SYNTHESIS OF HURRICANE RESPONSE HYDROGRAPHS

by

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ABSTRACT: A hindcasting methodology is described for the total water level and wave hydrographs at a coastal site during a hurricane. It accommodates phasing of the separate components of the sustained water level (astronomical tide, storm tide, breaking wave setup), as well as storm variability and coastal bathymetry. Complete hindcast models are utilised, but an intermediate cost and precision is achieved by compromising the number of complete hindcast storms, rather than the precision of the hindcast model. A synthesis technique is developed to predict the response hydrographs of the remaining storms in the historical data set.

INTRODUCTION

Rational design in the coastal environment should be based on long term frequency estimates of extreme water level and wave conditions but the duration and quality of historical records of both water level and wave conditions during hurricanes are rarely adequate to provide the necessary information. However, suitable historical records of meteorological conditions are often available, which can be used in conjunction with suitable meteorological tide and wave prediction models to hindcast meteorological tide and wave conditions respectively.

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In recent years, sophisticated numerical hindcast models have been developed to a respectable level of precision and acceptance. It is an inevitable consequence that they are computationally costly and this has inhibited their use in long term frequency studies where typically fifty storms would require hindcasting. Complete models, based on the long wave equations for storm tides or the radiative transfer equation for wind waves, hindcast the complete time history or hydrograph of the sea response to a storm, allowing consideration of the phasing of the peak storm tide, wave and breaking wave setup responses with the periodic astronomical tide as well as consideration of a number of topographical and shallow water influences. Less complete models rarely allow appropriate consideration of any of these points but they may nonetheless be used because of the frequently prohibitive cost of hindcasting a complete storm data set.

This paper describes a hindcasting methodology in a hurricane environment that provides an intermediate step between the above extremes. It is intermediate in both cost and precision. Site-specific experience is developed from a small number of complete storm hindcasts and this information is used to synthesise the response hydrographs for the remaining storms of the meteorological data set. The approach is broadly similar to the unit hydrograph procedure in surface water hydrology and it has been used successfully in a major hindcast study on Australia's North-West Shelf.

HISTORICAL RECORDS OF SEA RESPONSE

Under ideal circumstances, long term frequency estimates are based on long term records of the particular event. For storm tides, the relevant extreme value series would be drawn from long term records of total sustained water level at the particular site. For wind waves, it would be drawn from long term records of wind waves at the same site. Such ideal circumstances are rarely achieved in practice, for a variety of reasons.

If suitable records are available at all, they are rarely at the particular site in question. The data site may be sufficiently close that it is reasonable to ignore any difference in sea response at the two sites. In many cases however this may not be a reasonable assumption, especially in shallower nearshore areas where interest is frequently centred. Bathymetric and shoreline detail has a major impact on sea response and the storm tide in particular is very site sensitive. For a landfalling storm across a generally open coast, the peak surge level varies moderately rapidly along the coast and is particularly sensitive to the depth and width of the continential shelf, a wide shallow shelf inducing a much more intense surge. Coastal features such as bays and headlands control the local flow patterns and can have a significant local influence, whose spatial extent is roughly the same order as the spatial scale of the coastal feature. Shallower water influences on wind waves are often more complicated. In addition to spatial and temporal variations in the forcing, the propagation characteristics of wind waves are modified by the continental shelf bathymetry. The waves are refracted, shoal and eventually dissipate on the shore. Refraction may concentrate wave energy around headlands or disperse wave energy within bays. Wave energy may be dissipated by bottom friction, bottom percolation interaction with a cohesionless bed material, bottom motion in a cohesive bed material and perhaps bottom scattering from irregularities in the bathymetry. Wave diffraction will also have a significant influence around major headlands and man-made breakwaters, dispersing wave energy into the geometric shadow of the feature.

Even where records are available at a suitable site, a number of significant problems remain. Storm tide records are rarely collected as such but can often be established from automatically-recording tide gauges which have been standard equipment at most established ports for many decades. The height of the astronomical tide has a major influence on shipping movements in and out of port and records are maintained for this purpose, even though little more than a year of records is necessary for traditional harmonic analysis on which published tide predictions are based. These gauges are sited at the convenience of the port authority and designed to record only the astronomical tide. Storm surge is also a long wave motion and will be recorded by conventional tide gauges, unless the storm surge is sufficiently extreme to damage the instrument or send it off scale. Harbour resonance may also be recorded on the gauge but this component should not be difficult to separately identify. Access to these records is perhaps the major problem. Historical records are mostly in analogue form on strip charts and this recording technique has generally continued to the present day. Consistent quality of such records is not assured. Port authorities naturally see little value in maintaining historical records but it has fortunately become a reasonably established practice, although record achival is often a rather haphazard process. Apart from the record sequences used for harmonic analysis (often a single twelve month period), there will have been little consistent interest in these records. Problems with local datum changes and possible reconstruction, relocation or replacement of the gauge are anticipated, together with the laborious task of separating the storm tide component from the analogue strip charts.

