The Joint Probability of Waves and Water Levels: JOIN-SEA – Version 1.0

User manual

Report TR 71
November 1998
(Re-issued with minor amendments May 2000)

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HR Wallingford

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Summary

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With respect to coastal engineering, joint probability refers to two or more partially related environmental variables occurring simultaneously to produce a response of interest. Damage to sea defences and flooding are often associated with times of high waves and high water levels. It is therefore necessary to consider the joint probability of these variables when assessing design conditions for coastal structures.

New, practical and rigorous methods for the analysis of large waves and high water levels have been developed jointly by HR Wallingford and Lancaster University. The new methods consist of a series of computer programs; this report is intended as a guide for the day to day running of the programs. For a more detailed description of the theoretical aspects of the programs the reader is referred to the companion report SR 537 (HR Wallingford, 2000).

Version 1.0 of the software was released to industry specialists for beta-testing at a briefing workshop at Wallingford in February 2000. Whilst no active support is offered, HR Wallingford will try to assist suitably trained specialists in getting started with using the programs: please address any questions to Ben Gouldby or Peter Hawkes of the Coastal Department at HR Wallingford.

Contents

1. INTRODUCTION

1.1 Background

With respect to coastal engineering, joint probability refers to two or more partially related environmental variables occurring simultaneously to produce a response of interest. Examples are high waves and high water levels, high wind-seas and high swell, and large river flows and high sea levels. Damage to sea defences and flooding are often associated with times of high waves and high water levels. It is therefore necessary to consider the joint probability of these variables when assessing design conditions for coastal structures.

In the past, joint probability methods have involved complicated and/or subjective approaches unsuitable for use by non-specialists. However, new, more practical and rigorous methods for the analysis of large waves and high water levels have been developed jointly by HR Wallingford and Lancaster University. The new methods consist of a series of computer programs; their use is described in this user manual. Theory and validation of the methods are described in a companion report SR 537 (HR Wallingford, 2000).

1.2 List of programs and computer details

The JOIN-SEA software package should consist of the following:-

Programs – *TESTDATA*, *BVN*, *MIX*, *SIMBVN*, *SIMMIX* and *ANALYSIS*.

Example files – *datafile*, *testresult*, *transfer*, *diagnostic*, *rhovalues*, *transfer.mix*, *diagnostic.mix*, *marginals*, *simdata* and *extremes*.

The programs are written in Fortran 77 and have been compiled and tested under a UNIX operating system. They contain task specific numerical algorithms written by the Numerical Algorithms Group (NAG). In order to run these programs a NAG Licence is required.

To disseminate the software to users who do not have access to the NAG library, HR Wallingford has obtained a subset of the NAG Library that contains only the routines that are required to run the JOIN-SEA software. These subsets are available from HR Wallingford, together with a JOIN-SEA specific NAG Licence, on payment of the subset licence fee. These subsets of routines are suitable for PC based computer systems only and will not run under UNIX systems.

1.3 Description of methods

The programs take as input simultaneous records of wave height, period and water level, although within the programs wave period is handled in terms of the more robust wave steepness variable. Three variables, wave height, water level and steepness, are transformed to Normal scales. For steepness, the transformation is made using the empirical distribution function. For significant wave height (H_s), and water level, the transformation is made by first fitting a parametric model (the Generalised Pareto Distribution (GPD)) to the values of the variables greater than specified thresholds. To values below the thresholds, the empirical distribution function is used. The empirical distribution of steepness is modelled by a Normal distribution on wave height.

The next stage involves fitting the transformed data into Bi-Variate Normal (BVN) form. Two alternative partial dependence statistical models have been developed to represent the dependence between wave heights and water levels. These consist of a single BVN Distribution and a mixture of two BVN Distributions. These models were chosen since the dependence and extremes characteristics of these distributions are well understood and considered to be sufficiently flexible for all UK applications. The choice between the one and two BVN's is determined by the relative goodness of fit to the data. Typically, the single BVN is adequate at locations where the wave conditions all stem from a single population.

However, at locations where the wave conditions are thought to stem from two populations; for example, where swell is particularly prevalent as well as wind-sea, the mixture of two BVN's is more likely to capture the differing dependence between the two populations. Reference to a diagnostics file aids the decision as to which is the most suitable model to use.

Having determined the distributions of and the dependence between the marginal variables, the next step is to utilise this information in the simulation of a large sample of synthetic records. H_s, mean wave period (T_m) and water level records are generated for 1000's of years worth of data, the synthesised records having the same statistical characteristics as the original data. At this stage it is possible to refine the extremes predictions where additional information on the marginal variables is known. For example, simultaneous records of wave height and water level may only be available for say 10 years, whilst water level records may well extend over a longer period, say 20 years. It is obviously preferable to incorporate the information from the longer marginal data set into the joint probability analysis. Extremes from the longer-term data set may well be known already, or can be calculated separately. The initial extremes, based on the simultaneous records, can then be re-scaled to agree with the long-term extremes. This re-scaling takes place during the simulation. Consequently, the additional information is built into the large sample of generated synthetic data that is subsequently used in the structural analysis.

The final stage involves analysis of the simulated data set and in particular the derivation of extreme values. Water level or wave height thresholds are set, and corresponding wave height/water levels that are expected to occur once per specified joint exceedence return period are given. This stage also has the option of structural response variable analysis.

There are many different combinations of wave height and water level for any given joint exceedence return period. Past joint probability methods have involved selecting a number of different combinations and testing each combination in order to determine the worst-case, in terms of structural response. The simulation of a large sample of records allows extremes of the structural response variable to be predicted directly. Where the structure function is known, this method of analysis is preferable to the use of different combinations of marginal extremes, since it works directly in terms of the return period (and therefore risk) of the structural response variable.

1.4 Outline of the report

Chapter 2 briefly describes the function of the individual programs that constitute the software package. For a full description of the statistical theory see HR Wallingford (2000). The operation of the programs, including input and output requirements, are described in Chapter 3. Chapter 4 describes the use of the results and gives several warnings concerning the use of the software.

2. FUNCTION AND PURPOSE OF THE PROGRAMS

2.1 Introduction

Throughout the series of programs the user is required to answer a variety of questions, some of which are straight forward and self explanatory, however, others may not be as easily understood. This chapter aims to clarify the input requirements and details the subsequent output.

There are four types of program:

- *TESTDATA* gives information regarding the degree of dependence at different thresholds;
- *BVN* and *MIX* fit probability distributions to the real data;
- *SIMBVN* and *SIMMIX* synthesise large samples of data based on the fitted distributions; and
- *ANALYSIS* carries out extremes analysis based on the simulated data.

The first line of the original data file is automatically carried through to all the subsequent files, which provides some continuity and check on file identity. The program structure is outlined in a flow chart (Figure 1).

NB: The term starting point is used frequently. In several operations a number of parameters are to be optimised using maximum likelihood methods. For this to work efficiently it is necessary to provide initial estimates, or starting points, of the parameter values which the program will then improve upon. Guidance on the starting point estimates is provided in the form of default values (see Appendices 3-7 for actual values), which are usually accepted. Similarly, file names are described using their default names (e.g. datafile, transfer, diagnostic) but the user can choose to specify his own choice of names.

2.2 TESTDATA

Before running the joint probability software, *TESTDATA* may be used to provide information on the dependence between the two primary variables at different threshold levels. The results can be used to assist in the choice of the most suitable subsequent program (*BVN* or *MIX*).

Simultaneous records of wave height, water level and wave period are input to *TESTDATA*. The program then calculates log (z), where z is [-log (1-threshold)], and the test statistic T(z) defined in section 3.3.2 of LU section of HR Wallingford, 2000) and 95 % confidence intervals. The output can be plotted as shown in Figure 2. The gradient of the resulting line is $(1-\rho)/(1+\rho)$, where ρ is the correlation coefficient. Therefore, analysis of independent variables would result in a line with a constant gradient of one. Analysis of dependent variables would result in a horizontal line (gradient zero). Examples of different plots and their interpretation are given in Section 7.1.2 of the Lancaster University section of HR Wallingford (2000). Figure 2 shows a gradient of approximately ½ with a distinct change to a lower gradient associated with stronger dependence in the tail. *MIX* was chosen as the most suitable model for this data set (see also Section 2.3 'Output from *BVN*' for guidance on when to run *MIX*).

