major atmospheric studies but as a background for many of the other investigations. A large lake indisputably affects the climate and meteorology of the surrounding land areas. Conversely, a number of meteorological elements influence the lake itself — there are precipitation gains; evaporation losses; wind effects, such as waves, currents, set-up, and seiche; and temperature-related heat content and ice-cover changes. Some meteorological parameters also directly influence biological and chemical processes in the lake.

## 2.1 METEOROLOGICAL ANALYSES

Of major importance in the Meteorology Program was a series of meteorological analyses conducted on lakewide and, in some cases, basinwide scales. These were based on data acquired both by the regular data-gathering networks in Canada and the United States and by special networks or facilities operated specifically for the Field Year. Regular networks included climatological, upper air, and hourly surface weather stations, as well as ships of opportunity. These were augmented by additional shoreline and climatological stations, overlake buoys and towers, airborne radiation thermometer (ART) surveys, radar, sophisticated atmospheric sounding facilities, and five major research vessels.

Basic to many of the studies and of interest to most investigators was a complete record of the weather during the Field Year. Regrettably, it was not a "normal" year; it was colder and cloudier than usual, and precipitation averaged well on the high side. Indeed the annual rainfall in the southeastern sections of the basin bulged to 60 percent above normal owing mainly to the effects of the remnants of Hurricane Agnes, which edged into the area in June of 1972. Important, however, is that there is a good meteorological record for the Field Year which, when used in conjunction with the available normals, serves a most useful purpose in delineating a background for almost all the IFYGL programs.

IFYGL provided an excellent opportunity to resolve some of the uncertainties in synthesizing overlake meteorological data from land-based observations. In one undertaking almost 7,000 observations from meteorological buoys and research vessels in Lake Ontario were paired with observations taken from land stations upwind of the lake. Overlake-to-overland ratios of wind, air temperature, and humidity were then sorted into wind speed classes, atmos-

pheric stability, length of overwater fetch, and overlake residence time to assess the relative influence of each factor. Ratios of wind speed and differences in air temperature and dew-point temperature between lake and land were presented as monthly averaged, statistically sorted values for classes of stability, fetch, and overland wind speed; and regression equations for designated stabilities were formulated. Generally, the results confirm those of previous investigators, although the new values are less erratic and their standard deviations are smaller compared to earlier works. The wind ratio, with an average value of 1.53 for all data, was found to be strongly dependent on stability, fetch, and land wind speed.

One of the advantages of a comprehensive undertaking such as IFYGL was the opportunity to use and compare a number of methods for estimating evaporation losses from a large lake. A separate Evaporation Synthesis Panel was formed to assess and synthesize the results. As a contribution to this particular program, meteorological investigators examined several mass transfer or bulk aerodynamic formulations that could be used routinely, based on readily available data. These included:

- (1) Monthly evaporation estimates calculated from monthly mean wind and humidity data from near-lake land stations and monthly mean surface water temperatures derived from ART (airborne radiation thermometer), meteorological buoy, and climatological data.
- (2) Daily evaporation estimates based on daily mean wind and humidity data from upwind land stations, appropriate stability class, and daily mean water temperature estimated from ART and meteorological buoy data.
- (3) Daily evaporation estimates based on an aerodynamic technique in which regression equations are used, with upwind land-station wind and humidity data, stability, overwater fetch, and water temperature as inputs.

The last approach proved to be the most effective. It requires only routinely available meteorological and surface water temperature data, and it yields spatial patterns of wind speed, dewpoint temperature, and latent heat flux that compare well with values obtained by aircraft soundings over the lake. It was found that marked variations in the rate of evaporation are evident from day to day, and these are associated with changing weather patterns. A substantial portion of the yearly lake evaporation occurs during

the fall during a few intense outbreaks of cold air accompanied by strong winds; for example, during IFYGL 70 percent of the annual evaporation occurred on less than 25 percent of the days.

## 2.2 PRECIPITATION

It was agreed early in the IFYGL planning stage that the assessment of precipitation on the lake and its land basin was so large an undertaking and of such importance to a number of programs that it should be designated as a separate project. The IFYGL Precipitation Project had four primary objectives:

- (1) Measuring the daily total precipitation falling on Lake Ontario and the land portions of the basin.
- (2) Estimating the accuracy of the precipitation measurements.
- (3) Determining the type of precipitation falling on the lake.
- (4) Investigating the difference in the amounts of precipitation falling on the lake and on its surrounding land basin.

Data were available from almost 400 precipitation gages and three weather radar with digitizing capabilities. Most of the gages in the network were Canadian and United States first-order and climatological stations. In addition gage data were obtained from special IFYGL island, shoreline, and tower installations. Three precipitation gage mesonetworks were also installed for error analyses and for specific snow measurements.

This was the first large-scale effort to obtain precipitation estimates from combined radar and gage data over an entire year and under a wide variety of meteorological conditions. Although the combined radar/gage technique provided extensive detail in the precipitation field, the resulting land basin-averaged estimates were not significantly different from those derived from gage data alone. The reason, presumably, was that the gage network was already of sufficient density to accurately estimate the average precipitation over such a large land area. The overlake radar data, however, provided for the first time reasonably reliable estimates of precipitation over the lake.

Assuming the special mesonetworks of gages correctly measured the precipitation falling on them, the average error in monthly precipitation amounts was less than 5 percent over the watershed and 15 percent over the lake. In addition, it was estimated that rainfall measurements averaged 7 percent low (bias).

Snowfall water equivalents were 10 to 30 percent low in the United States and 15 percent high in Canada. It was believed that the snowfall underestimates in the United States were a result of gage undercatch caused primarily by wind effects, and that the Canadian overestimates resulted from the use of a conversion factor of 0.1 at second-order stations in converting from ruler snow-depth measurements to water equivalent. Surface measurements of snowfall proved to be particularly error-prone because of nonstandardization of measurement sites and techniques. The Oswego snow network, which was installed specifically for acquiring accurate snowfall measurements, demonstrated that high quality measurements are possible if great care is taken to locate gages in areas well protected from wind.

Lake effects were a factor on about one-half of the precipitation days, with the lake suppressing overlake rainfall during the warm season and increasing precipitation activity during the cold season. However, these effects were limited to days when the precipitation was relatively light and scattered, i.e., days on which convection was initiated more by local conditions than by large-scale dynamic weather processes. Thus, the overall effect of the lake on seasonal or yearly precipitation totals was not as pronounced as might have been expected from observations of the day-to-day precipitation patterns. For example, for scattered shower situations during the warm season (half the precipitation days), the land averaged five times more rainfall than the lake, but these days accounted for only 7 percent of the total season rainfall.

Of prime importance was that the best possible daily and monthly precipitation for Lake Ontario and its land basin over the full 12-month period was provided to the IFYGL Water Balance and Energy Balance Projects and are available in the IFYGL archives for future investigations.

## 2.3 ATMOSPHERIC WATER BALANCE

One portion of the IFYGL Meteorology Program was so massive that it was also designated as a separate project. The Atmospheric Water Balance Project, planned as a major contribution to the IFYGL evaporation estimates, made use of newly developed upper-air sounding instrumentation for measuring vertical profiles of temperature, humidity, and wind, and applied a technique never before attempted over such a relatively small area. Specific goals were to evaluate the heat and moisture budgets of the lower and middle troposphere and to estimate the evaporation from

Lake Ontario based on those budgets in conjunction with precipitation estimates supplied by the IFYGL Precipitation Project.

A chain of six sophisticated upper-air sounding stations was established around the shoreline, three in each country, approximately equally spaced, and placed so that pairs of stations across the lake formed lines approximately perpendicular to the mean lower tropospheric flow. The flight expendables were individually bench tested before use, and carried sensing elements of guaranteed higher quality than standard network sondes. The wind-finding system used the LORAN-C navigation system to identify accurately the position of the balloon in the atmosphere.

The Atmospheric Water Balance Project was conducted from mid-September to mid-December 1972. It consisted primarily of three, approximately 2-week intensive periods of observations, with a rawinsonde flight scheduled every 3 h from each of the six shoreline stations.