The systemic measurement of wave conditions has become a standard practice only in the last decade or so. Initially records were obtained on strip charts but present practice records only a discrete record with a typical time spacing of 0.5 s. Good quality records are regularly obtained and an enormous amount of data is amassed in a relatively short time. However, the limitations of this data is estimating extreme events must be clearly recognised (Sobey, 1982), as each year of data contributes only one point to the extreme value series. The total duration of the data series must be considered in the light of potential meteorological trends and multiyear weather cycles, even natural or man-made changes in the local environment. Based on a study by Petrauskas and Aagaard (8), Borgman (2) has suggested that it is unwise to extrapolate beyond twice the duration of the record from the largest observation. Typical record lengths in many situations rarely exceed a few years, whereas design often relates to average recurrence intervals of 50 or 100 years. There is a large measure of uncertainty attached to record extrapolation to such extreme events, even following the adoption of an appropriate probability distribution.

HINDCASTING THE SEA RESPONSE

It is clear from the above discussion that historical data alone is often insufficient to develop satisfactory estimates of long term frequencies of sea response. The alternative is system modelling, in which advantage is taken of long term meteorological records of storm conditions to hindcast the sea response corresponding to the historical storm data.

The long wave response of a homogeneous sea to the meteorological forcing of a hurricane is adequately described by a two-dimensional vertically integrated form of the Reynolds' Equations - the Long Wave Equations. These equations represent the conservation of mass and the conservation of momentum in horizontal directions x and y and time t:

$$\frac{\partial \eta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{1}$$

$$\frac{\partial U}{\partial t} + \frac{\partial}{\partial x}\left(\frac{U^2}{\eta-d}\right) + \frac{\partial}{\partial y}\left(\frac{UV}{\eta-d}\right) - fV = -g(\eta-d)\frac{\partial \eta}{\partial x} - \left(\frac{\eta-d}{\rho_w}\right)\frac{\partial p_s}{\partial x} + \frac{1}{\rho_w}(\tau_{sx}-\tau_{bx}) \tag{2}$$

$$\frac{\partial V}{\partial t} + \frac{\partial}{\partial x}\left(\frac{UV}{\eta-d}\right) + \frac{\partial}{\partial y}\left(\frac{V}{\eta-d}\right) + fU = -g(\eta-d)\frac{\partial \eta}{\partial y} - \left(\frac{\eta-d}{\rho_w}\right)\frac{\partial p_s}{\partial y} + \frac{1}{\rho_w}(\tau_{sy}-\tau_{by}) \tag{3}$$

The x-y datum plane is located at the mean water level with the z axis directed vertically upwards. The water surface elevation with respect to datum is $\eta(x,y,t)$, the sea bed is d(x,y) with respect to datum, U and V are depth-integrated flows per unit width, f is the Coriolis parameter and ρ_w is the mass density of sea water. The forcing influence of the hurricane is represented through the surface wind shear stress vector $\underline{\tau}_s(x,y,t)$, resolved into components τ_{sx} and τ_{sy}, and the x and y gradients of the M.S.L. atmospheric pressure $p_s(x,y,t)$. The effect of bottom stress is represented through the seabed shear stress vector $\underline{\tau}_b(x,y,t)$, resolved into components τ_{bx} and τ_{by}. Numerical solutions of these equations are readily accomplished under quite general conditions of bathymetry, coastal detail and meteorological forcing. One such example is the numerical hydrodynamic model SURGE described by Sobey, Harper and Mitchell (14) and Sobey, Harper and Stark (13). This model has been used extensively in northern Australia at some fifteen different sites for some one hundred and fifty different storms. It can be applied to most coastal regions and includes the effects of undersea bathymetry, offshore islands, reefs and other coastal features, as well as the flooding of low lying land. Tropical cyclone size, intensity and track can be varied continuously throughout a simulation to produce water flow patterns, contours of water level, coastal surge profiles at any time and water level and flow velocity time histories anywhere within the model area. SURGE is a comprehensive software system, in which particular attention has been given to the quite considerable problems of input data format and especially output data selection and presentation.

A complex wind sea is described in terms of the variance spectral densty $E(f,\theta;x,y,t)$ in directional fequency (f,θ) space. In the absence of current, wave energy conservation may be written as

$$\frac{\partial}{\partial t}(C\,C_gE) + C_g\cos\theta\,\frac{\partial}{\partial x}(C\,C_gE) + C_g\sin\theta\,\frac{\partial}{\partial y}(C\,C_gE) + \frac{C_g}{C}\left(\sin\theta\,\frac{\partial C}{\partial x} - \cos\theta\,\frac{\partial C}{\partial y}\right)\frac{\partial}{\partial\theta}(C\,C_gE) = C\,C_g\,S \qquad (4)$$

where C is the phase speed and C_g the group velocity. The source function $S(f,\theta)$ on the right hand side represents the net transfer of energy to or from or within the spectrum. This equation, known as the Radiative Transfer Equation, formally summarises all the various physical processes that contribute to the evolution of the directional spectrum. In recent years considerable success has been reported in the representation of the source terms and in the numerical solution of the complete Radiative Transfer Equation. One such example is the numerical hydrodynamic model SPECT described by Sobey and Young (16) and Young and Sobey (21). This is a quite general model, applicable in both shallow and deep water. It has been used successfully in Australia for a twenty-eight storm hindcast study on the North-West Shelf, where good agreement with field data was obtained.

