2 HYDRODYNAMIC MODELING IN THE GREAT LAKES FROM 1950 TO 1990 AND PROSPECTS FOR THE 1990S

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INTRODUCTION

Hydrodynamic processes in the Great Lakes directly affect the chemical, biological and ecological dynamics of the system. Horizontal and vertical transport and mixing influence the distribution of nutrients, contaminants, and biota. This paper discusses some of the conceptual and numerical hydrodynamic models that have been developed for the Great Lakes. It is not intended to serve as a tutorial on lake hydrodynamics but rather as a brief introduction to some of the different types of hydrodynamic models that have been developed for the Great Lakes and as a reference source for researchers who want to investigate the subject further. Several excellent tutorials and reviews on hydrodynamic modeling in the Great Lakes have already been published by Mortimer (1974 and 1984), Csanady (1984), and Boyce et al. (1989). A book on circulation modeling was written by Simons (1980), and a book on coastal hydrodynamics was published by Csanady (1982). The relation of hydrodynamic modeling to biological and chemical processes is covered specifically in reviews by Boyce (1974), Simons (1976c), and Bedford and Abdelrhman (1987).

Hydrodynamic models that have been developed for the Great Lakes can be categorized either as models dealing mainly with water level fluctuations in the lakes, which need not be particularly concerned with the details of horizontal motion in the lake, or models of lake circulation and thermal structure, which are mainly concerned with subsurface fluid motions and thermodynamics. Models of water level fluctuations include storm surge models, models of seiches and normal modes, tidal models, wind wave models, and hydrologic models. The main types of lake circulation and thermal structure models are those dealing only with the horizontal motions, and those that incorporate horizontal and

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Table 1. Physical Parameters Involved in Models of Water Level Fluctuations

Type of Model	Physical Parameters
Tides	Tidal force, surface slope, bottom friction, Coriolis force
Storm surge	Wind stress, pressure gradient, water surface slope, bottom friction, Coriolis force
Seiches and normal modes	Inertia, bottom friction, Coriolis force
Wind waves	Wind stress, wave energy, wave dissipation
Hydrologic models	Precipitation, runoff, evaporation, water level

vertical motion and thermal structure, physical (scale) models, and water quality models. This paper will describe the primary physical parameters involved in each of these types of models and provide references to some of the more important developments in each area.

WATER LEVEL FLUCTUATIONS

One of the first physical phenomena to be recognized as a significant hydrodynamic process in the Great Lakes was the elevation or depression of the water level at the shoreline. These fluctuations can be caused by astronomical forces (tides), by the force of storm winds or atmospheric pressure disturbances (storm surges and wind waves), or by the periodic oscillation of the lake surface after storm forcing has ceased (seiches). From a modeling standpoint, the primary dynamical variable in these processes is the water level fluctuation at each point in the lake. The physical parameters involved in modeling these phenomena are listed in Table 1.

TIDES

The dominant tides in the Great Lakes are the 12.42 h lunar and 12.00 h solar semidiurnal tides (M2 and S2). Diurnal water level oscillations have also been observed, but these are mainly a result of diurnal oscillations in the overlake wind field. The maximum range of the tidal oscillation is generally less than 10 cm. A pronounced resonance with the natural free oscillation period in Green Bay results in tidal ranges that can reach 18 cm at the head of the Bay. As described by Mortimer (1965), a Jesuit missionary named Father Louis Andre may have provided the earliest observations of tides in the Great Lakes in a 1676 report from Green Bay. As cited by Defant (1961), Harris (1907) a report that estimated the amplitude (half the range) of the combined lunar and solar semidiurnal tides as 1.1 cm at Milwaukee on Lake Michigan, 0.7 cm at Marquette and 3 cm at Duluth on Lake Superior. Endros (1930) used the data of Henry (1902) to estimate an amplitude of 7.1 cm for the combined tide at Amsterburg at the west end of Lake Erie. Platzman (1966) showed how diurnal oscillations of the wind over Lake Erie produce a "wind tide" oscillation in the water levels with an average amplitude of 1.5 cm at the ends of the basin. The rotation of the earth imparts a rotary character to the tides in the Great Lakes so that the high tide progresses around the shore of the lake in either a clockwise or counterclockwise direction. Mortimer and Fee (1976) describe the phase progression of the semidiurnal tides for Lakes Michigan and Superior. Hamblin (1976) discusses the theoretical basis for the sense of rotation of tides in the lakes. Hamblin (1987) includes a section on the tidal response of Lake Erie.

