CHAPTER 58

STORM SURGE FORECASTING METHODS IN ENCLOSED SEAS

P.F. Hamblin

Applied Research Division, National Water Research Institute,
Canada Centre for Inland Waters, Burlington, Ontario, Canada

Storm surges in enclosed seas although generally not as large in amplitude as their oceanic counterparts are nonetheless of considerable importance when low lying shoreline profiles, shallow water depth, and favourable geographical orientation to storm winds occur together. High water may result in shoreline innundation and in enhanced shoreline erosion. Conversely low water levels are hazardous to navigation.

The purpose of this paper is to discuss the problem of storm surge forecasting in enclosed basins with emphasis on automated operational procedures. In general, operational forecasting methods must be based on standard forecast parameters, require a minimum of computational effort in the preparation of the forecast, must be applicable to lakes of different geometry and to any point on the shore, and to be able to resolve water level changes on an hourly basis to 10 cm in the case of high water level excursions associated with large lakes and less than that for smaller lakes. Particular physical effects arising in lakes which make these constraints difficult to fulfill are the reflections of resurgences of water levels arising from lateral boundaries, the stability of the atmospheric boundary layer and the presence of such subsynoptic disturbances as squall lines and travelling pressure jumps.

METHODS AND STUDY AREA

Interest in the study was centred on Lakes Ontario, Erie, and St. Clair as representative examples of large and intermediate sized lakes. Observations of past storm surges were collected from water level recordings over the period 1961 to 1972 at sites at the ends of these lakes (see Figure 1). Meteorological data, namely surface winds at Belle River on Lake St. Clair, and surface barometric pressures at a number of points around the lakes, as well as archived operational forecast elements from the U.S. National Meteorological Center primative equation model, were gathered for the periods preceeding and during the observed occurrences of storm surges.

In the case of Lakes Ontario and Erie, surface barometric pressures were interpolated to the synoptic grid points of the numerical weather model by means of the nearest three surrounding stations. Longitudinal and transverse winds at the centers of these lakes were calculated from regression relations established between shipboard wind measurement and the various forecast elements computed by the numerical weather model by Feit and Barrientos (1974).

Unfortunately for Lake St. Clair neither the regression relations existed

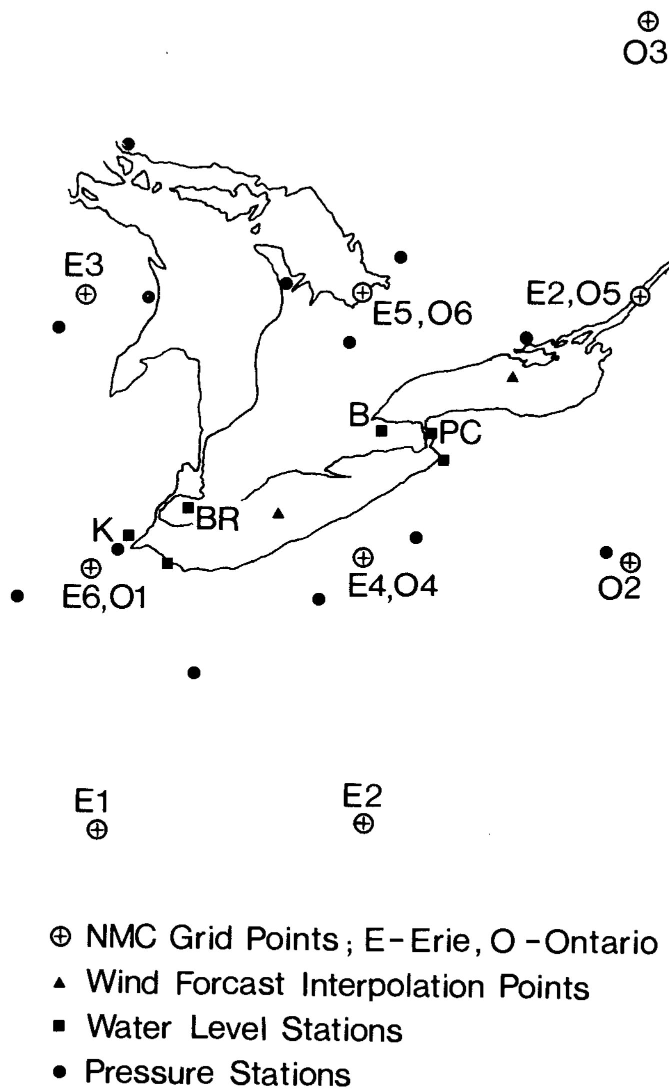


Figure 1. Study area and location of measurement points.

nor did the synoptic grid point pressures account for more than 3% of the water level variance. Relaxing somewhat our requirement for a standard automated forecast parameter, we chose the local hourly winds measured at Windsor Airport as an input parameter.

In Lake St. Clair, and in some cases in Lakes Ontario and Erie, the air-water temperature difference during the storm was computed from measured data.