The aerodynamics of the hurricane and the hydrodynamics of the underlying water body are coupled by the atmospheric pressure p_s and wind shear stress τ_s at the air-sea interface. Their estimation throughout the flow field during the passage of a tropical cyclone follows from the adoption of a suitable model of the near-surface meteorological structure of the storm. The model developed initially by Graham and Nunn (4) under the National Hurricane Research Project (NHRP) of the former U.S. Weather Bureau forms the basis of the storm sub-model in both cases. No claim is made that this model is entirely satisfactory; in fact our knowledge of tropical cyclone wind fields is far from complete. It was adopted in the absence of a more suitable alternative. More sophisticated models describing the dynamics of the atmospheric boundary layer in a moving hurricane could be used, but there is a significant computational penalty and the predictive capability of such models is not yet measurably superior for the NHRP model.

Many of the highly empirical aspects of the original NHRP model, such as rate of filling over land and the reduction of over-land wind speeds, have been omitted in favour of representing the major features of the tropical cyclone. In particular the radial wind and pressure profiles, the variation of the radial inflow angle and the asymmetry of the wind field are included and expressed in terms of the four parameters commonly assumed to characterise a hurricane: the central pressure p_o at M.S.L., the maximum sustained wind V_{10} at a height of 10 m above M.S.L., the radius of maximum winds R, the speed V_{FM} and direction θ_{FM} of storm forward movement. All four parameters are varied continuously to represent changes in storm intensity and track. Details may be found in Ref. 13. The over-water wind speed W_{10} at height 10 m above M.S.L. and the resulting shear stress τ_s on the water surface are assumed to be related as $\tau_s = C_{10} \rho_a W_{10}^2$, where C_{10} is a non-dimensional surface friction or drag coefficient and ρ_a is the mass density of air.

Now that sophisticated hindcast models have been developed to a respectiable level of precision and acceptance, hindcasting has many advantages in estimating the sea response to hurricanes. It permits an extreme value series to be esablished where no field records of sea response exist, the duration of which is the duration of the meteorological data and generally long enough to expect a satisfactory estimate of 50 and perhaps 100 year events. It also removes the temptation to use historical sea response data an another site whole characteristics are arguably different from the site in question. Where there is short term measured sea response data at the particular site, the hindcast data has a complementary role in confirming or defining the longer-term trends.

The major disadvantage of the complete hindcasting models (LWE and RTE) is their detail and hence computational and associated personnel costs. Hindcasting a complete data set (typically of order 50 storms) is mostly well beyond the budget and also the time that is typically allocated to long term frequency estimates. Some compromise is often sought, usually the adoption of a less sophisticated hindcast model which compromises the detail as well as the cost of hindcasting the sea response. The consequences need to be fully recognised. In particular the use of historical data to its fullest potential gives direct consideration to the influence of storm track variability and storm intensification and decay, aspects that are difficult to consider in any less sophisticated approach. A related and perhaps more significant aspect is the phasing of astronomical tide, storm surge and wave conditions (17). Astronomical tides are often significantly variable. On Australia's North West Shelf, for example, the mean spring tide range is large (of order 3 to 4 m) but the mean neap tide range is small (of order 1 m). A peak storm surge of order 2 m would be a major event and its impact clearly depends on the timing and duration of its peak with respect to the astronomical tide. Its arrival at low tide would be little cause for concern and even at a typical high water neaps the total water level would not differ significantly from the highest astronomical tide (HAT). At a typical high water springs however its impact would be substantal. Similar arguments are valid regarding breaking wave setup, with the additional complication that peak wave and surge conditions will not necessarily correspond. Surge and wave response to hurricanes are related but physically distinct phenomena, in their generation and propagation and especially in their reaction to shoaling waters and coastal bathymetry. There is a considerable margin of safety available in the tidal characteristics and a realistic analysis of extreme water levels must give reasonable consideration also to this situation.

The often critical significance of coastal detail and shelf bathymetry has already been mentioned above, yet it is this detail that is first abandoned in less sophisticated hindcast models. For storm tides, the Bathystrophic Storm Tide model proposed by Freeman, Baer and Jung (3) considers only the steady-state momentum balance normal to the coast at the site in question. Mass and longshore momentum conservation is not considered, nor are the dynamics of the sea response. Coastal detail and shelf bathymetry is represented by the seabed profile at the site, other detail being ignored. For this approach to have any validity, it must be restricted to open-coast situations and slowly-moving, large-scale storm systems. An alternative approach to a less sophisticated hindcast model for storm tides is the nomograph method of Jelesnianski (5). This method is also restricted to open-coast situations but is based on computations utilising the complete Long Wave Equations. A standard continental shelf region was defined with a straight coastline and a uniform linear slope as the seabed profile. A standard storm was defined and directed on a landfalling track normal to the coastline. These results are presented in terms of peak surge amplitude only, to which correction factors have been defined for different linear seabed profiles (the shoaling correction) and different forward speed and direction of the storm (the motion correction).

