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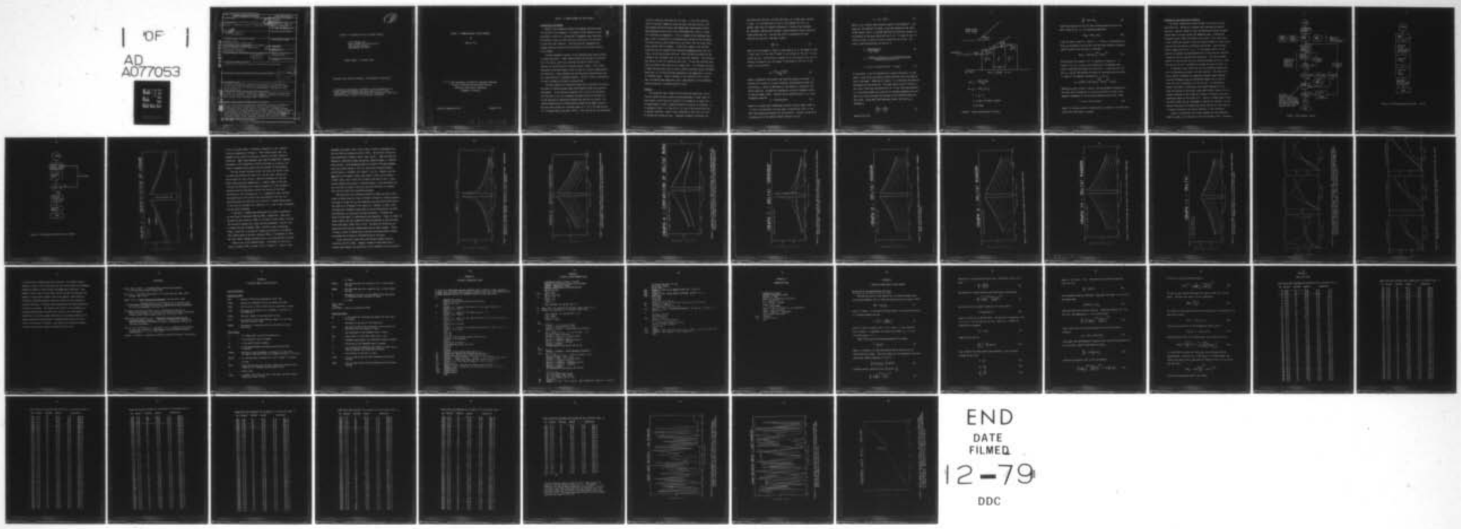

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20. ABSTRACT (*Continue on reverse side if necessary and identify by block number*)

(The) The use of computer simulation technique allows a comparison of the effects of varying the order of wave attacks on a developing river delta, which is supplied a constant amount of sediment per day. Conclusion is that random ordering produces approximately the same delta every time, whereas ordering the waves according to power results in a radical delta. ~~Paper~~ This paper includes sample data, computer program and several graphs.

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Delta7: A Computer Model of Delta Growth

CPT Dominic Izzo
HQDA, MILPERCEN (DAPC-OPP-E)
200 Stovall Street
Alexandria, VA 22332

Final Report - October 1979

A technical memorandum submitted to the Hydraulics and Water Resources Division of the Department of Civil Engineering, California Institute Of Technology, Pasadena, California as a result of individual research.

DELTA7: A COMPUTER MODEL OF DELTA GROWTH

by

Dominic Izzo

√ W. M. Keck Laboratory of Hydraulics and Water Resources
Division of Engineering and Applied Science
California Institute of Technology
Pasadena, California

Technical Memorandum 79-5 √ October 1979

DELTA7: A COMPUTER MODEL OF DELTA GROWTH

Introduction and Summary

Delta7 is an interactive Fortran IV Computer Program written for the PDP-11 mini-computer. It accepts initial beach and river conditions, as well as a varying set of deepwater wave conditions, and produces a data set that outlines a planview of the coastline at specified time intervals. The coastline can subsequently be graphed using the Calcomp 1037 Drum Plotter with the XPLOT instruction of MAGIC.

→ (cont on p 1473A)

Two main background sources in the literature were found valuable in developing Delta7. Komar (1973) studied the problem of the growth of a river delta, and Price, Tomlinson and Wilson (1972) used a computer to simulate coastal processes around a jetty. Kim-E (1978) attempted to duplicate Komar's data, as well as to add an approximation for refraction. Those programs and the discussion presented were used as a starting point in developing Delta7. Delta7 is then a continuation of Kim-E's extension of Komar's original work.

The main objective in developing Delta7 was to determine if varying the order of attacking waves would significantly affect the coastline development. It was strongly suspected that it would, and therefore that the practicality of a computer simulation would be limited, due to the necessity of generating ordered wave data for the future! An implied objective was to verify Delta7 by duplicating Komar's data on one year delta growth for a constant wave of $P = 5.0 \times 10^8$ ergs/cm-sec, at a 10 degree angle (see Komar (1973)). Also implied was the requirement to find a realistic wave data set for input. To this end, 564 days worth of the most frequently occurring waves from Wave Station 5 off the Southern California Coast (see Meteorology International (1977)) were extracted and put into a file called WAVE1.DAT, which is listed in its entirety in Appendix F. This is somewhat of an expedient data base, since it excludes all the extreme waves outside of the 40 degree fan within which α_0 most often occurs, and within that fan waves with a height greater than 2.5 meters. It was felt, however, that the main objective could be reached without adding the entire spectrum into the input, and the results bear this out. After the data set WAVE1.DAT was created it was "flipped"--that is, its order was reversed. (The original data being in order of increasing wave size.) It was then shuffled three times to produce three data sets in random order. The different versions of WAVE1.DAT were then used as input to Delta7 producing several different coastlines, all of which had been generated by the same waves, arriving in different order. Refer to Appendix F for Figures 15, 16, 19 which show the ordered data graphically and a representation of the different random curves over a selected period of time.

Analysis

The simulation uses a model which divides the beach/coast into an infinite series of cells, which are parallelepipeds of equal width Δx, equal depth d, which may vary linearly if the beach has a slope, and a variable height y, which is where accretion or erosion is reflected. It is assumed at time t = 0, that all y = 0, that is we are starting with a straight coastline. Sand is then introduced by the river at a rate of 20,000 cubic meters per day. Longshore transport distributes the sand along the coastline, building the delta, or in some cases, washing it away. It is assumed that no sand is lost between the cells, or gained, other than by longshore transport or from the river sediment. We, therefore, neglect wind transfer, onshore-offshore losses, erosion of larger particles, etc. One may then write a conservation of sand equation for each cell (see Komar (1976)).

$$\frac{\Delta V}{\Delta t} = \Delta S \tag{1}$$

where ΔV is the change in volume in cubic meters, Δt is the change in time, in days, and ΔS is the rate of change in sand volume for the cell in cubic meters per day. Substituting an expression for the volume of the cell, we develop an expression for the change in the height of the cell or the change in the coastline.

$$\Delta y = \frac{(S_{i-1} - S_i)\Delta t}{d\Delta x} \tag{2}$$

where Δy represents the distance the coastline erodes or accretes. In Equation (2), we set Δt, Δx and d constant; and therefore we need only to define S_{i-1} and S_i to determine Δy, and thence, by iteration, the entire coastline. An empirical expression, using the longshore current, is given by Komar (1976). Starting with an equation energy flux in the alongshore direction

$$I_\ell = K(ECn)\cos\theta\sin\theta \tag{3}$$

where K is an empirically determined constant, given by Komar (1976) as .77, ECn is an expression for wave power in ergs/cm-sec, and θ is the angle the breaking wave makes with the shoreline. Further, we can write an expression for the immersed weight transport rate as:

$$I_\ell = (\rho_s - \rho)ga'S \tag{4}$$

where ρ_s for a typical beach sand was taken as 2.65 grams/cm^3, ρ was taken as 1.00 grams/cm^3 for water, g was the constant at sea level of 980 cm/sec^2, and a' is another empirically determined constant for the porosity of the sand, which was set at .61. In order to get S in units of m^3/day, we must also add a conversion for cm^3/sec. The result, combining Equations (3) and (4) is

$$S = \frac{K(ECn)\cos\theta\sin\theta}{(\rho_s - \rho)ga'} \tag{5}$$

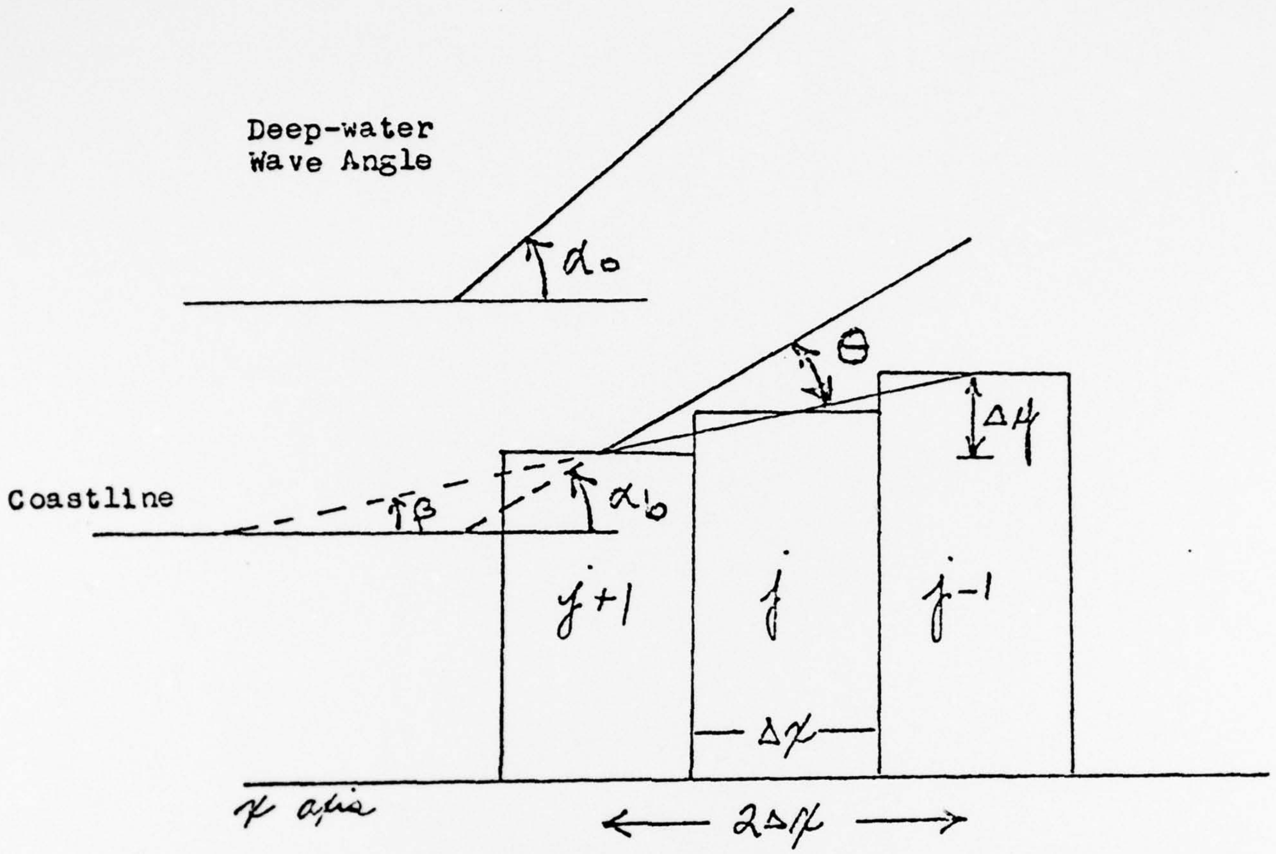
$$S = \frac{.77(ECn)\ \cos\theta\sin\theta\ (10^{-6}\ m^3/cm^3)(86{,}400\ sec/day}{.65\ gm/cm^3)(980\ cm/sec^2)\ .61}$$

$$S = 6.85 \times 10^{-5}(ECn)\cos\theta\sin\theta \quad (m^3/day) \tag{7}$$

At this point, it will be worthwhile to discuss the angle θ in some detail, since it was the source of some confusion during the development of the model. Referring to Figure 1, θ is the angle the breaking wave makes with the coastline. The other angles are all relative to the x-axis, which was the coastline at t = 0; our starting assumption. α_o is the angle between the crest of the refracted deepwater wave and the x-axis, and β the angle the contour of the coastline makes with the x-axis. Using small amplitude wave theory, the angle α_b is obtained as

$$\frac{\sin\alpha_o}{C_o} = \frac{\sin\alpha_b}{C_b} \tag{8}$$

wherein the ratio



$$\tan \beta = \frac{y_{j-1} - y_{j+1}}{2\Delta x}$$

$$\sin \alpha_b = (kh)_b \sin \alpha_o$$

$$\theta = \alpha_b - \beta$$

$$S = 6.85 \times 10^{-5}(ECn) \sin\theta\cos\theta$$

S in m^3/day

Figure 1 Angle relationships for Delta7.

$$\frac{C_b}{C_o} = \tanh\ (kh)_b \tag{9}$$

combining Equations (8) and (9) the following equation results for small values of kh, i.e., for breaking conditions:

$$\sin\alpha_b = (kh)_b \sin\alpha_o \tag{10}$$

since for small values of x, tanh x = x. Finally, a relationship for $(kh)_b$ was developed using the fact that the power between orthogonals remains constant when the wave is refracted:

$$(kh)_b = 1.901(H_o/L_o)^{2/5}(\cos\alpha_o)^{1/5} \tag{11}$$

The derivation for Equation (11) is presented in Appendix E. In Equation (11), H_o, L_o and α_o are respectively the deepwater wave height, wavelength and angles with the x-axis. Using Equations (10) and (11), we may then express the angle of the breaking wave entirely in terms of its deepwater parameters H_o, L_o and α_o:

$$\alpha_b = \text{arc}\left[\sin 1.901\ (H_o/L_o)^{2/5}(\cos\alpha_o)^{1/5}\sin\alpha_o\right].$$

Combining α_b and β we get θ, which is the key element in Equation (7). The other part of Equation (7) can also be written in terms of the deepwater parameters in the following expression from Kim-E (1978):

$$P = ECn = 9.55 \times 10^7 H_o{}^2 T \tag{12}$$

where T is the wave period in seconds and H_o as before is the deep water significant wave height, in meters.