Storm Surges

When a steady wind blows along a channel, the equilibrium condition of the water surface in the channel is a depression of the water level on the upwind end and an elevation of the water level on the downwind end. In a channel of uniform depth, the magnitude of the depression and elevation are the same and are proportional to the length of the channel, the square of the wind speed, and the inverse of the depth. Early studies of storm surges on the lakes such as Keulegan (1951) used this equilibrium condition to calculate water level deviations for given wind speeds. In some of the first models of storm surges on the Great Lakes, Hayford (1922), Keulegan (1953), and Hunt (1959) took account of variations in lake depth by segmenting the lake along its axis and calculating equilibrium solutions for each segment. The results of these studies were good when the prevailing wind could be approximated as a steady, uniform wind blowing along the main axis of the lake.

The hydrodynamics of storm surges in the Great Lakes are governed by the mass and momentum conservation equations of shallow water theory. The space- and time-dependent wind stress is the upper boundary condition. The equilibrium state of a channel is just a special case for which an analytic solution is possible. In general, time-dependent equations applied to a two-dimensional lake of arbitrary shape have no analytic solution, but can be solved approximately on a computer by applying them in a finite difference form on a mesh of points covering the lake. Platzman (1958, 1963) performed such calculations for moving pressure disturbances on Lake Michigan and for nine actual storm surge cases on Lake Erie. He showed how the earth's rotation causes the point of maximum water level displacement to progress counterclockwise around the edge of the lake. The results obtained for a moving pressure disturbance cannot be duplicated by an equilibrium model and the results for actual Lake Erie storm surges showed considerable improvement over the equilibrium method.

A linear dynamic model was applied to fifteen Lake Erie storm surge cases by Schwab (1978). In addition to the time-dependence and two-dimensionality of the windfield, this study also included the effect of atmospheric stability and wind speed on drag coefficient and land-lake wind speed ratio. These factors are significant in many storm surge episodes. The models of Schwab (1978) and Platzman (1965) now form the basis for routine operational storm surge forecast systems for Lakes Erie and Michigan respectively. Regression models, which develop a statistical regression relationship between storm surges and meteorological forcing, have also been used successfully in predicting storm surges, particularly on Lake Erie, by Harris and Angelo (1963) and Richardson and Pore (1969).

Several detailed case studies of storm surges have been published which provide insight into the meteorological conditions that are conducive to storm surges on the Great Lakes. Irish and Platzman (1962) examine and categorize the types of storms that generally cause storm surges on Lake Erie. Ewing et al. (1954), Donn (1959), Freeman and Murty (1972), Murty and Polavarapu (1975), Hamblin (1979), and Dingman and Bedford (1984) describe several specific episodes of extreme surges on Lakes Michigan, Huron, Ontario, and Erie.

Schwab (1978), Budgell and El-Shaarawi (1979), and Simons and Schertzer (1989) describe how the inherently linear dynamics of storm surges in the Great Lakes are amenable to solution by the impulse response function method. This technique represents the time-dependent water level fluctuation at a point on the lake as the superposition of responses to a series of impulsive wind stresses that approximate the continuously changing actual wind. Schwab (1982) showed further that this method could be inverted to provide an estimation of overlake wind fields from observations of water level fluctuations around the shore of the lake. Heaps et al. (1982) and Freeman et al. (1974) explore the problem of coupling the storm surge response of bays and harbors to the open lake. Hamblin (1987) provides a summary of these techniques and other research that has been done on Lake Erie storm surges.