There proved to be no firm theoretical basis for placing confidence limits on the values of evaporation determined in this manner. Consideration of the potential sources of error, together with an examination of the analysis results lead to the conclusion that standard errors may be as large as 2 to 3 mm day<sup>-1</sup> for averages over periods of 2 weeks, and around 1 mm day<sup>-1</sup> for periods on the order of 1 to 2 months. Daily averaged values appear to have standard errors on the order of 10 mm day<sup>-1</sup> and are thus of very limited value.

Relative variations from period to period in the averaged values of computed evaporation (7.4, 1.9, 6.5 mm day<sup>-1</sup>) were similar to those obtained from bulk aerodynamic computations. Surprisingly, however, the absolute values of evaporation derived from the atmospheric balance analysis were roughly twice those obtained by most other techniques. This apparent systematic difference in the results constitutes an important topic for further study.

Although the results of the Atmospheric Water Balance Project were of limited usefulness in the overall IFYGL investigations of evaporation, the project must be viewed as having inestimable value as a scientific experiment. Newly developed sophisticated rawinsonde equipment was tested under field conditions, resulting in a number of recommended improvements. In addition, the large volume of data generated by such an experiment required the development of new data analysis methods and quality control techniques. Many of these improvements and new techniques were incorporated in later undertak-

ings, such as the World Meteorological Organization's GARP program. All the verified data sets are available for more detailed analysis and exploitation by a future generation of scientists.

### 3. Atmospheric Boundary Layer

The boundary layer provides a coupling between the atmosphere and the lake via physical processes of wind stress, sensible heat exchange, and evaporation; and chemical processes of exchange, fallout, rainout, and gaseous flux. In IFYGL the focus of the Atmospheric Boundary Layer Program was on physical processes: to develop more precise estimates of the lake-air fluxes of sensible heat, water vapor, and momentum over Lake Ontario and the distribution and variability of these fluxes in time and space; to develop improved methods of estimating the lake-air fluxes based on routinely available observations; and to produce a data set that can be used to test theoretical and numerical models of the behavior of the atmospheric boundary layer over the lake and its interactions with larger-scale atmospheric processes and with lake circulation.

Direct measurements were made of the turbulent fluxes of sensible heat, water vapor, and momentum from specially instrumented (hot wire anemometer) intake tower facilities. Specially instrumented (gust probe) aircraft measured the turbulent fluxes during 2-week "alert" periods during stable, neutral, and unstable lapse conditions. Boundary layer profile measurements were made from the surface to a height of 12 m on three towers in the lake. The network of buoys and towers provided time-series data on surface wind, temperature, and moisture over the lake. An excellent experimental data base was obtained and is available from the IFYGL archives (app. C).

Boundary layer parameterization methods for estimating the turbulent fluxes of water vapor, sensible heat, and momentum over the water were refined and evaluated. Extensive measurements were made from towers of these fluxes with new levels of accuracy and resolution for the warm half of the year, making it possible to develop and test the bulk aerodynamic evaporation formula  $E = C_E \rho (q_s - q_a) U_a$ , where  $E$  is evaporation (kg m<sup>-2</sup> s<sup>-1</sup> or mm s<sup>-1</sup>),  $C_E$  is the dimensionless bulk evaporation coefficient,  $\rho$  is the air density (kg m<sup>-3</sup>),  $q_s$  is the saturation specific humidity at the water surface temperature (dimensionless),  $q_a$  is the specific humidity of the air (dimensionless), and  $U_a$  is the wind speed (m s<sup>-1</sup>). With atmospheric mea-

surements at 10-m height, the following results were obtained:

- (1)  $C_E = (1.2 \pm 0.2) \times 10^{-3}$ .
- (2)  $C_E$  increases with wind speed.
- (3) The expected differences in the bulk coefficient for evaporation ( $C_E$ ), sensible heat ( $C_H$ ), and momentum ( $C_D$ ) were not verified.
- (4) The expected stability dependence of the bulk coefficients is not supported by the data.

While the available experimental tower data do not support a stability dependence of the bulk evaporation coefficient ( $C_E$ ), a study of the space- and time-averaged aerodynamic drag coefficient ( $C_D$ ) estimated from a wind set-up formula and observations of lake levels, wind speed, and stability shows a slight direct dependence of drag coefficient on atmospheric stability (a larger value of  $C_D$  is associated with greater instability).

Based on the bulk aerodynamic method and the extensive buoy and tower data for wind, air and water temperature, and humidity, weekly flux calculations for sensible and latent heat yielded the following results:

- (1) Significant horizontal gradients occur.
- (2) The latent heat flux is larger than the sensible heat flux and shows greater week-to-week variability.
- (3) Storms cause pronounced disruptions (intermittencies) in the smooth seasonal cycle of heat fluxes.
- (4) During spring and early summer, periods with downward fluxes of water vapor and sensible heat occur.
- (5) In autumn cold air outbreaks produce intense intermittent transfers of sensible and latent heat with 60 percent of the lake heat loss occurring in 15 percent of the time period.
- (6) Lakewide evaporation rates rise abruptly in mid-July from small amplitude fluctuations about zero to large amplitude fluctuations about a large positive value.

Direct measurements from instrumented aircraft of the spatial variation of the surface fluxes of heat, moisture, and momentum yielded the following results:

- (1) There is general agreement with the surface fluxes estimated by the bulk aerodynamic method from buoy data.

- (2) During a storm episode (October 9 to 10, 1972) upwelling of cold water was associated with a strong horizontal gradient of surface latent and sensible heat flux.
- (3) During spring and early summer downward fluxes of latent and sensible heat were observed.

Several boundary layer processes over Lake Ontario were studied and are now more completely understood. The following results were obtained:

- (1) The amplitude of the variation of wind speed at the diurnal period is small compared with the amplitude at the 5- to 14-day period.
- (2) The vertical component of surface vorticity is large at the diurnal period compared with the 5- to 14-day period.
- (3) The surface horizontal divergence variation is larger than the vorticity variation at the diurnal period, suggesting direct radiative forcing and a lake breeze effect.
- (4) On the synoptic time scale (3- to 5-day period) and lake space scale, the divergence variability is much smaller than the vorticity and these variables are not significantly coherent.
- (5) With the passage of a cold front when the lake is stratified, strong northwesterly winds cause upwelling of cold water along the north shore and an associated reduction in latent and sensible heat flux.

A hypothesis was tested on the coherence of the horizontal wind over the lake compared with the coherence over the land, and it was verified that the coherence between the horizontal wind components decreases more slowly with spatial separation over water than over land.

Cospectral analysis of wind speed at several locations verified Taylor's hypothesis that high frequency eddies travel with the local wind.

Detailed analysis of surface and boundary layer observations provided a more precise description of the land-lake breeze circulation and its divergence and vorticity. It was found that the diurnal lake scale land-lake breeze is strongly developed during the 6-month warm season (May to October), with maximum intensity in July. On the diurnal cycle, the maximum surface horizontal divergence occurs at 1300, the minimum vorticity at 1530, and the maximum air temperature at 1700 local time.

The profiles of temperature, humidity, and horizontal wind over the lake can be modeled in terms of the

Monin-Obukhov scaling parameters and non-dimensional external parameters, such as boundary layer depth. However, carefully measured wind profiles over the water cannot be adequately described in terms of Monin-Obukhov stability scaling, which has been so successful over land, due, it is suspected, to the importance of surface wave effects.

Analysis of a large sample of 10-min averaged boundary layer profiles over Lake Ontario showed that the wind speed gradients on a logarithmic height scale tend to increase with height under both stable and unstable conditions. It is hypothesized that the difference between overland and overwater boundary layer profiles is due to wind wave effects.

#### 4. Energy Balance

Energy supply, which varies in both time and space, is basic to many limnological studies, from water circulation to the ecology of the lake. In addition, energy exchanges at the air-water interface are fundamental to an understanding of the effect of the water body on the atmosphere, and, conversely, of the effect of the atmosphere on the lake. A reasonably precise formulation of the lake energy balance, including the lake-atmosphere exchange processes, is required for numerical simulation of the seasonal variations in lake circulation, temperature, and contaminant transport. As a bonus, evaporation can be computed as a residual of the energy balance equation. With this in mind, the IFYGL Energy Balance Program was established with the following principal objectives.