Presentation and Discussion of Results

The actual program was evolved through six revisions, Delta7 being the last. Delta4 was a program that simulated one type of wave for a specific length of time, and Delta6 was similar to Delta7 except that it did not refract the deepwater wave. Although the program of Kim-E (1978) furnished a start point, it was clear that it was inefficient because it used an excessive amount of large arrays and did twice the amount of required calculations. Using instead, Komar's expression for $\Delta S = S_{i-1} - S_i$ (see Komar (1976)), it was possible to compute the approximation for ΔV only once per iteration instead of twice as had been done previously. This had the added benefit of insuring that sand was conserved between the cells, since the sand out of cell j automatically became the sand into cell j+1.

In addition, Kim-E (1978) had used the difference between two cells to determine the angle β for the coastline. The Delta series uses a central difference as suggested by Weggel (paper undated). A central difference uses the difference between the j-1 and j+1 cells over $2\Delta x$ to determine β at the jth cell. In verifying an example from Komar's (1973) data, the program developed in this study and denoted as Delta4 was closer than Kim-E as shown in Fig. 5, primarily because of the change to a central difference, which has a moderating effect on the values of β. Finally, although Komar (1973) and Kim-E (1978) use the trigonometric identity for $\tan(a \pm b)$, in this analysis the angles are added after taking the arc tan; this results in simpler processing, and avoids confusion in sign convention.

Delta7 is broken down into a main program and two subroutines INPUT and SWELL as illustrated in the flow diagrams, Figs. 2 through 4.

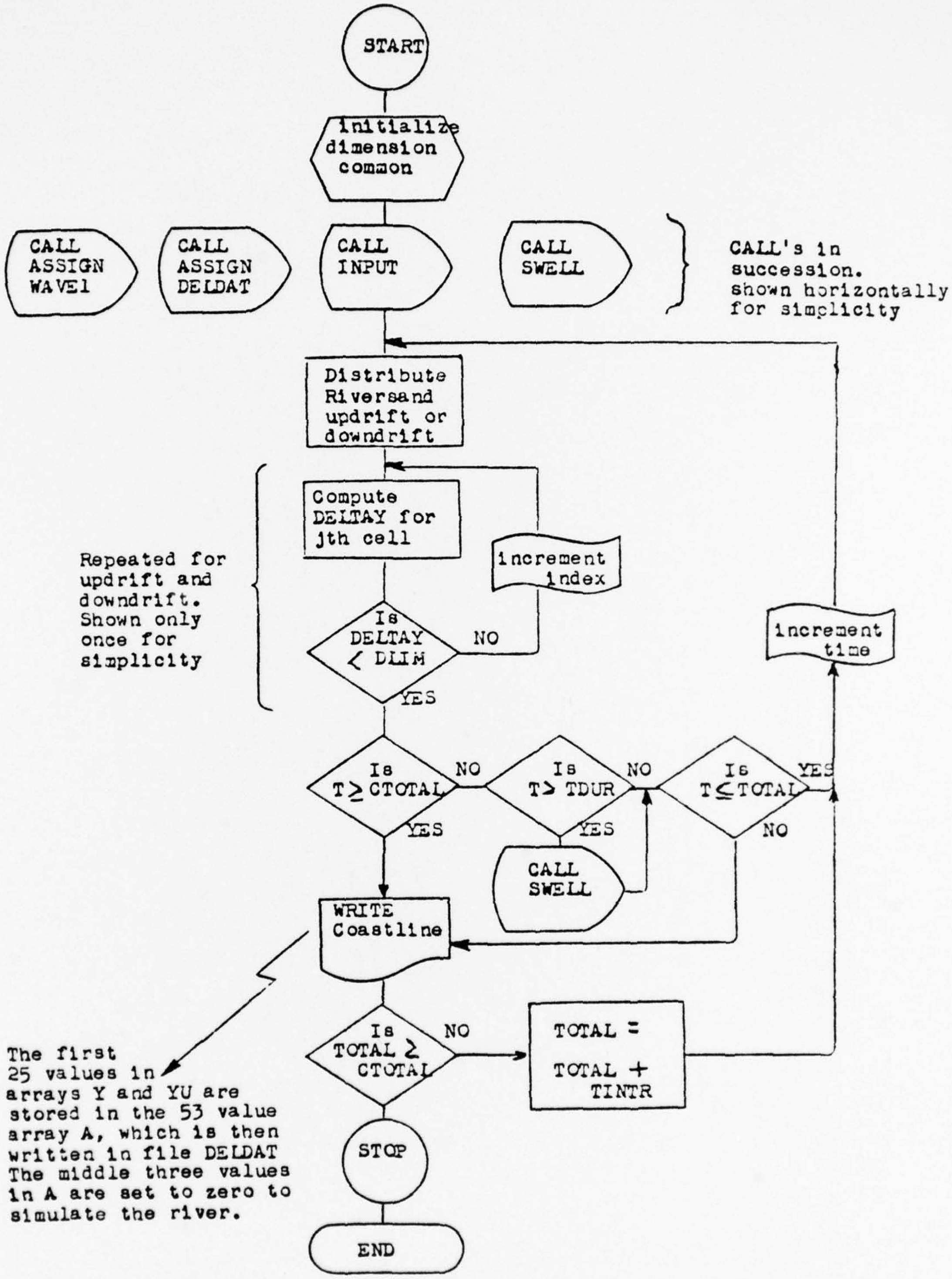


Figure 2 Main program - Delta7.

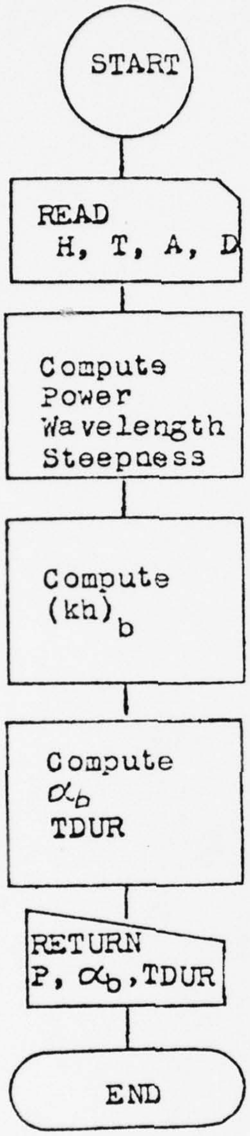


Figure 3 Flow diagram subroutine swell - Delta7.

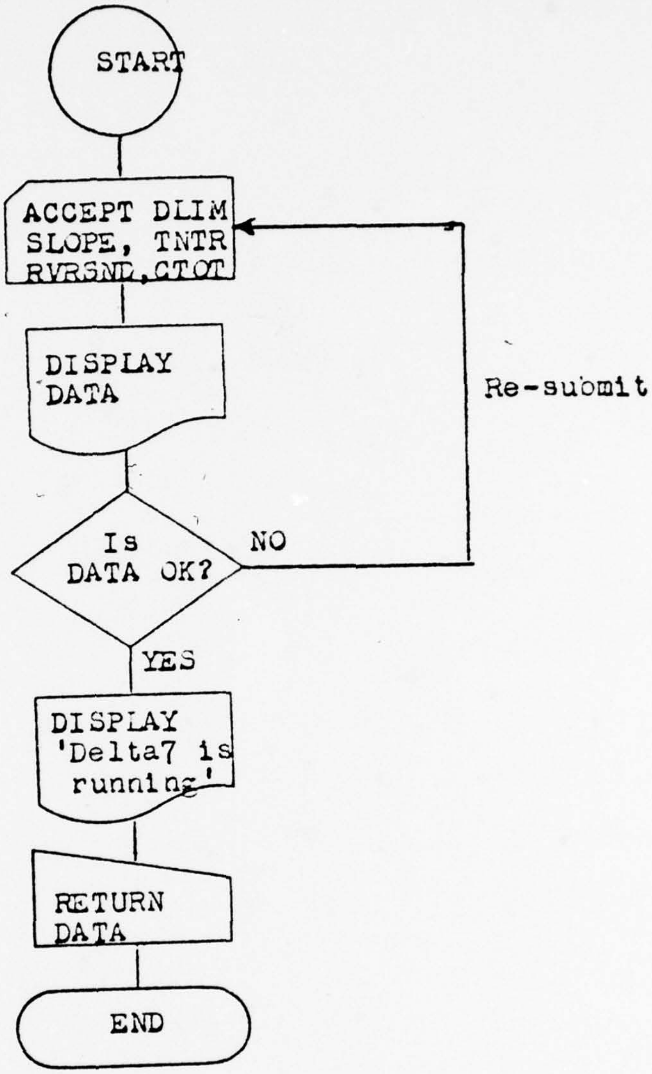


Figure 4 Flow diagram subroutine input - Delta7.

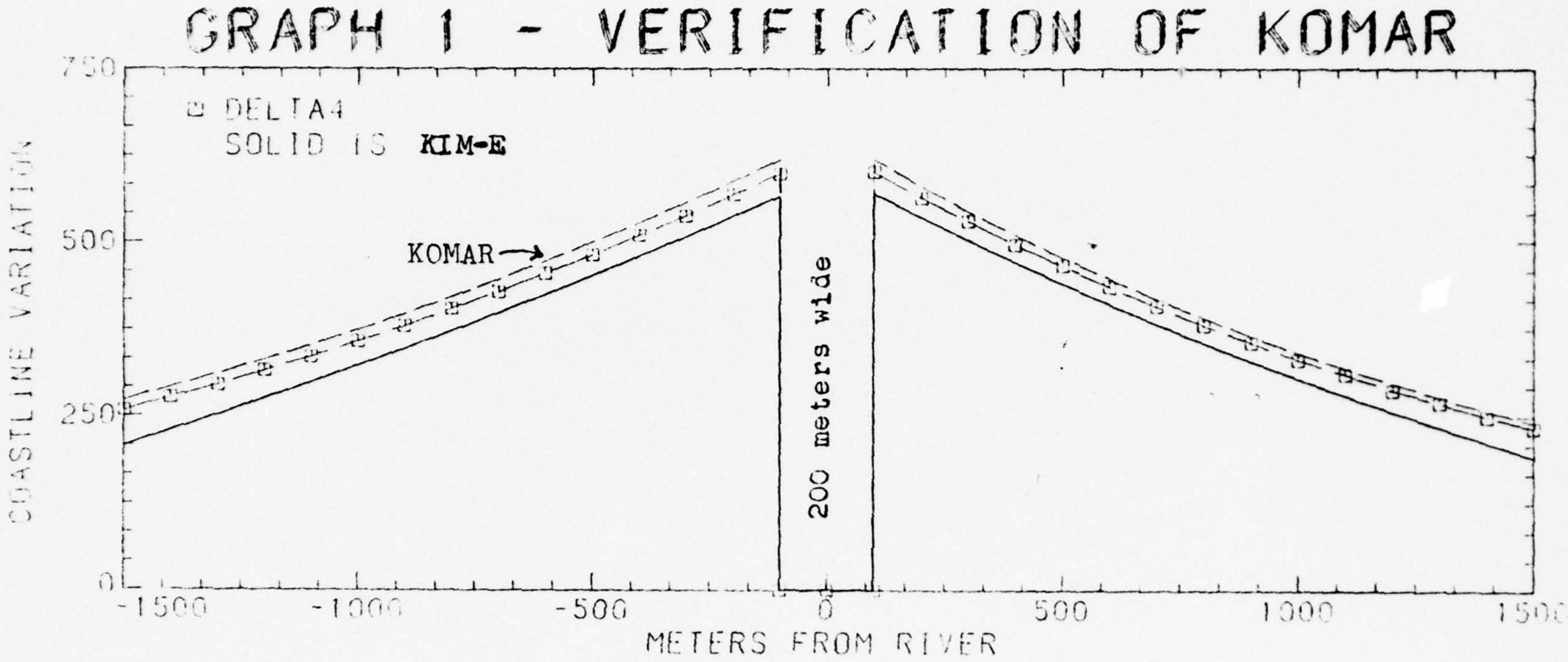


Figure 5 Comparison of Komar, Kim-E and Delta4 for verification.

A list of variable names is attached as Appendix A, and a complete listing as Appendices B through D. INPUT accepts beach data, and program utility values for accuracy, intervals and total length of simulation. SWELL reads deepwater data from file WAVE1.DAT, computes wave power in 10^8 ergs/cm-sec, refracts the angle α_0 to get α_b, and finally increments total duration by the duration of the new wave.

The main program functions within two loops; one travels along the beach and iterates for every cell, and the other iterates the entire beach for each 1/10 day. Both the increments of time and beach length could be changed easily. However, Komar (1973) uses 1/10 day and 100 meters and it does not appear as if the increase in accuracy could be justified by either the accuracy of the input information or the increased cost, i.e., computation time, required. The program moves first updrift and then downdrift from the river computing change for each cell until the cell is reached where growth is less than an inputted limit, generally .01. Time is then incremented and the process repeated.

A new wave is inputted and coastlines are written as determined by the values of variables TDUR and TOTAL, respectively. When time exceeds the total duration, TDUR, at the end of a wave, SWELL is called. The subroutine automatically reads new wave parameters, converts them to usable form and increments TDUR. Similarly, when time exceeds TOTAL, a coastline is printed for display and written on file DELDAT. Then, before going to the next iteration TOTAL is incremented by TINTR, the time interval between desired prints, in our data generally 90 days.

