HYDROMETEOROLOGICAL STUDIES
IN SUPPORT OF THE INTERNATIONAL FIELD YEAR
FOR THE GREAT LAKES

T.L. RICHARDS
Hydrometeorology Section, Meteorological Service of Canada

ABSTRACT

The Canadian and United States National Committees for the International Hydrologic Decade have agreed to sponsor an International Field Year on the Great Lakes,—a concentrated scientific investigation of one of the Great Lakes (likely Ontario) over an 18-month period beginning April 1, 1970. The Field Year will be preceded by several years of feasibility studies, project planning, and instrument development. Preliminary program proposals have been designed to evaluate, as accurately as possible, the atmospheric and terrestrial water budgets and the energy balance of a lake as well as the circulation, wave climatology and diffusion characteristics of the same lake. The program will be based on a limited number of primary projects to be sponsored by those agencies in Canada and the United States responsible for major observational programs. Universities, research institutes and individual scientists from all countries will be welcome to conduct studies and investigations in support of, or auxiliary to, the primary projects, and data from the major observing programs will be made available to assist such studies.

Many of the studies will be of a hydrometeorological nature, including an investigation of lake level variations as related to precipitation, evaporation and the inflow and outflow of surface and ground water. Evaporation will be assessed by all possible means including atmospheric water budget, energy balance, water budget, mass transfer and micrometeorological flux techniques. Preliminary studies are underway to determine the feasibility of using an atmospheric water budget technique, similar to that used by Palmen for the Baltic Sea which would employ a radiosonde network around the shoreline of Lake Ontario. The difference between over-lake and overland precipitation amounts will also receive special attention through improved rain gauge networks and weather radar film analyses by an optical scanning device under development which will digitize filmed data.

RÉSUMÉ

Études hydrométéorologiques dans le cadre de l’année internationale des grands lacs

Les comités nationaux du Canada et des États-Unis de la Décennie hydrologique internationale sont convenus de parrainer une année internationale des Grands lacs, probablement le lac Ontario, et qui sera poursuivie durant 18 mois à compter du 1er avril 1970. L’année internationale sera précédée de plusieurs années consacrées aux études sur les possibilités, à l’établissement du plan du projet et à la mise au point d’instruments. Les éléments du programme provisoire concernent l’évaluation aussi exacte que possible des bilans hydrologiques atmosphériques et terrestres et du bilan énergétique d’un lac, ainsi que les caractéristiques de ce lac quant à la circulation, à la climatologie des ondes et à la diffusion. Le programme se fondera sur un nombre limité de projets primaires qui seront poursuivis sous l’égide des organismes canadiens et américains chargés des programmes importants d’observation. Des universités, des instituts de recherches et des hommes de science de tous les pays seront invités à poursuivre des études et des recherches à titre de participation ou d’aide à la réalisation des projets primaires, et les données rassemblées dans le cadre des programmes importants seront mises à leur disposition afin de les seconder dans leurs recherches.

Plusieurs de ces études relèveront de l’hydrométéorologie, y compris des recherches sur les rapports entre les variations du niveau du lac et les précipitations, l’évaporation et les débits entrant et sortant des eaux de surface et des eaux souterraines. On évalua l’évaporation par tous les moyens possibles, notamment le bilan hydrologique atmosphérique, le bilan énergétique, le bilan hydrologique et les techniques de transfert de masse et de flux micrométéorologique. On a commencé les études préliminaires en vue de déterminer la possibilité de l’emploi d’une technique du bilan hydrologique
atmosphérique semblable à celle qu’a utilisée Palmen pour la mer Baltique et qui comporterait l’implantation d’un réseau de radiosondes autour du lac Ontario. La différence entre les précipitations qui tombent sur le lac et celles qui tombent sur le sol feront aussi l’objet d’une étude spéciale à l’aide de réseaux de pluviomètres perfectionnés et d’analyses de films radar météorologiques effectuées au moyen d’un appareil de balayage optique qu’on est en train de mettre au point et qui pourra chiffrer les données sur film.