Seiches

Because of the frequent passage of extra-tropical storms through the Great Lakes region, the lakes are often subject to sustained strong winds. The winds tend to push the water in the lake to the downwind end, elevating the water level there and depressing the water level on the upwind end. When the wind diminishes, the tilted water surface tends to return to its normal position, but sometimes oscillates several times before returning to normal. The subsequent oscillation of the water surface of the lake after a strong wind has subsided or after an atmospheric pressure disturbance has caused a water level disturbance to develop in the lake is called a seiche. Each lake has its own characteristic period of oscillation for the fundamental (unimodal) seiche and higher harmonics. The period of oscillation depends on the size of the lake and its mean depth. The simplest models of seiches assume that the lake can be approximated as a channel, with seiche motions confined to the longitudinal axis of the channel. Harris (1953) and Defant (1953) discuss the hydrodynamic theory of one-dimensional, or channel, seiche models. Platzman and Rao (1964a, 1964b) describe a comprehensive application of a one-dimensional numerical seiche model to lake Erie and comparisons with observations of periodic water level fluctuations at standard water level gaging stations around the lake. Mortimer (1965) applied the channel theory to Lake Michigan proper and to Green Bay separately to show the relation of seiche periods in the bay and in the lake to tidal periods. Rockwell (1966) systematically calculated seiche periods using a one-dimensional numerical model for all five lakes.

Some lakes, particularly Superior and Huron, have very complicated shorelines that cannot be simply approximated as a channel. In addition, the effects of the earth's rotation on seiching motions (which can significantly alter the structure of the longer period modes) cannot be fully accounted for in a one-dimensional channel model. Seiche, or normal mode, models based on the hydrodynamics in a fully two-dimensional rotating basin were developed by Hamblin (1972, 1987), Platzman (1972), Rao and Schwab (1976), Rao et al. (1976), and Schwab and Rao (1977). These models have been able to accurately depict the two-dimensional structure and amplitude of lake surface oscillations for all the lakes. The results of these models have been used to explain the dynamical response of the lakes to storm surges and tidal forces, particularly the rotational characteristics.

Wind Waves

The development of wind waves on the Great Lakes is governed by the same physical parameters as ocean wind waves, namely a balance between wind energy input, wave energy, and wave dissipation. The main distinguishing feature of lake wind waves is that they are generally locally generated, not propagated from a distance, as is the case for many large ocean waves. Therefore, many of the techniques used to model ocean wave generation can be successfully applied to lake waves. The simplest wave models consist of a single equation relating wave height at a particular place and time to an empirical function (sometimes a complicated mathematical formula) of wind speed and fetch distance. Another equation is used to calculate wave period. The evaluation of these equations can usually be carried out with a pocket calculator or looked up on a graph. The SMB (Sverdrup, Munk, Bretschneider-Bretschneider, 1970 and 1973) model has been widely used for ocean wave forecasting and is the basis of a method for automated operational Great Lakes wave forecasts (Pore, 1979). A one-dimensional model developed by Donelan (1980) can also predict the direction from which maximum wave energy will arrive at the forecast point, which may not be coincident with the wind direction. Bishop (1983) compared predictions from three different one-dimensional methods for wave forecasting to observations of wave height and wave period in Lake Ontario. His results showed that the Donelan method was slightly better than the ocean wave methods, particularly when the dominant wave direction differed from the wind direction. Two-dimensional models for wave prediction attempt to predict waves at all points in the lake (or region of the ocean) at the same time. Actually, waves are not predicted at every point, but rather the lake (or region of the ocean) is split into a very large number of subregions and average wave conditions are predicted for each subregion. The difference from one-dimensional prediction methods is that in two-dimensional methods the results for any one subregion depend not only on wind speed and fetch distance, but also on the energy fluxes from surrounding subregions. That is, a budget of wave energy is maintained for each subregion which includes energy input from the wind, energy propagated into this subregion from surrounding regions, and energy propagated out of the region to surrounding regions.

A two-dimensional wave prediction model for the Great Lakes has been developed by Schwab et al. (1984) and Liu et al. (1984). Given a description of the lake topography and the two-dimensional, time-dependent wind field over the lake, the model predicts wave height, wave period, and wave direction for an array of square grid boxes covering the lake. The model has been successfully tested against one-dimensional methods for steady conditions in ideal basins and against several sets of actual observations of wave height, period, and direction in the Great Lakes.