Results are in the attached graphs. The attempt to verify the results of Komar (1973) is shown in Fig. 5 (graph 1). There is close agreement with Komar (1973), and at least a relative improvement over the verification presented by Kim-E (1978). Wave Station 5 data were used unrefracted in Graphs 2 and 3, Figs. 6 and 7. When the waves are ordered by significant height and period, thence by power, a "radical" delta evolves. With decreasing power an initially flat delta becomes sharp and pointed (Graph 2, Fig. 6), while with increasing power a pointed delta is "pounded" flat (Graph 7, Fig. 9). However, when the same waves are randomly sorted, they result in what can be termed a "normal" delta, which varies only slightly from sort to sort. Since nature randomly sorts waves to a certain extent, it may be possible to use this model to predict long term coastline evolution to a degree that would be useful for engineering purposes.

The addition of the refraction equation to SWELL had only a minor effect on Delta Growth as shown in Graphs 6 through 10, probably because the range of values for α_0, the deepwater wave angle were scaled down to the range 0 to 10 degrees in the input set. However, as Komar (1973) indicates, the influence of wave angle is not as pronounced as we might have expected, at least over the range indicated. It appears the effect of wave power is significantly more important. Figure 13 (Graph 11) shows a Delta7 run with a WAVE1.DAT data set modified so that the deepwater angle again ranges from 0 to 40. The waves are refracted, and comparison with previous random graphs show no major changes. Figure 14 shows a series of graphs which indicated the marked effect ordered wave power has on growth at selected points on the coast.

Strict ordering of waves does significantly change coastline evolution with this model. However, randomly sorted waves tend to produce approximately the same delta, which indicates it may be possible

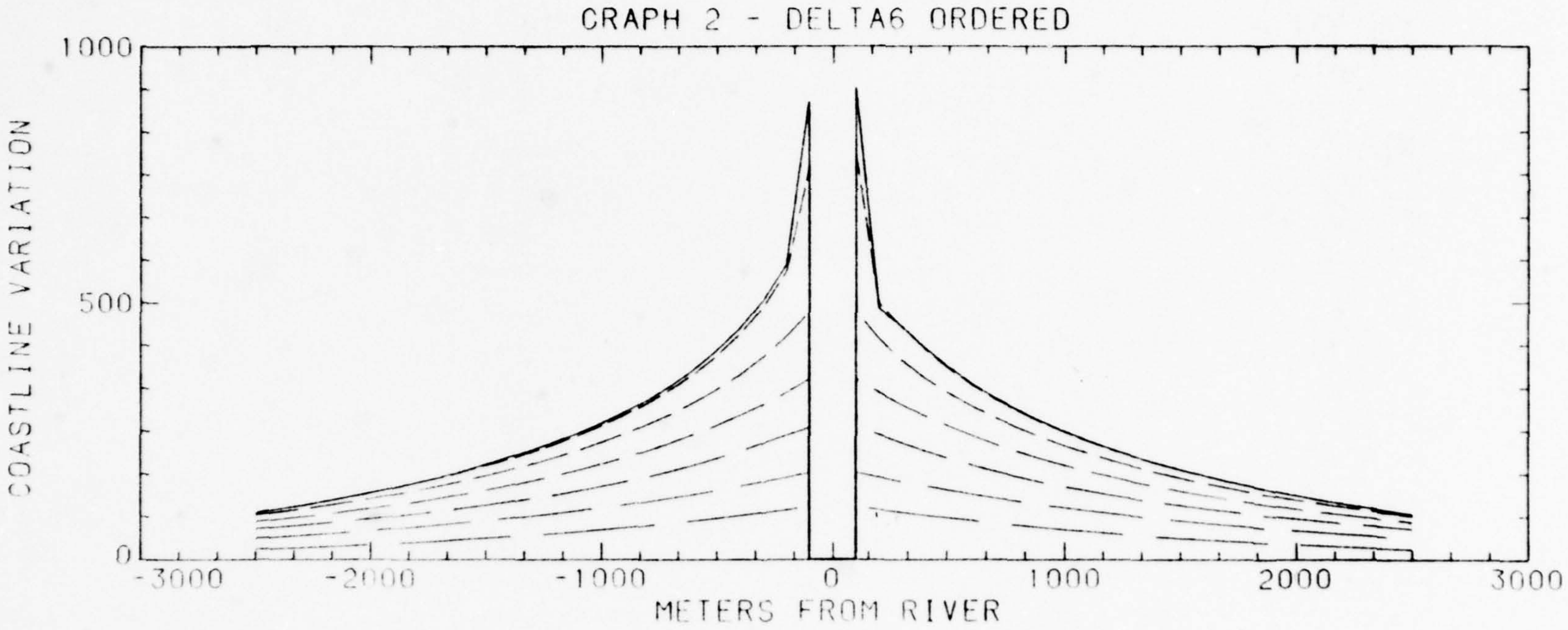


Figure 6 Delta6 with a 564 day simulation using waves in order of decreasing power. Unrefracted. Contours are at 90 day intervals. Solid line is final shoreline.

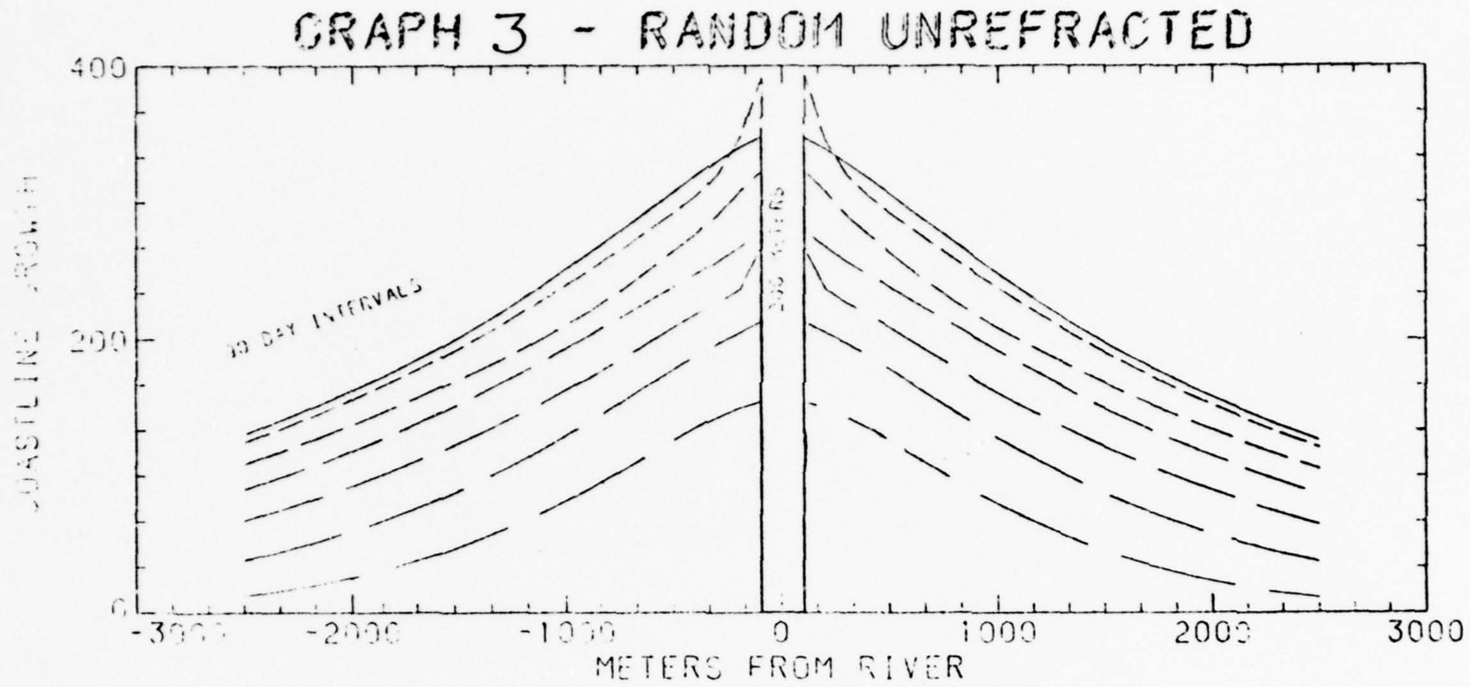


Figure 7 A 564 day simulation by Delta6 using a random file with deepwater angles between 0 and 10 degrees. Graph 2 (Figure 6) was the same data but ordered.

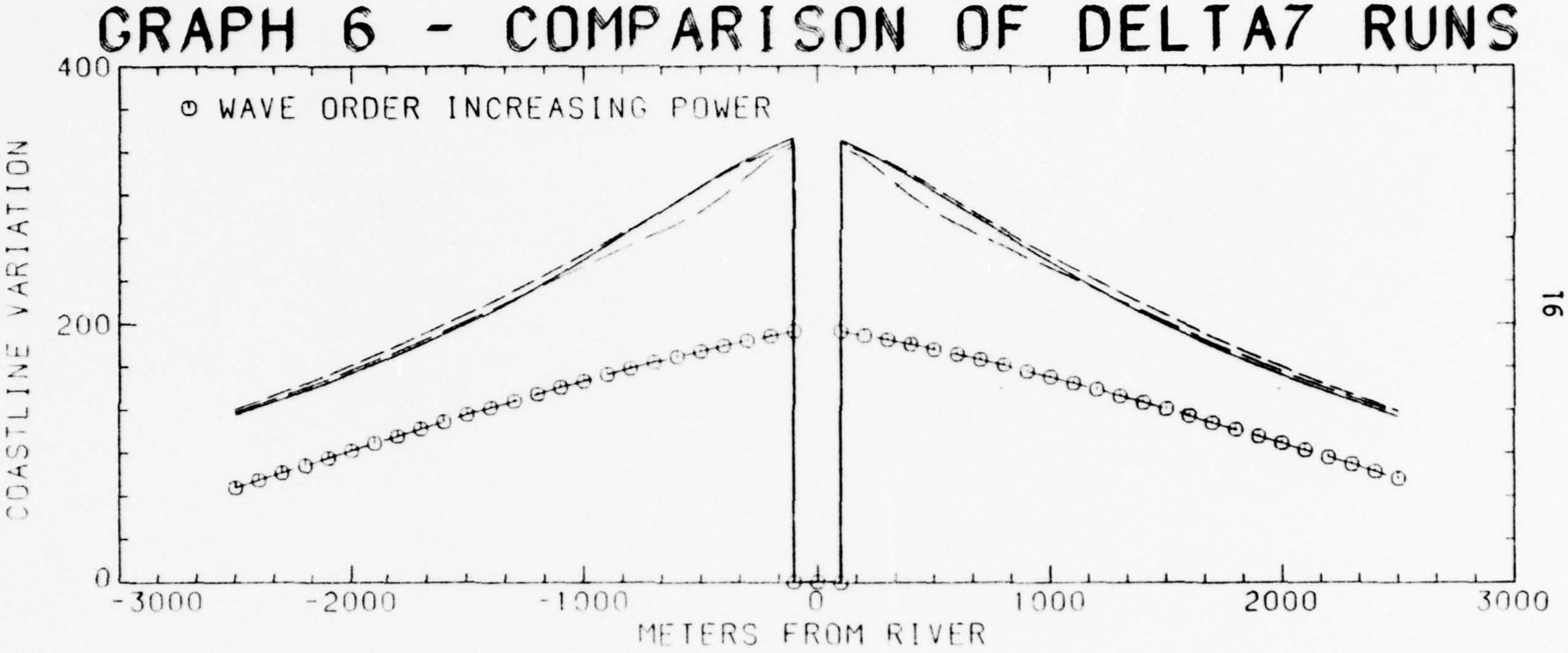


Figure 8 A comparison of the differences in Delta7 (refracted) runs. The symbols represent the outline of an ordered wave attack, with waves in order of increasing power as in Graph 7 (Figure 9). The other curves are the same waves but in three different random sorts.

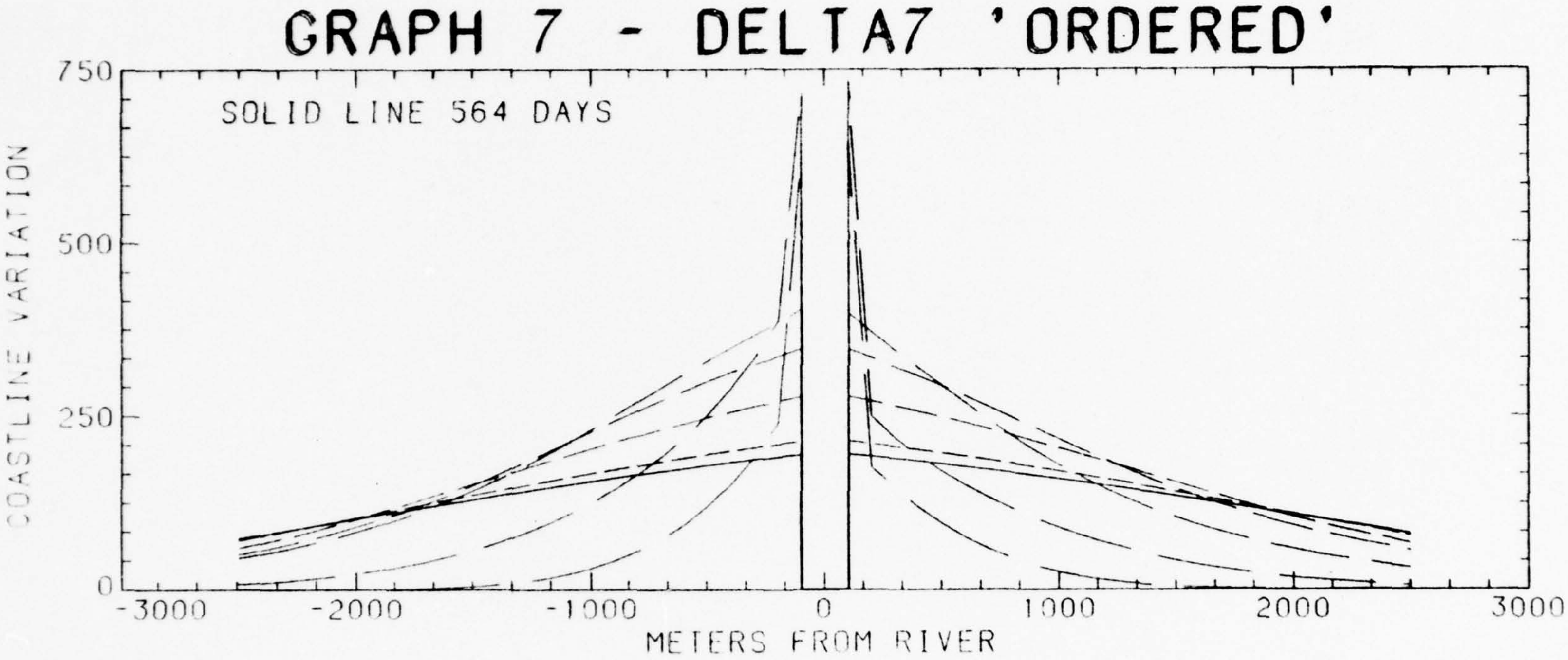


Figure 9 Delta7 (refracted) with a 564 day simulation shown at 90 day intervals with an increasing-ordered wave attack. Deepwater angles from 0 to 10 degrees.