INTRODUCTION

The Canadian and United States National Committees for the International Hydrologic Decade have recently decided to co-sponsor an International Field Year on the Great Lakes. Under the guidance of an eight-man Steering Committee, four from each country, the Field Year will be a concentrated scientific investigation of a representative lake of the Laurentian System (likely Ontario) over an 18-month period beginning April 1, 1970.

The decision to proceed with a Field Year was reached on the grounds that although there has been much very good physical research conducted in the Great Lakes and their basins it has become increasingly apparent that some of the problems are so large and so complex that only a large well coordinated study is likely to succeed. In instigating such an undertaking it is recognized that the Field Year will require not only all the resources and manpower that can be brought to bear from the scientific community in the Great Lakes area but also from elsewhere in the United States and Canada and indeed help is looked for from the rest of the world.

IFYGL Primary Objective

In a Policy Statement issued on April 12, 1967 the Primary Objective of the Field Year stated that, "It is proposed to investigate in depth, through an integrated and fully coordinated group of research programs a number of basic unsolved, or only partially solved physical problems associated with the hydrology, meteorology, physical limnology and geology of one of the Great Lakes and its drainage basin. In brief, these programs, although fundamental in nature, will seek to improve man’s knowledge of the available fresh water supply for such widely diverse purposes as domestic and industrial usage, navigation, power, recreation, and sewage disposal. In connection with the last named, studies will be directed at obtaining a better understanding of the physical factors which affect the dispersal of pollutants in the lake".

The Steering Committee recommended that the study should be concentrated on just one lake with the expectation that many of the findings may be proven valid not only for the other lakes of the Laurentian System, but for many of the large lakes of the world. Major benefits are also likely to accrue from the use of the lake as a model ocean in the study of air-water interface problems of global importance to oceanographers and meteorologists. At this particular time fundamental studies of the exchange of heat, humidity and momentum will be of vital assistance to such worldwide projects as the Global Atmospheric Research Program (G. A. R. P.) and World Weather Watch (W. W. W.).

Lake Ontario was designated as the lake to be studied unless feasibility studies planned for this year indicate otherwise. This decision was made on the basis of the need for scientific information, public interest, the representativeness of the lake, the likely quality of the data, logistics and operating costs.

LAKE ONTARIO

The choice of Lake Ontario for the IFYGL study was made by the process of elimination and perhaps deserves an explanation. Lake Michigan and Lake Huron are
one body of water, hydraulically speaking, and this combination was deemed too complex for the proposed study. Lake Erie, with an average depth of only 17 m (56 ft.) was thought to be too shallow to be representative and in addition as a result of its shallowness freezes over for several months of each year. There was much in favour of Lake Superior on the basis of representativeness and the quality of hydrologic data. However, Lake Ontario is also representative and on the strength of the urgent need for scientific information, public interest, simpler logistics and lower operating costs it was recommended for the Field Year. The fact that the Canadian Government has confirmed the building of a 17 million dollar Canada Centre for Inland Waters at Burlington on the west end of Lake Ontario may have also influenced the decision.

Physical Features

Lake Ontario is the most easterly and lowest lake of the Great Lakes system. It is fed from Lake Erie by the mighty Niagara River and is drained to the Atlantic by the even larger and longer St. Lawrence. Lake Ontario has the smallest area of the system,—just under 20,000 km² (7,600 sq. miles) and like the other Laurentian lakes has a drainage basin which is relatively small compared to the lake surface, i.e.—about 70,000 km² (34,800 sq. miles). It is a deep lake with an average depth of 86 m (282 ft.) and a maximum depth of 244 m (778 ft.).

Lake Ontario’s average elevation is 74.6 m (244.8 ft.) above m.s.l. However its level varies through an average annual cycle of 0.5 m (1.6 ft.) with a low in March and a high in August. One hundred and seven years of records reveal an overall range of stage (mean monthly levels) of 2 m (6.6 ft.).