- (1) To define the general and specific properties of the energy balance of Lake Ontario and evaluate all the terms in the heat budget for the Field Year.
- (2) To provide estimates of evaporation as a residual of the energy balance equation for comparison with estimates made by other techniques.
- (3) To study the formation, growth, and decay of ice, including heat transfer from water to the atmosphere through the intervening ice and snow.

The energy balance of a large lake, developed from the first law of thermodynamics, can be written as

$$Q_n - Q_e - Q_h - dQ_l - Q_v = 0,$$

where at the lake surface

- $Q_n$  = net radiation flux,
- $Q_e$  = evaporative heat flux,
- $Q_h$  = sensible heat flux,
- $dQ_l$  = change in heat storage, and
- $Q_v$  = heat transport.

All the terms were computed directly or derived from observations, except for the sum  $Q_h + Q_e$ , the separate values of which can be derived by the use of the Bowen ratio,

$$R = \frac{Q_h}{Q_e} = K_B P \frac{(T_1 - T_2)}{(e_1 - e_2)},$$

where

- $T_1$  and  $T_2$  = temperatures of the water surface and the air above the lake surface,
- $e_1$  and  $e_2$  = vapor pressures at the corresponding levels,
- $P$  = atmospheric pressure, and
- $K_B$  = an arbitrarily established constant.

IFYGL provided a unique opportunity to evaluate the individual terms of the energy balance equation and to assess this approach for estimating lakewide evaporation from Lake Ontario. Over the lake, 29 instrumented buoys and lake towers yielded nearly continuous water and atmospheric data. Overland, the regular network of weather reporting stations was augmented by an IFYGL shoreline network of 15 stations. Some of these land and lake facilities also recorded much-needed radiation data. Five research vessels conducted 43 lake-wide surveys, each of which included as many as 105 bathythermograph soundings in addition to regular meteorological and limnological observations. The volume and temperature of inflow and outflow were measured for the Niagara and St. Lawrence Rivers and for representative tributary rivers. Lake surface water temperature was measured on weekly aircraft surveys, which also included ice-cover observations during the winter months. Ice thickness data were also available for the ice-prone eastern portion of the lake. Although the data sets contain gaps, and the intensity of data collection was significantly reduced during winter, these gaps are randomly distributed. Redundant data sets allowed for detailed evaluation of problems for which solutions have been only conjectural in the case of the lakes of this size.

It was found that extrapolation of radiation observations from a limited number of shore stations produced estimates of net radiation flux  $Q_n$  over the lake that are not significantly different from the results obtained with an atmospheric radiation model. Differences when averaged over a 10-day period were less than  $\pm 10$  percent. Fog and cloud cover modify the net radiation significantly, but it is difficult to obtain observations of these elements over the large surface of the lake. As an example of the importance of accurate observations, winter time steam fog, which is shallow by nature, attenuates solar radiation by no more than 7 percent, in contrast to an average transmission function of 50 percent for radiation fog; an increase in cloud amount from 0 to 100 percent modifies the radiation estimate by 100 percent.

It was confirmed that the heat transport term,  $Q_v$ , tends to be relatively small. During the warming period the inflow and outflow terms are predominant. Heat transfer was found to be largest (1) during spring runoff, (2) when precipitation is frozen, and (3) during high precipitation events, such as Hurricane Agnes.

In assessing the latent and sensible heat flux terms  $Q_e + Q_h$ , the application of the Bowen ratio,  $R$ , to a water body the size of Lake Ontario presents a major problem for the heating portion of the year when the lake surface vapor pressure approaches that of the air. A number of IFYGL studies confirmed that with vapor pressures normally encountered at that time of year the Bowen ratio ranges between  $\pm$  infinity, whereas during the cooling portion of the year the range does not exceed 1.5. Because the Bowen ratio is extremely sensitive to small changes in moisture and temperature and the relation between these variables is not linear, it is important that space- and time-averaged Bowen ratios should be derived from space- and time-averaged temperature and moisture variables. It is most important to put the great variability and sensitivity of the Bowen ratio during the warming period into proper perspective. Comparison of total evaporation during IFYGL warming and cooling seasons indicated that 95 percent of the annual evaporation occurred between July 27, 1972, and February 29, 1973, and only 5 percent occurred during the warming period of April 6 to July 26, 1972, and March 1-28, 1973.

Lake Ontario is a large heat reservoir, with a weekly change in heat storage,  $dQ_t$ , ranging between  $\pm 700$  cal  $\text{cm}^{-2}$   $\text{day}^{-1}$  ( $\pm 339$  J  $\text{m}^{-2}$   $\text{s}^{-1}$ ). The IFYGL temperature surveys are one of the most extensive data sets available for so large a lake. They serve several purposes, including verification of numerical models of thermal stratification and lake circulation, in addition

to computation of the energy balance equation. The analog bathythermograph (BT) traces supplied the most reliable data for estimating lake heat storage changes. They were supplemented by more sophisticated temperature measurements recorded on magnetic tape with 0.1-s frequency on some of the ship cruises. Buoy data were used as baseline control for the ship surveys. As might be expected, major gains in heat storage were made in the spring and early summer, with the greatest losses taking place during the fall and winter. It was found that the epilimnion comprises only about 20 percent of the total volume of Lake Ontario during the period of density stratification, and about 90 percent of the solar energy is used to develop and maintain a stable epilimnion during the stratified period. Measurements and calculations can be tailored to concentrate on this relatively restricted portion of the total water mass and still fall within acceptable error limits.

Because Lake Ontario rarely, if ever, becomes fully ice covered, the ice effect on lake processes was evaluated as much for information transfer to the other Great Lakes as for use in the Energy Balance Program. A two-dimensional, time-dependent numerical nearshore ice model was derived that could be applied to other lakes. This model is applicable to any harbor or embayment to predict the short-term extent and thickness of ice cover. On the whole-lake scale, a quasi-one-dimensional form of the model produced realistic ice distributions when compared with observed ice charts and satellite images. Current interest in the navigation season extension warrants continued application of the model. The change in lake heat storage related to ice formation and decay on Lake Ontario is of the same magnitude as heat transport, but ice also has other indirect effects due to insulating and reflective properties.

Each term of the energy balance equation was measured or calculated over weekly intervals for the full Field Year. Weekly evaporation losses were then calculated as a residual of the equation. These results, which are judged to be the best energy balance data set yet available for such a large lake, are given in table 5 in the Energy Balance Chapter. Total evaporation from Lake Ontario during the Field Year based on energy balance calculations for 51 weeks and trend estimates for the few days at the beginning and end of the 12-month period was 692 mm. The weekly and monthly estimates were provided to the Evaporation Synthesis Panel for comparison with results obtained by other techniques and for an overall synthesis of evaporation estimates.

## 5. Terrestrial Water Balance

Lake Ontario is one of the two Great Lakes that have their outflow at least partly controlled by man. It is essential, therefore, that regulating procedures ensure that the lake contains sufficient water to meet the demands made upon it, while maintaining levels within a range to satisfy such interests as navigation, power development, shoreline properties, and recreational facilities. For these reasons, it was important that a thorough study of the water balance of the lake be made as part of IFYGL, with particular attention paid to the accuracy and relative importance of each of the terms of the water balance equation. In addition, the water balance equation provided yet another technique for assessing year-round evaporation from the lake.

The inflow-outflow terms are by far the largest in the Lake Ontario water balance equation. To assess these terms as accurately as possible, several techniques for determining river flow were evaluated. The standard stream-gaging "panel" technique proved to be the most reliable, and it was used during the Field Year to calibrate the continuous flows in the Niagara and St. Lawrence Rivers as regularly monitored at power houses on both sides of the border. It was also necessary to consider tributary inflow. Runoff data were collected on representative tributary streams throughout both the United States and Canadian basins, and were extrapolated to the un-gaged areas with similar physical and climatological characteristics.