STATISTICAL METHODS

The most widely employed statistical method for forecasting storm surges is the multiple regression method. It has the advantage of being simple to develop and straightforward to employ, and generally results in a minimum of computational effort in the preparation of the forecast. It has the disadvantage that a relatively long series of data, both water levels and meteorological data, must be available at the point of interest. For details of the development of the multiple regression relations given here the reader is referred to Venkatesh (1974). At the time this study was undertaken, routine forecast variables were available at six hourly intervals and at the synoptic grid points of the Canadian Meteorological Centre weather forecast model which is identical to the U.S. weather model in the Great Lakes region. Therefore, barometric pressure at the time of the surge and six hours previously at the synoptic grid points surrounding the lake were chosen as predictors.

In Lakes Erie and Ontario (also Huron) expressions of the type were developed,

$$\eta_i = A_i + \sum_{ijk} B_{ijk} P_{ijk} + \sum_j C_j \Delta T_j$$

where η_i = surge height at i hours after the time of the pressure forecast (i = 0, , ,5);

P_{ijk} = surface pressure at grid point j,k and at lag,i,hr;

ΔT_i = air-water temperature differences over the lake at a lag of i hours; and A,B, and C are regression coefficients.

An expression of the type

$$\eta = A + BV^2 + CV^2(\Delta T_o + D\Delta T_1)$$

was developed for Lake St. Clair, where V^2 is the average of the past three hours of the components of wind squared in the maximum fetch direction. In general two to three dozen storms were used to establish the regression coefficients, A,B,C and D.

A more advanced statistical analysis was undertaken on the Lake St. Clair data only involving a Box-Jenkins transfer function model, (Box and Jenkins, 1970).

As basic input data for this technique, the two normal components of surface wind stress, τ_x and τ_y, corrected for surface stability and wind speed dependence of the drag coefficient (to be outlined later), were prepared for each of the 24 storms. First, the nonstationarity of both the input and output series was removed by first order differencing. Then a transfer function model of the type

$$\Sigma C_j \eta_{t-j} = \Sigma_j A_j \tau_{x\,t-j} + \Sigma_j B_j \tau_{y\;t-j}$$

was fitted to the data.

If at some future time, histories of the past water levels could be made available at the time of forecast, then they could be usefully employed in a statistical procedure known as one-step-ahead forecasting. An autoregressive and moving average model of the type

$$\Sigma C_j \eta_{t-j} = \Sigma_j A_j \tau_{x\,t-j} + \Sigma_j B_j \tau_{y\;t-j} + \Sigma D_j a_{t-j}$$

was determined, where a_t is the observed water level history. For a detailed discussion of these more advanced statistical techniques the reader is referred to Budgell and El-Shaarawi, 1978.

DYNAMICAL METHODS

In enclosed seas on account of the relatively weak flows associated with storm surges, the linearized shallow water equations on a plane of constant rotation (2f) serve as the basic mathematical model along with the usual boundary conditions.

$$\frac{\partial u}{\partial t} - fv = -g\frac{\partial \eta}{\partial x} + \frac{\tau_x - \tau_{bx}}{\rho h}$$

$$\frac{\partial v}{\partial t} + fu = -g\frac{\partial \eta}{\partial y} + \frac{\tau_y - \tau_{by}}{\rho h}$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0$$

where g is the acceleration of gravity, h is the equilibrium depth, and τ_b is the bottom stress.

The conventional method of integrating this equation set is to discretize the differentials and solve for the free surface, η, and the velocity components, u and v at each point in a horizontal grid and at each time step. The classical computation of this type was performed by Platzman (1963) on Lake Erie in a simulation of nine storm surges. Unfortunately, this form of the dynamical method is too demanding computationally for routine forecasts. In general a large difference exists between the time step required for numerical stability (several minutes) and the forecast time step (here, 6 hrs.)