Less sophisticated hindcast models for wind waves differ in detail but not in spirit. The empirical models of Bretschneider (1), Ross (9), Lee (7) and Shemdin (10) have much in common. All neglect the dynamics of the sea response, assume exclusively deep water conditions and base their parameterisation of the sea response on the Sverdrup and Munk (18) or Kitaigorodskii (6) scaling relationships, which are identical. In quantifying the relationships, Bretschneider uses an integral interpretation of the Sverdrup-Munk fetch graphs, while Ross, Lee and Shemdin use field data from Gulf of Mexico hurricanes. Shemdin's model predicts the significant wave height and peak frequency of the dominant wave conditions ahead of a moving hurricane, giving specific consideration to the forward motion. The other three models predict the space and time variable wave field; the Bretschneider model is restricted to slowly-moving storms and the Ross and Lee models give no specific consideration to storm motion. None of these models predict dominant wave directions and quantitative agreement among the models is quite poor. In addition their is little consideration of storm variability in position and time and no consideration of important coastal detail and shelf bathymetry and associated shallow water effects.

AN ALTERNATIVE APPROACH

It is apparent from the above discussion that there are a range of influences on sea response to hurricanes that can be reasonably accommodated only by a complete hindcast model. The adopted methodology is a direct recognition of this situation. The separate steps are those of the complete approach: (i) hindcast the sea response (storm surge and/or wind waves) and the astronomical tide conditions during each hurricane of the historical storm data set, (ii) superimpose the storm surge, breaking wave setup and astronomical tide hydrographs to give the hindcast total water level hydrographs, and (iii) form extreme value series from total water level and wave hydrograph peaks during each of the historical storms for frequency analysis. The necessary compromise is in the number of storms that are hindcast by complete hindcast models. A limited number of project hurricanes (of order 5) are chosen as representative of the range of storm intensities and particularly storm tracks in the historical data set. Complete hindcasts of sea response for the project hurricanes together with the complete historical hurricane data set comprises the data base for hindcasting the sea response to all storms in the historical data set. A hindcast model developed from this data base gives explicit consideration to the whole range of site specific and predominantly shallow water influences described above as collectively having a potentially major impact on the sea response at a nearshore site on the continental shelf.

The suggested methodology has been used in the estimation of long term frequencies of extreme wave height and total sustained water level at Mermaid Sound on Australia's North-West Shelf. The historical storm data set contained forty-three tropical cyclones, from which six were chosen as project storms. The specific examples described below have been taken from this study.

SYNTHESIS OF STORM RESPONSE

To synthesise the sea response hydrographs for all storms in the historical data set from the complete hindcasts for the small number of project hurricances, certain assumptions about generalised storm response must be made. The first major assumption of this analysis is that at each site, distinct hydrograph segments (e.g. rising limb, falling limb) can be represented in terms of a single amplitude scale H and a single time scale T, such that in general

$$h(t)/H = f(t/T) \tag{5}$$

h(t) being the response hydrograph at time t. For the rising limb of a hydrograph, H might be the peak height and T the half-life. Each separate hydrograph segment is representated as a two parameter curve, uniquely defined once H and T and the function f are specified.

The second major assumption involves the application of dimensional arguments to determine H and T for each storm. It is assumed that H and T are dependent only on the following variables: $\Delta p_o = p_\infty - p_o$, the central pressure deficit of the storm eye at closest approach; R, the radius of maximum winds at closest approach; V_{FM}, the forward speed of the storm at closest approach; S, the distance of the storm from the site at closest approach; ρ_w, the mass density of sea water and g, the gravitational acceleration. Consequently

$$H,T = f(\Delta p_o, R, V_{FM}, S, \rho_w, g) \tag{6}$$

The variation of Δp_o, R, V_{FM} and S during the passage of a hurricane can be quite considerable and it is an assumption of this analysis that the parameter values at closest approach are applicable. It could be argued that some time-averaged value for each parameter might be more appropriate, but resolution of this point would almost require complete wave and surge hindcasts for each of the storms in the historical data set, just what the parametric approach is designed to avoid. A similar definition of the revelant storm parameters has been adopted by Ward, Borgman and Cardone (20) in extending hindcast wave data from twenty-six storms to a forty-eight storm historical data set.

Applying dimensional analysis to Equation 6 with R and V_{FM} as the recurring variables gives

$$\frac{H}{R}, \frac{T}{R/V_{FM}} = f\left(\frac{B_o}{R}, \frac{S}{R}, \frac{V^2_{FM}}{gR}\right) \tag{7}$$

where $B_o = \Delta p_o/\rho_w g$, the barometric head deficit of the storm eye at closest approach. It is generally recognised that R largely defines the horizontal or spatial scale of the sea response while B_o determines the intensity of the response, recognition of which leads to a reorgnaisation of Equation 7 as

$$\frac{H}{B_o}, \frac{T}{R/V_{FM}} = f\left(\frac{S}{R}, \frac{B_o}{R}, \frac{V^2_{FM}}{gR}\right) \tag{8}$$

The functions f are determined from the appropriate project storm hindcasts, as shown below. Intuitively one would anticipate a major dependence of the dimensionless amplitude at each site on S/R but perhaps only a minor dependence of the dimensionless time on B_o/R and S/R. No systematic dependence on the dimensionless Froude Number is anticipated.