Hydrologic Models

Hydrologic models are used to calculate the balance between precipitation, runoff, inflow, outflow, evaporation, and changes in the mean lake level. In the Great lakes, manmade control structures such as locks and dams, control some of the inflows and outflows. Since the lakes are a single, connected hydrologic system, changes in the water balance of the upstream lakes affect all of the lakes downstream. Table 2 (Derecki, 1976) shows the relative magnitudes of the terms in the water balance equation for the four hydrologic lake basins.

If values for some of the terms in the hydrologic balance equation are known accurately enough, it is possible to develop models to estimate the other terms. For example, observed water level changes, inflow, outflow, precipitation, and runoff can be used to estimate evaporation. During the 1972 International Field Year on the Great Lakes (IFYGL) experiment, an attempt was made to measure each of the terms in the water balance for Lake Ontario as precisely as possible. In the IFYGL summary (Aubert and Richards 1981), chapters on Meteorology, Precipitation, Atmospheric Water Balance, Energy Balance, Terrestrial Water Balance, and Evaporation Synthesis detail the methods and results.

A comprehensive operational hydrologic model for Lakes Michigan, Huron, St. Clair, and Erie, and their connecting channels is described by Quinn (1978). Another model for forecasting lake levels up to six months in advance was

Table 2. Average Hydrologic Water Budget (cm) for the Great Lakes, 1937–1969 (Derecki, 1976)

Lake	P	R	I	O	E
Superior	80	58	0	86	55
Michigan-Huron	80	67	60	139	65
Erie	88	72	640	706	85
Ontario	84	150	927	1077	70

Note: P = precipitation, R = runoff, I = inflow, O = outflow, E = evaporation.

developed by Croley and Hartmann (1986). These types of models are now used routinely by the U.S. Army Corps of Engineers and the International Joint Commission to develop lake level regulation and water management plans.

LAKE CIRCULATION AND THERMAL STRUCTURE

Currents in the lakes are the result of three main forcing mechanisms, namely, hydraulic (river) flow, wind forcing, and thermal forcing (heating by the sun). Because the ratio of horizontal scale (~100km) to vertical scale (~100m) for the lakes is so large, horizontal motions predominate over vertical motions. Models of lake circulation can be categorized as (1) those dealing primarily with the horizontal circulation due to hydraulic forces and wind stress, (2) those that include the effects of thermal forcing and vertical stratification, (3) physical models (scale models), and (4) water quality models that are more concerned with the effect of circulation on the advection, diffusion, and ultimate distribution of suspended or dissolved substances in the lakes. The primary physical parameters involved in these models are listed in Table 3.

Horizontal Circulation

In shallow lakes with sloping bottoms, a steady wind stress over the lake pushes surface water downwind. The water level at the downwind end of the lake rises and the resultant pressure gradient causes an upwind return flow in the deeper part of the lake. The first order force balance is between the wind stress and the water level slope, and a mass balance is established between downwind surface current and upwind return flow in the deeper part of the lake. In a lake with a sloping bottom, this results in strong currents in the direction of the wind in the nearshore region and weaker upwind currents in the deeper parts of the lake. This so called "two-gyre" pattern with a clockwise circulation cell on the left side of the wind direction and a counterclockwise cell to the right is the dominant response of the lake to steady wind forcing. When the wind stress diminishes or ceases, the rotation of the earth causes the gyre pattern to rotate

Table 3. Physical Parameters Involved in Models of Lake Circulation and Thermal Structure