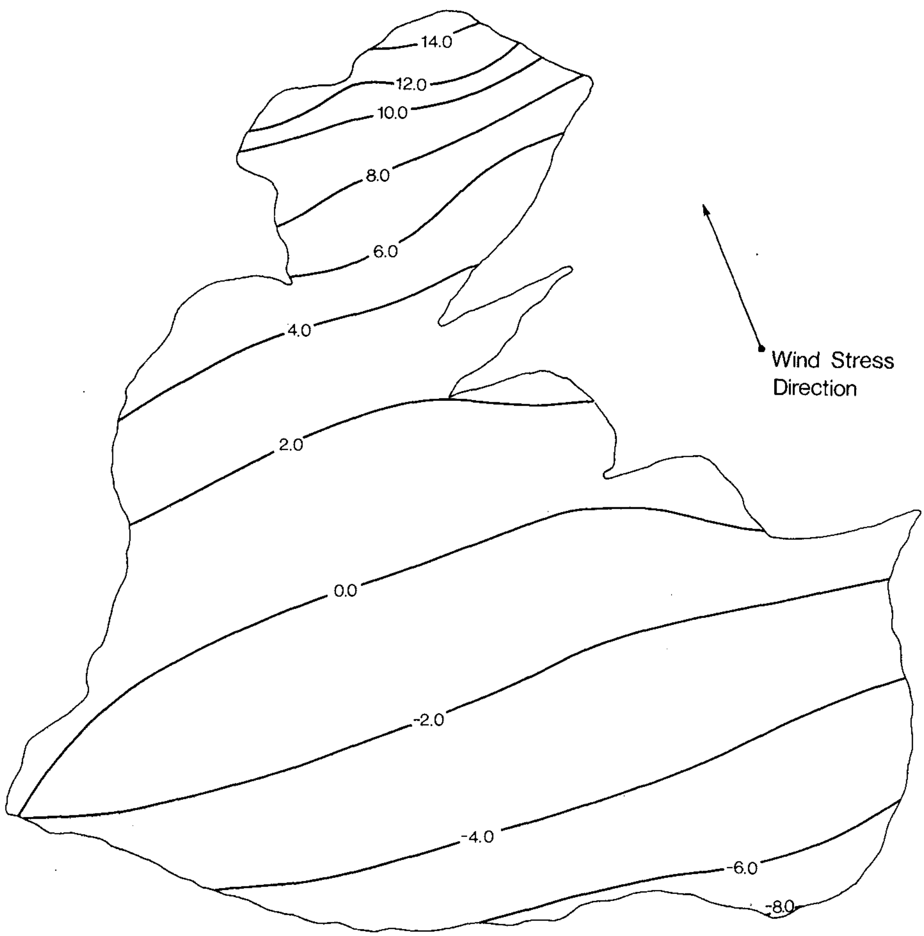


Figure 2. Free surface displacement (cm) for a steady wind stress of 1.0 dyne/cm for Lake St. Clair computed by the finite element method.

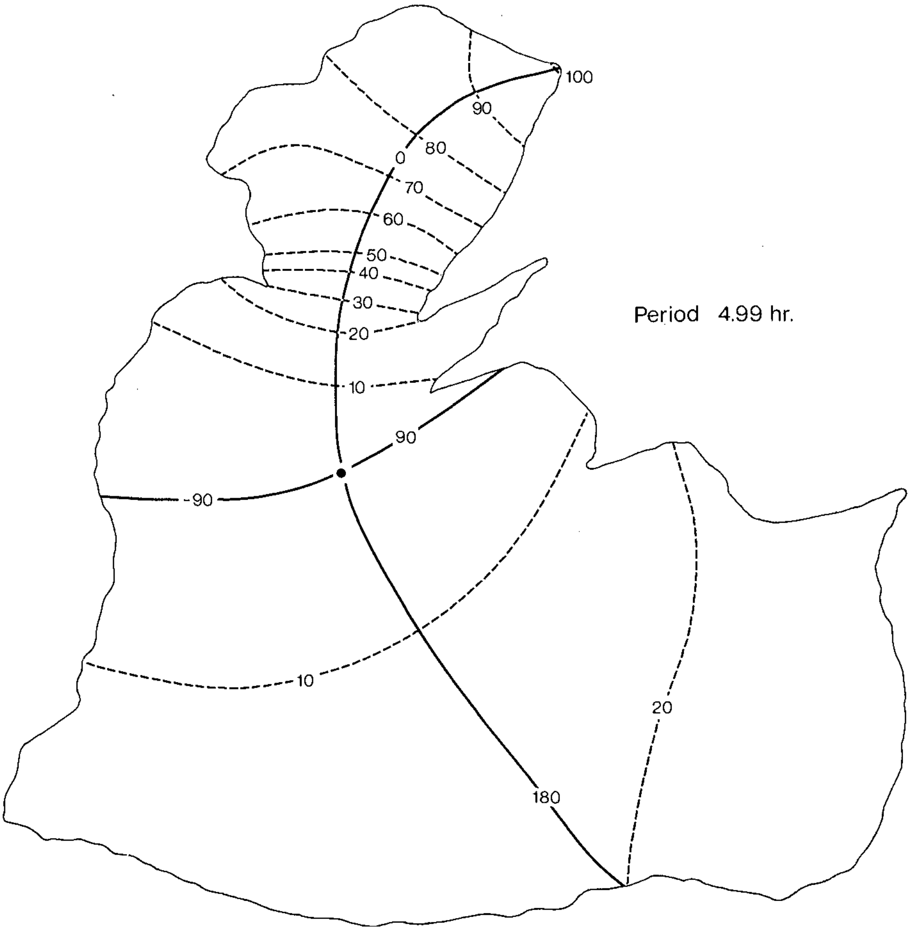


Figure 3. Free surface displacement (amplitude, - - -, ———) for the fundamental gravitational seiche of Lake St. Clair computed by the finite element method.