2.3 *BVN*

<u>Input to *BVN*</u>

Simultaneous records of wave height, water level and wave period are input to *BVN* from a file called *datafile*. The program then fits a Bivariate Normal Distribution (BVN) to the joint upper tail of H_s and water level and a regression line to the values of steepness corresponding to values of H_s higher than a fixed threshold.

The marginal variables are transformed to standard Normal Distributions. For H_s and water levels this transformation involves specifying a threshold; points below this threshold are transformed using the empirical distribution function, whilst points above the threshold are modelled using a Generalised Pareto Distribution (GPD) before being transformed. A regression line is fitted to the distribution of steepness over wave height, for values above the specified threshold, before transformation.

In order to fit the different distributions *BVN* requires various parameters as input. These are outlined below, and their default values are usually accepted: -

- Starting point for dependence of H_s and water levels (correlation coefficient).
- Starting point of H_s distribution fitting for shape parameter in the GPD (csi 1).
- Starting point of H_s distribution fitting for scale parameter in the GPD (sigma 1).
- Csi 2 and sigma 2 are as above but relate to the water level distribution fitting.

- Threshold of the GPD fitting for water level and H_s: The GPD is normally fitted to the top 5% of data; data below this threshold is transformed using the empirical distribution function. The threshold is specified as a probability of non-exceedance (for example, the top 5% would be expressed as 0.95).

The following parameters relate to the fitting of wave steepness. A threshold value (u) is specified as a probability of non-exceedance. The distribution is normal with a mean = constant + coefficient(H_s-u) and variance sigma^2.

- Starting point for the constant.

- Starting point for the coefficient.

- Starting point for the threshold (u specified as a probability of non-exceedance).

Output from *BVN*

The *diagnostic* file gives direct responses on the fitting of the distributions. Starting point and threshold values are quoted, information on the GPD fitting of H_s and water level and H_s on steepness are given; rho values (correlation coefficients) are quoted for different thresholds of non-exceedance. **It is important this file is checked before proceeding**. If *BVN* does not complete successfully, new starting values for the GPD fitting are recommended. *BVN* should then be re-run, changing the default starting values to the new values. However, if the intention is to re-scale the marginal extremes to more substantiated values (see Section 2.3) during the running of *SIMBVN*, it is not necessary to have a successful GPD fit. In such a situation, the GPD fitting error messages can be ignored.

There is however, the possibility of not being able to achieve a run without an error message, when the user is reliant on the extremes calculated by the program. If the program is still giving error messages in the *diagnostic* file, having been run several times with different starting values, then different options are available depending on the IFAIL number. If the IFAIL number is 2, 3 or 4 then the maximisation algorithm has not converged to a global maximum. This will occur if the maximum likelihood function does not have a solution. If this is the case the data set is not suitable for use with the software and an alternative method (CIRIA, 1996) should be considered. If IFAIL= 7 or 8, this is an indication that there is some doubt whether the point found is a maximum. It is feasible to proceed with *SIMBVN* following a warning of this type, however the subsequent extremes calculated in *SIMBVN* should be checked carefully, in order to confirm a sensible fit has been achieved.

Important information on the dependence between wave heights and water levels can be gained by analysis of the rho-values. If the values show minor changes (<0.1) in correlation coefficient with differing non-exceedance levels, this is considered normal and the user can select a threshold level above which the rho-value is approximately constant, for input to *SIMBVN*. However, if an apparently significant variation in rho (>0.15) is observed over a series of probability levels, this indicates that the correlation is varying with threshold, in which case *MIX* is a more suitable program to use, since it incorporates varying correlation. If there is doubt regarding the variation in rho-values then *MIX* should be run, as the model is able to cope with correlation varying throughout the data set, and the specification of a threshold is avoided (see Section 2.3).

The *rhovalues* file summarises the dependence between wave height and water levels above different thresholds. The format of the file is as follows: - the first column for the threshold is specified as a probability of non-exceedance; the second column for the best estimate of the correlation coefficient and the third and fourth columns represent the lower and higher bounds of the confidence interval. The best estimates are the values that are also given in the *diagnostics* file.

The *transfer* file stores parameters of the fitted distributions for H_s, water level and steepness, in a format suitable for input into the subsequent program, *SIMBVN*.

2.4 *MIX*

Background for use of *MIX*

This program performs a similar task to the *BVN* program. However it is more suitable for use where the data may be split into two populations or the correlation changes significantly over varying percentage exceedance thresholds. For example, if the location of the study area is such that it is exposed to wind-sea as well as swell wave conditions, the *MIX* program is more likely to pick out the two populations and thus produce a better fit to the data. Additionally the output from *BVN* may show the correlation to increase with an increase in the percentage of non-exceedance threshold. The input to *SIMBVN* (the program subsequent to *BVN*) is restrictive in that a constant correlation value is applied to a range of data above a given threshold; thus, this program is not suitable for such data. In this case, *MIX* should be used as varying correlation is incorporated in the method. (Alternatively it may be practical to separate the two populations manually, for example using a wave direction criterion, and then to analyse the two data sets separately.)

Analysis of the *diagnostic* and *rhovalues* files (Section 2.2) output from *BVN* may reveal the presence of two populations and give important information on the starting point for parameters that are required as input to *MIX*. As an illustration of when to run *MIX* the information on correlation output from *BVN* (*diagnostic/rhovalues* files) can be used. Figure 3 shows the variation in correlation as a function of the percentage of non-exceedance, for the five *simdata* sets used in the testing of the programs (HR Wallingford, 2000). The single BVN program was chosen as a suitable program for Dover, Dowsing and Cardiff (note the more horizontally constant nature of the lines associated with these areas). *MIX* was thought to provide a better fit to the other data sets (NB: it is the fluctuation in the gradient of the line, **NOT** the level of correlation that is the important factor when viewing such plots).

NB: **If there is considerable doubt over which program is to be run then MIX should be chosen, since it is the more versatile program**.

MIX input parameters

The *datafile* and input parameters to *MIX* are the same as for *BVN*. There are, however, additional parameters relating to the mixture of BVN's that need to be specified.

Please note the following paragraph is a guide for setting the starting values of the parameters required for the fitting of the mixture of two BVN's (see Appendix 4 'Example questions from *MIX*', section starting 'The following parameters are for the mixture of BVN's). However, experience has shown that selection of the default starting parameters rarely results in error: **it is therefore recommended that the default values for this section** be selected when running *MIX*. If errors result, the following paragraph can be used to give better starting values.

If analysis of the *diagnostic* file, produced by *BVN*, shows an apparently significant increase or decrease in the correlation coefficient at a certain threshold value, the P parameter (question 'starting point for prob. (of lower Hs/WL) from *MIX)* should take this value in *MIX*. Rho1 should take the mean value of the correlation coefficients before this threshold, and rho2 should take the mean value after the threshold. If a further decrease in the rho values is observed at a greater threshold, a negative but small (between -0.5 and –1.0) starting value for mu22 should be used together with a positive but small (between 0.5 and 1.0) starting value for mu21. If the rho values show an increase at greater thresholds mu22 and mu21 should be set to small (between 0.5 and 1.0) positive values. Sigma 21 and sigma 22 should be set to values between 0.1 and 2.

Output from *MIX*

The *diagnostic* file gives direct responses on the fitting of the distributions as in *BVN*. Starting point and threshold values are quoted, information on the GPD fitting of H_s and water level and H_s on steepness are given (these are the same whether *BVN* or *MIX* is run). Additionally, parameters relating to the fitting of the two BVN's to the H_s and water levels are given. **It is important this file is checked before proceeding**. If *MIX* does not complete successfully, new starting values for the GPD fitting are given. *MIX* should then be re-run, changing the default starting values to the new values.

There is however, the possibility of not being able to achieve a run without an error message. If the program is still giving error messages in the '*diagnostic*' file, having been run several times with different starting values, different options are available depending on the degree of warning, or IFAIL number (see Section 2.3).

The *transfer* file stores parameters of the fitted distributions for H_s, water level and steepness, as in *BVN*; however, the information regarding the fitting of the mixture of two BVN's is also supplied in the *transfer* file output from *MIX*. This data is read in and used in the subsequent *SIMMIX* program.