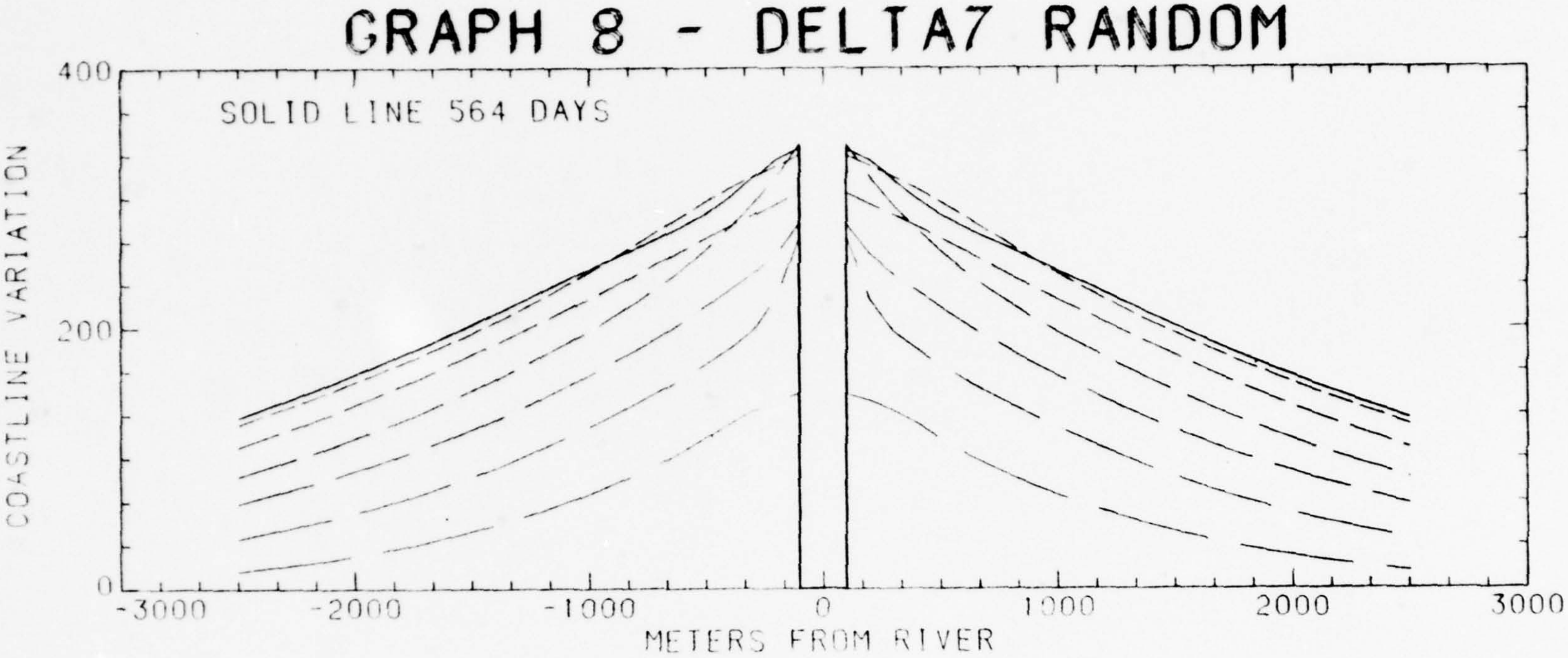


Figure 10 Delta7 (refracted) with a 564 day simulation with a random wave attack. Deepwater angles from 0 to 10 degrees.

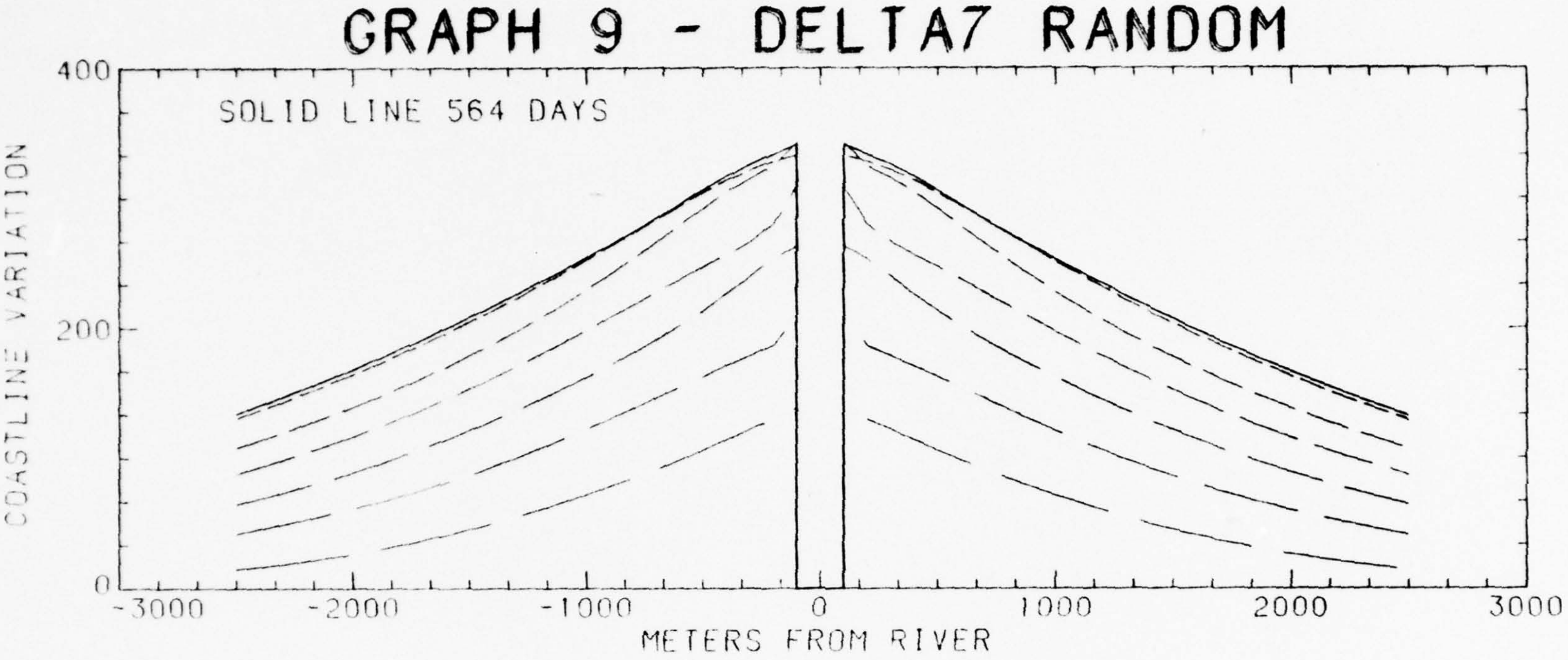


Figure 11 Delta7 (refracted) same as Figure 10, but a different random order.

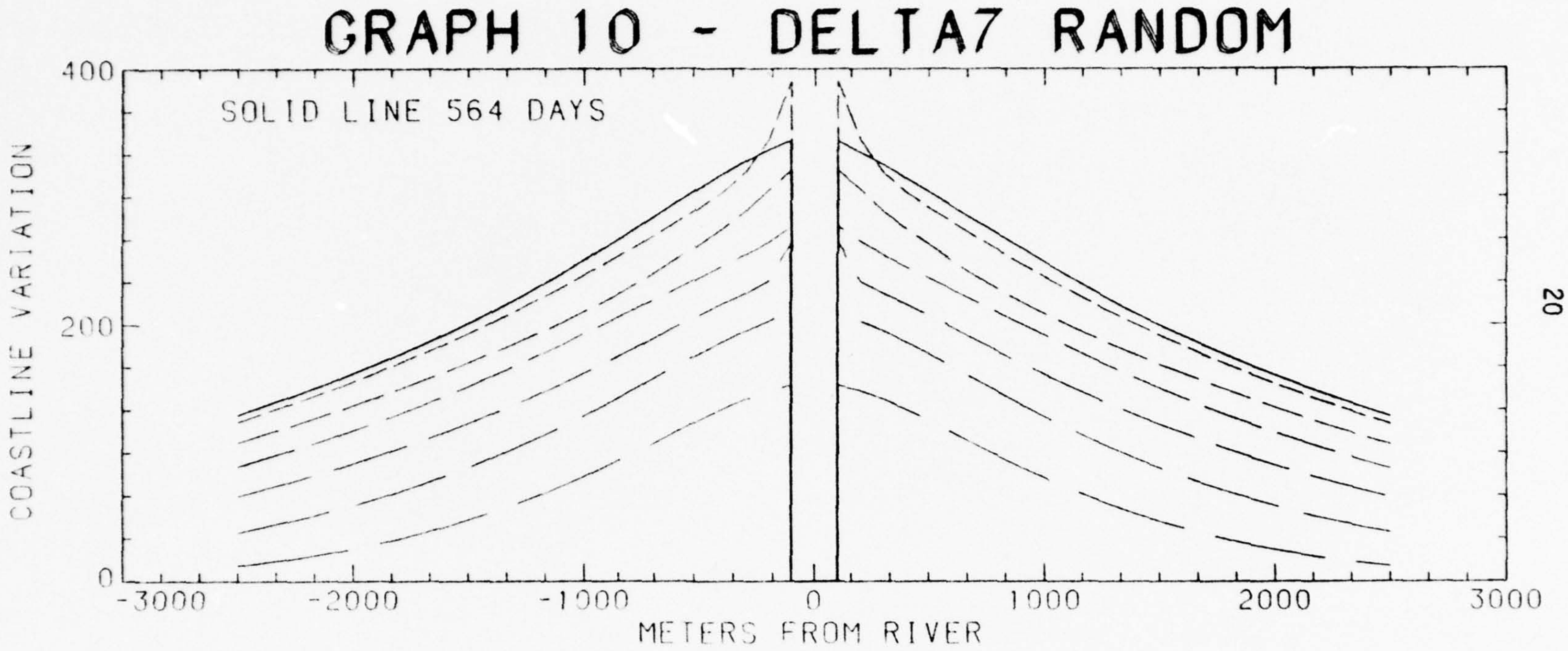


Figure 12 Delta7 (refracted) same as Figures 10 and 11, but a different random order.

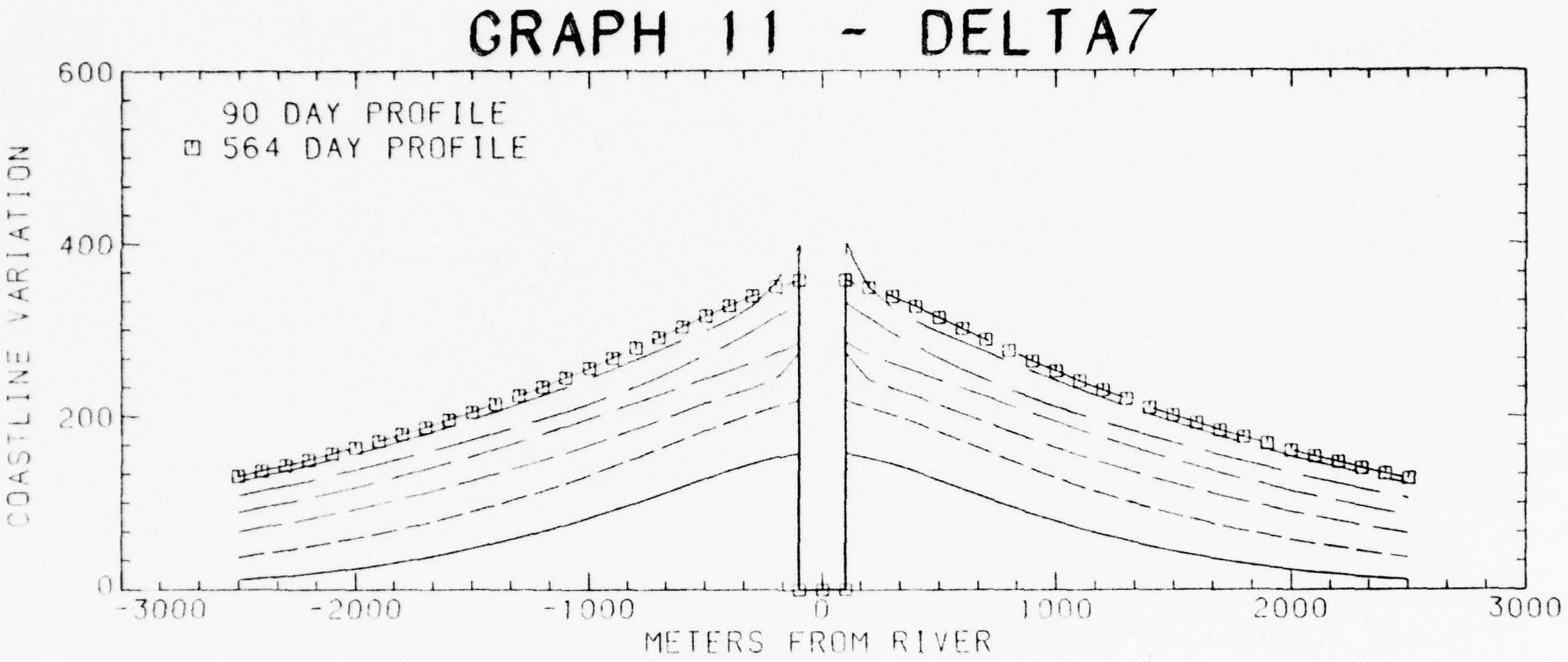


Figure 13 Delta7 (refracted) same as Figures 10, 11, 12 but the waves' angles have been increased by a factor of 4. Deepwater angles vary then from 0 to 40 degrees.