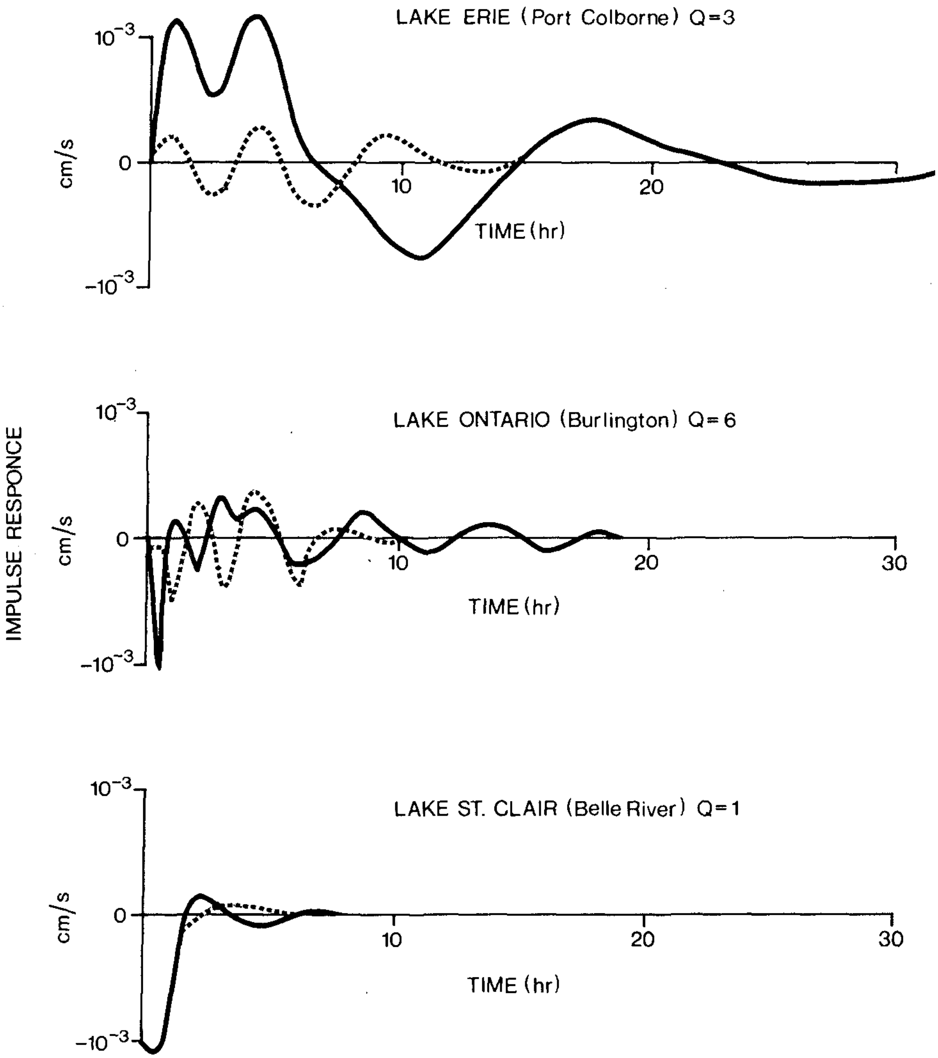


Figure 4. Impulse response functions computed by the spectral method. Lakes Ontario, Erie, and St. Clair, Q refers to the friction assumed.

An alternative approach which avoids the unnecessary routine computation of free surface and velocity components at points at which they are not needed is based upon the computation of the impulse response function or Green's function for the point of interest from a dynamical model such as equation (1). Once this function is determined, then the storm surge at a given point is simply the convolution of the impulse response function for that point with the forecast forcing function. If the weights of the impulse function are considered as regression coefficients, the two methods may be seen to be equivalent in computational effort. Thus the storm surge forecasting problem is reduced to the evaluation of one or more convolution integrals which are essentially digital filters in their discrete form.

Here we adopt the spectral method of determining the impulse response functions in which the impulse response function is expanded in terms of the steady solution and in terms of the lowest six to twelve free modes of oscillation. This number is based on power spectral analysis of water level fluctuations during storm surges which reveals that, in general, only the lowest modes of oscillation are excited at the points of largest storm surge excursion. The complex expansion coefficients are determined from least squares methods but essentially the amplitudes of the oscillation are determined from the steady solution of the free surface and the relative phases from the initial conditions. Both the steady state free surface displacement and the characteristic functions for the basin are computed by finite element methods. The spectral response method is developed in detail by Hamblin (1976) where it is applied to wind generated surges and by Hamblin and Hollan (1978) who applied this technique to excitation of surges by both barometric pressure gradients and winds.

A typical example of a finite element solution for the steady state free surface is given in Figure 2 and of a seiche solution in Figure 3. These solutions may be considered as components of the impulse response. Examples of the computed impulse response functions are given for three lakes of interest in Figure 4. The Q factor refers to the amount of frictional damping assumed in the bottom stress. Alternatively impulse response functions have been obtained for Lake Erie by Schwab (1978) by applying a unit wind stress to a time-stepping model for the first time step only. Results employing the two impulse response functions, determined by the spectral and the time stepping methods are in close agreement in Lake Erie.

