NUMERICAL SIMULATION OF THE TSUNAMI OF JUNE 23, 1946 IN BRITISH COLUMBIA, CANADA

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ABSTRACT

On June 23, 1946 an earthquake with a magnitude of about 7.3 occurred on Vancouver Island in the Province of British Columbia, Canada. The epicenter was on land at 49.76°N, 125.34°W, but close to the shore. Associated with the earthquake, there was a vertical displacement in the land and ocean bottom of up to three meters. The resulting tsunami which killed one person and caused some damage was observed at several locations along the coastline. Here results of a numerical simulation of this tsunami are reported. A time-dependent two-dimensional numerical model was used which included the Strait of Georgia, and parts of the Johnstone and Juan de Fuca Straits. A radiation type condition was used at the open boundaries. The numerically simulated results on the amplitudes of the tsunami waves and the travel times are in good agreement with the few available observations.

1. INTRODUCTION

Rogers and Hasegawa (1978) studied the earthquake of June 23, 1946 in British Columbia, Canada. Figure 1 shows the geography of the Pacific coast of Canada and specifically, the Vancouver Island and Strait of Georgia areas where the earthquake occurred. The epicenter given by these authors was 49.76°N, 125.34°W and the surface wave magnitude was 7.2 ± 0.1. The epicenter was on Vancouver Island, close to its east coast.

According to Rogers and Hasegawa (1978) no major tsunami was created by this earthquake. However due to landslides and slumpings triggered by the earthquake, some minor water level disturbances occurred, and one person died.

In this study we numerically simulated the water level disturbances that occurred following this earthquake. As input into the numerical model we used the ground motion diagram (Figure 9c of Rogers and Hasegawa, 1978). In this diagram they showed vertical ground motion of up to 3 m, mostly on land but some in the Strait of Georgia. Surely, a subsidence of up to 3 m in a water body will likely generate a tsunami, even if it does not spread far and wide. Indeed our numerical simulation showed that there was no major Strait of Georgia-wide tsunami, but the water level disturbances were large enough to be noticeable, if not destructive.

2. THE NUMERICAL MODEL

The x-axis of a right-handed Cartesian coordinate system is taken along the length of the Strait of Georgia and the y-axis is taken along its width, with the origin being at the upper left corner (i.e. north-west corner). The grid size (Figure 2) in both directions is 2.62 km. There are a total of 91 grid points in the x-direction and 36 grid points in the y-direction.

The partly linearized shallow water equations are (the subscripts denote differentiation) (Henry, 1982; Murty, 1977, 1984):

$$\eta_t = -(du)_x - (dv)_y \tag{1}$$

$$u_t = -g\eta_x + fv - F^{(u)} + G^{(u)} \tag{2}$$

$$v_t = -g\eta_y - fu - F^{(v)} + G^{(v)} \tag{3}$$

where

$\eta(x,y,t)$ = elevation of water surface above mean level
$u(x,y,t)$ = depth-averaged velocity in x-direction
$v(x,y,t)$ = depth-averaged velocity in y-direction
$d(x,y)$ = mean water depth
x,y = Cartesian coordinates in horizontal plane
f = Coriolis coefficient (assumed constant)
t = time

$F^{(u)}$ and $F^{(v)}$ represent friction terms. A quadratic bottom friction of the following form is used:

$$F^{(u)} = ku(u^2 + v^2)^{1/2}/d \;;\; F^{(v)} = kv(u^2 + v^2)^{1/2}/d \tag{4}$$

where k is a dimensionless bottom friction coefficient. The terms $G^{(u)}$ and $G^{(v)}$ in equations (1) - (3) represent forcing terms, such as surface wind stress, equilibrium tide gradient, etc., which may vary with x,y,t. For storm surge computations, these terms will represent the meteorological forcing terms and for tidal computations, they represent the tidal potential. For the present problem of tsunami generation and propagation, these terms are ignored and the forcing comes in the form of an increasing water level directly above the bottom (of the estuary) displacement.