Other data include a mean inflow of 5,600,000 l/sec. (200,000 cfs) and an outflow of 6,600,000 l/sec. (240,000 cfs). Rainfall on the basin has averaged about 860 mm (34 inches) annually since 1900 with a year to year variation of as much as ±20% (Richards (1)). Annual evaporation from the lake surface has been variously estimated at from 660 to 815 mm (26 to 32 inches) with a year to year variation of as much as ±40% (Richards and Rodgers (2)).

PROPOSED SCIENTIFIC PROGRAM

The IFYGL proposes to meet its objectives through four basic or primary programs:

(i) Atmospheric Water Budget;
(ii) Surface and Ground Water Budget;
(iii) Energy Balance;
(iv) Water Movement.

The core projects of each program will be the responsibility of those agencies in the United States and Canada currently undertaking the major observational and research programs in the Great Lakes area. In addition, universities, research institutes and individual scientists from all countries will be welcome to conduct studies and investigations in support of, or auxiliary to, the primary programs. Facilities for, and data from, the major observational programs will be made available to assist such studies.

In developing the overall program every effort will be made:

(i) To improve the time-density and space-density of standard observations to obtain an unimpeachable background of standard data;
(ii) To replicate the measurement of each parameter by as many methods as feasible to refine our knowledge of the capabilities of present methods;
(iii) To develop and/or utilize new methods and to test these against an exceptionally good background of standard observations and data.

Benefits

The Steering Committee notes that the benefits of such a study will be an increased understanding of such problems as:

— the variations of lake level as related to precipitation, evaporation and surface and ground water supply;
— the measurement of evaporation from large water bodies;
— the modification of climate by large water masses;
— the formation and dissipation of ice;
— the movement of water including circulation, diffusion, waves (surface and internal);
— the physical factors affecting the chemical, biological and material balance of a large body of water (eutrophication, pollution, sedimentation).

Evaporation Studies

One of the major benefits noted, and the one to be discussed in this paper is the opportunity to study in depth evaporation from large lakes. A review of the four major programs and suggested sub-topics reveals at least five techniques that will be available for assessing evaporation, i.e. water budget, energy balance, water vapour flux (micrometeorological), mass transfer and atmospheric water balance. Some of these have previously been limited to use on smaller lakes or reservoirs, others have been used mainly on oceans but the Field Year now offers the opportunity to test all at the same time on a relatively large body of water.

WATER BUDGET METHOD

One of the most straight forward, but not necessarily most reliable, methods for assessing evaporation from a lake is the Water Budget Method—a direct accounting of the gains and losses in the water balance of the lake, i.e.:

\[ E = P + I - O - S \]  

where

- \( E \) Evaporation;
- \( P \) Precipitation on the lake surface;
- \( I \) Inflow (Niagara + watershed streams + ground water gains);
- \( O \) Outflow (St. Lawrence + ground water losses);
- \( S \) Change in water volume (or level).

Of all the measurements required for the solution of this equation for Lake Ontario the water level measurements are probably the most reliable. These are recorded by a network of automated gauges which could be enlarged for more precise measurement during the Field Year if feasibility studies should so indicate.

Although there is a fairly adequate coverage of precipitation observing stations on the land portions of the Lake Ontario basin there has been little or no continuous measurement of precipitation over the lake itself and it is a matter of some concern as to whether measurements over land areas are representative of precipitation falling on the lake surface. A number of investigations involving over-water precipitation have been undertaken on the Great Lakes using gauges on islands and peninsulas. Most of these have indicated a deficiency in precipitation catch as compared to land,
particularly during the summer. However the matter of uniform exposure of the gauges is so critical that it is still a matter of some controversy. It is expected that this matter will receive major attention during the Field Year through all possible means including enlarged observing networks, more sophisticated analysis techniques (Changnon, (2)) and hopefully through improved radar coverage and automatic radar data analysis equipment currently under development.