SURFACE STRESS

In both the cases of the forecast winds in Lakes Ontario and Erie, and of the observed winds in Lake St. Clair, surface stress is taken as proportional to the product of the wind speed, and the wind vector, v.

$$\tau = \rho_a C_d |v| \vec{v}$$

where the air density, ρ_a, is assumed constant and the drag coefficient, C_d, is assumed to be a function of wind speed after the empirical studies

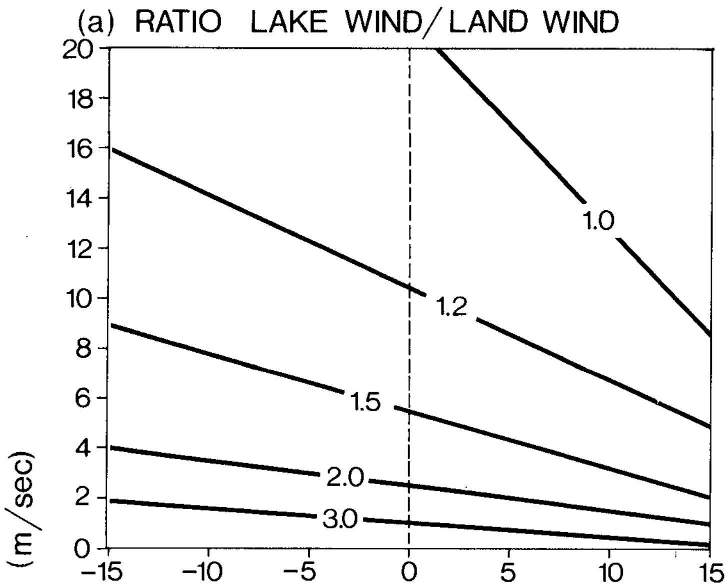


Figure 5a. Ratio of lake wind to land wind after Phillips and Irbe, 1978, as a function of wind speed and air-water temperature.

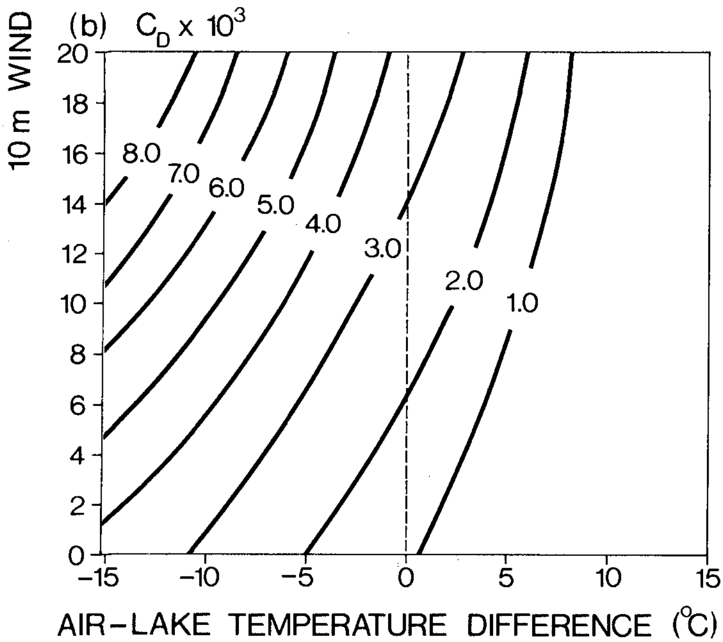


Figure 5b. Dependence of drag coefficient on wind speed and atmospheric stability employed in the study.

of Smith and Banke (1975) and a function of atmospheric stability of the form, $(1-AT_O)$ which has been employed by McClure (1970). The constant A, was arrived at by trial and error. The behaviour of C_d with wind speed and air-lake temperature difference is shown in Figure 5b. For neutral conditions C_d is 3.0×10^{-3} at a wind speed of 14 m/s which is a typical value employed for storm surge studies in enclosed basins. The effect of stability is to increase the effective drag coefficient under unstable conditions and to decrease it under stable conditions. In the case of Lake St. Clair, since the wind data were measured at the shoreline, experiments were performed employing an empirical relation for the overlake wind speed from the land wind which is based on fetch, wind speed, and atmospheric stability, (Phillips and Irbe, 1978). The behaviour of the wind ratio is shown in Figure 5a for the constant fetch case.

RESULTS

Statistical Methods

Multiple regression analysis of barometric pressures and air-water temperature difference accounted for approximately 60% of the variance of water level fluctuation as defined as the deviation from the undisturbed level before the storm and based upon dependent storms. The largest standard errors of the estimates of 20 cm occurred in the case of Lake Erie as a result of the higher excursions in that lake.

In the case of the smallest of the Great Lakes, Lake St. Clair, use of the six hourly temperatures and pressures at grid spacing separated by 380 km explained only several percent of the variation. Based on hourly wind observations one hour before the forecast time and air-water temperature differences the regression approach accounted for 54% of the variation of 24 dependent storms.

For Lake St. Clair a direct comparison was made between the three statistical techniques. The transfer function approach is evidently superior to the standard multiple regression approach, (Table 1), while the one-step-ahead forecast although not suitable for routine forecasting is the best of the three methods. It may be seen from the example shown in Figure 7 the regression method fails to predict the peak immediately following the main surge. It is thought that one reason for the improvement of the transfer function approach over the standard regression techniques is that it can readily account for resurgences or seiches which in certain cases such as Lake Erie form a significant portion of the storm surge response.