A simple Richardson grid (Figure 3) was chosen as the basis for the finite-difference scheme on the grounds that it minimizes storage and permits particularly simple representation of coastlines. At interior points of the grid, equations (1) to (3) are represented by the following finite-difference forms:

$$\frac{\eta'_{ij} - \eta_{ij}}{\Delta t} = - \frac{(d_{ij} + d_{i+1,j})u_{i+1,j} - (d_{i-1,j} + d_{ij})u_{ij}}{2 \cdot \Delta x} - \frac{(d_{ij} + d_{i,j+1})v_{i,j+1} - (d_{i,j-1} + d_{ij})v_{ij}}{2 \cdot \Delta y} \quad (5)$$

$$\frac{u'_{ij} - u_{ij}}{\Delta t} = - g \, \frac{\eta'_{ij} - \eta'_{i-1,j}}{\Delta x} + f\tilde{v}_{ij} - F^{(u)}_{ij} + G^{(u)}_{ij} \quad (6)$$

$$\frac{v'_{ij} - v_{ij}}{\Delta t} = - g \, \frac{\eta'_{ij} - \eta'_{i,j-1}}{\Delta y} - f\tilde{u}'_{ij} - F^{(v)}_{ij} + G^{(v)}_{ij} \quad (7)$$

where

Δt = time step
$\Delta x, \Delta y$ = grid interval sizes in x,y directions respectively
d_{ij} = mean water depth at elevation points η_{ij}

$$\tilde{u}_{ij} = \frac{1}{4} \; u_{i,j-1} + u_{i+1,j-1} + u_{ij} + u_{i+1,j} \quad (8)$$

$$\tilde{v}_{ij} = \frac{1}{4} \; v_{i-1,j} + v_{ij} + v_{i-1,j+1} + v_{i,j+1} \quad (9)$$

Primes indicate variables updated during the current time step; unprimed variables are those evaluated at the previous step. The use of old (unprimed) values of v in the Coriolis term in (6) and new (primed) values of u in the corresponding term in (7) is necessary for stability. Fortunately, it also eliminates the need to store any but the most recently updated values of each variable, provided that the equations are applied in the order given, that is, at each time step, all the η_{ij} are updated, then all the u_{ij}, and finally all the v_{ij}. The same stability and storage conclusions apply if variables are evaluated in the order η, v, u, using old values of u in the v-equation and new values of v in the u-equation. To reduce possible bias, the stepping subroutines evaluate the variables in the order η', u', v', on odd-numbered steps and η', v', u', on even-numbered steps.

Strictly speaking, equations (5) - (7) imply that u_{ij} and v_{ij} are evaluated $\Delta t/2$ later than η_{ij}, but normally they are regarded as pertaining to the same time level. The distinction is important only when calculating quantities which depend on phase differences between elevation and velocity, for example, energy flux, and then only when there are relatively few time steps per wave period.

A choice of a time step of 30 seconds satisfies the following stability criterion.

$$\Delta t \leq \frac{\Delta x \cdot \Delta y}{[g d_{max} \quad (\Delta x^2 + \Delta y^2)]^{\frac{1}{2}}} \tag{10}$$

where d_{max} is the maximum depth in the computational region.

Where there are good grounds for assuming that no waves enter the model area from an adjacent water body, it is appropriate to use a radiation condition on the sea boundary between the two. This permits waves reaching the sea boundary from the interior of the model to pass out of the model domain (Henry, 1982).

When choosing the model grid initially, radiating sea boundaries parallel to the x-axis of the model should be placed to run through v-points on the grid. Similarly, those parallel to the y-axis should run through u-points. It is assumed that the radiation problem can be treated one-dimensionally at each velocity point on the sea boundary and thus that the surface elevation and normal velocity at the boundary are related by

$$\text{outward normal velocity} = (g/d)^{\frac{1}{2}} \text{ x elevation}$$

Since there are no elevation points actually on the boundary, the nearest interior elevation value is taken instead, so that the formulas used in the stepping subroutines for u-points on radiating boundaries facing in the positive or negative x-direction are respectively:

$$u_{ij} = (g/d_{i-1,j})^{\frac{1}{2}} \cdot \eta_{i-1,j}$$

or

$$u_{ij} = -(g/d_{ij})^{\frac{1}{2}} \cdot \eta_{ij}$$

Similarly, at radiating sea boundaries facing in the positive or negative y-directions, the formulas used are respectively:

$$v_{ij} = (g/d_{i,j-1})^{\frac{1}{2}} \cdot \eta_{i,j-1}$$

or

$$v_{ij} = - (g/d_{ij})^{\frac{1}{2}} \cdot \eta_{ij}$$

When this type of radiation boundary condition is used, the permissible time step may be reduced by 50%. Hence, in the stability criterion (10) the denominator should be multiplied by a factor of 2.

3. DISCUSSION OF RESULTS

The vertical ground displacement of up to 3 m as suggested by Rogers and Hasegawa (1978) was prescribed as the initial condition. Actually a mound of water 1 to 3 m high was prescribed initially in the area designated in Rogers and Hasegawa's paper and the numerical simulation involved propagation of this initial elevation (mound of water). As expected, the tsunami did not propagate Strait of Georgia-wide with significant amplitudes.

Figures 4a and b show the time series of the computed water levels at various locations along the west and east shores of the Strait of Georgia including some islands. Table 1 lists the approximate range of the water level associated with the tsunami at these locations. From Figures 4a and b and Table 1 the following important results can be deduced. Some areas farther from the initial ground subsidence associated with the earthquake have greater tsunami range than areas closer. This is mainly due to damping of the tsunami waves in shallow areas and amplification in some inlets due to resonance.

In particular, we first will examine the tsunami range along the western shores of the Strait of Georgia. Even though Comox is farther than Campbell River, the tsunami range was greater at Comox. A similar situation exists with reference to Parksville and Nanaimo. Even though Parksville is closer to the epicenter than Nanaimo, the tsunami amplitude at Parksville is somewhat smaller because the extensive shallows and tidal flats at Parksville damped the tsunami waves significantly. The tsunami amplitudes at Galiano and Orcas Islands were also small due to damping and absence of resonance effects.

Next directing our attention to the east shore of the Strait of Georgia, some amplification of the tsunami in Howe Sound and Burrard Inlet is noticeable. Also associated with this tsunami, a regular seiche occurred in Jarvis Inlet. It would have been better if comparisons could be made between these computer water levels and water levels recorded on tide gauges. Rogers and Hasegawa (1978) mentioned that the Vancouver and Victoria tide gauges showed no tsunami.

In conclusion, the computed water levels shown in Figure 4 and Table 1 are unverified against any observations. It is not claimed here that these water levels necessarily occurred; rather it is shown that, if the vertical ground motion as given in Figure 9c of Rogers and Hasegawa (1978) has occurred, then a small tsunami would have occurred in the Strait of Georgia.

TABLE 1

Approximate range of the tsunami (m) at several locations in the Strait of Georgia, associated with the June 23, 1946 earthquake. The locations are listed from north to south separately for the western and eastern shores of the Strait

Locations along the west shore	Tsunami range	Locations along the east shore	Tsunami range
Quadra Island	-0.5 to 1.2	Sutil Channel	-0.4 to 1.0
Campbell River	-0.9 to 1.4	Powell River	-0.8 to 1.0
Comox	-1.3 to 1.4	Jarvis Inlet	-0.4 to 0.4
Parksville	-0.2 to 0.3	Sechelt	-0.3 to 0.4
Nanaimo	-0.9 to 0.9	Howe Sound	-0.9 to 0.9
Galiano Island	-0.2 to 0.2	Vancouver (Burrard Inlet)	-0.8 to 0.7
Orcas Island	-0.1 to 0.2	White Rock	-0.4 to 0.4