2.5 SIMBVN and SIMMIX

Introduction

SIMBVN uses the information gained from the fitting of the distributions in *BVN* to simulate 1000's of years worth of data. The marginal distributions of wave height and water level can be altered by the re-scaling of extreme values if more substantiated extremes are known.

Input to *SIMBVN*

The information regarding the fitting of the GPD's and the empirical distribution fitting of steepness, is stored in the output file *transfer*, from *BVN*. This file is used as direct input to *SIMBVN*. The information regarding the correlation between wave heights and water levels is carried forward manually, since it is necessary to make a judgement as to the most representative level of correlation to use.

Analysis of the *diagnostic* file reveals the extent of correlation at different thresholds (expressed as a probability of non-exceedance). A threshold value is then selected, above which the correlation coefficient should remain more or less constant. This information is input to *SIMBVN*. Another input parameter is the number of events per year. If the water level data is from a semi-diurnal tidal regime, and wave heights at every high water are extracted, the number of events per year is 707 (the default value). However, if genuinely calm records are missing from the original data, for any reason, this value should be adjusted accordingly (see Section 3.2). In addition, if the original data were split into sub-sets (for example, northerly and southerly waves) before using JOIN-SEA, then the number per year refers to the number per year in the sub-set.

The user is also asked to supply the number of records to be synthesised. This depends on the maximum return period event required. The minimum length of simulated data should be 10 times the maximum return period required. For example, if the number of records per year is 707, and the maximum return period event required is 1000 years; the number of records to synthesise is 7070000. The file generated for such a large number of records can cause storage and handling problems. In view of this potential problem, an option limiting the number of synthesised records written to the output file is available. Threshold values of wave height and water level can be input, if the synthesised record falls below both of the values the record is not written to the output file. Where this option is used, the program notes that the number of events stored per year is therefore reduced.

Specifying the number of events per year, and already knowing the properties of the GPD's for the marginal distributions of wave height and water level, enables *SIMBVN* to calculate marginal extremes for different return periods. Obviously, these results are based only on the period of data where simultaneous results are held. If a longer data set of water levels, for example, is available, extremes calculated from the longer data set are preferable to those calculated from the shorter period. The program thus offers the option of re-scaling the marginal extremes to more established values.

Output from *SIMBVN*

Output from *SIMBVN* consists of two files. *Simdata* contains records of wave heights, water levels and wave periods corresponding to many years worth of data. It also holds information on the number of records per year and the total number of records in the file. This file is used directly as input to the *ANALYSIS* program. The *marginals* file contains details of the marginal wave height and water level extremes calculated by *SIMBVN*. If the option of re-scaling (see Section 3.4) is selected the re-scaled values are also detailed.

SIMMIX

SIMMIX performs a similar task to *SIMBVN*, only it is used after *MIX*. The *transfer* file output from *MIX* is different from that output from *SIMBVN* (although the default name is the same) and is therefore not compatible with *SIMBVN*.

2.6 ANALYSIS

Description of program

ANALYSIS takes as input the *simdata* file containing the synthesised records. It carries out a number of extremes analyses, beginning, as a check, with the marginal extremes of wave height and water level. These are not based on fitting distributions, but by counting back through the simulated data. For example, since one would expect the 100 year value to be exceeded, on average, ten times in a one thousand year sample, it is determined by counting back to the tenth highest value in the sample.

Wave height or water level values can be specified by the user. Data above these specified values is analysed in order to derive joint exceedance probability combinations, for different joint return periods. These combinations can be used as input to coastal engineering projects using traditional methods. However, to gain full use of the long data set, structural response variables can be calculated for every synthesised record, thereby allowing a direct calculation of structural response extremes. Presently, four structural response variables (detailed below) are coded into the software. The user is warned that these methods are intended for demonstration purposes and are not suitable for all locations. Therefore, careful consideration and a full understanding of the methods used should be gained before using this section of the software.

NB: The method of Owen (1980) to determine wave conditions at the toe of the structure is used in all of the following calculations.

Example runs, showing the listing of required input parameters for all the following structural response variables, are shown in the appendices.

Overtopping rate

The overtopping rate for sloping structures is calculated using the method of Owen (1980).

Runup

Runup levels ($ru_{2\%}$) are calculated using formulae described in CIRIA/CUR (1991) (Section 5.1.2.1, pg 248).

Rock armour

The rock armour size is calculated using the method of Van der Meer described in CIRIA/CUR (1991) (Section 5.1.3.2, pg 265).

Wave forces on vertical walls

Methods based on Allsop et al (1996) are used to calculate wave forces on vertical walls, although these methods are somewhat simplified by assuming the wall is of infinite height and has no berm at the toe.

Output from *ANALYSIS*

Output from the *ANALYSIS* program is in four different forms. The marginal extremes of wave height and water level are quoted. Wave heights are given for increasing water level thresholds and vice-versa (NB: the return periods quoted are joint exceedance return periods). These joint exceedance probability combinations are then summarised in a format more suitable for adoption into a spreadsheet. If any of the structural response options are selected extremes for default return periods are then detailed (for reference, parameters input to structural response calculations are written to the *ANALYSIS* output program).

3. OPERATION OF THE PROGRAMS

3.1 Introduction

This chapter describes the actual operation of the programs. Example runs of the different programs are shown in appendices. A flow chart giving an overall impression of how the programs are linked is shown in Figure 1. The default values can be accepted in the vast majority of cases by entering ‘return’.

NB. Where the parameter default value is specified as a real number, integer number or text string, the input should be of the correct type specified.

3.2 Data preparation (not included in JOIN-SEA package)

The software requires simultaneous, independent records of wave height, period and water level as input. In order to meet the specified requirements a considerable amount of preparation is often required. A standard method of achieving the required input file is described below. However, as long as the data is sufficient in volume (at least 2800 records) and meets the above criteria, the method of preparation is not critical.

1) Obtain sequential hourly water level records from a tide gauge, as close to the site of interest as possible. If necessary, convert the water level data to the site and datum of interest, using factors based on the difference in tidal range between the two sites (this is only advisable for relatively small changes in tidal range).

2) Obtain sequential hourly wave height and period records (usually synthetic data), corresponding to the period of data water level records are held for. Depending on the location and the purpose of the joint probability study, it may be necessary to transform the wave conditions before simulating the data. For example, if time series offshore wave data is obtained, and the structural response variable requires significant wave height at the toe of the structure as an input parameter, it will first be necessary to transform the offshore data to inshore conditions, using a refraction model. Then, depending on the

preferred method of calculating wave conditions at the toe of the structure (see Section 2.6), it may be necessary to convert these further.

3) Having obtained individual records of wave conditions and water levels for the same period, these records are then combined. Combined hourly, sequential records are not independent. In order to address this requirement, consecutive high waters (in practice the only case of interest) are extracted from the time series data. HR Wallingford's experience is that results are not very sensitive to possible errors in the assumption that consecutive high waters represent independent events.

An example of a prepared *datafile* is shown in Appendix 1.

Having generated the appropriate *datafile* it is recommended that a scatter plot of wave height against water level be plotted. The scatter plot is a good way of obtaining an overall view of the data. Skewness of the plotted points is indicative of correlation and will provide insight into the expected results of the joint probability study. Another method, sometimes employed at HR Wallingford, is to manually analyse the top few percent of water level records and assess the mean direction of the wind over the previous twelve hours. If the wind is off the land at the times of the highest water levels (as is the case at some locations on the East Coast of the UK) the extent of correlation will be limited, possibly negative. Once an overall 'feel' for the data has been established, checks can be made on the results produced by JOIN-SEA.

If there are two populations of data at a site then it may be helpful to separate them and to analyse them separately. For example, wind-sea and swell could be separated using a wave steepness criterion, or easterlies and westerlies could be separated using a wave (or wind) direction criterion. Alternatively, if it is not practical to separate them manually, then the MIX option should be considered.

3.3 Operation of *BVN*

1) On execution of *BVN* the user is prompted for the input filename (default = *datafile*), output filenames (default = *rhovalues, diagnostic* and *transfer*) as well as various parameters that are described in Section 2.1. Initially the default values will usually be selected for all parameters by entering 'return', at every prompt (obviously, filenames can be changed, but the names should not exceed ten characters). For the purposes of this example, an assumption is made that all the default values have been accepted. The program will then display a "working…" message, followed by percentage complete messages.