The Dynamical Method

An example of a dynamical forecast employing the spectrally determined impulse response function is compared to the standard regression method in Figure 6 for Lake Erie. In general both methods account for disturbances lasting for periods of half a day or more and that when seiches are present the dynamical model alone accounts for these

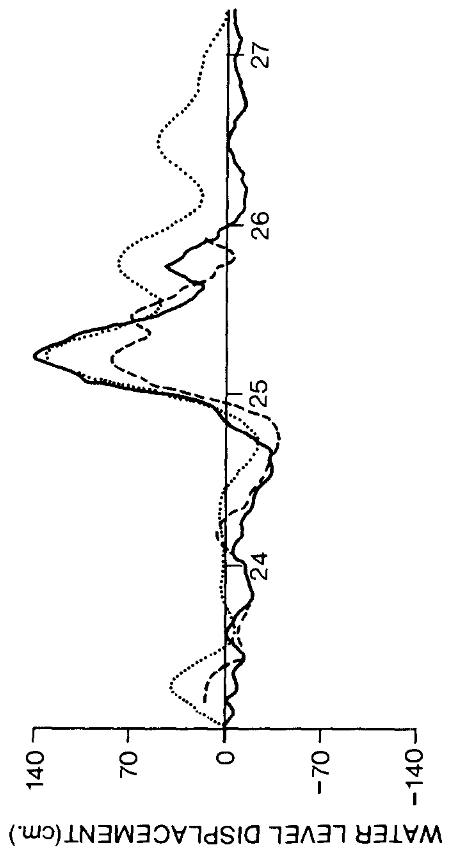


Figure 6. Simulation of a storm surge forecast. Port Colborne, Lake Erie, January 1972.

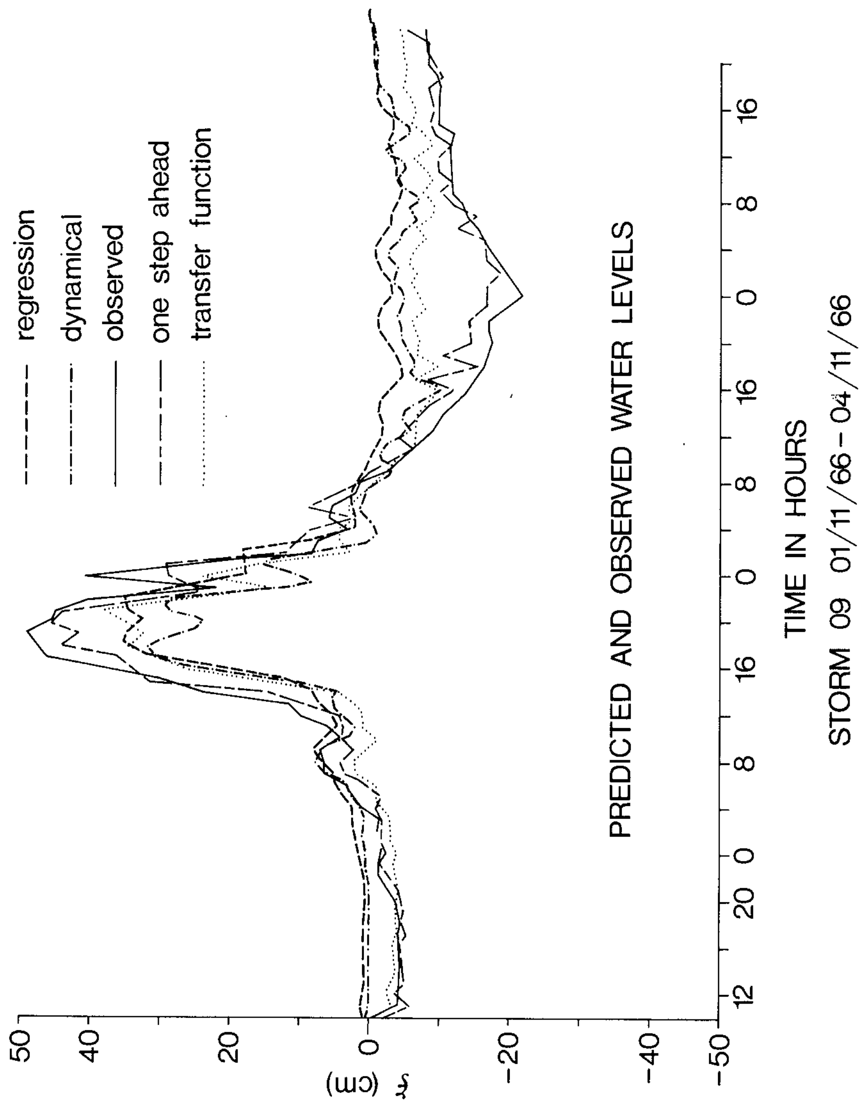


Figure 7. Comparison of various storm surge prediction methods, Lake St. Clair.

TABLE I

% Explained Variance of 24 Storms Lake St. Clair

(1)	Dynamical	Unfiltered	49
		Filtered	54
(2)	Regression		54
(3)	Transfer Function		68
(4)	Transfer Function plus one step ahead		90

seiches when the period of the seiche is longer than the six hour forecast period. Of course, neither method can account for seiches when the seiche period is less than the forecast period.