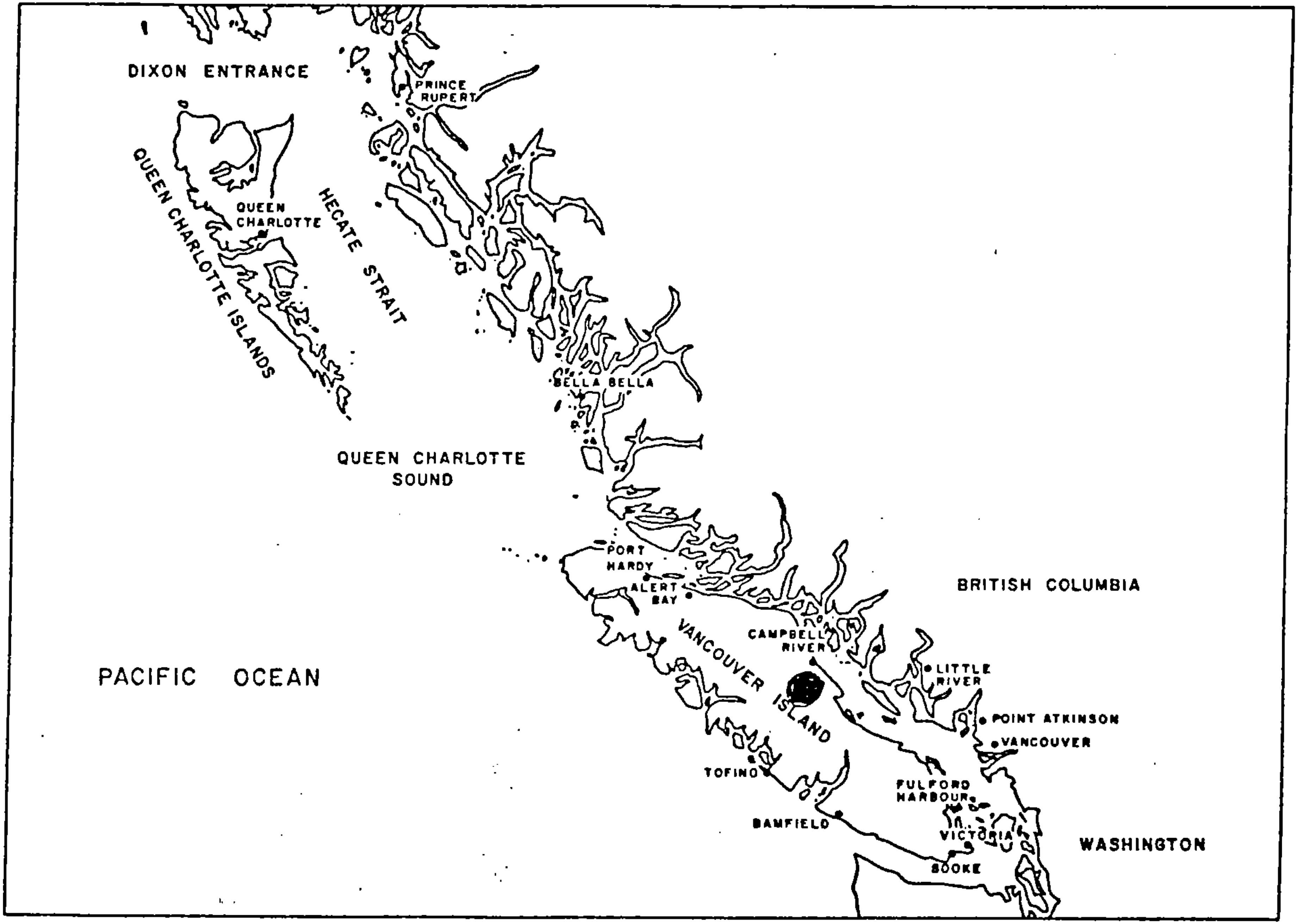