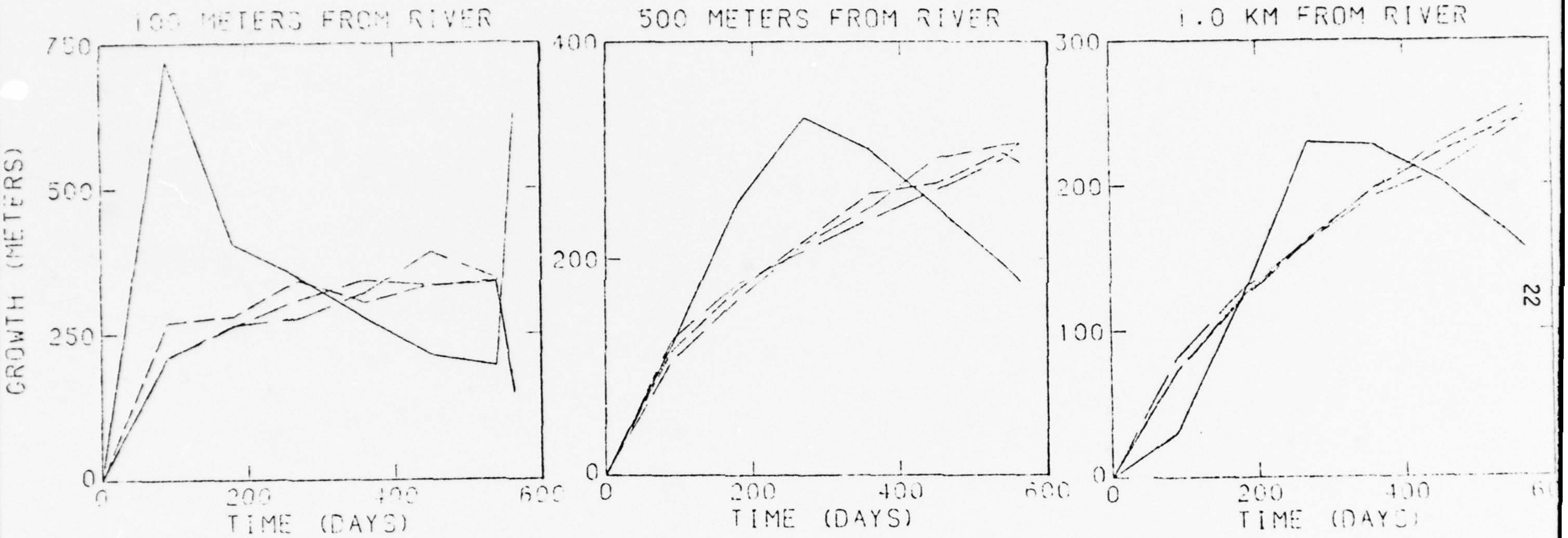


Figure 14a Growth at fixed points on the delta plotted against time. The solid line is wave data ordered to be increasing with respect to power. The dashed lines are the three different random sortings of the same data. The waves were refracted. Data is shown here for 100, 500, and 1000 meters from the river, while Figure 14b has points at 1500, 2000 and 2500 meters.

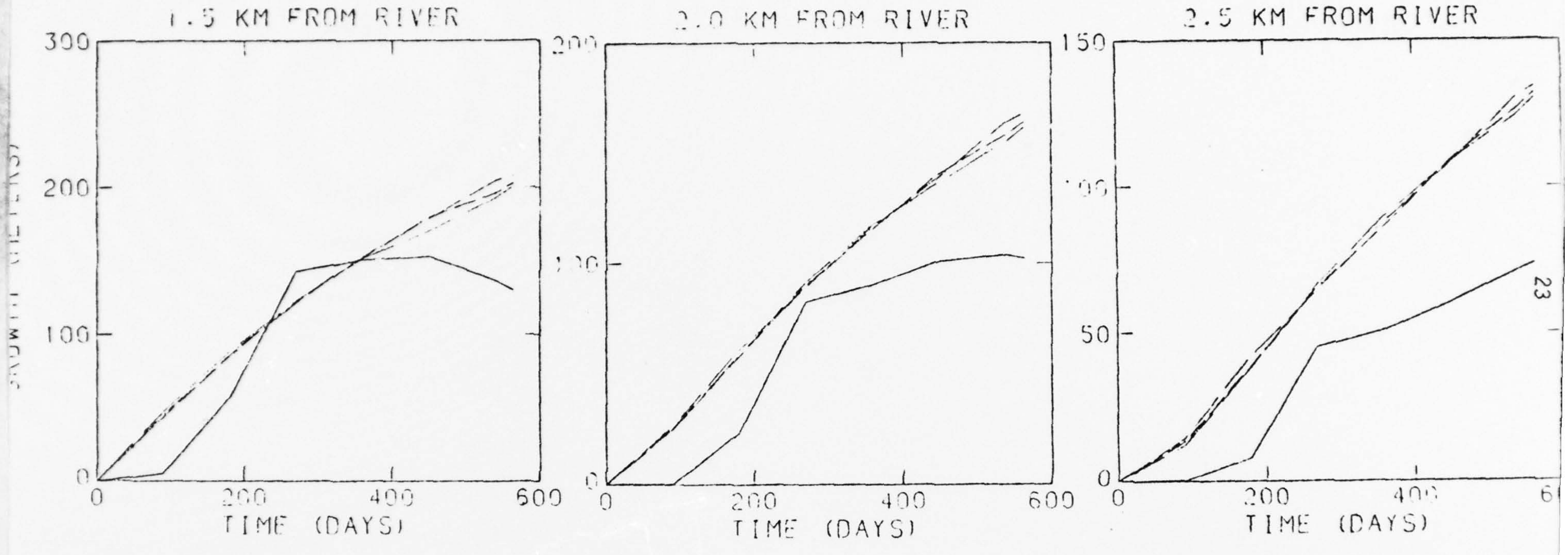


Figure 14b The waves were refracted. Data is shown here for 1500, 2000 and 2500 meters from the river, while Figure 14a has points at 100, 500 and 1000 meters from the river.

to realistically simulate coastline evolution. The problem remains, however, to have a valid input data set, and this may have to be somewhat ordered to reflect at least winter and summer wave conditions. Wave Station 5 data allows us to do this, and we can take into account, for example, a particularly stormy, once in the century, month that will introduce a profound change in the delta similar to that produced by ordering the waves. The model should become much more sophisticated to be useful in practice. For example, the input of river sediment as a constant 20,000 m^3/day is unrealistic, and will vary with weather conditions in the river system, which may or may not be related to the weather producing the waves that is spreading the sand at the delta. Further investigation is needed, which should also include an attempt to start from an actual coastline instead of the x-axis.

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APPENDIX A

A COMPUTER MODEL OF DELTA GROWTH

List of Variables

Subroutine INPUT

KYES - constant filled with alphanumeric value 'YES'

KCHECK - accepts an alphanumeric value to compare with KYES

TINTR - time interval at which Delta7 writes a coastline, in days

SLOPE - the slope of the beach, not in degrees, rise over run, non-dimensional

CTOTAL - the total length of the simulation in days

DLIM - the accuracy of the approximation; when Δy is less than DLIM the iteration stops

RVRSND - the amount of riversand carried to the delta in cubic meters/day

Main Program

A - is a dummy array to write the coastline in

Y - is the downdrift coast in meters

YU - is the updrift coast in meters

AB - θ, the angle between the breaking wave and the coast in radians

RVRMTH - the angle of the rivermouth in radians; since the river is fixed at 200 meters width it's tangent is [YU(1) - Y(1)]/200

DELTAY - Δy, the accretion or erosion of a cell's height Y in meters

I - an index

TEST - stores the maximum value of AB in radians in order to print a warning if it becomes unrealistically large

T - time in days

TOTAL - a counter that stores the total time until the next printed coastline is due; in days

J - an index

SANDIN - the inputted sand for a specific cell in cubic meters per day

SANDOT - the outputted sand for a specific cell in cubic meters per day

D - the depth of the cell; or the depth of the sand which is affected by mass transport, in meters

K - an index

TINTR, SLOPE,
CTOTAL,
DLIM RVRSND - same as in subroutine INPUT

Subroutine SWELL

AO - α_b the angle the refracted wave makes with the x-axis in radians

P - the power of the wave in 10^8 ergs/cm-sec

TDUR - the total length of the simulation at which point the particular wave has passed, in days

L - the wavelength of the deepwater wave in meters

KHB - $(kh)_b$ where h is the water depth and $k = 2\pi/L$

H - deepwater wave height, the significant height in meters

T - the period of the deepwater wave in seconds

A - α_o, the angle the deepwater wave makes with the x-axis, input as degrees and converted to radians

D - the duration of the wave, in days

SINA - $\sin \alpha_b$; used to save an extra processing of the sine routine

COSA - $\cos \alpha_b$; used to save an extra processing of the cosine routine

APPENDIX B

LISTING OF SUBROUTINE INPUT

```
C THIS IS A MODIFIED DELTA4 PROGRAM WHICH ACCEPTS LARGE BLOCKS OF
C WAVE DATA TO CHECK DELTA GROWTH RATHER THAN JUST ONE SPECIFIC WA
C BASE PROGRAM DELTA4 IS STORED ON DXO: AS DELTA4.FTN;1
C
C
        SUBROUTINE INPUT
        COMMON TINTR,SLOPE,CTOTAL,DLIM,RVRSND
        DATA KYES/'NO'/
92      TYPE 1
1       FORMAT (/,' AT WHAT INTERVALS DO YOU WANT PRINTS?',/)
        ACCEPT 101, TINTR
        TYPE 2
2       FORMAT (/,' WHAT IS THE BEACH SLOPE ?',/)
        ACCEPT 201, SLOPE
        TYPE 3
3       FORMAT (/,' WHAT IS THE SUM-DURATION OF THE SIMULATION?',/)
        ACCEPT 101, CTOTAL
        TYPE 22
        ACCEPT 101, RVRSND
        TYPE 7
7       FORMAT (/,' WHAT IS THE DESIRED ACCURACY? [ABOUT .01]',/)
        ACCEPT  701, DLIM
        TYPE 8
        TYPE 83
        TYPE 81
        TYPE 82,TINTR,CTOTAL,SLOPE,RVRSND,DLIM
        RVRSND = .5 * RVRSND
        TYPE 9
        ACCEPT 901, KCHECK
        IF(KCHECK.EQ.KYES) GO TO 92
        TYPE 39
        TYPE 4
        RETURN
8       FORMAT(/,10X,'CHECK YOUR INPUT!!!')
81      FORMAT(5X,'DAYS',15X,'CUBIC METERS/DAY')
82      FORMAT(2X,2F5.0,4X,F7.3,5X,F8.2,5X,F8.6,/)
83      FORMAT('  INTER CTOTAL     SLOPE  ',4X,'RVRSND',7X,'DLIM')
22      FORMAT(/,' HOW MUCH SAND IN THE RIVER PER DAY?',/)
9       FORMAT(' IS THIS INPUT CORRECT? [YES OR NO]',/)
901     FORMAT(A2)
4       FORMAT(/,10X,' DELTA6 IS RUNNING, BE PATIENT',/)
39      FORMAT(/,5X,' DX IS SET AT 100 METERS, DT AT .1 DAYS')
101     FORMAT(F8.2)
201     FORMAT(F6.3)
701     FORMAT(F8.5)
        END
```