Previous computations of the water balance equation for large lakes had revealed a lack of reliable observations of precipitation falling on the surface of the lake itself. Indeed, this has been a matter of some controversy in the Great Lakes scientific community for several decades. IFYGL planners felt that this lack was so critical that the problem was turned over to a separate Precipitation Project, discussed above in section 2.2, which was provided with the digitized output from three weather radars and a substantially enhanced precipitation network. As a result, the project was able to provide overlake and overland data that were significantly more accurate than those previously available.

Prior to IFYGL, it had been assumed that the groundwater contribution to Lake Ontario could be neglected in the computations of the water balance. Studies at selected areas during the Field Year confirmed that the groundwater contribution was indeed very small, about 0.1 percent of the inflow from the Niagara River.

Two methods were used for calculating the change in storage of the lake. One was based on data from the operational 6-gage network; the other, on an expanded 19-gage IFYGL network. The results showed that, although the expanded network improved the computation of the monthly water balance, the 6-gage network is adequate for operational purposes.

Evaporation estimates were calculated as a residual of the water balance equation for both weekly and monthly periods, and were provided to the Evaporation Synthesis Panel for assessment and further investigation.

Of the Lake Ontario water supply during the Field Year, 18 percent came from the basin runoff; 2 percent from the net atmospheric flux (7 percent precipitation, 5 percent evaporation); 80 percent from the upstream lake; and less than 1 percent from groundwater. Of this water supply, 5 percent increased the storage in Lake Ontario, and 95 percent flowed down the St. Lawrence River.

To determine the impact of measurement errors on the computed evaporation, each term of the equation was varied by an amount based on the estimate of the measurement error as provided by other IFYGL investigators. Not unexpectedly, this evaluation showed that small errors in the very large inflow and outflow terms had a major impact on the calculated evaporation.

The water balance of the land basin was also investigated, again through the assessment of the individual terms of a standard water balance equation. As indicated earlier, runoff data collected on representative tributary streams throughout both the United States and Canadian basins were extrapolated to un-gaged areas. Overland precipitation estimates, the most accurate to date, were provided by the Precipitation Project based on data from the enhanced gage network and weather radar coverage.

Natural gamma radiation surveys were conducted to determine water storage in the snow cover, and, despite a relatively sparse snow cover, were found to be a feasible means of obtaining such data. Selected studies on groundwater suggested that a net increase in groundwater storage was related to the excess precipitation over the long-term average.

Two methods were used to compute monthly evapotranspiration, and both yielded results that compared favorably for the fall and winter. However, significant differences during the spring and summer months indicate the need for further studies.

In addition to the computation of the terms in the water balance equation, other investigations were un-

dertaken. Landsat (formerly ERTS) satellite data and aircraft multispectral scanner data were used with some success to delineate standing water and to classify and map watershed characteristics. A precise geodetic survey level line was run around Lake Ontario to validate the elevations of the water level gage sites; this study indicated that no major error was incurred using the standard water-level transfer technique.

In summary, analysis of the results obtained during IFYGL indicates that the present gage networks and the present standard inflow/outflow determination technique are suitable for use in the weekly decisions required for the management of Lake Ontario levels and flows. Refinements in the measurement or calculation of the water balance terms, however, are desirable. Also, IFYGL showed that it is possible, within the present state-of-the-art, to obtain an indication of the soil moisture and the standing water within the basin through analysis of remotely sensed (multispectral, natural gamma, radar) data. In particular, the water resource manager is now able to evaluate changes, such as in patterns of snow and ice cover from repetitive satellite coverage, and reflect these changes in estimated potential future water supplies. The use of repetitive satellite coverage will also provide the resource manager with a constant update of land uses, by terrain categories, from which he can determine the effect on the terrestrial hydrology of the basin. A number of maps developed during IFYGL (Lake Ontario Drainage Basin; Overburden Well Yields; Bedrock Well Yields) and the information gathered by satellite, will provide useful data for planners in the future.

## 6. Evaporation Synthesis

Methods to simulate or forecast water supply, water levels, and flows in the Great Lakes system are dependent upon a hydrometeorological data base that includes estimates of lake-averaged evaporation. Improved prediction of lake levels and the resulting flows is critically dependent upon improved methods for assessing the evaporation term. The massive data collection during IFYGL made it possible to determine more accurately the extent of evaporation losses from Lake Ontario by means of several techniques. To assess and synthesize this wealth of information, an Evaporation Synthesis Program was established with the following objectives:

- (1) Summarizing and evaluating the results of the various techniques.

- (2) Recommending the best technique(s) for future operational use.
- (3) Developing a definitive coefficient for the application of the aerodynamic (mass transfer) method to Lake Ontario and the other Great Lakes.

Evaporation estimates established as residuals for the terrestrial water balance and energy balance equations were calculated on weekly and monthly time scales over the full year. Several aerodynamic techniques provided data for daily, weekly, and monthly intervals. Aerodynamic estimates requiring overwater data were limited to the period April to October 1972, when the overwater instrument platforms were in place. However, year-round estimates of evaporation using the aerodynamic technique were made with overwater meteorological data estimated from shoreline station data. In the very special case of the sophisticated Atmospheric Water Balance Project, data collection was limited to periods of intensive investigations during the fall of 1972.

The components in the various evaporation formulations and their effect upon the computed evaporation rate were analyzed in detail by established sensitivity and error analysis techniques. When warranted, and based on supporting data, the individual components were adjusted, and evaporation rates computed on both weekly and monthly time scales. The three major techniques — water balance, energy balance, and aerodynamic — gave total evaporation estimates for the Field Year of between 552 mm and 689 mm, a range of 20 percent. As indicated in table 2 in the evaporation synthesis chapter, all techniques revealed similar seasonal progressions, with a high regime in the late summer, fall, and winter and a low regime in the spring and early summer. The overwater buoy and aircraft measurements confirmed the occurrence of periods of condensation during the spring and early summer. The same measurements also revealed large spatial variability in evaporation from the lake surface, with a gradient increasing from west to east. On the basis of error analyses of the different techniques, "recommended" lake-averaged evaporation was established for each month of the Field Year and these results are also given in table 2 in the Evaporation Synthesis Chapter.

Error analyses of the different techniques indicated that the aerodynamic (mass transfer) technique was the most reliable for estimating evaporation from Lake Ontario. To be of routine use, the technique requires the simulation of overwater meteorological

data based on data from overland stations. Procedures developed during IFYGL produced data in good agreement with actual observations, making such simulation a reliable tool.

An important accomplishment in estimating lake-averaged evaporation was the determination for the first time, of a mass transfer coefficient specifically for Lake Ontario. This coefficient (0.107) was found to be significantly smaller than the Lake Hefner coefficient (0.124) previously used in most Great Lakes studies. It was also established that, although evaporation is primarily a daily or even an hourly phenomenon associated with specific meteorological events, evaporation estimates based on weekly or monthly average values of the mass transfer product ( $U\Delta e$ ) are acceptable for most lakewide investigations.

Finally, regression analysis based on evaporation estimates by the water balance, energy balance, and mass transfer techniques led to the following recommended mass transfer equations for data at the 3- and 8-m levels:

$$E_3 = (0.052 + 0.0066 U) (e_s - e_3) U_3,$$

and

$$E_8 = (0.047 + 0.0046 U) (e_s - e_8) U_8,$$

where  $e$  is a vapor pressure (mb) and  $U$  is wind ( $\text{m s}^{-1}$ ) at the designated height, and  $E$  is evaporation ( $\text{mm day}^{-1}$ ).

## 7. Water Movements

In the IFYGL Water Movements Program, aimed at a better understanding of the water movement dynamics of Lake Ontario, particular attention was given to the forced and free lake responses to surface wind stress and to the seasonally varying density and temperature distributions. Studies included the following:

- (1) Lake-scale circulation in midlake and coastal regions in response to the seasonal heating cycle of the lake and to storm-induced variable surface wind stress.
- (2) Internal waves that are most pronounced during the stratified season including crosslake progressive waves associated with upwelling and downwelling events, nearshore waves that progress around the lake, and inertial waves that are most

pronounced in midlake and respond to wind stress impulses.

- (3) Dynamic modeling, diffusion, and surface waves.

