AN OPERATIONAL STORM SURGE MODEL FOR THE BAY OF FUNDY

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MAES 4-81

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1. Introduction

A storm surge is usually defined as the difference between the observed and the predicted water level as related to wind and atmospheric pressure gradient. Storm surges can be caused by raising the water level or by a phase shift in the tidal oscillation. However, there is a feedback mechanism which operates between these two effects.

During 1978, AES in the Atlantic Region accepted responsibility for alerting the public whenever water levels are likely to be significantly higher than normal. Subsequently an interest in objective approaches to the problem was generated.

Pore, et al (1974) applied a statistical technique to storm surge prediction in the eastern United States. The meteorological variables selected by him were atmospheric pressures at a set of grid points near the east coast taken at the time of the surge occurrence and also 6 and 12 hours earlier. P. Galbraith (1979) applied an approach very similar to that of Pore to the prediction of storm surges at Halifax, Yarmouth and Saint John, these three population centres being provided with tide gauges for which a sufficiently long data set was available for the project. The resulting regression equations explained 80 per cent of the variances in the data for Halifax, 60 per cent for Yarmouth and only about 50 per cent for Saint John. Clearly a different approach was indicated for the Bay of Fundy.

The shape of the Bay of Fundy is somewhat complex, making it very difficult to apply analytical methods. Numerical methods can, however, be applied to specific scenarios. The burdensome work involved can be readily performed by an electronic computer. Numerical methods have been applied to the storm surge problem by a number of researchers to a number of lake and ocean scenarios. Complex models exist for the Bay of Fundy, such as that of Greenberg (1977). Such models are much to large and too time consuming to be of operational use.

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2. Basic Equations

In the following:

(u,v) are the (x,y) - components of velocity

(U,V) are the (x,y) - transport vectors defined by $U = \int_{-h}^{\zeta} u.dz$,

$$V = \int_{-h}^{\zeta} v.dz$$

ζ is the elevation of the sea surface from its undisturbed state

p^a is the atmospheric pressure

f is the coriolis force

g is the acceleration due to gravity

H is the depth of the sea bed

(F_s, G_s) are the (x,y) components of surface stress

(F_b, G_b) are the (x,y) components of bottom stress

ρ is the water density

ρ_a is the air density

(u_a, v_a) are the (x,y) - components of the 10 metre wind

$V_a = (u_a^2 + v_a^2)^{1/2}$

Assuming that 1, the amplitude of the surge is small compared to the depth of the sea and 2, the horizontal scale of the surge is large compared to H, the integrated basic equations can be written:

$$\frac{\partial U}{\partial t} - fV + gH\frac{\partial \zeta}{\partial x} = -\frac{H}{\rho}\frac{\partial p^a}{\partial x} + \frac{1}{\rho}(F_s - F_b)$$

$$\frac{\partial V}{\partial t} + fU + gH\frac{\partial \zeta}{\partial y} = -\frac{H}{\rho}\frac{\partial p^a}{\partial y} + \frac{1}{\rho}(G_s - G_b) \qquad (1)$$

with the continuity equation in the form

$$\partial\zeta/\partial t = -\left(\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y}\right)$$

Following Das *et al* (1974) the following forms are taken for the stress components:

$$F_s = k\rho_a|V_a|u_a, \quad F_b = \frac{\alpha\rho}{H^2}U$$

$$G_s = k\rho_a|V_a|v_a, \quad G_b = \frac{\alpha\rho}{H^2}V$$

k and α are constants whose values are taken (initially) as:

$k = 2.8 \times 10^{-3}$ and $\alpha = 0.02\ m^2 s^{-1}$

The system (1) is expressed in the form:

$$\zeta^{n+1}_{j,k} = \zeta^{n}_{j,k} - \frac{\Delta t}{2\Delta s}\left(U^{n}_{j+1,k} - U_{j-1,k} + V^{n}_{j,k+1} - V^{n}_{j,k-1}\right)$$

$$U^{n+1}_{j,k} = U^{n}_{j,k}\left(1 - \frac{\alpha \Delta t}{H^2_{j,k}}\right) + f\Delta t V^{n}_{j,k} - g\frac{\Delta t}{2\Delta s} H_{j,k}\left(\zeta^{n+1}_{j+1,k} - \zeta^{n+1}_{j-1,k}\right)$$

$$- \frac{\Delta t}{\rho} H_{j,k} \left(\frac{\partial p^a}{\partial x}\right)^{n+1}_{j,k} + \Delta t . C_1 . (V_a . v_a)^{n}_{j,k} \qquad (2)$$

$$V^{n+1}_{j,k} = V^{n}_{j,k} \frac{(1-\alpha\Delta t)}{H^2_{j,k}} - f.\Delta t U^{n}_{j,k} - \frac{g\Delta t}{2\Delta s} H_{j,k}\left(\zeta^{n+1}_{j,k+1} - \zeta^{n+1}_{j,k-1}\right)$$

$$- \frac{\Delta t}{\rho} H_{j,k} \left(\frac{\partial p^a}{\partial y}\right)^{n+1}_{j,k} + \Delta t . C_1 (V_a . u_a)^{n}_{j;k}$$

where:

$C_1 = k\rho_a/\rho$ and Δs, Δt are the grid length and time interval respectively. The indices (j,k,n) denote a point with coordinates $(x,y,t) = (j\Delta x,\ k\Delta y,\ n\Delta t)$ of the discrete grid.

3. Description of the Model

The equations are identical with the storm surge equations of Anita Sielecki (1968) save for the addition of stress components F_s, F_b, G_s and G_b. When evaluated in the order indicated in (2) the system of difference equations becomes explicit and no iterative process is required. No storage of old fields is necessary. After each field has been evaluated its previous values are not used in the remaining equations.

Not all of the fields are evaluated at the same points, transport vectors (U and V) are computed at points where the sum (j+k) is even and surge height (ζ) values are computed at grid points where (j+k) is odd. This scheme results in a considerable saving of computer time.

The computational stability condition for the set of equations formulated without stress terms is, according to Platzmann (1962):

$$gh_{max}\frac{\Delta t^2}{\Delta s^2} \leqslant \frac{4-f^2\Delta t^2}{2-f\Delta t}$$, where h_{max} is the maximum water depth.

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For all practical purposes this relationship can be reduced to

$$\frac{\Delta t}{\Delta s} < \left(\frac{2}{gh_{max}}\right)^{1/2}$$

In the model under discussion grid length $\Delta x = \Delta y = \Delta s = 6570.8$ metres. Maximum water depth in the model is about 100 fathoms or approximately 200 metres. Calculations yield a maximum time interval of about 208 seconds. The time interval actually used in solving the set of difference equations is 180 seconds.

Fischer (1959) showed that the equations with stress terms included must satisfy also the condition

$$\Delta t < \alpha/f^2$$

No problem is encountered in satisfying this condition.

An 18 x 41 grid network is used over the Bay of Fundy modelled as shown in Fig.1. Water depths, H, vary to reflect the bottom contours. H values are smoothed initially in order to prevent computational instability generated by rapidly changing values.

The Bay of Fundy experiences the highest tides in the world. Maximum tidal heights range from around 16 feet at Yarmouth to about 28 feet at Saint John, with much higher water levels occurring east of Saint John. Garrett (1974) and others have noted that the resonance period of the Fundy - Gulf of Maine system is around 13.3 hours, close to the period of the M_2 tide, 12.42 hours. This explains the high tidal range in the Bay. In the model tidal depths are very simply generated as sinusoidal waves travelling the length of the Bay with amplitudes increasing from west to east. That there will be an interaction between the tidal variations of water depths and the meteorologically induced storm surges is evident from the basic equations.

Referring to Fig.1 the left-hand boundary, along lines AB and BC is open, with surge heights, ζ, constrained to remain zero throughout the integration process. At the Nova Scotia and New Brunswick shorelines (C to D and A to E) transport of water perpendicular to the shoreline is prohibited, with both U and V made to vanish at corner points. At the right hand boundary DE compensation for truncation of the Bay is attempted, following Hendershott and Speranza (1971), by setting $U = k.\zeta$, where k is a constant which has been set tentatively at 0.2.

The model is designed for successive entries of pressure gradient and 10-metre wind data representative of averages over the area covered in Fig.1, along with time intervals during which each of these sets of input data are valid during the course of the storm under consideration. In other words information is conveyed to the model in successive steps. This procedure in its ease of implementation conforms to operational requirements.

4. Results

The model appears to yield consistently conservative storm surge estimates. However, these results are superior in accuracy to those obtained from the statistical procedure.

A good example illustrating this point relates to the storm of 2 February 1976, the so-called "Groundhog Day Storm". This storm was a spectacularly violent development which originated off the eastern seaboard and moved north-northeastwards rather rapidly, its trajectory passing through about the centre of the State of Maine thence northeastwards (see Fig.2). For many communities in southwestern Nova Scotia and along the Fundy coast of New Brunswick, the period in increasing winds coincided with the rising tide. Most localities in Nova Scotia and New Brunswick reported their strongest winds occurring between 1:00 and 3:00 p.m. In the Bay of Fundy these winds were from the southwest. At Saint John, N.B., the observed highest water level was 1.46 metres above the level predicted in the tide tables. At Yarmouth, N.S., the difference was 1.48 metres. Using "perfect progs", that is, actual weather charts and data, the statistical technique gave a storm surge of .8 metres for Saint John, whereas the application of the numerical model to this scenario gave 1.28 metres, much closer to the actual figure, but still on the conservative side.