The comparison between the various methods has been examined in most detail for the case of Lake St. Clair. For the purpose of comparison, the storm exhibiting the largest excursion is shown in Figure 7. In this example the dynamical method underestimates the peak slightly more than the other methods. All methods except the one-step-ahead forecast fail to account for the negative surge occurring after the end of the storm. The dynamical method accounts for 49% of the variance of 24 storms. This compares favourably with the regression method when it is considered that the storms are dependent storms as far as the regression technique is concerned and in consideration that no attempt has been made to optimize the coefficients in the stability and wind speed dependence of the drag coefficient.

A characteristic feature of the Lake St. Clair storm surge is the gradual and continuous build up of water level during the storm. The source of these long term trends is not known but it is suspected that they may be due to enhanced river discharge during the storm. In order to remove this influence, both the water levels and winds were filtered by means of a high pass filter. The proportion of explained variance was augmented to 54% in the filtered dynamical forecasts. It may be noted that removal of trends is another reason for the superiority of the transfer function approach.

Finally, it is worth mentioning that correcting the land wind for the overlake effect after the empirical relations of Phillips and Irbe (1978) unexpectedly does not improve the dynamical forecasts. At high wind speeds the lake-land wind ratio approaches unity whereas at low winds, land winds are amplified considerably. Probably at low wind speeds the land winds are more representative of the local conditions on land than over the lake and thus fail to account for the surge.

DISCUSSION

In the regression study treatment of the air-water temperature difference as an independent predictor indicated that taking account of the stability of the atmospheric boundary layer over the water could improve the forecast. The effect of stability is greatest for the smallest lake studied, Lake St. Clair, where 5% of the variance is accounted for by the air-water temperature difference. Taking account of the stability in Lake St. Clair also improved the dynamical forecast results. Unfortunately it was impossible to account for this effect on the dynamical forecasts in the other lakes studied since the air-water temperature difference is not at present a standard forecast element.

Among the storms considered there were frequently cases of sudden changes in water level or shifted peaks in water level that could not be accounted for by either the dynamical or the regression methods.

It is likely that these effects are caused by spatially varying wind fields. In order to examine this method of generation of rapid fluctuations in water level occurring over several hours a simple analytical model was formulated for the generation of storm surges by a travelling stress field.

In a one-dimensional channel of constant depth, h, and length, L, the model equations,

$$\frac{\partial u}{\partial t} = -g\frac{\partial \eta}{\partial x} + \tau/\rho h$$

$$\frac{\partial \eta}{\partial t} + h\frac{\partial u}{\partial x} = 0$$

have the solution for a suddenly turned on uniform wind stress, τ,

$$\eta(x,t) = -\sum_{m=1,3,5--}^{\infty} \left[\frac{1}{\sigma_m^2}\frac{4\tau}{L\rho}[1-\cos\sigma_m t] + \eta(o)\cos\sigma_m t + \frac{\partial \eta(o)}{\partial t}\frac{\sin\sigma_m t}{\sigma_m}\right] \cdot \cos\chi_m x$$

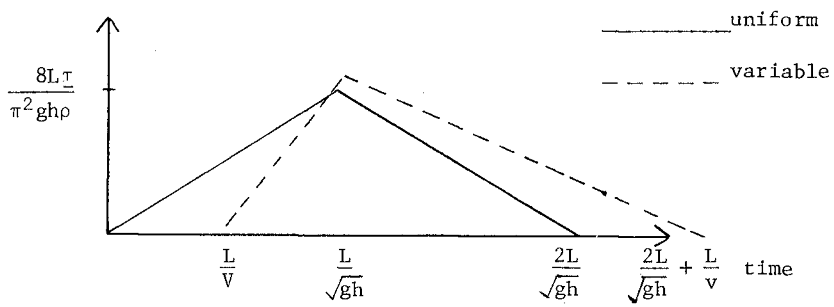
where $\sigma_m = \frac{\sqrt{gh}\,m\pi}{L}$ and $\chi_m = \frac{\sigma_m}{\sqrt{gh}}$

In the case of a semi-infinite stress band travelling at a speed $v \neq \sqrt{gh}$, starting from a state of rest,

$$\eta(x,t) = \sum_{m=1,2--}^{\infty} \frac{2\tau}{\sigma_m L\rho}\left[\frac{\cos\sigma_m t-1}{\sigma_m} + \frac{\cos\chi_m vt\cos\sigma_m t}{2\sigma_m + 2\chi_m v} + \frac{\cos\sigma_m t - \cos\chi_m vt}{2\chi_m v - 2\sigma_m}\right]\cos\chi_m x$$

As seen in the accompanying figure in the case of a semi-infinite wind stress, taking account of spatial variation results in a more sharply rising surge than in the uniform case although the peaks occur concurrently when the wind is measured at the shoreline on the side of the lake opposite to the water level gauge.