APPENDIX C

LISTING OF MAIN PROGRAM DELTA7

```
      DIMENSION A(53),Y(100), YU(100)
      COMMON TINTR,SLOPE,CTOTAL,DLIM,RVRSND
      COMMON /WAVE/AO,P,TDUR
      DOUBLE PRECISION AB,RVRMTH,DELTAY
      DO 10,I=1,50
      Y(I) = 0.
10    YU(I) = 0.
      DO 11 I=1, 53
11    A(I) =  0.
      TEST = 0.
      TDUR = 0.
      T = 0.
      CALL ASSIGN (2,'WAVE1 DAT',9)
C
C   NOTE THAT THE METHOD OF VARYING WAVE DATA IS TO
C   CHANGE THE CONTENT OF THE WAVE1 DATA FILE
C
      CALL ASSIGN (3,'DELDAT.DAT',10)
      CALL SWELL
      CALL INPUT
      TOTAL = TINTR
C
100   J = 1
      RVRMTH = (Y(1)-YU(1))*.005
      RVRMTH = ATAN(RVRMTH) + AO
      SANDIN = RVRSND - 3425.*P*SIN(2.*RVRMTH)
20    J = J + 1
      AB = ATAN((Y(J-1) - Y(J+1))*.005) - AO
      IF(AB.GT.TEST)TEST=AB
      SANDOT = 3425. * P * SIN(2.*AB)
      D = 4.0 + SLOPE * Y(J-1)
      DELTAY = (SANDIN -SANDOT)*.001/D
      Y(J-1) = Y(J-1) + DELTAY
      SANDIN = SANDOT
      IF(ABS(DELTAY).GT.DLIM) GO TO 20
C
200   K = 1
      SANDIN = RVRSND + 3425.*P*SIN(2.*RVRMTH)
220   K = K + 1
      AB = ATAN((YU(K-1) - YU(K+1))*.005) + AO
      IF(AB.GT.TEST) TEST = AB
      SANDOT = 3425. * P * SIN(2.*AB)
      D = 4.0 + SLOPE * YU(K-1)
      DELTAY = (SANDIN - SANDOT)*.001/D
      YU(K-1) = YU(K-1) + DELTAY
      SANDIN = SANDOT
      IF(ABS(DELTAY).GT.DLIM) GO TO 220
C
      T = T + .1
      IF(T.GT.CTOTAL)GO TO 28
      IF(T.GT.TDUR) CALL SWELL
      IF (T.LT.TOTAL) GO TO 100
28    TYPE 29, T
29    FORMAT (/, 5X, 'THE ',F6.0,' DAY SHORELINE PROFILE, Y VALUES')
```

```
        IF(SLOPE.EQ.0)GO TO 292
        TYPE 291, SLOPE
        GO TO 293
291     FORMAT (/,9X,'AT A BEACH SLOPE OF ',F6.3,/)
292     TYPE 294
294     FORMAT(/,9X,'PLANE BEACH ASSUMED, SLOPE = 0',/)
293     CONTINUE
        TYPE 600
        TYPE 601
        DO 30, I = 1, 24, 3
30      TYPE 31,Y(I+2),Y(1+I),Y(I),YU(I),YU(I+1),YU(I+2)
31      FORMAT (/, 6F8.2)
        IF (TEST.GE.0.8) TYPE 311
311     FORMAT (/,5X,' *****WARNING*****  AB MAY BE TOO BIG!!',/)
        TEST = 0.
C
        DO 301, I=1,25
        A(I+28)=YU(I)
301     A(I) = Y(26-I)
        WRITE (3) (A(I),I=1,53)
        IF (TOTAL.GE.CTOTAL)GO TO 32
        TOTAL = TOTAL +TINTR
        GO TO 100
32      STOP
601     FORMAT(/,3X,'J+2',6X,'J+1',6X,'J',7X,'J',6X,'J+1',5X,'J+2')
600     FORMAT(/,8X,'UPDRIFT',18X,'DOWNDRIFT')
        END
```

APPENDIX D

SUBROUTINE SWELL

```
      SUBROUTINE SWELL
      COMMON /WAVE/AO,F,TDUR
      REAL*4 L, KHB
      READ (2,111,END=110) H,T,A,D
      A = .01745 * A
      F = .955 * T * H**2
      TDUR = TDUR + D
      L = 1.56 * T**2
      KHB = 1.901 * (COS(A) * (H/L)**2)**.2
      SINA = KHB * SIN(A)
      COSA = SQRT(1. - SINA**2)
      AO = ATAN(SINA/COSA)
110   RETURN
111   FORMAT(4F6.1)
      END
```

APPENDIX E

A COMPUTER SIMULATION OF DELTA GROWTH

Derivation of the approximation for $(kh)_b$

The starting point is that energy flux is constant between wave rays as the deepwater wave is refracted towards the shore (Komar (1976)).

$$ECnb = E_oC_on_ob_o \qquad (1)$$

where P is power, E is energy as defined below, C is wave group celerity, b = distance between rays and

$$n = \frac{1}{2}\left[1 + \frac{2kh}{\sinh kh}\right] \qquad (2)$$

where h is depth in meters and $k = 2\pi/L$, where L is the wavelength, also in meters. In deepwater as kh gets very large, $n_o = 1/2$, and in shallow water, $n = 1$.

Komar (1976) uses the following expression for energy

$$E = \frac{1}{8}\rho gH^2 \qquad (3)$$

where ρ is density, g is the acceleration due to gravity and H is significant wave height. Using the subscript o for deepwater conditions we may then combine Equations (1) and (3)

$$\frac{1}{8}\rho gH_o{}^2C_on_ob_o = \frac{1}{8}\rho gH^2Cnb \qquad (4)$$

arranging terms, simplifying and solving for $\frac{H}{H_o}$

$$\frac{H}{H_o} = \left[\frac{C_o}{2Cn}\right]^{1/2}\left[\frac{b_o}{b}\right]^{1/2} \qquad (5)$$

Refraction of the approaching waves over a plane beach allows us to write

$$\frac{b_o}{b} = \frac{\cos \alpha_o}{\cos \alpha} \qquad (6)$$

and thence for a wave refracting and shoaling on a plane beach:

$$\frac{H}{H_o} = \left[\frac{C_o}{2Cn}\right]^{1/2} \left[\frac{\cos \alpha_o}{\cos \alpha}\right]^{1/2} \qquad (7)$$

Now starting with a general expression for wave celerity

$$C^2 = (g/k)\tanh kh \qquad (8)$$

where all terms are as defined above. We note that in deepwater, that is as $h \gg 1$, tanh kh goes to one, e.g. tanh 6.5 = 0.999996 and therefore for deepwater

$$C_o{}^2 = g/k_o \qquad (9)$$

Combining (8) and (9)

$$\left[\frac{C}{C_o}\right]^2 = \frac{k_o}{k} \tanh kh \qquad (10)$$

Now, assuming that wave period stays constant as the wavelength changes we may write

$$C = \frac{\sigma}{k} \qquad (11)$$

$$C_o = \frac{\sigma}{k_o} \qquad (12)$$

$$\frac{C}{C_o} = \frac{k_o}{k} \qquad (13)$$

where $\sigma = 2\pi/T$ and $k = 2\pi/L$. Therefore we may introduce equations (13) into (10)

$$\frac{C}{C_o} = \tanh kh \tag{14}$$

As we approach breaking conditions, $(kh)_b$ gets very small ($\ll 1$) and we may approximate

$$\tanh(kh)_b \cong (kh)_b \tag{15}$$

where the subscript b denotes breaking. Combining Equations (7), (14) and (15), and remembering $n = 1$ for shallow depth

$$\frac{H_b}{H_o} = \left[\frac{1}{2}\,\frac{1}{(kh)_b}\right]^{1/2} \left[\frac{\cos \alpha_o}{\cos \alpha}\right]^{1/2} \tag{16}$$

Komar (1976) gives the following equation for the wave height at breaking:

$$H_b = .142\, L_o \tanh^2(kh)_b \tag{17}$$

Using again the approximation of Equation (15) and dividing Equation (17) by H_o we have a second relationship for H_b/H_o

$$\frac{H_b}{H_o} = .142\, \frac{L_o}{H_o}\, (kh)_b{}^2 \tag{18}$$

Substituting Equation (16) in (18) one obtains:

$$\left[\frac{1}{2}\,\frac{1}{(kh)_b}\right]^{1/2} \left[\frac{\cos \alpha_o}{\cos \alpha_b}\right]^{1/2} = .142\, \frac{L_o}{H_o}\, (kh)_b{}^2 \tag{19}$$

Solving for $(kh)_b$ the following results:

$$(kh)_b^{5/2} = \frac{H_o}{.142\sqrt{2}\,L_o}\left[\frac{\cos\alpha_o}{\cos\alpha_b}\right]^{1/2} \tag{20}$$

The term α_b must now be eliminated from Equation (20) for it to be useful. We start with Snell's Law for refraction

$$\frac{\sin\alpha}{C} = \frac{\sin\alpha_o}{C_o} \tag{21}$$

and thence to the breaking condition which allows us to use Equation (15) once more to write

$$\sin\alpha_b = (kh)_b \sin\alpha_o \tag{22}$$

which after application of the Pythagoreum Theorem yields

$$\cos^2\alpha_b = 1 - (kh)_b^2 \sin^2\alpha_o \tag{23}$$

Raising Equation (20) to the fourth power we may substitute (23)

$$(kh)_b^{10} = \left(\frac{H_o}{L_o}\right)^4 (5.1)^4 \left[\frac{\cos^2\alpha_o}{1-(kh)_b^2\sin^2\alpha_o}\right] \tag{24}$$

It is difficult to solve for $(kh)_b$ here, so we introduce another approximation. Since $\sin\alpha_o < 1$ and $(kh)_b \ll 1$, we may neglect the entire term $(kh)_b^2 \sin^2\alpha_o$, and solve for $(kh)_b$ on the L.H.S. by taking the 10th root.

$$(kh)_b = 1.901\left(\frac{H_o}{L_o}\right)^{2/5} (\cos\alpha_o)^{1/5}$$

which is the expression used in this study.