5. Conclusion

It is possible that a simple model such as here described, may provide sufficiently accurate guidance to the operational weather forecaster to assess the probability of significant meteorologically induced increases in water level at coastal sites coincident with high tides.

There are several ways in which the model may be improved without making it too cumbersome or time consuming for operational use. A great deal of work has been carried out in recent years on drag coefficient relationships over the water. Some of these findings might be incorporated in the model. In addition, the boundaries assigned to the Bay of Fundy should probably be extended in the eastern and western directions in order to approximate the correct resonant frequency in the Bay. It is possible that water current behaviour in the Bay, especially at the mouth of the Saint John River, might be included. There is also possibly an improved technique for the inclusion of tidal effects.

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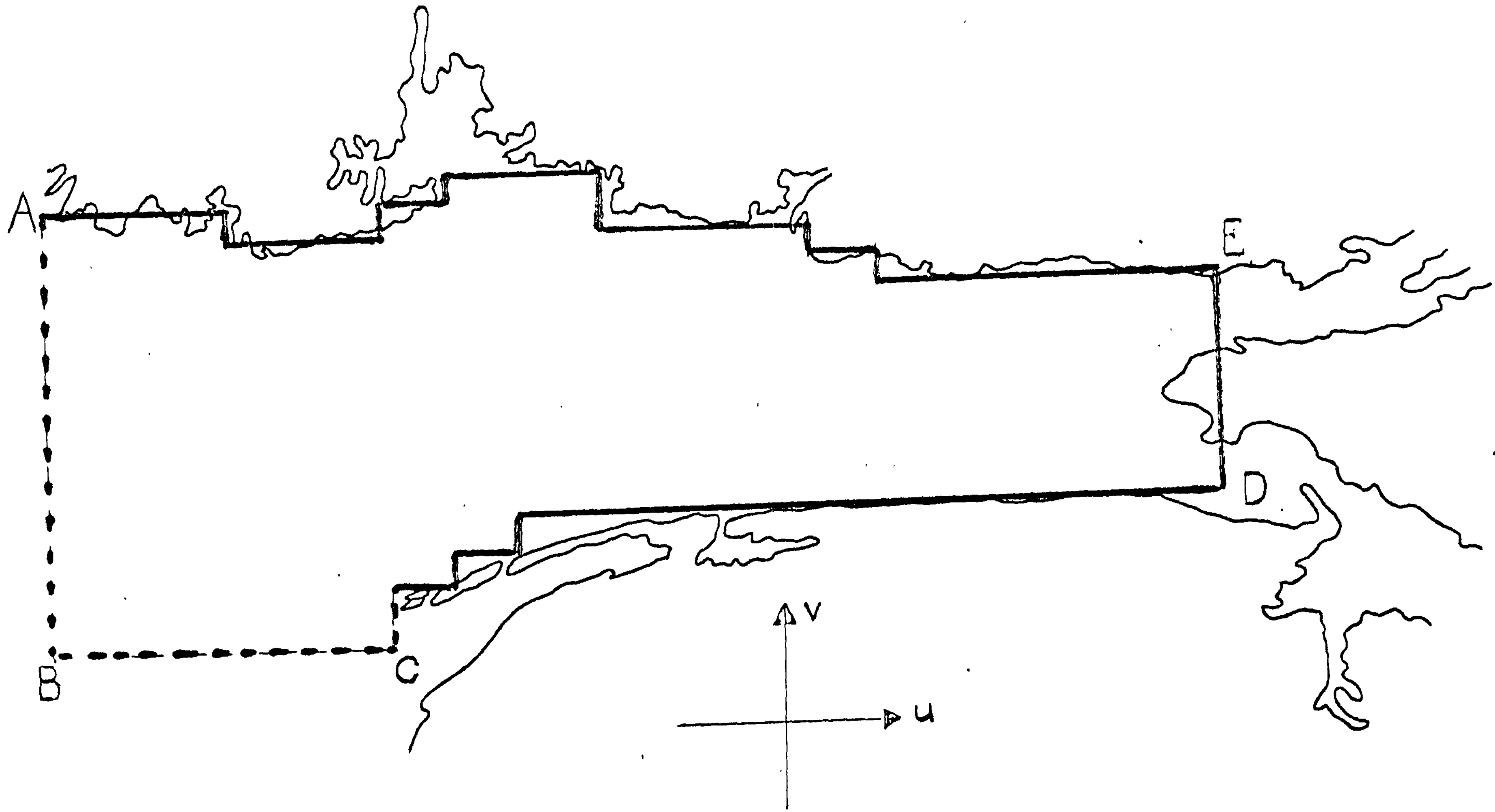