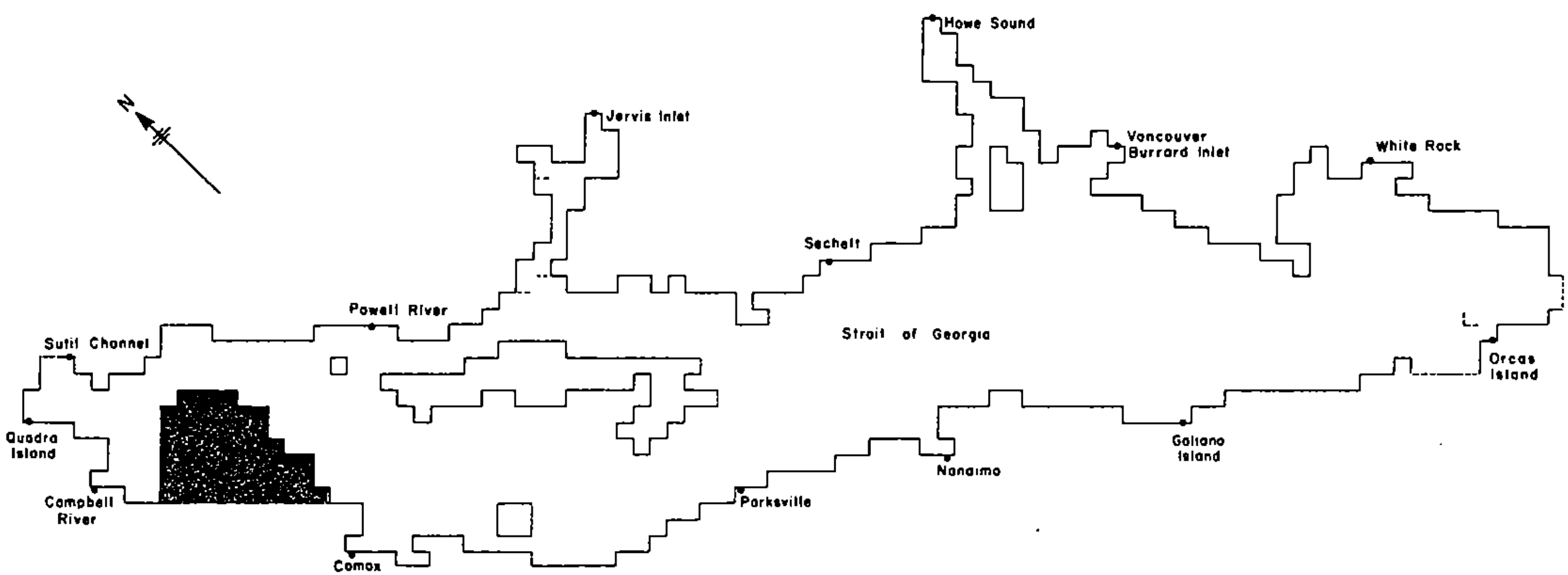