SIGNIFICANT WAVE HYDROGRAPHS

Hindcast significant wave hydrographs typically have the same general shape, a rising limb to a single peak and a falling limb at a different and generally faster rate. An appropriate universal profile is sketched in Figure 1, both the rising and falling limbs being represented as Gaussian curves with different half-lives, T_1 and T_2 respectively:

$$h(t) = \begin{cases} H \exp\left[- c\left(\frac{t-T_p}{T_1}\right)^2\right] & \text{for } t \leq T_p \\ H \exp\left[- c\left(\frac{t-T_p}{T_1}\right)^2\right] & \text{for } t > T_p \end{cases} \tag{9}$$

where H is the peak amplitude, T_p is the time of the hydrograph peak and c = ln 2.

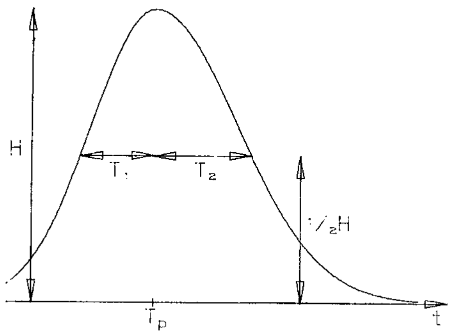

Figure 1. Parameterised Significant Wave Hydrograph

The complete hydrograph can be represented in terms of a single amplitude parameter H and three time parameters $T_p - T_o$, T_1 and T_2, T_o being the time of closest approach of each project storm. Each of these parameters have been extracted from the project storm hindcast hydrographs and non-dimensionalised and plotted in accordance with Equation 8. The final result for one site within Mermaid sound is shown in Figure 2. Several trial presentations were attempted before these plots were finalised. A major dependence on the direction of rotation of the track about Mermaid Sound was apparent and this was accommodated within the existing dimensional variables by afixing a sign to S, the distance at closest approach. A plus sign implied clockwise rotation and a negative sign anti-clockwise rotation.

The functional dependence indicated by Equation 8 was investigated in as much detail as the data allowed and no systematic dependence on either parameter was established. It seemed most appropriate to represent each dimensionless time as a constant value. The amplitude curve at the top of Figure 2 shows an anticipated intensification of significant wave height for storms passing anti-clockwise about Mermaid Sound. This H/B_o curve was used directly in estimating the peak amplitude for each of the forty-three storms. Each curve has been extrapolated outwards to its intersection with the S/R axis. Outside these intersection points, H/B_o is assumed zero, the storm passing sufficiently far from Mermaid Sound for this to be a reasonable assumption. It is of course possible that significant waves generated closer to the storm centre may propagate to and penetrate into Mermaid Sound. To the extent that such behaviour is not included among the six project storms it can not be accommodated within the present analysis.

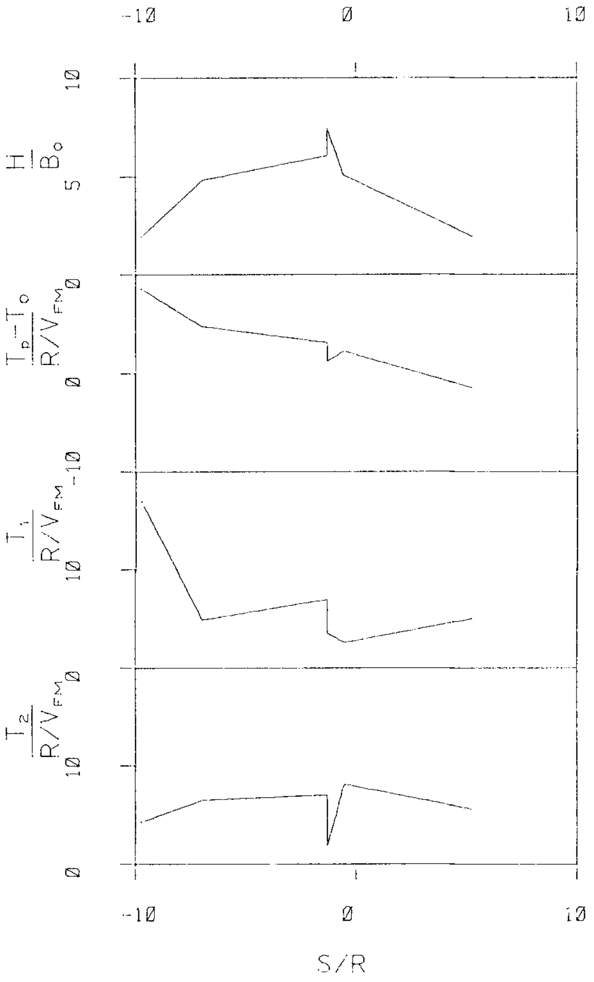

Figure 2. Dimensionless Parameters of Significant Wave Hydrographs

Breaking wave setup is a nearshore phenomenon related to the conversion of the kinetic energy of wave motion to quasi-steady potential energy for waves breaking on a beach slope. Where required, it was estimated from significant wave height in the manner recommended in the Shore Protection Manual (19).