Fig. 1. Outline of the Bay of Fundy as Used in Storm Surge Model

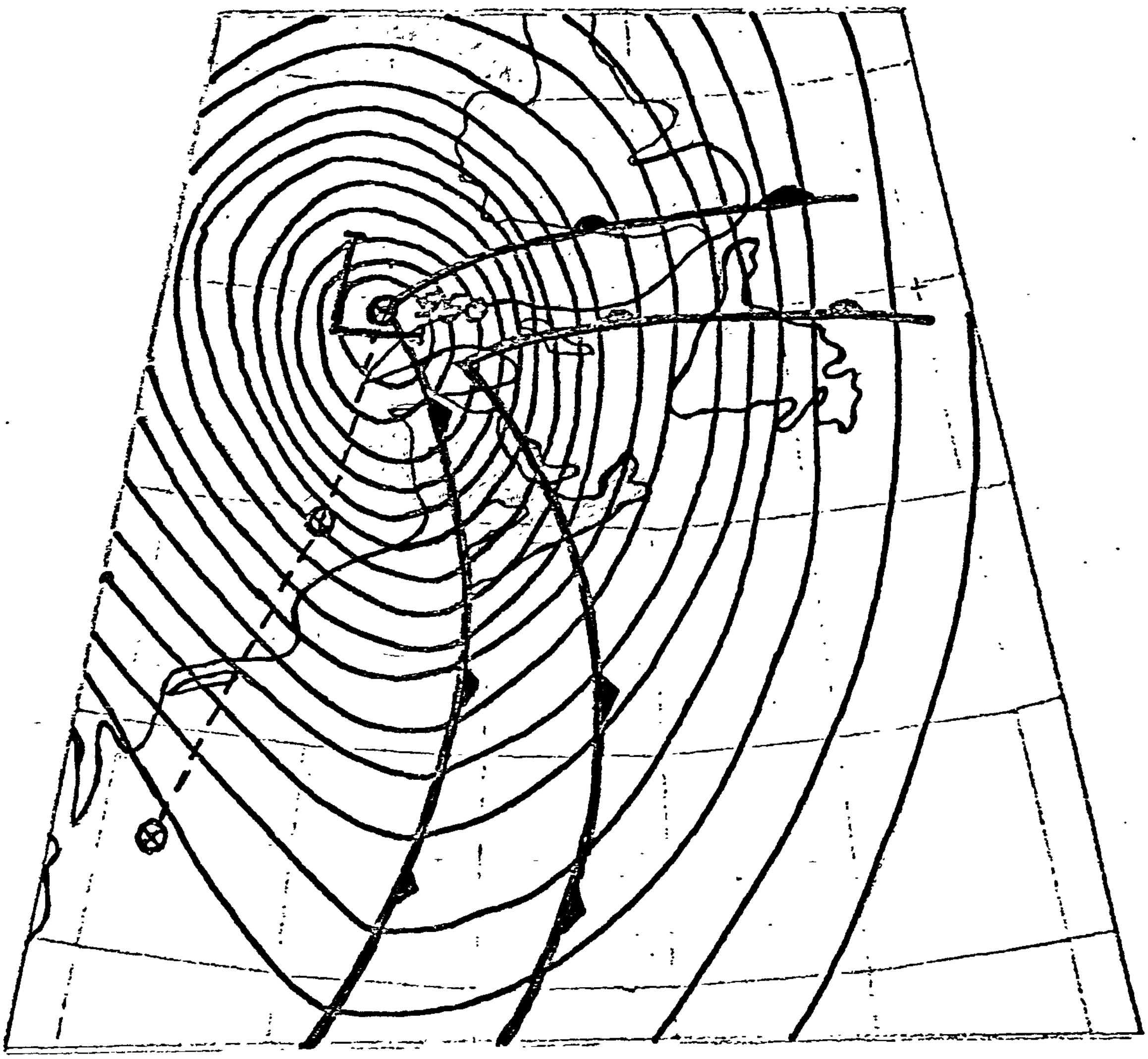

Fig.2: Surface Weather Chart for 1800 GMT, February 2, 1976.