Measurement systems to support the lakewide and coastal experimental projects included a network of limnological/meteorological buoys and towers to measure currents, water temperature, surface wind, air temperature, and moisture; Waverider buoys to measure surface waves; towed undulating profilers to measure temperature cross sections; ship surveys with bathythermographs to measure water temperature profiles; nearshore coastal chains to measure cross sections of current, water temperature, and wind; and aircraft-mounted radiation thermometers to measure surface temperature. Excellent data were obtained, and analyses provided new insights into the physics of large lakes and a basis for verification of dynamical models of the water movements. These data are available from the IFYGL archives for future analyses and model verification (app. C).

The lake-scale circulation has two seasonally different regimes. In the warm season the lake is thermally stratified with a cooler central core below the thermocline, and the predominant circulation is a single counterclockwise rotating gyre. Current speeds are largest at or near the surface and generally decrease with depth. A longshore current speed maximum occurs within 2 to 7 km of the shore, generated by relatively short wind-stress impulses from passing storms. This longshore current is in balance, geostrophically, with the nearshore thermal (density) distribution. Nearshore current speed maxima persist for 1 to 2 weeks, depending upon subsequent wind-stress impulses, and once formed decrease in intensity as they propagate counterclockwise around the coastal region of the lake. Examination of power spectra of hourly mean time-series data shows that the current variability offshore is greatest near the inertial frequency, with a second peak occurring at the lower frequency meteorological cyclone scales. Power spectra of temperature time-series data show the greatest energy at the lake surface for meteorological scales, a second peak at the thermocline at near-inertial scales, and a small diurnal peak at the lake surface. Nearshore, the maximum variability occurs in the longshore currents at the meteorological cyclone scales.

In the cold season the lake vertical temperature profile is nearly isothermal. During the Field Year overturning began near the end of November 1972. Monthly resultant current speeds show little variation

with depth and appear to be barotropic. Sparse monthly resultant current data appear to support a two-gyre counterrotating flow for most winter months, but a single counterclockwise gyre at other times. Since simple vertically integrated numerical models yield a two-gyre counterrotating circulation, an extensive, although not conclusive, scientific analysis was made to explain the apparent observed single-gyre circulation or two-gyre counterrotating circulation with a dominant counterclockwise rotating cell. While the seasonal resultant flow represents mean conditions, an examination of hour-to-hour and day-to-day currents in both summer and winter shows considerable variability about the mean state associated with the intermittent and variable surface wind stress associated with the passage of storms over the lake. The power spectra of time series of hourly averaged current data in winter shows that the energy predominates in the lower frequency meteorological scales (periods of more than 3 days) and that the energy at the near-inertial frequencies in winter is an order of magnitude smaller than in summer.

Analyses of data along three cross sections of the lake for three 1-week intensive measurement periods during the warm season (when the lake is stratified) show the existence of long wavelength internal waves. Examination of successive cross sections shows that, following a strong wind-stress impulse and associated coastal downwellings and upwellings, oscillations of the thermocline are initiated that propagate lakeward as internal surges and thermal fronts. Long-lived tilts of the thermocline surface were found to be associated with geostrophically balanced current flows. After thermal stratification, intermittent bursts of inertial waves followed strong wind-stress impulses at all observation stations except very close to shore. The lake response took two closely related forms: (1) inertial motions with rotary currents, and (2) resonance of the inertial motions in the baroclinic (Poincaré) modes to produce near-inertial motions.

Coastal currents were measured along five coastal chains perpendicular to the north and south shore during three summer (stratified) months. Several case studies give considerable insight into the effects of atmospheric forcing (wind stress) on the lake circulation and thermal distribution. Episodes of strong wind stress generate longshore coastal currents (jets) within a coastal strip 10-km wide. Current directions initially are usually in the direction of the wind stress. Current maxima, 20 to 70 cm s<sup>-1</sup>, occur at or near the lake surface, with the core located 3 to 7 km offshore. Most of the water transport is in the upper layer when the

lake is stratified. Typically, along the south shore, the most persistent flow is toward the east, with a downwelled thermocline surface establishing a quasi-geostrophic balance. Along the north shore, the volume transport during summer stratification predominates westward, opposite to the prevailing wind stress. Long-period wavelike motions and important flow reversals were observed along the north shore, probably related to internal Kelvin and topographic waves. Superimposed on the prevailing coastal currents is a variable storm wind stress that induces a large hour-to-hour and day-to-day current variability. The flow is also influenced by the boundary configuration, bathymetry, Coriolis force, presence of density gradients, and the counterclockwise propagation of coastal topographic or Kelvin waves around the lake.

Several numerical models were developed and tested to simulate the lakewide distribution of currents, temperature, and water levels; to assist in understanding the phenomena and the variability in the observations; to support ecological and water quality models; and to simulate the transport and dispersion of elements. The model framework consists of the basic hydrodynamic equations and is essentially the same as the one developed for numerical weather prediction and storm surge forecasting. Data from current-meter arrays, on water levels, from nearshore coastal chains, and on mean temperature distributions were used for verification. Testing demonstrated that results are sensitive to mathematical deficiencies. At the present state of development, it is easier to improve model results by improving the resolution of the coastal zone than by modifying the model parameters, i.e., surface wind stress, bottom drag, vertical eddy viscosity and heat diffusivity. Although much remains to be done to develop sufficiently precise numerical models for useful applications, much was also accomplished. Model integrations were completed, and comparisons of time series of computed and observed currents, filtered to eliminate inertial motions, for the 3-day storm of Hurricane Agnes (June 22 to 24, 1972) show considerable agreement, although precision is not great. Numerical experiments were run with a simulated pollutant (dye) introduced as a Niagara River load and as an Oswego River load to Lake Ontario. The results look reasonable, but verification data are lacking. To examine the potential for water quality applications, a model experiment was run for 1 year and verification performed of the weekly measured and computed heat gain in various lake zones. In some zones the comparison looks good; in others the error is considerable. In

these verification studies, the lack of adequate observation density may be the cause for some of the discrepancies.

Theoretical and experimental studies of turbulent diffusion processes were undertaken to develop useful models to estimate dispersion of chemical and biological systems and pollutant discharges. In coastal diffusion experiments continuous fluorescent dye plumes were released and the plume dispersion measured. Analyses of the data established diffusion characteristics of the cross plume relative concentration, including mean profiles, variance, horizontal diffusivity, and the length scale of diffusion.

In the open lake, dye patches were released and then measured over periods of 5 days. Concentrations were plotted relative to a drogue and isopleths mapped to conserve area into a radially symmetric distribution. A plot of the horizontal variance of concentration,  $S$ , versus time yields the empirical relationship  $S_x^2 = 7.9 \times 10^{-2} t^{2.3}$  and  $S_y^2 = 9.9 \times 10^{-5} t^{2.8}$ , where  $x$  is in the direction of and  $y$  is normal to the mean current,  $S$  is in centimeters, and  $t$  is in seconds. The empirical result shows that in Lake Ontario horizontal diffusion takes place much faster than in the Fickian diffusion model (exponent of  $t=1$ ), faster than in the shear diffusion model (exponent of  $t=2$ ) and slower than in the inertial subrange diffusion model (exponent of  $t=3$ ). These data indicate that the dispersion along the mean flow is greater than the dispersion normal to the mean flow for periods up to 10 days. They also show that the eddy diffusivity in the surface layer (0 to 6 m) is an order of magnitude greater than the eddy diffusivity at depth (15 to 50 m).

Experimental data on vertical diffusivity support the empirical formulae developed by Kullenberg for wind speeds both greater and less than  $5 \text{ m s}^{-1}$ .

Surface wind waves were measured to describe the wind-wave climate, and to relate the observed wave characteristics to the surface wind stress. Measurements were made from a network of seven Waverider buoys. Probability distributions of significant wave height (0.0 to 4.0 m) and wave period (1 to 7 s) were developed for the ice-free period. The most frequent condition is a significant wave height of 0.5 m and average wave period of 2.5 s. Wave height in autumn is much higher than in summer. For the higher wave heights, the wave steepness (wave height/wave length) ranges between 1:10 to 1:20. The growth of the wave spectrum during storm episodes shows that the increase in energy during wave growth takes place in the low frequency band (0.15 to 0.35 Hz), and during wave growth the frequency of peak energy shifts

to lower frequency. Numerical wave models were tested and provide reasonably satisfactory estimates of the wave spectrum at deepwater stations when measurements of the wind velocity are given.