DIXON ENTRANCE
PRINCE RUPERT
QUEEN CHARLOTTE
HECATE STRAIT
QUEEN CHARLOTTE ISLANDS
BELLA BELLA
QUEEN CHARLOTTE SOUND
PORT HARDY
ALERT BAY
BRITISH COLUMBIA
CAMPBELL RIVER
VANCOUVER ISLAND
LITTLE RIVER
POINT ATKINSON
VANCOUVER
PACIFIC OCEAN
TOFINO
FULFORD HARBOUR
BAMFIELD
VICTORIA
WASHINGTON
SOOKE

FIGURE 1


N
Jervis Inlet
Howe Sound
Vancouver
Burrard Inlet
White Rock
Sechelt
Powell River
Sutil Channel
Strait of Georgia
Orcas
Island
Quadra
Island
Galiano
Island
Nanaimo
Campbell
River
Parksville
Comox

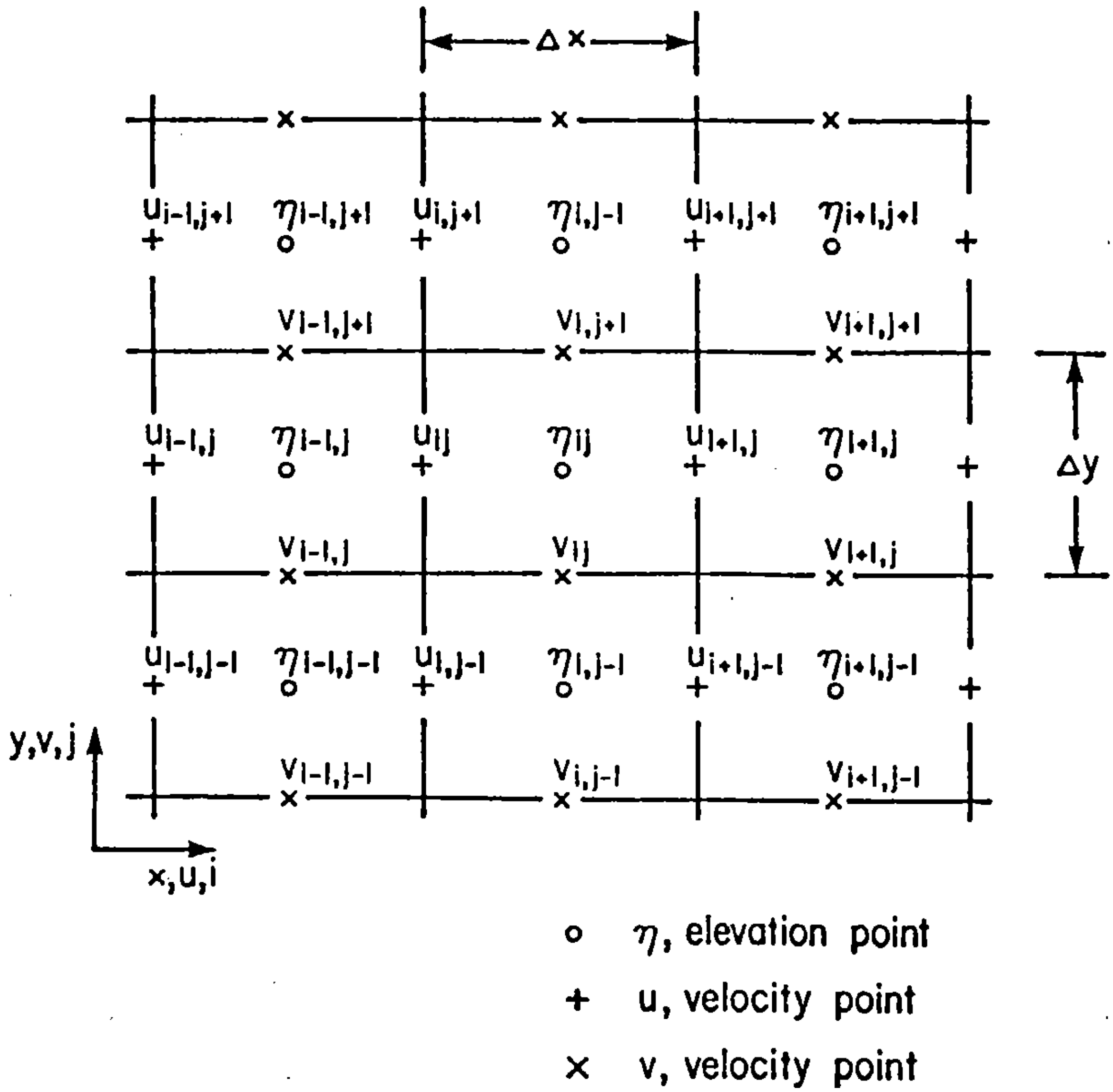
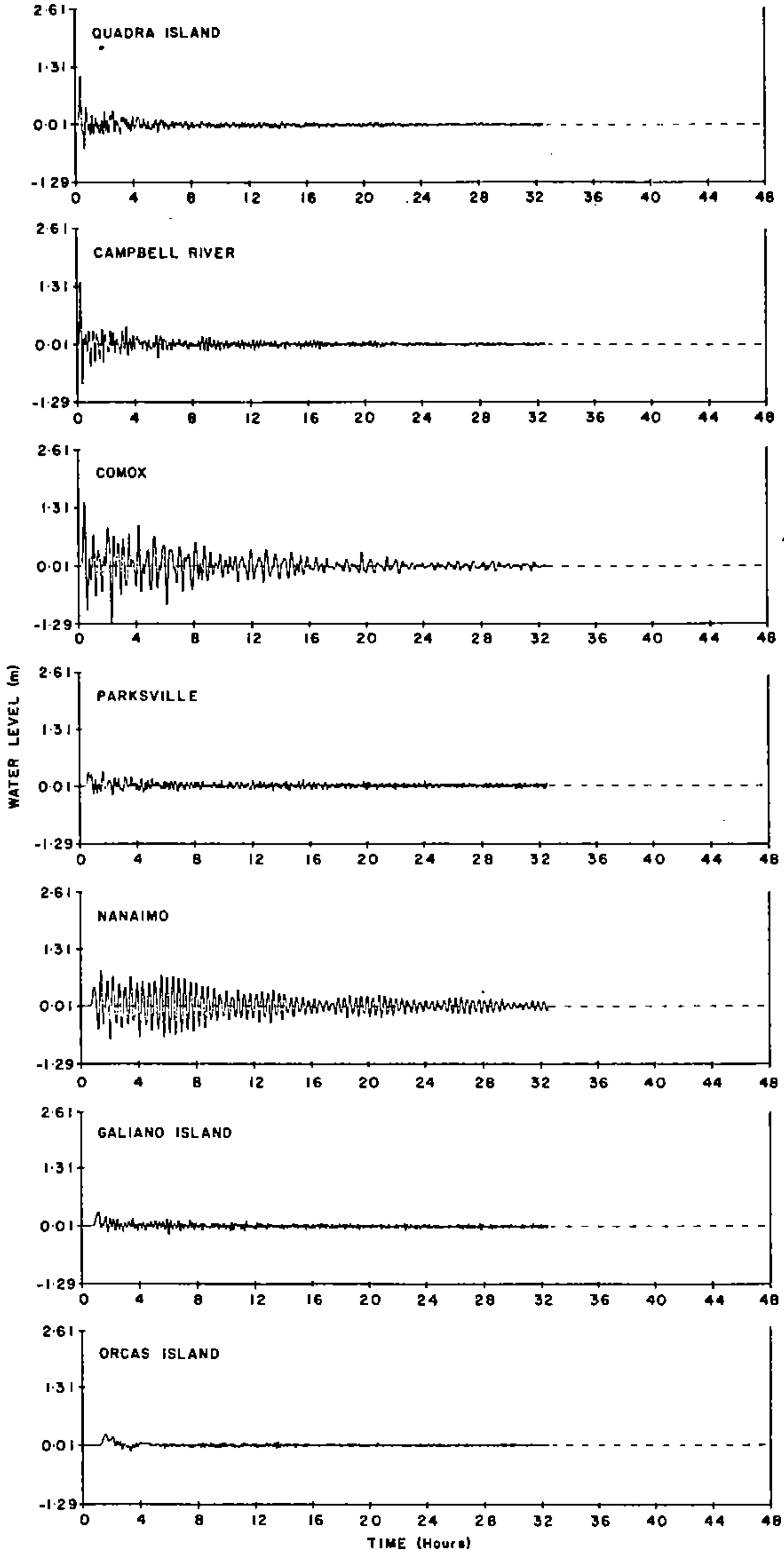
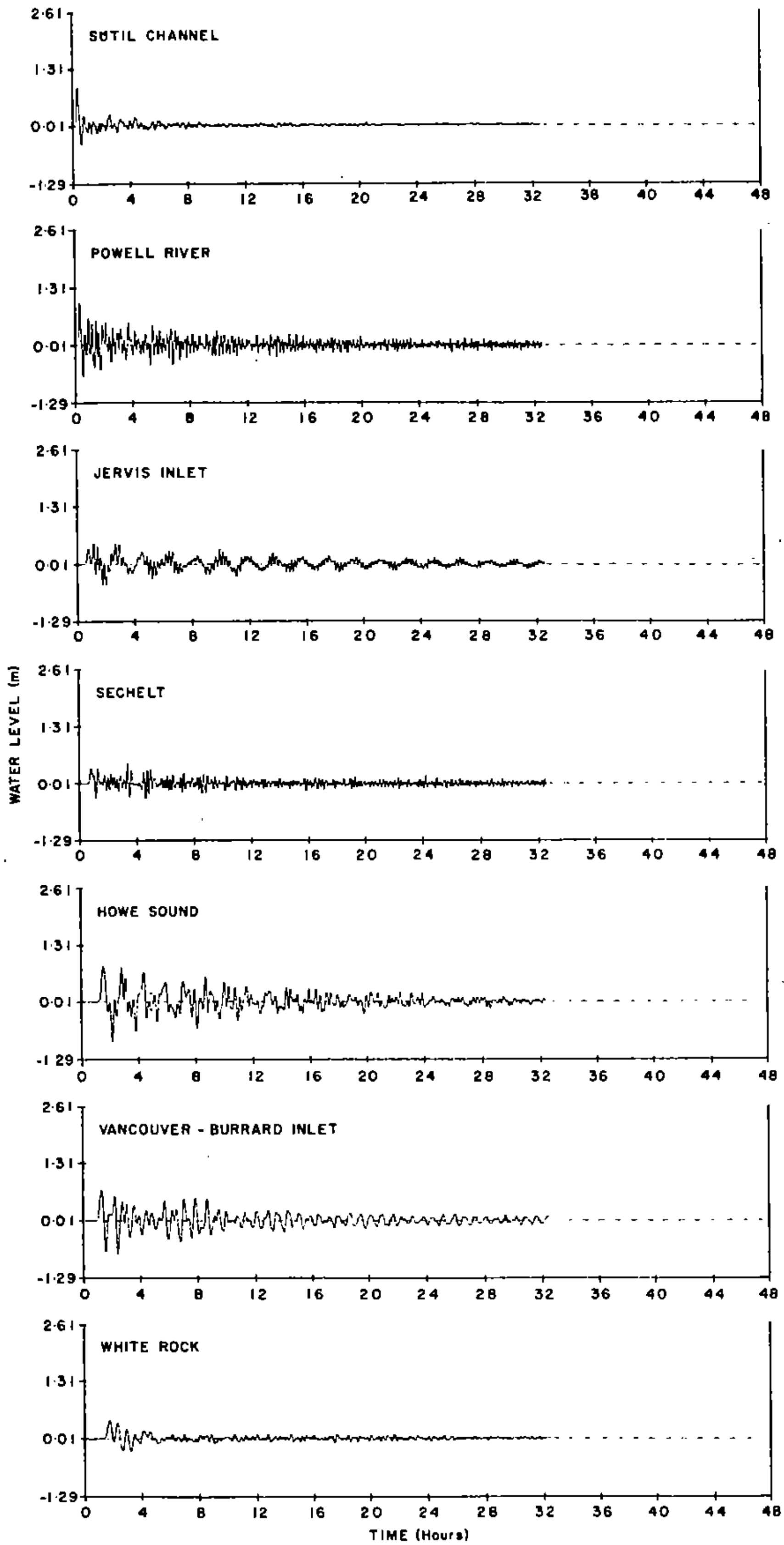


FIGURE 3. Computational scheme on the Richardson grid.


QUADRA ISLAND
CAMPBELL RIVER
COMOX
PARKSVILLE
NANAIMO
GALIANO ISLAND
ORCAS ISLAND
WATER LEVEL (m)
2·61
1·31
0·01
-1·29
0 4 8 12 16 20 24 28 32 36 40 44 48
TIME (Hours)

a.


SUTIL CHANNEL
POWELL RIVER
JERVIS INLET
SECHELT
HOWE SOUND
VANCOUVER - BURRARD INLET
WHITE ROCK
WATER LEVEL (m)
2·61
1·31
0·01
-1·29
0 4 8 12 16 20 24 28 32 36 40 44 48
TIME (Hours)

b.