APPENDIX F

WAVE INPUT DATA

```
WAVE DATA MIX PRINTED ON 19-SEP-79 AT 14:15:05 PAGE  1

 NO  HEIGHT    PERIOD   ANGLE          DURATION

   1  0.5       4.        0.0        1.5          1.5
   2  0.5       4.        2.5        2.1          3.6
   3  0.5       4.        5.0        2.5          6.1
   4  0.5       4.        7.5        2.4          8.5
   5  0.5       4.       10.0        1.5         10.0
   6  0.5       5.        0.0        1.5         11.5
   7  0.5       5.        2.5        2.1         13.6
   8  0.5       5.        5.0        2.5         16.1
   9  0.5       5.        7.5        2.4         18.5
  10  0.5       5.       10.0        1.5         20.0
  11  0.5       6.        0.0        1.5         21.5
  12  0.5       6.        2.5        2.1         23.6
  13  0.5       6.        5.0        2.5         26.1
  14  0.5       6.        7.5        2.4         28.5
  15  0.5       6.       10.0        1.5         30.0
  16  0.6       4.        0.0        1.5         31.5
  17  0.6       4.        2.5        2.1         33.6
  18  0.6       4.        5.0        2.5         36.1
  19  0.6       4.        7.5        2.4         38.5
  20  0.6       4.       10.0        1.5         40.0
  21  0.6       5.        0.0        1.5         41.5
  22  0.6       5.        2.5        2.1         43.6
  23  0.6       5.        5.0        2.5         46.1
  24  0.6       5.        7.5        2.4         48.5
  25  0.6       5.       10.0        1.5         50.0
  26  0.6       6.        0.0        1.5         51.5
  27  0.6       6.        2.5        2.1         53.6
  28  0.6       6.        5.0        2.5         56.1
  29  0.6       6.        7.5        2.4         58.5
  30  0.6       6.       10.0        1.5         60.0
  31  0.7       4.        0.0        1.5         61.5
  32  0.7       4.        2.5        2.1         63.6
  33  0.7       4.        5.0        2.5         66.1
  34  0.7       4.        7.5        2.4         68.5
  35  0.7       4.       10.0        1.5         70.0
  36  0.7       5.        0.0        1.5         71.5
  37  0.7       5.        2.5        2.1         73.6
  38  0.7       5.        5.0        2.5         76.1
  39  0.7       5.        7.5        2.4         78.5
  40  0.7       5.       10.0        1.5         80.0
  41  0.7       6.        0.0        1.5         81.5
  42  0.7       6.        2.5        2.1         83.6
  43  0.7       6.        5.0        2.5         86.1
  44  0.7       6.        7.5        2.4         88.5
  45  0.7       6.       10.0        1.5         90.0
  46  0.8       4.        0.0        1.5         91.5
  47  0.8       4.        2.5        2.1         93.6
  48  0.8       4.        5.0        2.5         96.1
  49  0.8       4.        7.5        2.4         98.5
```

```
WAVE DATA MIX PRINTED ON 19-SEP-79 AT 14:15:05 PAGE  2

 NO  HEIGHT    PERIOD    ANGLE          DURATION

  50  0.8        4.      10.0          1.5         100.0
  51  0.8        5.       0.0          1.5         101.5
  52  0.8        5.       2.5          2.1         103.6
  53  0.8        5.       5.0          2.5         106.1
  54  0.8        5.       7.5          2.4         108.5
  55  0.8        5.      10.0          1.5         110.0
  56  0.8        6.       0.0          1.5         111.5
  57  0.8        6.       2.5          2.1         113.6
  58  0.8        6.       5.0          2.5         116.1
  59  0.8        6.       7.5          2.4         118.5
  60  0.8        6.      10.0          1.5         120.0
  61  0.9        4.       0.0          1.5         121.5
  62  0.9        4.       2.5          2.1         123.6
  63  0.9        4.       5.0          2.5         126.1
  64  0.9        4.       7.5          2.4         128.5
  65  0.9        4.      10.0          1.5         130.0
  66  0.9        5.       0.0          1.5         131.5
  67  0.9        5.       2.5          2.1         133.6
  68  0.9        5.       5.0          2.5         136.1
  69  0.9        5.       7.5          2.4         138.5
  70  0.9        5.      10.0          1.5         140.0
  71  0.9        6.       0.0          1.5         141.5
  72  0.9        6.       2.5          2.1         143.6
  73  0.9        6.       5.0          2.5         146.1
  74  0.9        6.       7.5          2.4         148.5
  75  0.9        6.      10.0          1.5         150.0
  76  1.0        4.       0.0          1.9         151.9
  77  1.0        4.       2.5          2.7         154.6
  78  1.0        4.       5.0          3.2         157.8
  79  1.0        4.       7.5          3.1         160.9
  80  1.0        4.      10.0          1.9         162.8
  81  1.0        5.       0.0          1.9         164.7
  82  1.0        5.       2.5          2.7         167.4
  83  1.0        5.       5.0          3.2         170.6
  84  1.0        5.       7.5          3.1         173.7
  85  1.0        5.      10.0          1.9         175.6
  86  1.0        6.       0.0          1.9         177.5
  87  1.0        6.       2.5          2.7         180.2
  88  1.0        6.       5.0          3.2         183.4
  89  1.0        6.       7.5          3.1         186.5
  90  1.0        6.      10.0          1.9         188.4
  91  1.1        4.       0.0          1.9         190.3
  92  1.1        4.       2.5          2.7         193.0
  93  1.1        4.       5.0          3.2         196.2
  94  1.1        4.       7.5          3.1         199.3
  95  1.1        4.      10.0          1.9         201.2
  96  1.1        5.       0.0          1.9         203.1
  97  1.1        5.       2.5          2.7         205.8
  98  1.1        5.       5.0          3.2         209.0
  99  1.1        5.       7.5          3.1         212.1
```

```
WAVE DATA MIX PRINTED ON 19-SEP-79 AT 14:15:05 PAGE   3

NO  HEIGHT    PERIOD    ANGLE          DURATION

100  1.1        5.       10.0        1.9         214.0
101  1.1        6.        0.0        1.9         215.9
102  1.1        6.        2.5        2.7         218.6
103  1.1        6.        5.0        3.2         221.8
104  1.1        6.        7.5        3.1         224.9
105  1.1        6.       10.0        1.9         226.8
106  1.2        4.        0.0        1.9         228.7
107  1.2        4.        2.5        2.7         231.4
108  1.2        4.        5.0        3.2         234.6
109  1.2        4.        7.5        3.1         237.7
110  1.2        4.       10.0        1.9         239.6
111  1.2        5.        0.0        1.9         241.5
112  1.2        5.        2.5        2.7         244.2
113  1.2        5.        5.0        3.2         247.4
114  1.2        5.        7.5        3.1         250.5
115  1.2        5.       10.0        1.9         252.4
116  1.2        6.        0.0        1.9         254.3
117  1.2        6.        2.5        2.7         257.0
118  1.2        6.        5.0        3.2         260.2
119  1.2        6.        7.5        3.1         263.3
120  1.2        6.       10.0        1.9         265.2
121  1.3        4.        0.0        1.9         267.1
122  1.3        4.        2.5        2.7         269.8
123  1.3        4.        5.0        3.2         273.0
124  1.3        4.        7.5        3.1         276.1
125  1.3        4.       10.0        1.9         278.0
126  1.3        5.        0.0        1.9         279.9
127  1.3        5.        2.5        2.7         282.6
128  1.3        5.        5.0        3.2         285.8
129  1.3        5.        7.5        3.1         288.9
130  1.3        5.       10.0        1.9         290.8
131  1.3        6.        0.0        1.9         292.7
132  1.3        6.        2.5        2.7         295.4
133  1.3        6.        5.0        3.2         298.6
134  1.3        6.        7.5        3.1         301.7
135  1.3        6.       10.0        1.9         303.6
136  1.4        4.        0.0        1.9         305.5
137  1.4        4.        2.5        2.7         308.2
138  1.4        4.        5.0        3.2         311.4
139  1.4        4.        7.5        3.1         314.5
140  1.4        4.       10.0        1.9         316.4
141  1.4        5.        0.0        1.9         318.3
142  1.4        5.        2.5        2.7         321.0
143  1.4        5.        5.0        3.2         324.2
144  1.4        5.        7.5        3.1         327.3
145  1.4        5.       10.0        1.9         329.2
146  1.4        6.        0.0        1.9         331.1
147  1.4        6.        2.5        2.7         333.8
148  1.4        6.        5.0        3.2         337.0
149  1.4        6.        7.5        3.1         340.1
```

```
WAVE DATA MIX PRINTED ON 19-SEP-79 AT 14:15:05 PAGE  4

 NO  HEIGHT   PERIOD   ANGLE         DURATION

 150  1.4       6.      10.0        1.9        342.0
 151  1.5       4.       0.0        0.3        342.3
 152  1.5       4.       2.5        0.4        342.7
 153  1.5       4.       5.0        0.4        343.1
 154  1.5       4.       7.5        0.4        343.5
 155  1.5       4.      10.0        0.3        343.8
 156  1.5       5.       0.0        0.3        344.1
 157  1.5       5.       2.5        0.4        344.5
 158  1.5       5.       5.0        0.4        344.9
 159  1.5       5.       7.5        0.4        345.3
 160  1.5       5.      10.0        0.3        345.6
 161  1.5       6.       0.0        0.3        345.9
 162  1.5       6.       2.5        0.4        346.3
 163  1.5       6.       5.0        0.4        346.7
 164  1.5       6.       7.5        0.4        347.1
 165  1.5       6.      10.0        0.3        347.4
 166  1.6       4.       0.0        0.3        347.7
 167  1.6       4.       2.5        0.4        348.1
 168  1.6       4.       5.0        0.4        348.5
 169  1.6       4.       7.5        0.4        348.9
 170  1.6       4.      10.0        0.3        349.2
 171  1.6       5.       0.0        0.3        349.5
 172  1.6       5.       2.5        0.4        349.9
 173  1.6       5.       5.0        0.4        350.3
 174  1.6       5.       7.5        0.4        350.7
 175  1.6       5.      10.0        0.3        351.0
 176  1.6       6.       0.0        0.3        351.3
 177  1.6       6.       2.5        0.4        351.7
 178  1.6       6.       5.0        0.4        352.1
 179  1.6       6.       7.5        0.4        352.5
 180  1.6       6.      10.0        0.3        352.8
 181  1.7       4.       0.0        0.3        353.1
 182  1.7       4.       2.5        0.4        353.5
 183  1.7       4.       5.0        0.4        353.9
 184  1.7       4.       7.5        0.4        354.3
 185  1.7       4.      10.0        0.3        354.6
 186  1.7       5.       0.0        0.3        354.9
 187  1.7       5.       2.5        0.4        355.3
 188  1.7       5.       5.0        0.4        355.7
 189  1.7       5.       7.5        0.4        356.1
 190  1.7       5.      10.0        0.3        356.4
 191  1.7       6.       0.0        0.3        356.7
 192  1.7       6.       2.5        0.4        357.1
 193  1.7       6.       5.0        0.4        357.5
 194  1.7       6.       7.5        0.4        357.9
 195  1.7       6.      10.0        0.3        358.2
 196  1.8       4.       0.0        0.3        358.5
 197  1.8       4.       2.5        0.4        358.9
 198  1.8       4.       5.0        0.4        359.3
 199  1.8       4.       7.5        0.4        359.7
```

```
WAVE DATA MIX PRINTED ON 19-SEP-79 AT 14:15:05 PAGE  5

 NO  HEIGHT   PERIOD   ANGLE          DURATION

 200  1.8       4.      10.0       0.3          360.0
 201  1.8       5.       0.0       0.3          360.3
 202  1.8       5.       2.5       0.4          360.7
 203  1.8       5.       5.0       0.4          361.1
 204  1.8       5.       7.5       0.4          361.5
 205  1.8       5.      10.0       0.3          361.8
 206  1.8       6.       0.0       0.3          362.1
 207  1.8       6.       2.5       0.4          362.5
 208  1.8       6.       5.0       0.4          362.9
 209  1.8       6.       7.5       0.4          363.3
 210  1.8       6.      10.0       0.3          363.6
 211  1.9       4.       0.0       0.3          363.9
 212  1.9       4.       2.5       0.4          364.3
 213  1.9       4.       5.0       0.4          364.7
 214  1.9       4.       7.5       0.4          365.1
 215  1.9       4.      10.0       0.3          365.4
 216  1.9       5.       0.0       0.3          365.7
 217  1.9       5.       2.5       0.4          366.1
 218  1.9       5.       5.0       0.4          366.5
 219  1.9       5.       7.5       0.4          366.9
 220  1.9       5.      10.0       0.3          367.2
 221  1.9       6.       0.0       0.3          367.5
 222  1.9       6.       2.5       0.4          367.9
 223  1.9       6.       5.0       0.4          368.3
 224  1.9       6.       7.5       0.4          368.7
 225  1.9       6.      10.0       0.3          369.0
 226  1.5       6.       0.0       1.1          370.1
 227  1.5       6.       2.5       1.7          371.8
 228  1.5       6.       5.0       1.9          373.7
 229  1.5       6.       7.5       1.9          375.6
 230  1.5       6.      10.0       1.1          376.7
 231  1.5       7.       0.0       1.1          377.8
 232  1.5       7.       2.5       1.7          379.5
 233  1.5       7.       5.0       1.9          381.4
 234  1.5       7.       7.5       1.9          383.3
 235  1.5       7.      10.0       1.1          384.4
 236  1.5       8.       0.0       1.1          385.5
 237  1.5       8.       2.5       1.7          387.2
 238  1.5       8.       5.0       1.9          389.1
 239  1.5       8.       7.5       1.9          391.0
 240  1.5       8.      10.0       1.1          392.1
 241  1.6       6.       0.0       1.1          393.2
 242  1.6       6.       2.5       1.7          394.9
 243  1.6       6.       5.0       1.9          396.8
 244  1.6       6.       7.5       1.9          398.7
 245  1.6       6.      10.0       1.1          399.8
 246  1.6       7.       0.0       1.1          400.9
 247  1.6       7.       2.5       1.7          402.6
 248  1.6       7.       5.0       1.9          404.5
 249  1.6       7.       7.5       1.9          406.4
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WAVE DATA MIX PRINTED ON 19-SEP-79 AT 14:15:05 PAGE  6

 NO  HEIGHT   PERIOD   ANGLE         DURATION

 250  1.6       7.      10.0          1.1         407.5
 251  1.6       8.       0.0          1.1         408.6
 252  1.6       8.       2.5          1.7         410.3
 253  1.6       8.       5.0          1.9         412.2
 254  1.6       8.       7.5          1.9         414.1
 255  1.6       8.      10.0          1.1         415.2
 256  1.7       6.       0.0          1.1         416.3
 257  1.7       6.       2.5          1.7         418.0
 258  1.7       6.       5.0          1.9         419.9
 259  1.7       6.       7.5          1.9         421.8
 260  1.7       6.      10.0          1.1         422.9
 261  1.7       7.       0.0          1.1         424.0
 262  1.7       7.       2.5          1.7         425.7
 263  1.7       7.       5.0          1.9         427.6
 264  1.7       7.       7.5          1.9         429.5
 265  1.7       7.      10.0          1.1         430.6
 266  1.7       8.       0.0          1.1         431.7
 267  1.7       8.       2.5          1.7         433.4
 268  1.7       8.       5.0          1.9         435.3
 269  1.7       8.       7.5          1.9         437.2
 270  1.7       8.      10.0          1.1         438.3
 271  1.8       6.       0.0          1.1         439.4
 272  1.8       6.       2.5          1.7         441.1
 273  1.8       6.       5.0          1.9         443.0
 274  1.8       6.       7.5          1.9         444.9
 275  1.8       6.      10.0          1.1         446.0
 276  1.8       7.       0.0          1.1         447.1
 277  1.8       7.       2.5          1.7         448.8
 278  1.8       7.       5.0          1.9         450.7
 279  1.8       7.       7.5          1.9         452.6
 280  1.8       7.      10.0          1.1         453.7
 281  1.8       8.       0.0          1.1         454.8
 282  1.8       8.       2.5          1.7         456.5
 283  1.8       8.       5.0          1.9         458.4
 284  1.8       8.       7.5          1.9         460.3
 285  1.8       8.      10.0          1.1         461.4
 286  1.9       6.       0.0          1.1         462.5
 287  1.9       6.       2.5          1.7         464.2
 288  1.9       6.       5.0          1.9         466.1
 289  1.9       6.       7.5          1.9         468.0
 290  1.9       6.      10.0          1.1         469.1
 291  1.9       7.       0.0          1.1         470.2
 292  1.9       7.       2.5          1.7         471.9
 293  1.9       7.       5.0          1.9         473.8
 294  1.9       7.       7.5          1.9         475.7
 295  1.9       7.      10.0          1.1         476.8
 296  1.9       8.       0.0          1.1         477.9
 297  1.9       8.       2.5          1.7         479.6
 298  1.9       8.       5.0          1.9         481.5
 299  1.9       8.       7.5          1.9         483.4
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WAVE DATA MIX PRINTED ON 19-SEP-79 AT 14:15:05 PAGE  7

 NO  HEIGHT   PERIOD   ANGLE           DURATION

 300  1.9        8.       10.0          1.1          484.5
 301  2.0        6.        0.0          0.8          485.3
 302  2.0        6.        2.5          1.1          486.4
 303  2.0        6.        5.0          1.3          487.7
 304  2.0        6.        7.5          1.3          489.0
 305  2.0        6.       10.0          0.8          489.8
 306  2.0        7.        0.0          0.8          490.6
 307  2.0        7.        2.5          1.1          491.7
 308  2.0        7.        5.0          1.3          493.0
 309  2.0        7.        7.5          1.3          494.3
 310  2.0        7.       10.0          0.8          495.1
 311  2.0        8.        0.0          0.8          495.9
 312  2.0        8.        2.5          1.1          497.0
 313  2.0        8.        5.0          1.3          498.3
 314  2.0        8.        7.5          1.3          499.6
 315  2.0        8.       10.0          0.8          500.4
 316  2.1        6.        0.0          0.8          501.2
 317  2.1        6.        2.5          1.1          502.3
 318  2.1        6.        5.0          1.3          503.6
 319  2.1        6.        7.5          1.3          504.9
 320  2.1        6.       10.0          0.8          505.7
 321  2.1        7.        0.0          0.8          506.5
 322  2.1        7.        2.5          1.1          507.6
 323  2.1        7.        5.0          1.3          508.9
 324  2.1        7.        7.5          1.3          510.2
 325  2.1        7.       10.0          0.8          511.0
 326  2.1        8.        0.0          0.8          511.8
 327  2.1        8.        2.5          1.1          512.9
 328  2.1        8.        5.0          1.3          514.2
 329  2.1        8.        7.5          1.3          515.5
 330  2.1        8.       10.0          0.8          516.3
 331  2.2        6.        0.0          0.8          517.1
 332  2.2        6.        2.5          1.1          518.2
 333  2.2        6.        5.0          1.3          519.5
 334  2.2        6.        7.5          1.3          520.8
 335  2.2        6.       10.0          0.8          521.6
 336  2.2        7.        0.0          0.8          522.4
 337  2.2        7.        2.5          1.1          523.5
 338  2.2        7.        5.0          1.3          524.8
 339  2.2        7.        7.5          1.3          526.1
 340  2.2        7.       10.0          0.8          526.9
 341  2.2        8.        0.0          0.8          527.7
 342  2.2        8.        2.5          1.1          528.8
 343  2.2        8.        5.0          1.3          530.1
 344  2.2        8.        7.5          1.3          531.4
 345  2.2        8.       10.0          0.8          532.2
 346  2.3        6.        0.0          0.8          533.0
 347  2.3        6.        2.5          1.1          534.1
 348  2.3        6.        5.0          1.3          535.4
 349  2.3        6.        7.5          1.3          536.7
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WAVE DATA MIX PRINTED ON 19-SEP-79 AT 14:15:05 PAGE   8

 NO  HEIGHT   PERIOD   ANGLE             DURATION

 350  2.3        6.       10.0          0.8         537.5
 351  2.3        7.        0.0          0.8         538.3
 352  2.3        7.        2.5          1.1         539.4
 353  2.3        7.        5.0          1.3         540.7
 354  2.3        7.        7.5          1.3         542.0
 355  2.3        7.       10.0          0.8         542.8
 356  2.3        8.        0.0          0.8         543.6
 357  2.3        8.        2.5          1.1         544.7
 358  2.3        8.        5.0          1.3         546.0
 359  2.3        8.        7.5          1.3         547.3
 360  2.3        8.       10.0          0.8         548.1
 361  2.4        6.        0.0          0.8         548.9
 362  2.4        6.        2.5          1.1         550.0
 363  2.4        6.        5.0          1.3         551.3
 364  2.4        6.        7.5          1.3         552.6
 365  2.4        6.       10.0          0.8         553.4
 366  2.4        7.        0.0          0.8         554.2
 367  2.4        7.        2.5          1.1         555.3
 368  2.4        7.        5.0          1.3         556.6
 369  2.4        7.        7.5          1.3         557.9
 370  2.4        7.       10.0          0.8         558.7
 371  2.4        8.        0.0          0.8         559.5
 372  2.4        8.        2.5          1.1         560.6
 373  2.4        8.        5.0          1.3         561.9
 374  2.4        8.        7.5          1.3         563.2
 375  2.4        8.       10.0          0.8         564.0
TTO  --  STOP
>
```