STORM SURGE HYDROGRAPHS

A characteristic of the storm surge hindcasts for Mermaid Sound was the early and sustained response. In addition to the normal peak setup or setdown around the time of closest approach there is typically an initial peak setup or setdown several hours earlier, in response to the regional bathymetry and particularly the coastal topography. For landfalling storms passing to the east of (i.e. clockwise about) Mermaid Sound, an initial setdown is followed by a period of sustained setdown until a fairly rapid fall away after the second peak. For landfalling storms passing to the west of (i.e. anti-clockwise about) Mermaid Sound, an initial setup is followed by a period of sustained setup until the second peak around the time of storm landfall, after which there is again a fairly rapid fall away. For parallel moving storms tracking down the coast (i.e. anti-clockwise about Mermaid Sound), an initial setdown is followed by a somewhat more substantial setup. The reverse pattern of behaviour appears certain for parallel moving storms tracking up the coast although there is no such storm among the six project storms.

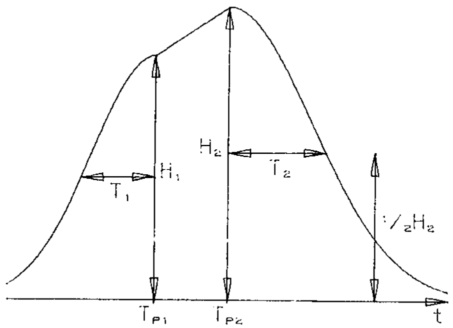

Figure 3. Parameterised Storm Surge Hydrograph

An appropriate universal profile to describe this complex hydrograph is sketched in Figure 3. The initial peak is at T_{p1} and the rising (falling) limb has a Gaussian profile with a half-life of T_1. The intermediate segment between T_{p1} and the major peak T_{p2} is assumed to follow a straight line, both peak water levels H_1 and H_2 being potentially positive (setup) or negative (setdown). The falling limb from T_{p2} is again a Gaussian profile with half-life T_2.

$$h(t) = \begin{cases} H_1 \exp\left[- c \left(\frac{t-T_{p1}}{T_1}\right)^2\right] & \text{for } t \leqslant T_{p1} \\ H_1 + \frac{H_2-H_1}{T_{p2}-T_{p1}} (t-T_{p1}) & \text{for } T_{p1} < t \leqslant T_{p2} \\ H_2 \exp\left[- c \left(\frac{t-T_{p2}}{T_2}\right)^2\right] & \text{for } t > T_{p2} \end{cases} \qquad (10)$$

The complete hydrograph can be represented in terms of two amplitude parameters H_1, H_2 and four time parameters $T_o - T_{p1}$, T_1, $T_{p2} - T_o$ and T_2. Each of these parameters has been extracted from the hindcast hydrographs, non-dimensionalised and plotted in accordance with Equation 8, in a similar manner to the previous section. The final result for one site within Mermaid Sound is shown in Figure 4.

Following the introductory discussion to this section it was necessary to distinguish between landfalling and parallel moving storms, in addition to the distinction based on direction of rotation about Mermaid Sound. This reduced the data set from six storms to two sets of three storms and required additional assumptions about the surge response to distant storms. This specific assumption has been that storms that do not approach closer than 10R to Mermaid Sound have no influence on water levels within the Sound and that response amplitude falls away towards the 10R position. The project hindcasts and experience elsewhere indicate that this is a reasonable assumption and it has been incorporated into Figure 4 as straight line segments.

Once again it seemed most appropriate to represent each dimensionless time as a constant value over all sites, with different values for landfalling and parallel moving storms. As also in the previous section, the H/B_o curves were used directly in estimating surge peaks for each of the forty-three storms. The shape of these curves follow the anticipated pattern, especially for landfalling storms which show the classic along-coast profile with setdown to the east and more substantial setup to the west.