The inflow and outflow rivers (Niagara and St. Lawrence) and most of the main streams from the local watershed are reasonably well gauged although flows during periods of ice may be unreliable at times. Unfortunately, the real weakness of the Water Budget Method is that the inflow and outflow figures are much larger than the evaporation figure. The difference is so great that a 1% bias in the inflow or outflow will introduce an error of the order of 25% in the likely evaporation. For this reason every effort will be made to more precisely monitor river and stream flows during the 18-month Field Year period.

The gains or losses through ground water exchange in Lake Ontario have never been assessed. Although the net effect is thought to be small the ground water experts are planning a thorough study of this factor and it is expected that a figure will be available by 1970.

Although precise evaporation measurements from Lake Ontario may never come from the Water Budget Method the additional and more precise data collected during the Field Year will certainly improve the estimates and will no doubt lead to a better understanding of the hydrology of the lake.

ENERGY BALANCE METHOD

Perhaps the most theoretically acceptable technique for arriving at an estimate of evaporation from a body of water the size of Lake Ontario is the Energy Balance Method. This is an accounting of the energy gains and losses where all but the evaporation term may be independently measured or estimated with reasonable accuracy:

The basic equation is:

\[ Q_s - Q_r - Q_b - Q_h - Q_e = Q_t - Q_v \]  

(2)

Where

- \( Q_s \) amount of solar radiation incident to the water surface;
- \( Q_r \) reflected solar radiation;
- \( Q_b \) net long wave radiation loss;
- \( Q_h \) transfer of sensible heat to the atmosphere;
- \( Q_e \) energy of evaporation (or condensation);
- \( Q_t \) energy storage within the lake;
- \( Q_v \) net advection term.

Equating for \( Q_e \), the equation becomes:

\[ Q_e = \frac{Q_s - Q_r - Q_b + Q_v - Q_t}{1 + R} \]  

(3)

Where

\[ R = \frac{Q_h}{Q_e} \]
The introduction of the ratio $R$ is a convenient device since with our present knowledge the term $Q_h$ can be related only to $Q_e$ through a relationship first derived by Bowen (196) i.e.

$$R = \frac{Q_h}{Q_e} = 0.61 \left[ \frac{T_w - T_a}{e_w - e_a} \right] \frac{p}{1000}$$

where

- $T$ temperature, degrees Celsius;
- $e$ vapour pressure, mbs.;
- $p$ atmospheric pressure, mbs.;
- subscript $w$ denotes water;
- subscript $a$ denotes air.

The energy balance of Lake Ontario has been assessed several times during the past few years, i.e. by Bruce and Rodgers (4) in 1962 and more recently by Rodgers in 1965 (5). Although each study employed improved data and more refined techniques a brief review of the individual terms in the equation reveals how an intensive study such as the Field Year could make possible a much improved estimate of annual and monthly evaporation.

$Q_s$—Incident Solar Radiation

Up to the present time this term has been evaluated from average over-land values documented by Mateer (6). However since 1960 $Q_s$ has been measured over-lake by the research vessel C.C.G.S. “Porte Dauphine” and on the basis of these observations a technique is now available to translate land observations to estimates of incident solar radiation over the water areas (Richards and Loewen (7)). More recently radiation observations have also been made by the research vessel M/V “Brandal”. A prerequisite for the Field Year would be a more intensive program of observing this term both by ships and by more land stations around the perimeter of the lake. Satellite photographs could also be used for assessing cloud cover over the lake.

$Q_r$—Reflected Solar Radiation—Albedo

To date the albedo has been estimated from graphs developed by Anderson (8) for the Lake Hefner studies. This term can now be measured by aerial surveys and such a program during the Field Year would assure improved accuracy. It is known that ice cover increases albedo. This has never been taken into account in Lake Ontario studies but regular aerial ice reconnaissance since 1959 by the Canadian Meteorological Service now provides a substantial amount of ice cover information and an increased program of ice reconnaissance during the Field Year is entirely possible.