At this point the program will either complete 100% of the fitting successfully, in which case step 2 should be ignored, or will fail.

2) If the initial fitting of the data has failed, the *diagnostic* file should be examined. Error messages suggesting new starting values for the input parameters may be displayed, in which case *BVN* should be re-run with the new values input. If after several attempts an error free run can not be achieved, different options are available (see Section 2.1).

3) Having successfully fitted all the distributions and consequently generated all the required output files, the user should then examine the *rhovalues* and *diagnostic* files, as described in Section 2.1.

At this point it may be necessary to use the *MIX* program as an alternative to *BVN*. Steps 1 and 2 are then repeated with *MIX*. *SIMMIX* as opposed to *SIMBVN* is subsequently used. If this is not the case then the user can proceed with *SIMBVN*.

NB: Both *SIMBVN* and *SIMMIX* default to the same output filenames, *transfer* and *diagnostic.*

3.4 Operation of *SIMBVN*

1) On execution of *SIMBVN* the user is prompted for the input files (*datafile* and *transfer*) and output filenames (default = *marginals* and *simdata*). **The information on the dependence between water levels and wave heights is input manually at this point (Section 2.5) with reference to the *diagnostic* file**. A threshold of non-exceedance is selected, above which the correlation coefficient should be approximately constant. The user is also required to specify a lower limit of steepness, this cut-off prevents the generation of spurious sea states (i.e. high wind-sea H_s coupled with a very high period, more typical of a swell-sea steepness). **Care should be taken when selecting this value if the data is from a source where low steepness waves are important (i.e. where swell is predominant).**

2) The number of records per year and number of records to be synthesised are input at this point. The program then calculates the marginal extremes of wave height and water level based on the fitted GPD's, and offers the option of re-scaling (Section 2.5). If the re-scaling option is selected the user is prompted to input fifteen extreme values (real numbers with a space between each number) for the return periods specified, in place of those calculated by the program. Care should be taken when entering these values to ensure the correct numbers are input (a single error means having to begin the program again). Additional checks can be made by reference to the *marginals* output file and the marginal results (determined by counting back) detailed in the *extremes* file output from *ANALYSIS*.

3) If the number of records to be simulated is potentially sufficient to cause file storage and handling problems an option of filtering the output written to the *simdata* file is given.

Having successfully completed the previous steps the program then simulates the data. This can take a long time (several hours) depending on the speed of the cpu being used, and the number of records being synthesised.

3.5 Operation of the *ANALYSIS* program

1) Operation of the *ANALYSIS* program is relatively straight forward; the user specifies the input filename containing the long-term simulation (*simdata*) and output filename (default = *extremes*) and then selects the options required (see Section 2.6).

2) It is recommended that a visual check be made on the summarised joint exceedance results output from *ANALYSIS*. These joint exceedance combinations can be plotted as contours overlaid on a scatter plot of the original H_s and water level data. The expected number of exceedances of a specified joint exceedance return period contour can be calculated for independent and dependent cases by the following formulae

$\mu_T = t/T \ln (nT)$ for independence

$\mu_T = t/T$ for dependence

Where:-
μ_T = expected number of exceedances of the T year contour
T = joint exceedance return period
n = number of events per year
t = number of years of observations

If the two variables are positively correlated the number of expected values should lie between the calculated dependent and independent cases. Figure 4 shows an example plot of 14 years of wave height and water level data for North Wales. The number of events per year was 662. The expected number of exceedances of the 10 year joint exceedance contour would be 12.8 (if wave heights and water levels were independent). The actual number counted on the plot is 14. This is slightly higher then expected considering there is a small positive correlation (for the majority of the data) at the site. However, the data does include two exceptionally high joint exceedance return period events that occurred in early 1990. If these two events are discounted the number of exceedances of each contour are consistent with the above formulae.

The equation given for the dependent case also applies to single variable extremes, and can be used to make an approximate check on the accuracy of the marginal extremes predictions if required.

4. USE OF THE RESULTS

4.1 Introduction

The new approach can provide all of the outputs available from alternative methods. For example, marginal distributions and extremes, joint exceedance extremes, joint probability density, direct calculation of the distribution and extremes of structural response variables and parameters of all fitted distributions. It can thus provide input to both 'design sea state' and 'risk-based' analysis of sea defences.

4.2 Warnings

<u>Use of joint exceedance probability combinations</u>

There are many different combinations of wave heights and water levels for any given joint exceedance return period. The output from *ANALYSIS* details some of them. It is not always obvious which combination is the 'worst case', in terms of structural response. **Therefore, all combinations should be considered**. Generally, even when a 'worst case' has been found, the return period of the structural response calculated from it will be less (typically by a factor of about two) than the joint exceedance return period (see Section 1.2 of report SR 537 (HR Wallingford, 2000)).

<u>Structural response functions</u>

The section of software that offers direct calculation and simulation of structural response variables is intended for demonstration purposes, and should therefore be used with caution. The coded equations represent only one method of calculating the response of interest. This may not be a suitable method for the site of intended use. **Therefore a full understanding of the coded equations, paying particular interest to the method of calculating the 'inshore wave conditions', should be gained before making use of this option**. It is suggested that for final design, users may prefer to apply their own design formulae directly to the simulated data, rather than using the *ANALYSIS* program.

<u>Re-scaling (event duration)</u>

As the input to the programs consists of wave records at high waters, the marginal extremes calculated from these records have, implicitly, an event duration of 12 hours (assuming 2 high waters per day). Often extreme wave heights are calculated assuming an event duration of 3 hours from a population of all wave heights (be they hourly or 3 hourly records). The subsequent 3-hour duration extremes could then be used for re-scaling purposes irrespective of water level. This would provide an inherently conservative estimate of extreme wave heights for use in joint probability analysis since, on average, only one in four 3-hour extremes will occur at high water. If it is required to re-scale wave heights using refined marginal extremes, then a convenient way to avoid this arbitrary conservatism is to re-calculate the refined marginal extremes using a 12-hour duration.

5. REFERENCES

1) Allsop N W H, Vicinanza D, Calabrese M and Centurioni L (1996) 'Breaking wave impact loads on vertical faces' ISOPE Conference, Los Angeles, California, USA.

2) CIRIA (1996) 'Beach management manual' Construction Industry Research and Information Association' Report 153.

3) CIRIA/CUR (1991) 'Manual on the use of rock in coastal and shoreline engineering' CIRIA special publication 83/CUR Report 154.

4) HR Wallingford (2000) 'The joint probability of waves and water levels: JOIN-SEA - A rigorous but practical new approach' HR Wallingford Report SR 537.

5) Owen M W (1980) 'Design of seawalls allowing for wave overtopping' HR Wallingford Report EX 924.