ASTRONOMICAL TIDE HYDROGRAPHS

Hindcasts of astronomical tide hydrographs are generated from the classical harmonic series represetation of the vertical tide:

$$h(t) = H_o + \sum_{n=1}^{R} f_n H_n \cos(\omega_n t + V_n + u_n - g_n) \qquad (11)$$

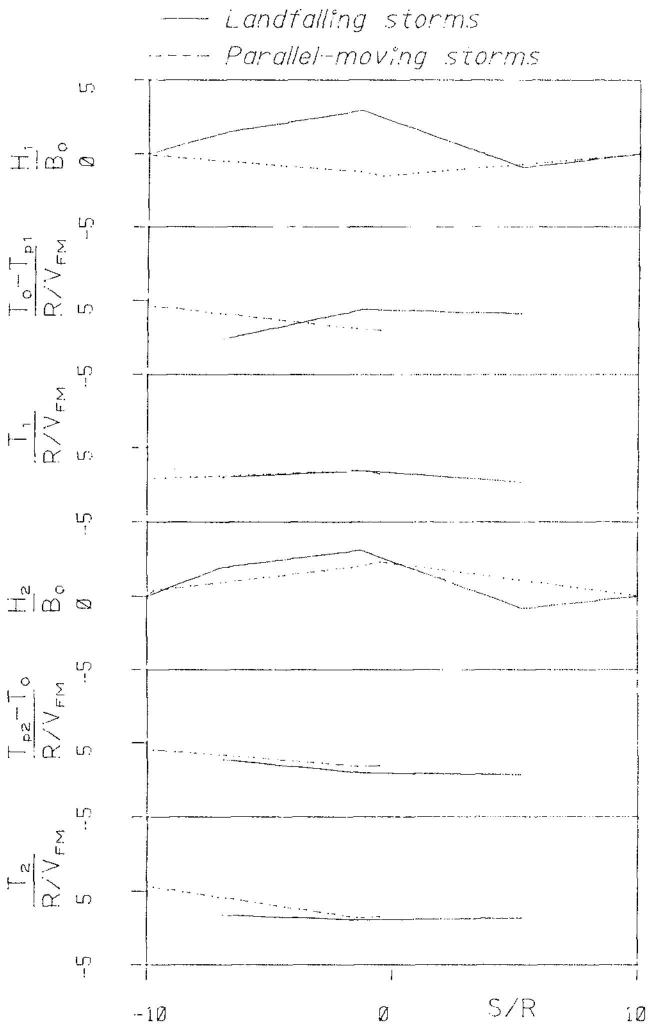

Figure 4. Dimensionless Parameters of Storm Surge Hydrographs

where H_o is the height of the M.W.L. above datum, n identifies a tidal constituent, R is the number of tidal constituents, f_n the node factor for the nth constituent, H_n the amplitude of the nth constituent, ω_n the angular speed of the nth constituent, t the local time, V_n the uniformly changing part of the phase of the nth constituent according to equilibrium theory, u_n the correction of V_n for regression of the lunar nodes, and g_n the phase of the nth constituent. The tidal constituent amplitudes and phases (H_n and g_n), determined originally by harmonic analysis from an historical data set normally of a year's duration, are appropriate for tidal prediction at both past and future time. The astronomical tide can be predicted with greater certainty than perhaps any other geophysical event in the coastal environment.

The hindcasts were completed using computer program HTIDE2 developed by the author, in which the definitions of the separate tidal constituents and the associated astronomical arguments f_n, V_u and u_n are those of Schureman (11). In a typical application the sixty-four major tidal constituents are used.

COMBINED WATER LEVEL HYDROGRAPHS

Hindcast sustained water level hydrographs have been determined from linear superposition of the hindcast astronomical tide hydrograph, the hindcast storm surge hydrograph and, where appropriate, the hindcast breaking wave setup hydrograph for a particular site. Breaking wave setup is only included for coastal sites. No attempt was made to consider any interaction among the separate components.

Figures 5 to 8 are typical results within Mermaid Sound, chosen to illustrate the scope of the technique and not the magnitude of especially extreme events. Figure 5, during Tropical Cyclone 194 (February 1948), is a good illustration of the influence of the diurnal inequality in the astronomical tide. A sustained peak surge of about 1.7 m (M.S.L. datum) coincides with an unusually low high water of +0.3 m and the total water level does not reach HAT. The immediately preceding high water reached +1.2 m and gives a good indication of the safety margin provided by the astronomical tide behaviour. Another characteristic of Figure 5 is the longer duration of the wave setup and its peaking at 0.5 m five hours or so after the peak storm surge.

Figure 6, during Tropical Cyclone 300 (March 1961), almost shows the combination of circumstances that is most dangerous, the coincidence of the peak surge, the peak wave setup and a higher high water (HHW) tide. Neither the storm