$Q_b$—Net Long Wave Radiation

This term has been evaluated from an adaptation of an equation by Anderson (8) as developed by Tabata (9). Although the term is comparatively small it could be improved by more precise measurement of cloud cover and cloud height over the lake, of surface water temperature and of air temperature and vapour pressure at 2 meters above the lake surface. Such measurements could be made more often and more accurately during a concentrated study such as the Field Year.

$Q_h$—Transfer of Sensible Heat

The relationship of this term to the Bowen Ratio has been already described and it is no doubt evident that the terms in the Bowen Ratio could also be measured more
often and more accurately during an intensive study. In addition the abundance of data promised by the Field Year might well allow a more thorough investigation of conditions in which the Bowen Ratio is valid over water.

$Q_t$—Energy Storage

This term is one of the largest, and most variable, in the equation. It is measured by surveys of water temperature to depth by bathythermographs. Although there have been fairly regular surveys of Lake Ontario since 1959 a program of observations at more frequent intervals, as planned for the Field Year, would certainly lead to improved data.

$Q_v$—Net Advection

Although this term is relatively small it could be more precisely measured especially through an improved water budget study already proposed for the Field Year.

In review, although there are apparent weaknesses in the Energy Budget Method, an intensive data collection program using more ships, aircraft, buoys and lake towers over an 18-month period as envisaged for the IFYGL could develop much improved estimates of monthly and annual evaporation.

**MASS TRANSFER METHOD**

A popular technique for determining evaporation from Lake Ontario and other large lakes has been the Mass Transfer Method. In the well known Lake Hefner (10) and Lake Mead (11) studies it was found that a simple quasi-empirical form of the Dalton equation:

$$E = 0.0024(e_s - e_{ae})V$$

(5)

gave satisfactory results where

- $E$ evaporation;
- $e_s$ saturation vapour pressure at surface water temperature, in. Hg;
- $e_{ae}$ vapour pressure of air over water (8 m) in. Hg;
- $V$ wind speed at 8 m in miles per day.

This method requires only wind, humidity and surface water temperature data and is relatively easy to apply. Earlier objections to using over-land climatological data for wind and humidity have been largely overcome by employing land/lake ratio techniques described by Richards (12) to simulate representative over-lake conditions. Equation 5 then becomes:

$$E = 0.0024(e_s - e_{ae}H) V \cdot R$$

(6)

where

- $e_{ae}$ vapour pressure over land;
- $H$ monthly humidity ratio (Richards and Fortin (13));
- $V$ monthly wind ratio (Lemire (14)).

The value of this method is still further enhanced through the addition of regular aerial surveys of all the Great Lakes with the infrared thermometer which now provides a fast and efficient means of augmenting surface water temperature observations usually made by ship (Richards (15)).

The usefulness of the Mass Transfer Method could be further improved during the Field Year by the addition of more climatological stations about the perimeter of the
lake (already underway) and an increase in the number of water temperature surveys by ship and aircraft.

There is however, still one serious drawback in using the equation in Lake Ontario. The coefficient 0.0024 was originally calculated for Lake Hefner, a relatively small lake (reservoir), some five to ten degrees of latitude south of Lake Ontario and in a distinctly different climatic region. Although the present equation produces reasonably realistic estimates it has long been agreed that the equation should be thoroughly checked for use on the Great Lakes. One of the prime objectives of the IFYGL is to provide this important check.

MICROMETEOROLOGICAL TECHNIQUES

In addition to the conventional methods for assessing evaporation it is expected that the IFYGL will also attract the attention of the micro-meteorologist using very specialized instrumentation on fixed lake towers or buoys. Precise vertical profile measurements of wind, temperature and humidity could lead to evaporation estimates based on the well-tested equation of Monin and Obukhov (16) or on more sophisticated methods as described by Sheppard (17). It may also be possible to employ eddy-correlation techniques as described by Dyer (18) and others. Although such methods are essentially experimental it is hoped that more precise and reliable sensors and more rugged towers will be available by 1970 to ensure data from a network of micrometeorological observing sites for at least part of the Field Year.