Figures

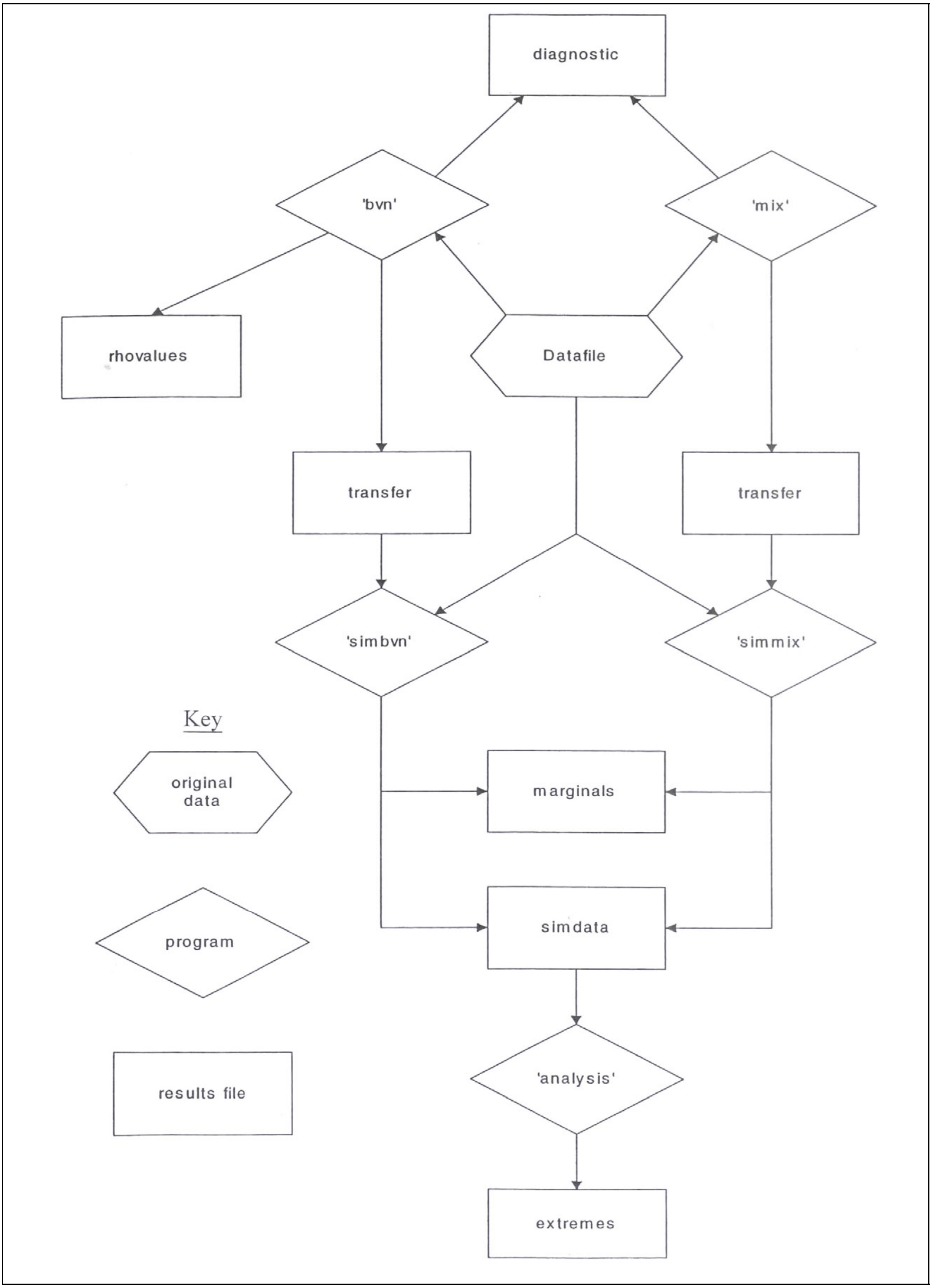

Figure 1 Diagram of program structure

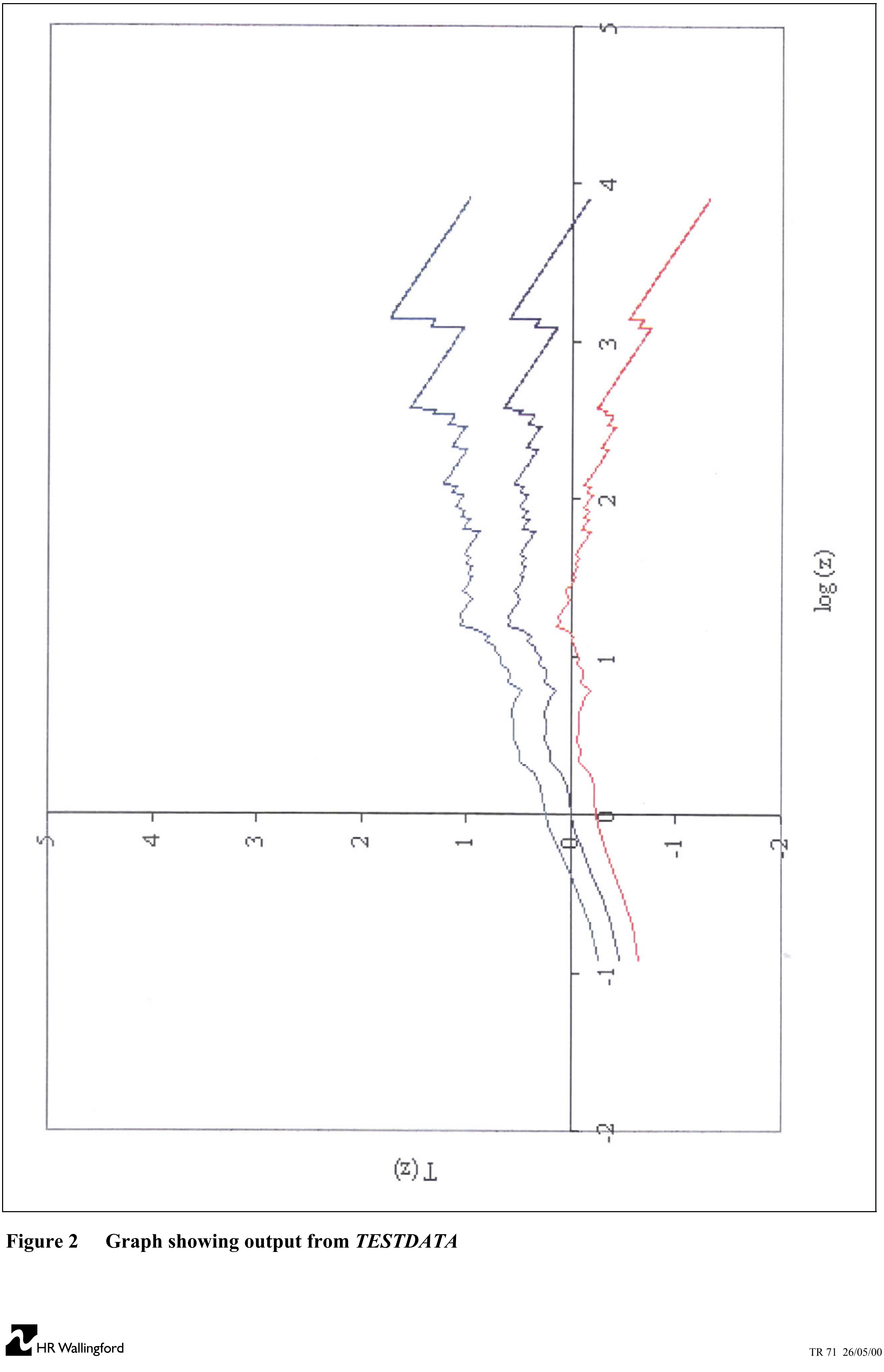

Figure 2 Graph showing output from *TESTDATA*

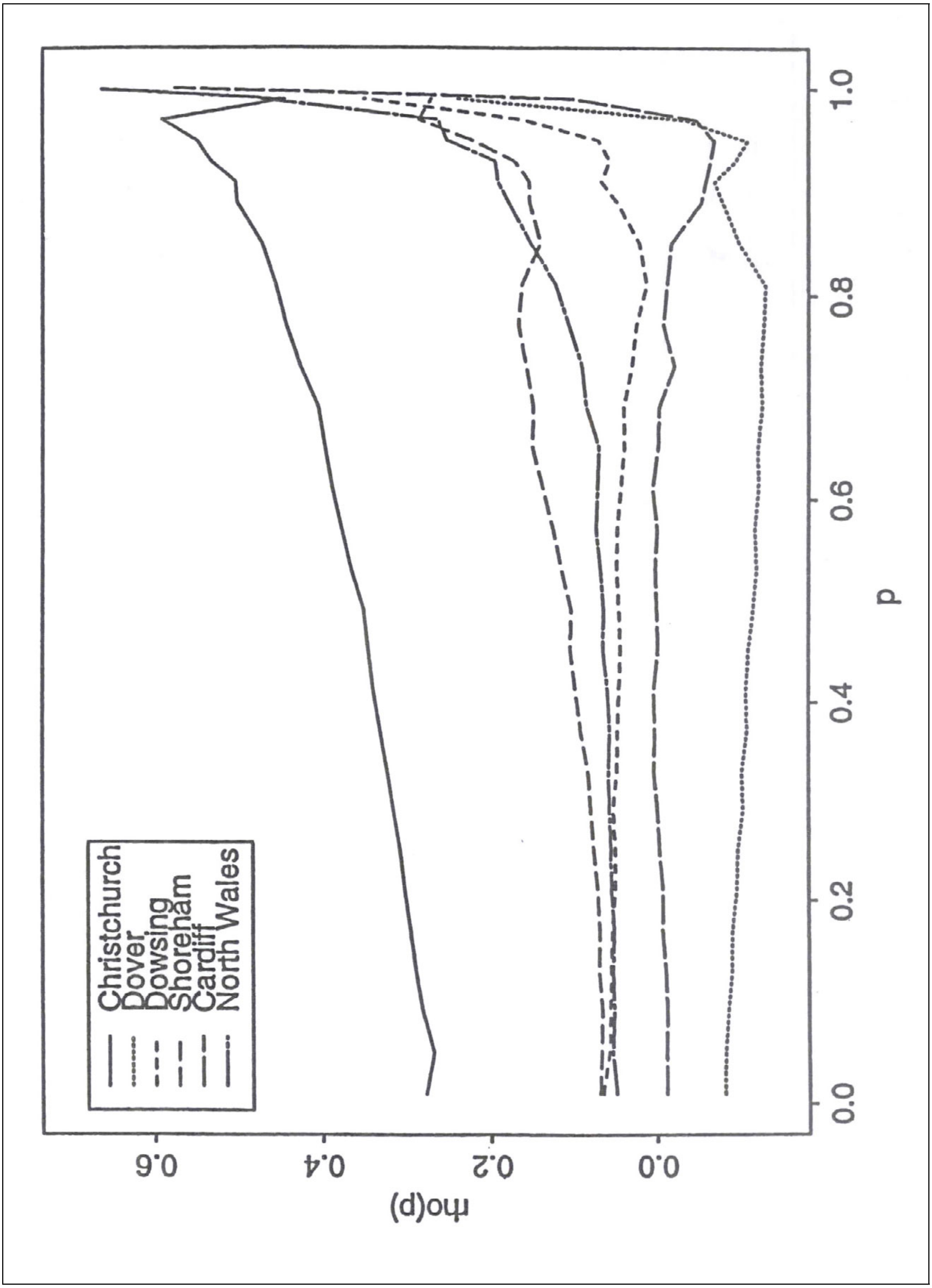

Figure 3 Correlation coefficient (rho) v's P(non-exceedance) for the six simdata sets

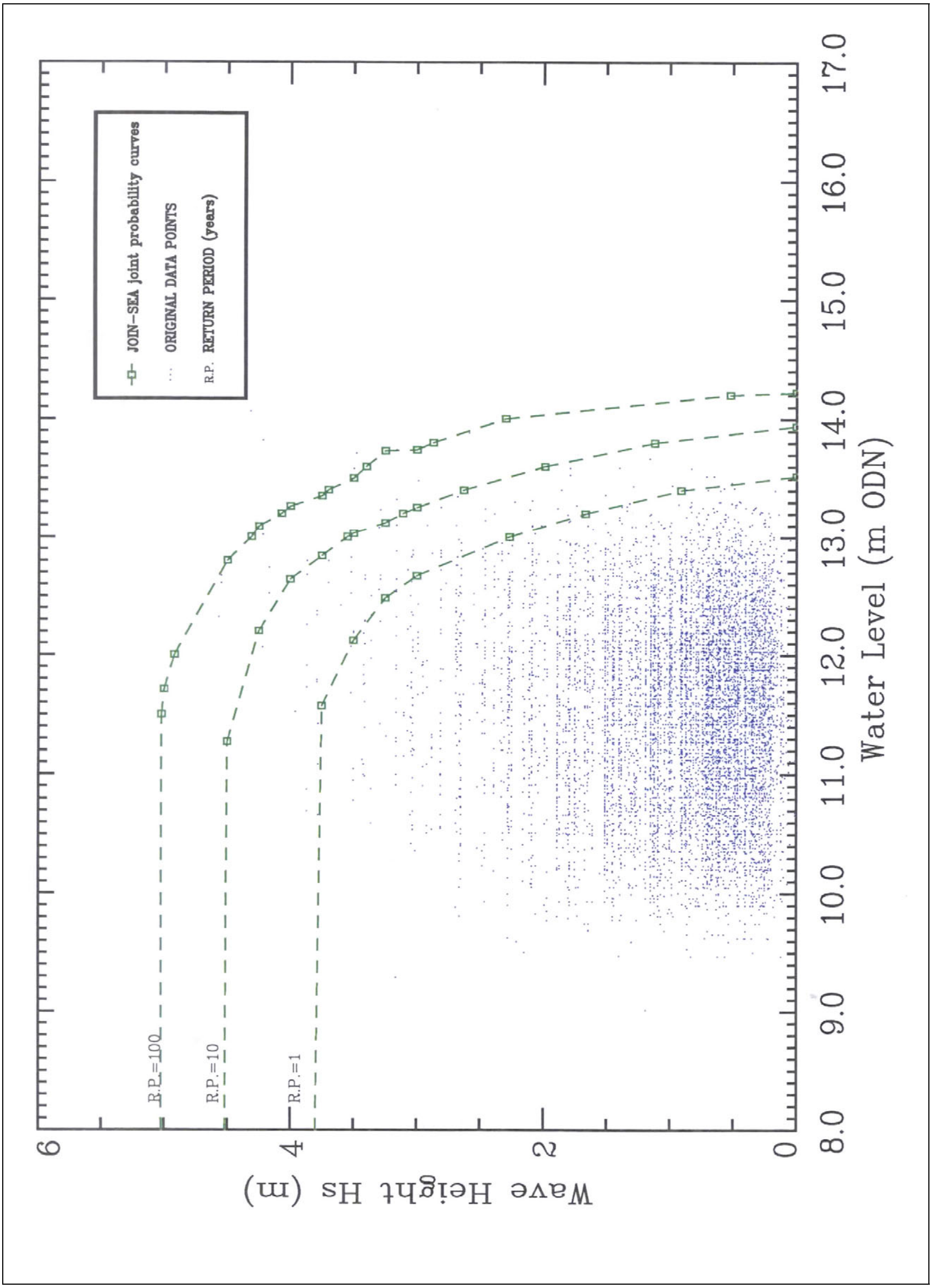

Figure 4 Joint exceedence contours overlaid on original data

Appendices

Appendix 1

Example *datafile*

Appendix 1 Example *datafile*

Example *datafile* (input *to TESTDATA, BVN, MIX, SIMBVN* and *SIMMIX*)

```
North Wales data
Column 1: Wave height
Column 2: Water level
Column 3: Period
 0.2000  10.3550   2.0200
 0.7700  10.6920   3.5200
 1.0000  10.3870   5.2100
 1.5100  10.6610   6.0200
 1.0900  10.4470   5.1700
 0.8800  10.7220   4.2200
 1.3000  10.7220   5.0400
 0.6900  11.0570   4.0300
 0.2700  11.1490   2.6500
 1.1900  11.6350   4.3100
 2.6500  11.6050   6.7300
 1.8900  11.7580   6.2400
 0.4600  11.9720   3.0300
 0.7000  12.2770   3.5900
 1.6100  12.3680   4.9200