Type of Model	Physical Parameters
Horizontal circulation	Wind stress, bottom topography, bottom friction, internal shear stresses, Coriolis force
Three-dimensional circulation and thermal structure	Wind stress, heat flux, internal pressure gradients, bottom topography, bottom friction, internal shear stresses, Coriolis force, buoyancy
Physical models (scale models)	Wind stress, bottom topography, bottom friction, Coriolis force, scale effects
Water quality models	Advection, diffusion, partition between dissolved and suspended states, reaction rates, deposition, resuspension

counterclockwise around the basin with a characteristic period that depends on the specific geometry of the basin and the latitude. For a 2 × 1 elliptic paraboloid at 45°N this period is about 5 days. Conceptual models of the horizontal circulation in the lakes due to steady wind forcing were developed by Birchfield (1967, 1969, 1972a, 1972b), Csanady (1967, 1968b, 1973b, 1976b), Bennett (1974), Thomas (1975), and Lien and Hoopes (1978). Numerical models which incorporated the particular geometry of a specific lake and could make predictions of circulation patterns for different wind directions were developed by Hamblin (1969), Murty and Rao (1970), Rao and Murty (1970), Freeman et al. (1972), Bonham-Carter and Thomas (1973), and Gallagher et al. (1973). Sheng et al. (1978) compare the results of a model of Lake Erie that includes free surface fluctuations as one of the dynamic variables to results from one that does not. They found that for changes in lake circulation over periods longer than about half a day, free surface fluctuations were not an important factor. Pickett (1980) showed that this type of model was able to explain many of the observed characteristics of wintertime circulation in all five lakes.

If an assumption is made about the distribution of eddy viscosity in the vertical direction, the vertical distribution of currents can also be estimated in the steady-state pattern. Models by Gedney and Lick (1972) and Witten and Thomas (1976) are good examples. Of course in natural conditions, the wind over a lake cannot usually be approximated as a steady wind so that time-dependent changes in the wind must also be taken into account. The time-dependent response of lake circulation to wind stress was treated in numerical models by Liggett (1969, 1970), Liggett and Hadjitheodorou (1969), Birchfield and Murty (1974) and analyzed mathematically by Birchfield and Hickie (1977). The time-dependent response of the lake is linked to the characteristic rotational mode of the lake as discussed above. These modes were noted in the work of Rao and Schwab (1976) on seiches, and modeled in more detail by Csanady (1976a), Saylor et al. (1980), Bennett and Schwab (1981), Huang and Saylor (1982), and Schwab (1983). The work of Simons (1983, 1984, 1985, 1986) demonstrates the dependence of the response of the lake to wind stress on the topographic modes. He also shows that the time-averaged mean circulation pattern in the lake depends on the rectified effects of nonlinear topographic wave interactions. This explains the difficulty linear models have in reproducing the details of observed long term circulation patterns.

Three Dimensional Circulation and Thermal Structure

The Great Lakes undergo an annual cycle of heating and cooling that typically takes the mean temperature of the lake both above and below the temperature of maximum density for freshwater (close to 4°C). When water temperatures in the lake are near the temperature of maximum density (usually in the spring and fall, sometimes throughout the winter), the forces of buoyancy and internal horizontal pressure gradients are small and generally do not have a significant effect on horizontal circulation patterns. During the period of the year when the net radiation flux to the lake is positive, typically February through September, a balance is maintained in the water column between vertical mixing due to surface wind stress and buoyancy of the warmer surface water. Wind-induced mixing tends to distribute temperature uniformly throughout the water column while the buoyancy forces tend to establish a vertical gradient with warmer water at the surface and cooler water at depth. The result is the development of a surface-mixed layer of warm water separated from a deep layer of cold water by a thermal transition zone whose depth and thickness depend on the relative magnitudes of mixing and buoyancy forces. These processes were observed by Church (1943, 1945) and Millar (1952). Ayers (1956) and Ayers and Bachman (1957) modeled the circulation patterns associated with thermal gradients as a simple geostrophic balance between pressure gradients and Coriolis force. The thermal transition zone, or thermocline, acts as a barrier to vertical mixing of mass or momentum between the upper mixed layer and the lower layer. Models of the development of the surface mixed layer and vertical thermal structure are described by Ivey and Boyce (1982), Ivey and Patterson (1984), Lam and Schertzer (1987), Schertzer et al. (1987), and McCormick and Meadows (1988) whose results point out the limitations of models that assume horizontal homogeneity. Gorham and Boyce (1989) show how the depth of the mixed layer in a lake depends on lake surface area and maximum depth.