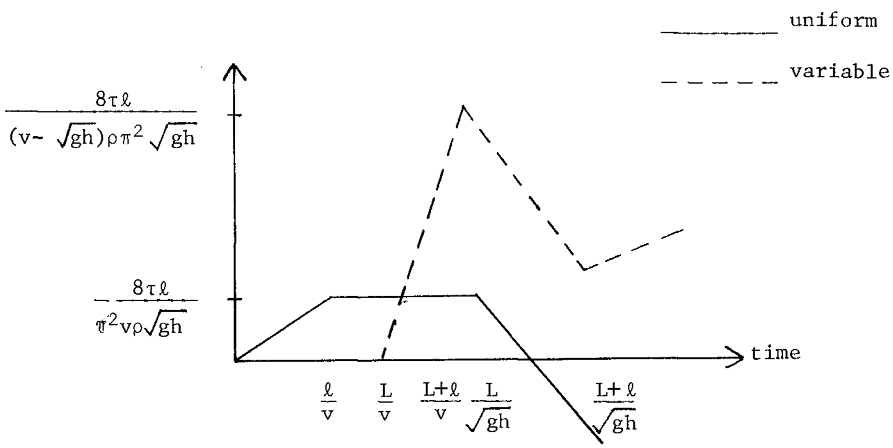
I Semi-infinite Stress Band Travelling at Speed, v



Downwind water level with respect to wind measured on upwind shoreline versus time.

Solutions for a finite stress field may be constructed from a superposition of the fundamental solutions presented above.

II Stress Band of Finite Width $\ell < L$



In the above example it may be seen that resonant excitation of the surge results in amplitudes much larger, of different shape and time of arrival than in the spatially uniform case.

CONCLUSIONS

Strictly speaking the results are not exactly comparable; for instance, only in the cases of dynamical forecasts in Lakes Erie and Ontario were true storm surge forecasts simulated. Nonetheless it is possible to draw a number of conclusions from the study.

Based on the applications of several statistical methods and a new dynamical approach to the simulation and forecasting of over three dozen storm surges in the Great Lakes reveals that in most cases all methods account for disturbances lasting for periods of half a day or more, that when seiches are present the dynamical and transfer function methods account for the seiche when the period of the seiche is longer than the forecast period and that these methods fail to account for seiches when the seiche period is shorter than the forecast period.

Horizontal variations in the wind field are particularly important in accounting for fairly rapid fluctuations in the water. Operational forecasts may be improved by a more detailed temporal and spatial resolution of the forecast data including the specification of such subsynoptic disturbances as squall lines and atmospheric pressure jumps. In particular, synoptic forecast surface pressures do not offer sufficient resolution in subsynoptic scale lakes such as Lake St. Clair.

Atmospheric stability is a significant factor in storm surge prediction in enclosed seas as it affects the surface momentum transfer, especially in smaller water bodies. At present the air-water temperature difference is not a standard automated forecast element. Wind speed dependence of the drag coefficient is also a significant influence. The question of correction of land winds for overlake modification is not yet resolved for storm surge forecasting in the Great Lakes but does not appear to improve the forecasts in the case of Lake St. Clair.

It is recommended that attention be given to the removal of long term trends in water levels and meteorological input data when developing and testing forecast relations and that trend removal may result in an improved forecast.

It is concluded from a comparison of various approaches to storm surge forecasting that dynamical and statistical methods give comparable errors. The fact that the discrepancy between the methods is less than between observation and forecasts suggests that the main source of error is due to uncertainties in the meteorological forecasts rather than to the failings of the methodology.

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REFERENCES

Box, G.E.P., and G.M. Jenkins. 1970. Time Series Analysis Forecasting and Control. Holden Day.

Budgell, W.P., and A. El-Shaarawi. 1978. Time Series Modelling of Storm Surges on a Medium Sized Lake. Weather and Sea State Prediction. Proc. 10th Internat. Conf. on Ocn. Hydrodyn. Edited J.C. Nihoul. Elsevier, Amsterdam.

Feit, D.M., and C.S. Barrientos. 1974. Great Lakes Wind Forecasts Based on MDS. Proc. 17th Conf. Great Lakes Research. pp 725-32

Hamblin, P.F. 1976. Seiches, Circulation and Storm Surges of an Ice-free Lake Winnipeg. J. Fish Res. Bd. Can. Vol. 33, No. 10, pp 2277-2391.

Hamblin, P.F., and E. Hollan. 1978. On the Gravitational Seiches of Lake Constance and Their Generation. Schweizerische Zeitschrieft für Hydrologie.

McClure, D.J. 1970. Dynamic Forecasting of Lake Erie Water Levels Report No. 70-250-H. Hydro-Electric Power Commission of Ontario. Research Div. Report.

Phillips, D.W., and J.G. Irbe. 1978. Lake to Land Comparison of Wind Temperature and Humidity on Lake Ontario During the International Field Year for the Great Lakes. Report No. CL1-2-77. Atmospheric Environment, Fisheries and Environment Canada.

Platzman, S.W. 1963. The Dynamical Prediction of Wind Tides on Lake Erie. Meteor Monogr. Vol 4, No. 26, 44p.

Schwab, D.J. 1978. Simulation and Forecasting of Lake Erie Storm Surges. Unpublished Report Great Lakes Environmental Research Laboratories. N.O.A.A., Ann Arbor, Michigan.

Smith, S.D., and E.G. Banke. 1975. Variation of the Sea Surface Drag Coefficient With Wind Speed. Quart.J. Roy. Meteoro. Soc. 101.

Venkatesh, S. 1974. The Development of Manual Techniques for the Real Time Prediction of Storm Surges on the Great Lakes. Unpublished Report Canada Centre for Inland Waters.