 1.4400  12.3970   4.7100
 0.9900  13.0380   4.1100
 0.8700  12.6420   3.3300
 0.7400  13.0080   3.1400
 0.4000  12.6420   2.9300
 0.9000  12.9460   3.9400
 0.7900  12.5500   3.7300
 0.4800  12.7950   2.6600
 0.3600  12.0620   2.8900
 0.9800  12.5200   4.1000
 0.5500  11.4230   3.2800
 0.3700  10.4470   2.6000
 1.0800  10.6920   4.2400
 0.9600  10.3550   4.0100
 1.1100  10.3870   4.2400
 1.2600  10.8120   3.8400
 0.8700  10.8120   3.3300
 0.9900  10.6920   4.1100
 1.0000  11.0270   3.5100
 0.8700  11.4230   3.3300
 0.7400  11.1780   3.1400
 1.1300  11.8800   3.6800
 0.8700  11.6350   3.3300
 0.4400  11.8190   2.6200
 0.6700  11.6660   3.5000
 1.4400  11.9720   4.7100
 1.0800  11.7580   4.2400
 0.7100  11.8800   3.6100
 0.8400  12.0320   3.8600
 0.4800  12.1850   2.6600
 0.6000  11.7270   2.9200
 0.2300  12.0320   2.2700
 0.1800  11.6050   2.3500
 0.2400  11.8190   2.6500
 0.4600  11.4230   3.0300
 0.5500  11.5740   3.2800
   .        .        .
   .        .        .
   .        .        .
```