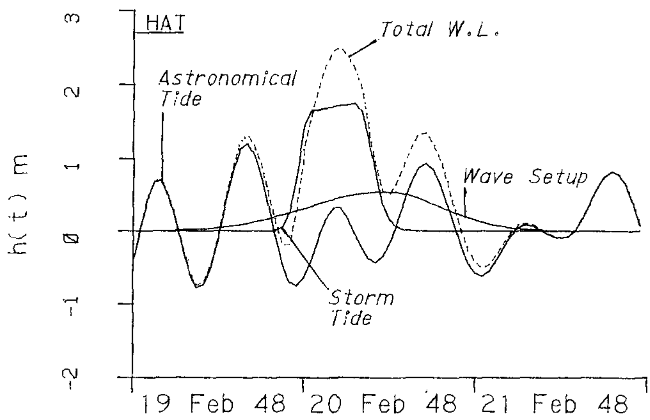

Figure 5. Hindcast Hydrographs during Tropical Cyclone 194

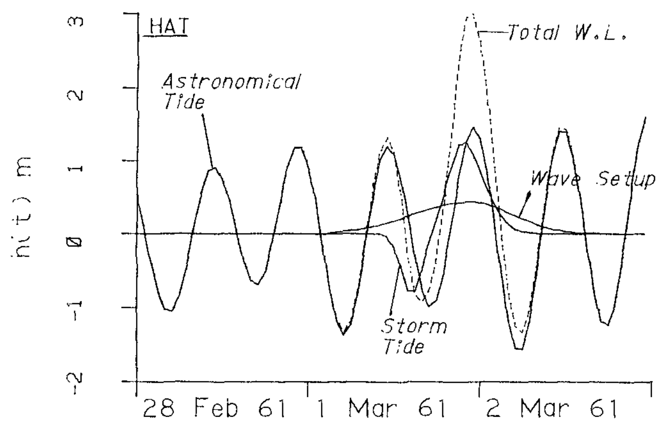

Figure 6. Hindcast Hydrographs during Tropical Cyclone 300

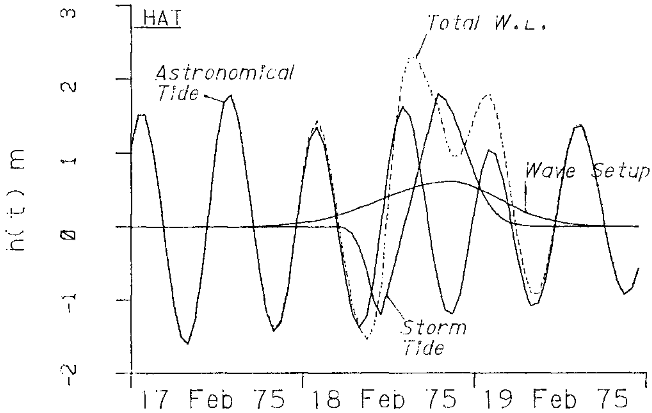

Figure 7. Hindcast Hydrographs during Tropical Cyclone TRIXIE

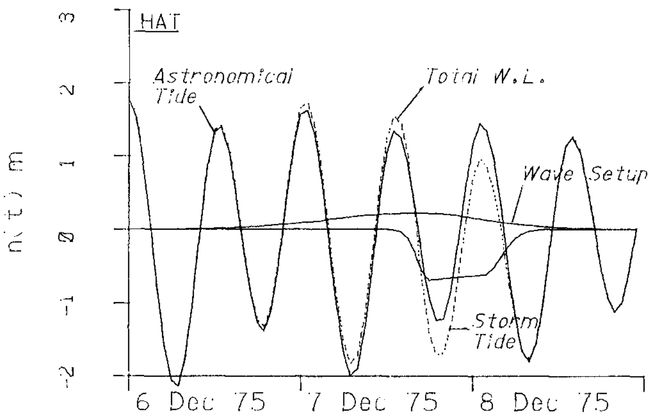

Figure 8. Hindcast Hydrographs during Tropical Cyclone JOAN

surge (+1.2 m) nor the high tide (+1.5 m) are extreme but the total water level nonetheless exceeded HAT by some 0.4 m. Another illustration of the potential safety margin inherent in the astronomical tide behaviour is provided in Figure 7, during Tropical Cyclone 448 TRIXIE (February 1975). The storm tide peaked at 1.8 m and wave setup at 0.6 m, but only an hour or two before the low tde. The maximum water level of +2.3 m is predicted some four to five hours earlier, just after a high tide of +1.6 m, and does not even reach HAT (+2.6 m, M.S.L. datum). Had the storm tide, breaking wave setup and the astronomical tide peaks all coincided a sustained water level of order +4.0 m might have been recorded, emphasising the importance of the phasing of the separate components.

The final example, Figure 8, illustrates the importance of storm track and coastal bathymetry on the storm tide and wave conditions. Tropical Cyclone 600 JOAN (December 1975) was a very significant storm whose central pressure fell to 920 mb but the storm track passed north of Mermaid Sound where predominantly offshore winds were experienced. A sustained storm setdown of order 0.7 m was hindcast in Mermaid Sound, coinciding with a low tide of -1.2 m and little wave setup. This however is perhaps a design constraint in its own right, as the drawdown level is potentially significant in the location of cooling water intakes for industrial plants, especially if the level falls below LAT (-2.6 m). The low water immediately before is -2.2 m and a major setdown at that time might have caused the total water level to fall below LAT.

CONCLUSIONS

A methodology has been demonstrated for hindcasting the total water level and wave hydrographs at a coastal site during a hurricane. It accommodates phasing of the separate components of the sustained water level hydrograph, as well as storm variability and coastal bathymetry. An intermediate cost and precision is achieved by compromising the number of complete hindcast storms, rather than the precision of the hindcast model. Dimensional analysis and the hindcast sea response from a few project storms is used to synthesise the response hydrographs for the remaining storms in the meteorological data set.

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