## 8. Biology and Chemistry

The Biology and Chemistry Program was initiated in 1970, late in the overall IFYGL planning process, to fill an increasingly apparent research gap. Goals were to collect scientific information on lake processes in support of water pollution control management and the development of fisheries resources. Among water quality problems, control of the eutrophication process by limiting nutrient loads to the lake figured prominently in management plans. The need was recognized to collect and to organize nutrient data in the form of materials balance. In addition, the status of the lake both biologically and chemically was considered important to identify important trends, and mathematical models of Lake Ontario's ecosystem were developed and tested.

### 8.1 BIOLOGY

For the IFYGL biological studies, water samples were collected at several depths, and vertical hauls with plankton nets were made at 60 stations on 10 lakewide cruises from May 1972 to June 1973. Other experiments were conducted near the shore, along transects from the shore to deep water, in bays, and at continuous nearshore and offshore monitoring stations. Remote sensing was used to measure cladophora with a multispectral scanner mounted on an aircraft, and to measure zooplankton abundance with sonar mounted on a vessel.

These studies were undertaken to: (1) identify the status of biota in Lake Ontario, including species type, abundance, succession, and spatial variation; (2) better understand the life history, production, and intra-taxon relationships; (3) better understand inter-taxon relationships; and (4) develop general models.

Accomplishments pertain primarily to objectives (1) and (2). The main value of the biology program is that it provided a baseline for comparison with future work and a data base for development and testing of ecosystem and water quality models. In addition, anthropogenic effects, while predominating in the nearshore areas, were detected in all parts of the lake and at all trophic levels.

Phytoplankton studies showed the virtual absence of species characteristic of oligotrophic waters. The

once abundant species *Cyclotella* assemblage was rare. The diatom species found are tolerant of eutrophic and saline conditions.

Seasonal and spatial variations of phytoplankton were large. In the spring, species abundance was greatest in the warmer nearshore waters; as the lake stratified, the abundance in midlake increased. The greatest abundance of biomass in the vertical profile was found at 10-m depth. A year-to-year variation in spring abundance of particular species was noted.

The sessile alga *Cladophora* was abundant in the shallow nearshore waters, with the maximum growth in late June and early July. Remote sensing measurements from aircraft with a multispectral scanner showed that 66 percent of the nearshore to a distance of 277 m offshore was covered by *Cladophora* from the Niagara River to Rochester, N.Y., and 79 percent from Rochester to Stony Point, N.Y.

Benthic fauna provide a stable biological index of trophic condition of the lake. Mean estimated invertebrate densities for the inshore (0- to 35-m depth), intermediate (35 to 90 m) and offshore (> 90 m) regions were 11,800 m<sup>-2</sup>, 7,000 m<sup>-2</sup>, and 1,200 m<sup>-2</sup>, respectively. Oligochaetes dominate the fauna of the inshore region (71 percent of all organisms), with *Limnodrilus hoffmeisteri* the most common and widespread form; the amphipod *Pontoporeia affinis* dominates the intermediate (61 percent) and offshore (58 percent) regions. Benthic species typical of more polluted waters were found off Toronto and the Niagara River.

The most abundant zooplankton crustacean groups found were cyclopoids, copepods, and cladocerans. On the annual cycle, peak abundance of zooplankton crustaceans occurred in late August 1972, with maximum concentrations of 60,000 to 70,000 m<sup>-3</sup>. Minimum values of 2,000 m<sup>-3</sup> were measured from late fall to early spring. Cultural stresses were noted, with eutrophic indicator species most abundant near metropolitan Toronto and the Oswego River. Types and number of zooplankton crustaceans were compared for nearshore regions off urban and rural areas. Fewer species of crustacea were found off urban areas. Off rural areas the cladocerans (*Daphnia*, *Ceriodaphnia*, and *Chydorus*) were more abundant. Off urban areas *Bosmina longirostris* and *Cyclops* were more abundant. A comparison of the zooplankton abundance between 1939 and 1972 indicated a shift in relative abundance for various zooplankton crustacean groups; calanoid copepods have decreased in relative abundance, while cyclopoids and cladocerans have increased. At the generic level the relative importance of *Diaptomus* has decreased, and *Bosmina* and *Cy-*

*clops* have increased. Measurements of zooplankton biomass with sonar indicated that previous measurements of abundance with plankton net hauls are much too low.

Some 68 species of fishes were collected with some changes of species from recent compilations. The distribution in the vertical of gillnet catch shows that 79 percent and 91 percent of all fish caught were in depths shallower than 25 m and 55 m, respectively. The abyss of the main lake has a paucity of fish. Over Canadian main lake transects, alewife (69 percent) and rainbow smelt (26 percent) were dominant among the 18 species caught in a 91-m gillnet of 38- to 152-mm mesh, set overnight. At fishing depths of 9 m, 27 m, and 55 m, the percentage catch of these dominant species was 83 and 10, 54 and 45, and 31 and 66, respectively. Along U.S. main lake transects, sculpin catches were more numerous than along Canadian transects.

## 8.2 MATERIALS BALANCE

A materials balance for a conservative variable represents an experiment in the application of the principal of Newtonian mechanics, which state that mass cannot be created or destroyed, but only transferred from one volume to another. Complications arise for mass balance studies of nonconservative variables that change form due to chemical and biological processes of transformation and dynamics. For such nonconservative variables, the materials balance formulation and measurement program must include processes of both mass balance and transformation.

The IFYGL Materials Balance Project was undertaken to improve the understanding of the major processes which on a lake and seasonal scale made up the balance for selected chemicals in Lake Ontario; to assess the experimental ability and theoretical understanding of processes to achieve a lakewide materials balance from an experimental program; and to identify the relative importance of the terms in the materials balance. Many chemicals of interest, e.g., the nutrients, are not conservative, and are involved in the chemical and biological dynamics of the food chain. With the present state-of-the-art in measurement systems, such nonconservative chemicals are difficult to deal with in a materials balance. In IFYGL, a materials balance for Lake Ontario was attempted for total phosphorus, total nitrogen, and carbon.

Monitoring of the tributary discharge rates and chemical loads is an ongoing program in the United States and Canada. During the Field Year the major tributaries were sampled at 2- to 3-day intervals; the

minor tributaries were sampled 12 to 18 times during the 12-month period from April 1972 to March 1973. The change in chemical storage in Lake Ontario was measured by the collection of samples at multidepths on lakewide cruises. The chemical load from precipitation was estimated from 23 monitoring stations around the lake.

A materials balance was computed for total phosphorus on a monthly basis, with estimates derived for the total load for the tributaries, the Niagara and St. Lawrence Rivers, and precipitation. The change in storage was estimated from 12 cruises. Sedimentation and resuspension were not calculated, but were estimated as residuals. Seasonally, the total phosphorus load to Lake Ontario is greater in winter ( $1.3 \times 10^6$  kg month<sup>-1</sup>) than in summer ( $0.6 \times 10^6$  kg month<sup>-1</sup>). The total phosphorus content in Lake Ontario averaged about  $40 \times 10^6$  kg and increased over the 12-month period by  $5 \times 10^6$  kg. The annual residual in the balance between the net tributary load and change in storage indicates that  $5 \times 10^6$  kg of phosphorus was added to the Lake Ontario sediments during the Field Year.

A materials balance was computed for total nitrogen on a monthly basis, in the same way as for total phosphorus. Seasonally, the total nitrogen load is greater in winter ( $8.6 \times 10^6$  kg month<sup>-1</sup>) than in summer ( $3.6 \times 10^6$  kg month<sup>-1</sup>). The total nitrogen concentration in the lake averaged about  $600 \times 10^6$  kg, and decreased over the Field Year by  $26 \times 10^6$  kg. The annual residual in the balance indicates that  $100 \times 10^6$  kg of nitrogen was added to the Lake Ontario sediments during the 12-month period.