In lakes with sloping bottoms, springtime heating warms nearshore shallow water faster than deep water, and a thermal barrier or bar develops which separates warm nearshore water from cooler offshore water. The location of the bar progresses offshore until warm water covers the entire surface of the lake and becomes the upper-mixed layer. Hydrodynamic models of this process were developed by Rodgers (1965, 1966), Scott and Lansing (1967), Csanady (1968a), Elliot (1971), Huang (1971), and Bennett (1971).

During the summer stratification, there is generally a sufficient density gradient between the upper and lower layers to allow internal waves to develop. For internal waves, volume transport in the upper layer at any point in the lake is very nearly compensated for by an equal and opposite volume transport below the thermocline so that large fluctuations of the thermocline can occur without a noticeable change in the free surface level. Internal seiches are generally of longer period than free surface seiches, and therefore are influenced more strongly by the earth's rotation. Observations of internal wave motions in Lake Michigan Lakes were made by Verber (1964, 1966) and interpreted as Kelvin and Poincaré type waves by Mortimer (1963, 1968). Similar observations in Lake Ontario (Boyce and Mortimer 1978), and Lake Erie (Boyce and Chiocchio 1987) demonstrate the ubiquitous nature of internal waves. Internal waves were also observed during a period of wintertime stratification (mixed layer temperatures less the temperature of maximum density) in Lake Ontario by Marmorino (1978). Schwab (1977) developed a numerical hydrodynamic model to calculate the structure of the internal modes of oscillation in Lake Ontario.

The first numerical models of three-dimensional lake circulation approximated the vertical structure of the lake as the superposition of two or more horizontal layers with either permeable or impermeable interfaces. Models of internal normal modes generally incorporate two layers with an impermeable interface. Surface-mixed layer models on the other hand require that heat and momentum can be freely exchanged between layers. Lee and Liggett (1970), Liggett (1970), Liggett and Lee (1971), Bennett (1971, 1977, 1978), Simons (1971, 1972, 1973, 1974, 1975, 1976a, 1976b), Gedney et al. (1973), Kizlauskas and Katz (1973), Allender (1977), and Allender and Saylor (1979) used layered models of varying degrees of sophistication to simulate three-dimensional circulation and thermal structure in the lakes. Bennett and Lindstrom (1977) showed how a simple empirical model of thermocline oscillations in the coastal boundary layer of Lake Ontario could be an effective tool for predicting the response of the nearshore thermocline to wind stress events. Csanady (1971, 1972, 1973a), Bennett (1973, 1975), and Simons (1979) contributed considerably to the understanding of the limitations of this type of model by considering analytic or semi-analytic solutions for several idealized cases.

Physical (Scale) Models

Physical scale models have been used successfully to simulate large scale hydrodynamic properties in rivers, reservoirs, and embayments. The key to making accurate simulations is to attain dynamic similarity of all important physical processes between the scale model and the prototype. For the Great Lakes, three considerable obstacles stand in the way of developing successful physical models. First, the large ratio of horizontal scale to vertical scale of the lakes (~1000:1) is difficult to duplicate in the laboratory, so that vertically distorted models must be used. Second, the processes of turbulent transfer of energy from wind to water and of frictional dissipation of energy at the lake bottom are not well understood and are difficult to simulate in a scale model. Third, the effect of the earth's rotation on circulation in the lakes must be incorporated into the scale model. Despite these obstacles, several scale models have been constructed. For example, Harleman et al. (1964) built a model of Lake Michigan with a horizontal scale of 1:500,000 and a vertical scale of 1:1000. Infrared lamps were used to simulate solar heating and a fan to simulate wind stress. The model was operated on a rotating (7.56 rpm) platform. Aluminum powder was used to track surface currents. Circulation patterns that developed in the scale model for different combinations of thermal forcing and wind stress were similar to patterns produced by numerical models and infrared from direct observations. Physical models were also developed for Lake St. Clair by Ayres (1964), for Lake Erie by Rumer and Robson (1968), Buechi and Rumer (1969), and Howell et al. (1970), and for Lake Ontario by Li et al. (1975).