Appendix 2

Example questions and output from *TESTDATA*

Appendix 2 Example questions and output from *TESTDATA*

```
This program does a diagnostic test on Hs/WL data
 -------------------------------------------------


 To choose the default file names just hit return


 Give the name of the input data file with Hs/WL/Tm records    [default = datafile  ]:
 And the name of the output file for the diagnostic messages   [default = testresult]:

 North Wales data

 Information on diagnostic statistic "T(z)"
 ------------------------------------------

 Number of records in file =    9272

 Starting calculations ...

  log(z)       T(z)   95% confidence limits for T(z)
  ------       ----   ------------------------------

 -0.91629   -0.46011    -0.65262    -0.26761
 -0.69315   -0.39225    -0.59135    -0.19316
 -0.51083   -0.29043    -0.49779    -0.08308
 -0.35667   -0.19277    -0.40929     0.02376
 -0.22314   -0.11445    -0.34029     0.11138
 -0.10536   -0.04088    -0.27658     0.19481
  0.00000    0.00000    -0.24427     0.24427
  0.09531    0.02149    -0.23034     0.27332
  0.18232    0.02714    -0.23116     0.28543
  0.26236    0.08201    -0.18651     0.35054
  0.33647    0.20365    -0.08154     0.48884
  0.40547    0.20462    -0.08710     0.49633
  0.47000    0.24705    -0.05524     0.54934
  0.53063    0.23602    -0.07144     0.54348
  0.58779    0.23105    -0.08203     0.54413
  0.64185    0.25109    -0.07031     0.57249
  0.69315    0.21921    -0.10443     0.54286
  0.74194    0.19023    -0.13574     0.51619
  0.78846    0.14371    -0.18226     0.46967
  0.83291    0.25008    -0.09454     0.59469
  0.87547    0.23105    -0.11664     0.57874
  0.91629    0.23902    -0.11519     0.59322
  0.95551    0.30516    -0.06380     0.67412
  0.99325    0.29559    -0.07748     0.66866
  1.02962    0.34883    -0.03778     0.73545
  1.06471    0.34549    -0.04610     0.73708
  1.09861    0.41337     0.00518     0.82156
  1.13140    0.38058    -0.02761     0.78877
  1.16315    0.46216     0.03428     0.89004
  1.19392    0.60574     0.14492     1.06656

  A full set of results is stored in file: testresult
```

Appendix 3

Example questions and output files from BVN

Appendix 3 Example questions and output files from BVN

Example questions from *BVN*

```
This program fits a Bivariate Normal to Hs/WL data
--------------------------------------------------


To choose the default values just hit return


Give the name of the input data file with Hs/WL/Tm records  [default = datafile  ]  :
Give the name of the output file for the dependence values  [default = rhovalues ]  :
And the name of the output file for the diagnostic messages [default = diagnostic]  :
And the name of the output transfer parameters storage file [default = transfer  ]  :

Reading input data from file named: datafile
Title: North wales data
Number of records in the input file =  9272

Input of the starting points and thresholds

Starting point for dependence (Hs/WL)  : between -0.50 and  0.80 [default =  0.10]  :

Csi1 and sigma1 relate to the GPD fitting of Hs
Csi2 and sigma2 relate to the GPD fitting of WL
Starting point for parameter csi1 (Hs) : between -0.50 and  0.50 [default =  0.01]  :
Starting point for parameter csi2 (WL) : between -0.50 and  0.50 [default =  0.01]  :
Starting point for value   sigma1 (Hs) : between  0.00 and 10.00 [default =  0.30]  :
Starting point for value   sigma2 (WL) : between  0.00 and 10.00 [default =  0.30]  :

Threshold prob-less-than of Hs GPD fit : between  0.00 and  0.99 [default =  0.95]  :
Threshold prob-less-than of WL GPD fit : between  0.00 and  0.99 [default =  0.95]  :

The remaining parameters relate to wave steepness:
Starting point for constant for (S/Hs): between -10.00 and 10.00 [default =  0.10]  :
Starting point for coefficient  (S/Hs): between -10.00 and 10.00 [default =  0.10]  :
Starting point for sigma^2 for  (S/Hs) : between  0.00 and 10.00 [default =  0.30]  :

Threshold prob-less-than-Hs for (S/Hs) : between   0.00 and 0.99 [default =  0.95]  :

Working ...

  10%
  20%
```

Example output from *BVN* - *rhovalues* file

JOIN-SEA Version 1.0

North Wales data

% less	rho best	rho low	rho high
0.00000	0.05086	0.03055	0.07111
0.02500	0.05112	0.03077	0.07142
0.05000	0.05165	0.03122	0.07203
0.07500	0.05386	0.03334	0.07433
0.10000	0.05550	0.03487	0.07606
0.12500	0.05475	0.03400	0.07545
0.15000	0.05469	0.03381	0.07552
0.17500	0.05325	0.03223	0.07422
0.20000	0.05568	0.03451	0.07681
0.22500	0.05736	0.03602	0.07866
0.25000	0.05658	0.03503	0.07808
0.27500	0.05850	0.03673	0.08017
0.30000	0.05734	0.03533	0.07926
0.32500	0.05930	0.03707	0.08145
0.35000	0.06124	0.03874	0.08365
0.37500	0.05922	0.03643	0.08193
0.40000	0.05867	0.03555	0.08171
0.42500	0.06280	0.03931	0.08621
0.45000	0.06583	0.04198	0.08958
0.47500	0.06457	0.04032	0.08873
0.50000	0.06790	0.04322	0.09250
0.52500	0.06712	0.04192	0.09223
0.55000	0.06923	0.04347	0.09491
0.57500	0.07436	0.04801	0.10063
0.60000	0.07439	0.04739	0.10132
0.62500	0.07119	0.04345	0.09887
0.65000	0.07280	0.04424	0.10129
0.67500	0.08018	0.05066	0.10962
0.70000	0.08982	0.05928	0.12026
0.72500	0.09475	0.06303	0.12639
0.75000	0.09775	0.06455	0.13088
0.77500	0.10637	0.07148	0.14112
0.80000	0.11643	0.07951	0.15314
0.82500	0.13903	0.09977	0.17798
0.85000	0.15232	0.10998	0.19425
0.87500	0.16323	0.11691	0.20904
0.90000	0.17532	0.12336	0.22657
0.92500	0.21720	0.15777	0.27531
0.95000	0.25735	0.18423	0.32781
0.97500	0.32404	0.22232	0.41898
0.99000	0.47336	0.33040	0.59467