A carbon budget estimated on a monthly basis shows that the two major carbon sources to Lake Ontario are the inflow of inorganic carbon in tributary streams and the fixation of CO<sub>2</sub> in organic matter by primary production. The major sinks are the inorganic carbon outflow in the St. Lawrence river and the net CO<sub>2</sub> exchange between the atmosphere and the dissolved inorganic carbon pool in the lake. Seasonally there is a net carbon inflow to the lake in the warm months and a net outflow during the cold months. This cycle is driven by the seasonability of primary production. During the warm season high rates of primary production result in the fixation of large amounts of carbon, which, in turn, cause a depletion in the dissolved CO<sub>2</sub> in the lake and a net influx of CO<sub>2</sub> from the atmosphere. During the cold months decomposition of organic matter predominates, resulting in a large flux of CO<sub>2</sub> from the lake to the atmosphere.

### 8.3 ECOSYSTEM AND WATER QUALITY MODELING

The Ecosystem and Water Quality Modeling Project was undertaken to improve understanding of the Lake Ontario ecosystem, with particular emphasis on the seasonal dynamics of plankton and nutrients, by providing a comprehensive mathematical synthesis of a variety of limnological processes and components; to generate testable hypotheses on the ecosystem properties and mechanisms; and to further the state-of-the-art of quantitative diagnosis and prognosis of the lake ecosystem, including the phenomena of eutrophication.

A mathematical model is an abstraction of the real world that attempts to draw together within a simple framework the principal phenomena and processes pertinent to the problem at hand. A model of water quality of Lake Ontario is, therefore, a synthesis of certain hydrological, hydrodynamic, chemical, and biological phenomena and processes. Such a synthesis applies the basic principle of mass conservation through one or more equations that incorporate the essence of each of the key phenomena.

Mathematical models were developed during IFYGL by several groups of investigators and provide, for the first time, for the Great Lakes a comprehensive synthesis of a variety of limnological processes and compartments, particularly with respect to the seasonal dynamics of plankton and nutrients. Since testing and evaluation has been limited, the precision of these models for prediction purposes is not yet well defined, but the following accomplishments pertaining to the Lake Ontario ecosystem can be cited:

- (1) In the epilimnion, the rank sequence in carbon turnover time (the seasonal average concentration/seasonal averaged inflow) by trophic compartment is herbivores, producers, carnivores, and detritis; rank by season is summer, spring, fall, and winter.
- (2) In the summer epilimnion, the rank sequence of the important factors affecting nutrient dynamics are phytoplankton uptake, plankton excretion, detritus decay, and diffusion from the hypolimnion. In the summer epilimnion the pool of available phosphorus would be depleted in about 1 day if it were not for recycling — excretion from plants and animals, and detritus decay; most of the assimilated phosphorus (86 percent) is recycled within the epilimnion.
- (3) The phytoplankton settling velocity and vertical dispersion are both first-order vertical transport mechanisms in phytoplankton dynamics.

- (4) For the seasonal cycle of net phytoplankton production, phosphorus deficiency is a major limiting factor, although nitrogen and silica shortages also seem to be important.

A limnological mathematical model provides a means for making engineering estimates of the water quality response under different levels of external control. The usefulness of a mathematical model as a tool for planning and management is, of course, dependent upon the precision with which observed behavior is reproduced. While the mathematical models developed in IFYGL have contributed to our understanding of the processes of Lake Ontario and to our ability to make statements about the behavior, precision is not great. Therefore, at this early stage in the development of water quality and ecosystem models, caution must be used in interpreting predictive results. The models have been useful, however, in organizing information on the effect of reduced lake loads on phosphorus concentrations.

Additional questions have been raised in the analyses of mathematical models of phytoplankton-nutrient dynamics. Studies still to be pursued include:

- (1) The nature of nearshore-openlake interactions.
- (2) The relationship between phytoplankton species and the response to nutrient controls.
- (3) The availability of phosphorus forms loaded to the lake.
- (4) The role of sediment as a source or sink for nutrients.

## 9. Major Accomplishments

In a research program with the scientific breadth of the International Field Year for the Great Lakes and with the large number of competent, participating principal investigators from Canada and the United States, it is difficult to be truly objective in the selection of the major IFYGL accomplishments. Nevertheless we choose to highlight the following topics.

### *The International Organization*

The publication of this book marks the completion of 15 years of productive integrated Canadian-United States research related to one of the Great Lakes — Lake Ontario. It is remarkable that the scientists of both countries, representing many disciplines, have persevered over this long period, evolving suitable organizational structures, as required, first in concep-

tualization, then the development of the four-volume *IFYGL Technical Plan*, the Field Year operations, the data management, the analysis, the archives, and the publication of results.

### *Evaporation Synthesis*

Lakewide evaporation from Lake Ontario was estimated during the Field Year by three methods: energy balance, water balance, and bulk aerodynamics (mass transfer). The results were compared and all showed similar seasonal variations, with high evaporation in the fall and winter and low evaporation, with some periods of condensation, during the spring and summer.

An improved mass transfer method was developed for making evaporation estimates on a routine basis using only readily available data. It was also possible to establish, for the first time, a mass transfer coefficient for Lake Ontario. This coefficient was found to be significantly less than the coefficient established for Lake Hefner, which had been previously used in estimating evaporation losses from the Great Lakes.

### *Intermittencies*

Lake Ontario responds rapidly and intensely in terms of water movements and temperature variations to forcing by the surface wind stress, especially during the thermally stratified season. Several water movement phenomena are involved: surface wind waves, near-inertial motions, upwelling and the coastal jet, and topographic waves. Away from the coast the lake responds to a wind-stress impulse in two closely related forms: (1) inertial motions with rotary currents, and (2) resonance of the inertial motions in the baroclinic modes to produce near-inertial motions.

Near shore, episodes of strong wind stress initially generate longshore coastal currents, or jets, usually in the direction of the wind stress, and coastal topographic or Kelvin waves that propagate counterclockwise around the lake. In the warm season a quasi-geostrophic balance is established between the longshore jet and a tilt of the thermocline normal to the shoreline.

Lake evaporation is episodic, with a temporal scale related to cyclonic storm passage. Large horizontal gradients of lake evaporation occur and are strongly influenced by the upwelling phenomena.

### *Interdependencies of the Atmosphere, Lake, and Basin*

IFYGL brought increased awareness, and more

precise estimates, of known effects and improved our understanding of the lake, the atmosphere, and the basin interdependencies. The following examples are noted:

- (1) Of the Lake Ontario water supply during the Field Year, 18 percent came from the basin runoff, 2 percent from the net atmospheric flux (7-percent precipitation, 5-percent evaporation), 80 percent from the upstream lakes, and less than 1 percent from groundwater. Of this water supply, 5 percent increased the storage in Lake Ontario and 95 percent flowed down the St. Lawrence River.
- (2) Lake Ontario warms from March to September owing to the net radiation flux to the lake, and cools from September to March owing to the combined effects of latent and sensible heat flux to the atmosphere.
- (3) During the Field Year the sources of total phosphorus to Lake Ontario were 47 percent from the Niagara River, 21 percent from the tributaries, 21 percent from municipal outfalls, 10 percent from precipitation, and less than 1 percent each from industrial and groundwater. Of this total load 49 percent was transported down the St. Lawrence River, 26 percent was stored in the lake, and 25 percent was stored in the sediments.
- (4) The main source of energy for water movements comes from the atmosphere. In the spring the net radiation warms the shallower nearshore region while the offshore central core remains cool. This mass distribution is associated with a mean, single counterclockwise rotating gyre. After thermal stratification, wind stress impulses, associated with cyclonic storms, initiate inertial and near-inertial motions in the central lake and longshore currents within the coastal region.

#### *Seasonal Cycle*

The seasonal variation in lake variables is related primarily to the annual variation in solar radiation. Also of importance are the interdependencies between the lake, the atmosphere, and basin, and the intradependencies within the lake. The following major seasonal cycles were noted during the Field Year.