Water Quality Models

One of the principal reasons for developing models of lake hydrodynamics is to use the circulation patterns predicted by the model to better predict the transport of suspended and dissolved chemical and biological material that can affect water quality. Particulate matter can enter the water column from atmospheric deposition, from river inflow, or from resuspension of benthic material. Once the material is in the water column, some of it may dissolve and some may remain as particulates. In either case, the advection and diffusion of the material are governed by hydrodynamic processes. For particulate material, deposition and resuspension are also controlled by hydrodynamics.

In order to model the distribution of chemical and biological material in the lake, currents and diffusion coefficients determined from hydrodynamic models must be incorporated into the advection terms of the diffusion equation along with appropriate boundary and initial conditions for the substance(s) being modeled. If the substances are reactive, equations governing reaction rates and products must also be incorporated into the model. Thomann et al. (1981) discuss the utility and limitations of comprehensive water quality and ecosystems models using models developed for the 1972 International Field Year on the Great Lakes as examples. These models include the models of Chen et al. (1975), Thomann et al. (1977), Robertson and Scavia (1979), Scavia (1979, 1980), Simons (1976c), Simons and Lam (1980), and a two-dimensional cross section model by Scavia and Bennett (1980).

Some simpler models of advection and diffusion of conservative elements (usually chloride) over long time scales have successfully reproduced observed average concentration patterns in Lake Erie (Boyce and Hamblin 1975, Lam and Simons 1976) and Lake Superior (Lam 1978). Pickett and Dossett (1979) applied a similar advection-diffusion model to the distribution of mirex in Lake Ontario. The models developed by Paul and Lick (1974) for thermal plumes and river discharges in Lake Erie and by Murthy et al. (1986) for pollutant transport along the north shore of Lake Ontario also belong to this category. Csanady (1970) discusses the general characteristics of this type of model.

In western Lake Erie, periodic occurrences of anoxic conditions near the shallow bottom have been a recurring threat to water quality. Models have been used to evaluate hypotheses about the causes of anoxia there (Lam et al. 1983, DiToro et al. 1987, Snodgrass 1987, Lam and Schertzer 1987, Lam et al. 1987a and 1987b) with emphasis on the role of vertical exchange processes and the timing and intensity of thermal stratification.

Many toxic materials attach to particulate matter and are deposited either permanently or temporarily in the lake sediments. Models of sediment resuspension in the bottom boundary layer have been studied by Sheng and Lick (1979), Lee et al. (1981), Bedford and Abdelrhman (1987), and Lesht and Hawley (1987). For tracking oil spills or conservative tracers, a simple particle trajectory model based on calculated horizontal or three-dimensional circulation patterns can be used. This type of model was investigated by Bennett and Clites (1987), Schwab and Bennett (1987), and Schwab et al. (1980) and used for operational oil spill trajectory predictions in models by Simons et al. (1975) and Schwab et al. (1984a).

PROSPECTS FOR THE FUTURE

The contributions that lake hydrodynamic models have made to models of chemical, biological, and ecological dynamics include incorporation of horizontal transport processes in models of the dynamics of dissolved substances, the effect of the springtime nearshore circulation structure on biological activity, and the effect of lake scale circulation on the distribution of toxic chemicals in sediments. Some of the prospects for new contributions to our understanding of environmental fate processes in lakes that can be made by hydrodynamic models in the next decade are improved models of monthly and seasonal mean circulation, models of frontal dynamics, coupling of sedimentation and resuspension models with lake circulation models, coupling of chemical and biological dynamics with lake circulation models, and the prospects for routine operational lake circulation and thermal structure forecasting. Some of the key remaining problems in hydrodynamic modeling of the Great Lakes include adequate specification of boundary conditions and forcing functions, modeling of subtle dynamical balances that can occur in time-averaged flows, and the impact of nonlinear processes and hydrodynamic instability on parameterizations of turbulence and diffusion in numerical models.

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Chemical Dynamics in Fresh Water Ecosystems

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