Original data had angles α_0 from 0 to 40°. These caused the model to "explode" without refraction, i.e., for Delta6. Therefore, all angles were reduced by 1/4 for Delta6. In order to retain a basis for comparison with the refracted wave, the same angles were used for Delta7 to produce graphs 7, 8, 9 and 10 (Figs. 9-12). The wave angles were returned to their original magnitude for Graph 11 (Fig. 13).

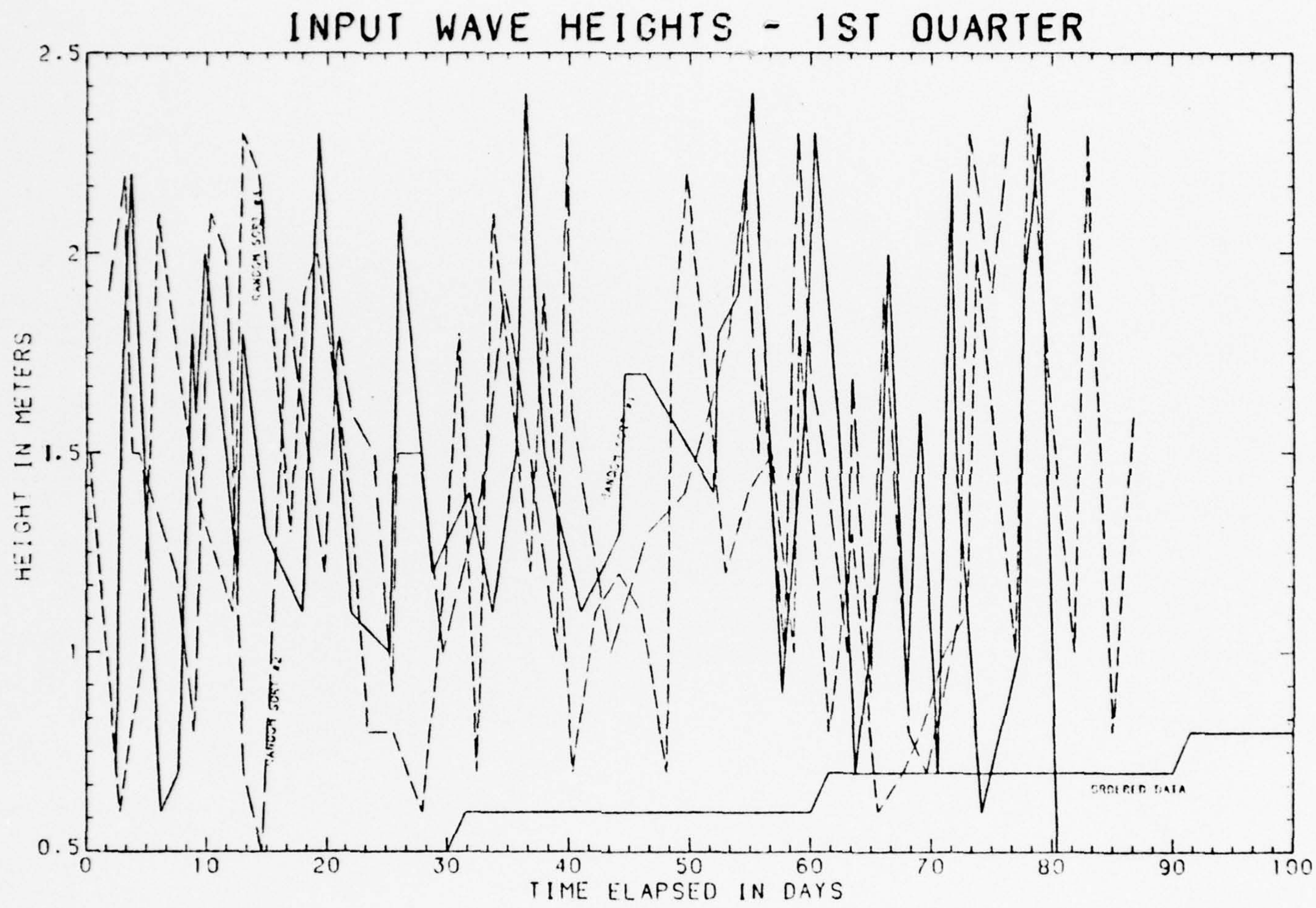

Figure 15 Ordered wave data compared to three random sorts. Note that there are different total durations for each curve since each wave had a different duration, and waves were "shuffled" with all their parameters as one record.

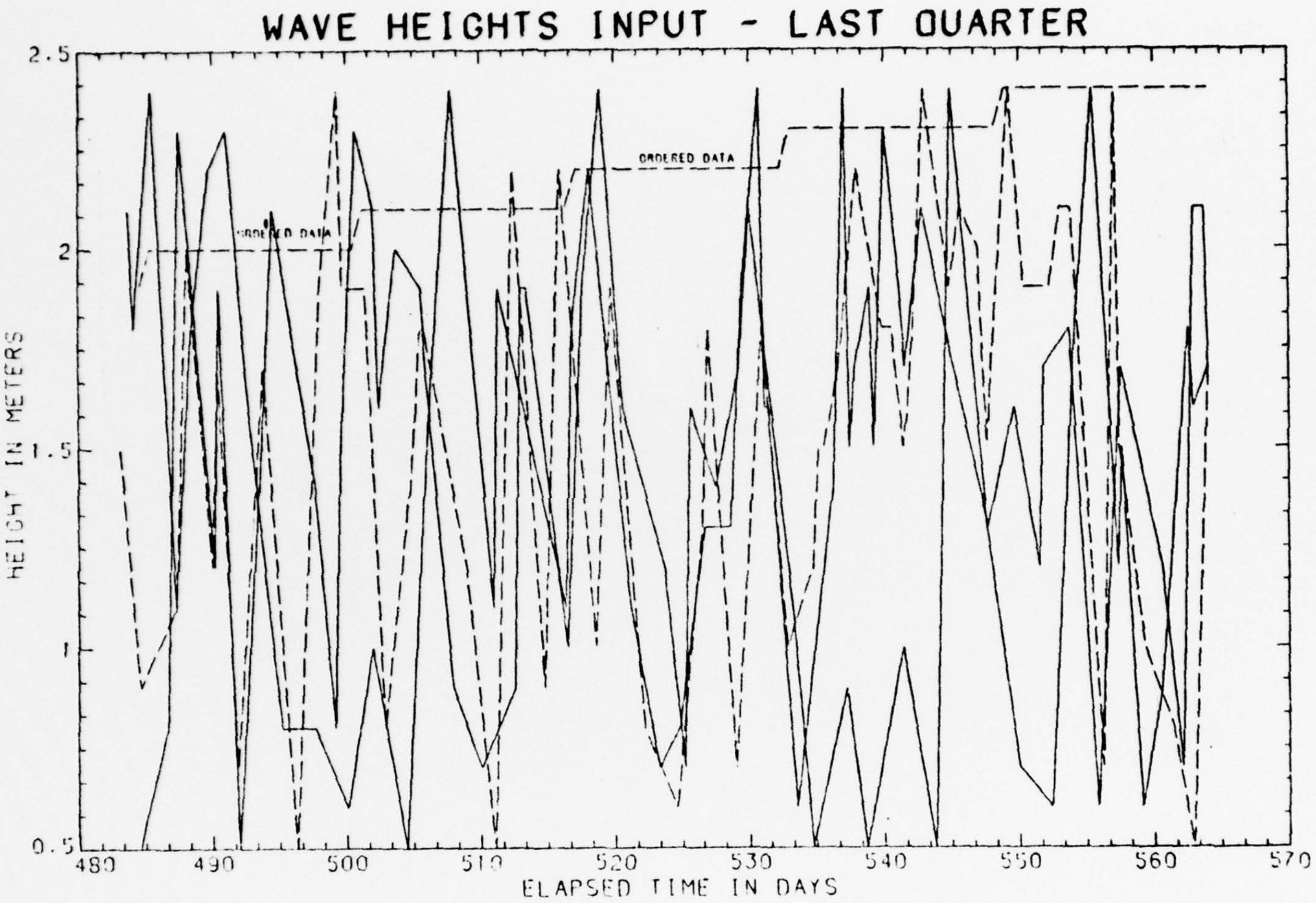

Figure 16 Input wave heights for approximately the last quarter of the 564 day. Simulation are shown for the four cases run. One ordered three random. These are the deepwater characteristics only.

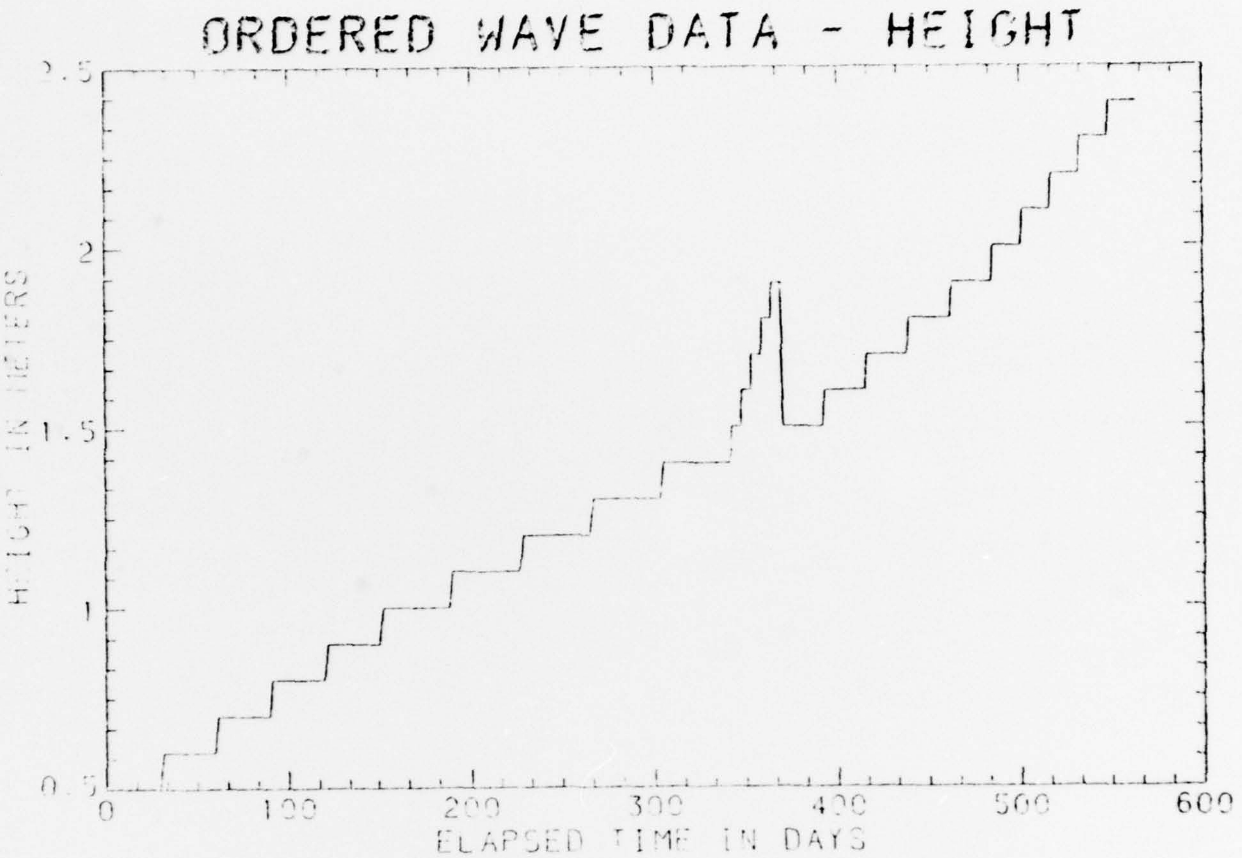

Figure 17 Delta7 ordered increasing wave heights. Wave height was the primary method of ordering waves. Although within height ranges, the waves were also ordered by increasing period. Random wave data as shown by the quarterly representations in Figures 15 and 16. Does not follow this pattern in any way.