- (1) For the Lake Ontario water balance, the basin runoff peaked in the spring (March through May) and was a minimum during August through October. The monthly lakewide evaporation was large — about 100 (74–128) mm per month — from September through January and was small — about 30 (9–49) mm per month — from March through July. The lake water level reached a seasonal maximum in June, consistent with the long-term normal, but the November minimum was 2 months earlier than the normal.
- (2) The lake temperature structure in the early spring was essentially isothermal. As spring progressed, the lake surface layer was heated by solar radiation, the temperatures in the shallow coastal waters increased rapidly relative to the offshore waters, and the thermal bar formed. By July, a sharp thermocline was established lake-wide; it persisted through September and progressively and intermittently moved to greater depth owing to wind-induced turbulence and wave action associated with storms. By October, the surface layers cooled, and vertical mixing progressed to greater depth. Overturning of the complete water column occurred by late November.
- (3) The stability of the atmospheric boundary layer, depicted by the difference between water surface and air temperature, progressed through an annual cycle. During the warming season, April through June, the atmospheric boundary layer was usually stable (the lake was colder than the air) and during the cooling season, September through February, the atmospheric boundary layer was most frequently unstable (the lake warmer than the air). The boundary layer stability influences the surface wind stress on the lake and the lake-atmosphere fluxes of heat and water vapor, and presumably chemicals (e.g., carbon dioxide).
- (4) With respect to total phosphorus, the lake load from the tributary rivers was a maximum in the spring associated with the peak in basin runoff. From March through October the sediment was a sink for lake total phosphorus. From November through February the total phosphorus in the lake increased as a result of a net load from both the tributaries and the sediments.
- (5) For phytoplankton, the spring species abundance was greatest in the warmer nearshore waters and the abundance in midlake increased as the lake stratified. For major phytoplankton groups (e.g., Bacillariophyta and Microflagellates) the greatest abundance occurred from March through July and the least from August through February.

### Numerical Modeling

Numerical ecosystem models of Lake Ontario were developed and were exceedingly useful for a better understanding of the functioning of the Lake Ontario ecosystem, e.g., nutrient dynamics, and the seasonal cycle of phytoplankton production. While significant advances were made in the development of numerical ecosystem models that simulate nutrient cycling in the lake for a small number of ecosystem compartments, a long-term research program is required to develop numerical models that accurately predict natural changes in the ecosystem, and changes that result from a variety of anthropogenic stresses. At the present state of development, numerical ecosystem models can be useful tools for limnologists who provide information to resource planners and managers.

Numerical models of lakewide circulation were developed and tested. These models are useful to assist in interpreting data and understanding phenomena. While these models are now being used as indications of the transport and dispersion of chemical and biological variables, caution must be exercised since tests and evaluations are quite limited and considerable additional model research is required.

### Publications

Perhaps the major accomplishment of IFYGL is the 454 publications produced by Canadian and United States scientists that have appeared in the scientific literature, in agency reports, and in the official IFYGL publications.

In the *IFYGL Bulletin* series, 22 issues were published from January 1972 to March 1978. This series was essentially a management tool, a vehicle to pull together and to exchange information among the 78 United States and 118 Canadian separate but interdependent projects and management activities.

In the *Technical Manual* series, 7 issues were produced that describe major measurement systems and methods used in IFYGL.

The final Canadian and United States data catalogues (referenced in app. C) describe the data and information available upon request from the Canadian and the United States archives at the nominal cost of retrieval.

An IFYGL bibliography is contained in appendix A.

### The IFYGL Archives

One of the major IFYGL accomplishments was the

development of the IFYGL archives that contain both data and information — articles and reports developed by scientists from Canada and the United States. The data base was derived from the many systems used in IFYGL to measure the physical, chemical, and biological variables in the lake, the atmosphere, and the basin. As was pointed out by the IFYGL Panels in the proceedings of the IFYGL Wrap-Up Workshop (*IFYGL Bulletin* No. 22, 1978), a significant research need exists for further analysis of this valuable data base. These data will continue to be useful for both scientific and engineering analyses, and for development, testing, and evaluation of numerical simulation models. These archives, stored both in the United States and in Canada, are described in more detail in appendix C.

### 10. Summation

One cannot close this final chapter without reflecting on the IFYGL accomplishment. The early planning for this research program, which has spanned 15 years (1966–81), was performed by scientists during a period when international scientific research was encouraged in both the United States and Canada. The scientific objectives and experimental approaches were planned on the basis of our understanding of variability, processes, and phenomena, and the state-of-the-art in measurement systems of a decade ago. During IFYGL the environmental research emphasis of both nations shifted to a problem orientation, due in part to the awareness of nutrient enrichment (e.g., eutrophication) problems and, more recently, the problems of toxic substances. With the shift in the national emphasis, a program in chemistry and biology and numerical modeling was later included in IFYGL.

While most of the IFYGL research was planned to meet single disciplinary objectives, multidisciplinary aspects were apparent. Typical of scientific research, in the process of achieving the various project objectives and in obtaining a better understanding of the physical, chemical, and biological processes, we become more aware of what we do not know — the gaps in knowledge. In October 1977, a Wrap-Up Workshop was convened to reflect on the IFYGL program, to ask the question "How did we do?" There were three main objectives: to review accomplishments, to identify priority research problems, and to develop recommendations for future Great Lakes research. The workshop was attended by 61 scientists who were invited in recognition of their active participation in, or

contributions to, the Field Year (*IFYGL Bulletin* No. 22, 1978).

The workshop was organized into eight groups, with most participants active in more than one group, along the lines of the seven IFYGL panels and with a cross-panel topic — the Lake Ontario ecosystem. In their separate ways each group examined their original research objectives, the research organization, approach, and accomplishment. Each group critiqued its program with respect to successes and failures, whether research objectives were achieved, and how in hindsight they would modify the research program if they had it to do over. The groups also identified their perception of research gaps and developed recommendations on future Great Lakes research that should be pursued, including experimental studies, analyses, and numerical modeling.

The following are highlights of critical and essential multidisciplinary research recommendations extracted from the Wrap-Up Workshop proceedings.

- (1) Experimental studies are needed to improve understanding and parameterizations of the following key processes and phenomena:
  - (a) Particulate and sediment transport processes including source, cycling, and fate of toxic substances, tributary input of chemicals, availability of nutrients.

- (b) Physical and chemical turbulent fluxes within the lake and across the air-lake and lake-sediment interfaces.
  - (c) Nearshore-offshore dynamics, including source, transport, cycling, and fate of chemicals; coastal and nearshore flow, and scales of phenomena.
- (2) Improved monitoring systems should be developed for key physical, chemical, and biological variables.
- (3) A hierarchy of improved numerical models should be developed, tested, validated, and implemented to predict and simulate the circulation, ecosystems, and water quality variables to support management and use of the lakes.

IFYGL was a major research focus in the United States and Canada for over a decade. A team effort between scientists and research managers in both countries was needed to plan, to conduct the field operations, to analyze the data, and to document and synthesize the research results. A multidisciplinary, interagency, and international spirit of cooperation was developed and sustained that in no small measure contributed to the substantial research successes. Much was accomplished, but significant research remains to be done.

GLERL LIBRARY

# IFYGL- THE INTERNATIONAL FIELD YEAR FOR THE GREAT LAKES

---

March 1981



Edited by  
**E. J. AUBERT**  
**T. L. RICHARDS**

**UNITED STATES**

DEPARTMENT OF COMMERCE  
DEPARTMENT OF DEFENSE  
DEPARTMENT OF INTERIOR  
DEPARTMENT OF TRANSPORTATION  
ENVIRONMENTAL PROTECTION AGENCY  
NATIONAL SCIENCE FOUNDATION  
NEW YORK STATE DEPARTMENT OF  
ENVIRONMENTAL CONSERVATION  
NATIONAL AERONAUTICS AND SPACE  
ADMINISTRATION

**CANADA**

DEPARTMENT OF ENERGY, MINES, AND  
RESOURCES  
DEPARTMENT OF THE ENVIRONMENT  
DEPARTMENT OF FISHERIES AND OCEANS  
DEPARTMENT OF TRANSPORT  
ONTARIO MINISTRY OF THE ENVIRONMENT  
ONTARIO MINISTRY OF NATURAL RESOURCES