ATMOSPHERIC WATER BUDGET

It was the hope of those who first conceived the IFYGL that the forementioned techniques for estimating evaporation could be definitively verified by means of the Atmospheric Water Budget or Flux Divergence Technique. This technique was first used by Benton, Blackburn and Snead (19) over the North American continent and more recently by Palmén (20) over the Baltic Sea.

To date the method has made use of regular radiosonde data from existing networks with the solution being:

\[
E - P = \frac{1}{g} \int_{P_H}^{P_0} \frac{\partial q}{\partial t} dp + \frac{L}{gA} \int_{P_H}^{P_0} \frac{qV_n}{q} dp
\]

(7)

where

- \(E\) evaporation;
- \(P\) precipitation on area;
- \(A\) area under study;
- \(L\) length of periphery of above area;
- \(g\) gravity constant;
- \(\frac{\partial q}{\partial t}\) mean specific humidity at a given isobaric surface;
- \(\frac{qV_n}{q}\) mean horizontal flux of water vapour normal to the boundary.

Because of systematic errors in the computed flux divergence it is apparent that the relative size of the area under study is critical,—i. e. there is a minimum area per number of observing sites and observations a day for which the technique will produce realistic results. Rasmusson (21) concludes that when twice daily observations are used from the basic North American radiosonde network fairly accurate estimates of \(E - P\)
may be obtained on a mean monthly basis for areas of $2 \times 10^6 \text{km}^2$ and larger. He also suggests that doubling the number of observations is more important than doubling the size of the network.

Since the area of Lake Ontario is of the order of $2 \times 10^4 \text{km}^2$ it has been suggested that a network of 4 to 8 stations situated around the perimeter of the lake reporting 4 times daily would be necessary to obtain the required accuracy. However, it is feared by others that the area is entirely too small for the technique. Before proceeding with such a relatively expensive operation the IFYGL Steering Committee has recommended that a comprehensive feasibility study of the technique as it applies to Lake Ontario be undertaken.

If the study confirms that the technique is feasible for Lake Ontario it is expected that the Canadian Meteorological Service and the United States Environmental Sciences Service Administration will cooperate in the undertaking.

**SUMMARY**

The International Field Year for the Great Lakes offers an excellent opportunity to investigate many physical problems associated with large lakes. As indicated in the paper one of the major benefits will be the comparison of at least five techniques for assessing evaporation from large bodies of water. Even if some of the methods prove deficient the additional and more precise data collected during the 18-month period should still result in much improved evaporation estimates and will no doubt also lead to a better understanding of many other hydrologic problems as well.

Scientists from all countries will be welcome to participate in the Field Year by conducting studies in support of, or auxiliary to, the primary IFYGL programs and it is the sincere hope of all those associated with the Field Year that a large and well coordinated research effort will solve some of the major outstanding physical problems not only of the Great Lakes of the Laurentian System but of many of the large lakes of the world.

**REFERENCES**


DISCUSSION

**Intervention of C.H. De Jong**

*Question*: In the Netherlands, a similar investigation (water balance, energy budget, mass transport, etc.) on a lake of 500 km², will be closed next month. Experience with instrumentation, elaboration of the data, are at the disposal of Mr. RICHARDS.

*Answer of Mr. Richards*

Thank you for the information. Although Lake Ontario is considerably larger, many of our problems will be similar. I will be most interested in seeing a description of your program and eventually the results of your studies.

**Intervention of Jan Douglas**

*Question*: Around Lake Ontario, there are several large cities which cause air pollution and water pollution. Are these effects likely to bias your results or to render them inapplicable to other lakes, less polluted, such as Lake Superior?

*Answer of Richards*

I do not think that air and water pollution in and around Lake Ontario has reached the level where results would be biased. The fact that such pollution does exist in the Lake Ontario area does, however, add sense of urgency to studying that particular lake.