Example output from *BVN – diagnostic* file

```
JOIN-SEA Version 1.0

North Wales data

Starting point and threshold information
----------------------------------------

Starting point for dependence (Hs/WL)  :  0.10
Starting point for parameter csi1 (Hs) :  0.01
Starting point for parameter csi2 (WL) :  0.01
Starting point for value   sigma1 (Hs) :  0.30
Starting point for value   sigma2 (WL) :  0.30
Threshold prob-less-than of Hs GPD fit :  0.95
Threshold prob-less-than of WL GPD fit :  0.95
Starting point for constant for (S/Hs) :  0.10
Starting point for coefficient  (S/Hs) :  0.10
Starting point for sigma^2 for  (S/Hs) :  0.30
Threshold prob-less-than-Hs for (S/Hs) :  0.95


Information on GPD fitting of Hs
--------------------------------

csi1   = -0.158331
sigma1 =  0.611912
prob. of exceedance      =  0.049827
Hs at this probability   =  2.270000
Standard error of csi1   =  0.043258
Standard error of sigma1 =  0.038616


Information on GPD fitting of WL
--------------------------------

csi2   = -0.050147
sigma2 =  0.226524
prob. of exceedance      =  0.050043
WL at this probability   = 12.777000
Standard error of csi2   =  0.047554
Standard error of sigma2 =  0.015046


Information on dependence Hs/WL
-------------------------------

Probability of non-exceedance =  0.000000   Rho =   0.050859
Probability of non-exceedance =  0.025000   Rho =   0.051120
Probability of non-exceedance =  0.050000   Rho =   0.051651
Probability of non-exceedance =  0.075000   Rho =   0.053864
Probability of non-exceedance =  0.100000   Rho =   0.055496
Probability of non-exceedance =  0.125000   Rho =   0.054750
Probability of non-exceedance =  0.150000   Rho =   0.054692
Probability of non-exceedance =  0.175000   Rho =   0.053247
Probability of non-exceedance =  0.200000   Rho =   0.055680
Probability of non-exceedance =  0.225000   Rho =   0.057360
Probability of non-exceedance =  0.250000   Rho =   0.056577
Probability of non-exceedance =  0.275000   Rho =   0.058499
Probability of non-exceedance =  0.300000   Rho =   0.057338
Probability of non-exceedance =  0.325000   Rho =   0.059300
Probability of non-exceedance =  0.350000   Rho =   0.061238
Probability of non-exceedance =  0.375000   Rho =   0.059221
Probability of non-exceedance =  0.400000   Rho =   0.058667
Probability of non-exceedance =  0.425000   Rho =   0.062802
```

```
Probability of non-exceedance =  0.450000   Rho =   0.065826
Probability of non-exceedance =  0.475000   Rho =   0.064570
Probability of non-exceedance =  0.500000   Rho =   0.067905
Probability of non-exceedance =  0.525000   Rho =   0.067115
Probability of non-exceedance =  0.550000   Rho =   0.069227
Probability of non-exceedance =  0.575000   Rho =   0.074359
Probability of non-exceedance =  0.600000   Rho =   0.074392
Probability of non-exceedance =  0.625000   Rho =   0.071189
Probability of non-exceedance =  0.650000   Rho =   0.072801
Probability of non-exceedance =  0.675000   Rho =   0.080184
Probability of non-exceedance =  0.700000   Rho =   0.089824
Probability of non-exceedance =  0.725000   Rho =   0.094750
Probability of non-exceedance =  0.750000   Rho =   0.097754
Probability of non-exceedance =  0.775000   Rho =   0.106375
Probability of non-exceedance =  0.800000   Rho =   0.116425
Probability of non-exceedance =  0.825000   Rho =   0.139032
Probability of non-exceedance =  0.850000   Rho =   0.152316
Probability of non-exceedance =  0.875000   Rho =   0.163235
Probability of non-exceedance =  0.900000   Rho =   0.175319
Probability of non-exceedance =  0.925000   Rho =   0.217204
Probability of non-exceedance =  0.950000   Rho =   0.257351
Probability of non-exceedance =  0.975000   Rho =   0.324037
Probability of non-exceedance =  0.990000   Rho =   0.473359


Information on fitting of S/Hs
------------------------------

cons (S/Hs)    = -0.148705
coef (S/Hs)    =  0.288735
sigma^2 (S/Hs) =  0.176975
standard error of cons    =   0.029305
standard error of coef    =   0.052234
standard error of sigma^2 =   0.011633
```

Example output (input to *SIMBVN) – transfer* file

```
North Wales data

-0.15833087783879D+00 | csi1    for GPD fitting of Hs
 0.61191175414712D+00 | sigma1  for GPD fitting of Hs
 0.95017255102058D+00 | non-exceedance prob.   for Hs

-0.50146550697460D-01 | csi2    for GPD fitting of WL
 0.22652434724318D+00 | sigma2  for GPD fitting of WL
 0.94995689445115D+00 | non-exceedance prob.   for WL

-0.14870462297776D+00 | cons for fitting of S/Hs data
 0.28873477949965D+00 | coef for fitting of S/Hs data
 0.17697508235531D+00 | sigma^2 for fitting S/Hs data
 0.95001000000000D+00 | non-exceed prob for S/Hs data
```

Appendix 4

Example questions and output from *MIX*

Appendix 4 Example questions and output from *MIX*

Example questions from *MIX*

```
This program fits two overlapping BVNs to Hs/WL data
----------------------------------------------------


To choose the default values just hit return


Give the name of the input data file with Hs/WL/Tm records    [default = datafile  ]
And the name of the output file for the diagnostic messages   [default = diagnostic]
And the name of the output file for the diagnostic messages   [default = diagnostic]
And the name of the output transfer parameters storage file   [default = transfer  ]

Reading input data from file named: datafile
Title: North Wales data
Number of points in the input file =  9272

Input of the starting points and thresholds

Csi1 and sigma1 relate to the GPD fitting of Hs
Csi2 and sigma2 relate to the GPD fitting of WL
Starting point for parameter   csi1 (Hs) : between -0.50 and  0.50 [default =  0.01]
Starting point for parameter   csi2 (WL) : between -0.50 and  0.50 [default =  0.01]
Starting point for value of  sigma1 (Hs) : between  0.00 and 10.00 [default =  0.30]
Starting point for value of  sigma2 (WL) : between  0.00 and 10.00 [default =  0.30]

Threshold prob-less-than for Hs GPD fit  : between  0.00 and  0.99 [default =  0.95]
Threshold prob-less-than for WL GPD fit  : between  0.00 and  0.99 [default =  0.95]

The following parameters are for the mixture of BVNs
Starting point for prob (of lower Hs/WL) : between  0.03 and  0.97 [default =  0.80]
Starting point for dep. (of lower Hs/WL) : between -0.50 and  0.80 [default =  0.10]
Starting point for dep. (of upper Hs/WL) : between  -0.50 and 0.80 [default =  0.30]
Starting point for mu21 (of upper Hs/WL) : between  0.05 and 10.00 [default =  0.30]
Starting point for mu22 (of upper Hs/WL) : between -1.00 and 10.00 [default =  0.30]
Starting point for sigma21 (upper Hs/WL) : between  0.00 and 10.00 [default =  0.30]
Starting point for sigma22 (upper Hs/WL) : between  0.00 and 10.00 [default =  0.30]

The remaining parameters relate to wave steepness:
Starting point for constant for  (S/Hs) : between -10.00 and 10.00 [default =  0.10]
Starting point for coefficient of(S/Hs) : between -10.00 and 10.00 [default =  0.10]
Starting point for sigma^2 for    (S/Hs) : between  0.00 and 10.00 [default =  0.30]

Threshold prob-less-than-Hs for   (S/Hs) : between  0.00 and  0.99 [default =  0.95]

Working ...



Marginal distributions of Hs and WL are fitted

Now fitting the two BVNs: this can take a long time,
roughly proportional to the number of data records,
and even longer if the starting estimates were poor

Now calculating standard errors of the fitted BVN
parameters: this does not take quite so long

Finished:
Please check the diagnostic file for messages
```

<u>Example output from *MIX* (input to *SIMMIX*) – *transfer*</u>

```
North Wales data

-0.15833087783879D+00 | csi1    for GPD fitting of top Hs
 0.61191175414712D+00 | sigma1  for GPD fitting of top Hs
 0.95017255102058D+00 | non-exceedance prob.   for top Hs

-0.50146550697460D-01 | csi2    for GPD fitting of top WL
 0.22652434724318D+00 | sigma2  for GPD fitting of top WL
 0.94995689445115D+00 | non-exceedance prob.   for top WL

 0.63391672832839D-01 | probability of BVN1 (lower Hs/WL)
 0.39819015779044D+00 | dependence of Hs/WL rho1 for BVN1
 0.22353994612344D-01 | dependence of Hs/WL rho2 for BVN2
 0.12517571187171D+00 | fitted parameter of mu21 for BVN2
-0.78283597857019D+00 | fitted parameter of mu22 for BVN2
 0.31918780334845D+00 | fitted parameter sigma21 for BVN2
 0.85292139258196D+00 | fitted parameter sigma22 for BVN2

-0.14870462297776D+00 | cons for fitting of top S/Hs data
 0.28873477949965D+00 | coef for fitting of top S/Hs data
 0.17697508235531D+00 | sigma^2 for fitting top S/Hs data
 0.95001000000000D+00 | non-exceed prob for top S/Hs data
```

<u>Example output from *MIX – diagnostic*</u>

```
JOIN-SEA Version 1.0

North Wales data

Starting point and threshold information
----------------------------------------

Starting point for parameter   csi1 (Hs) :  0.01
Starting point for parameter   csi2 (WL) :  0.01
Starting point for value of  sigma1 (Hs) :  0.30
Starting point for value of  sigma2 (WL) :  0.30
Threshold prob-less-than for Hs GPD fit  :  0.95
Threshold prob-less-than for WL GPD fit  :  0.95
Starting point for prob (of lower Hs/WL) :  0.80
Starting point for dep. (of lower Hs/WL) :  0.10
Starting point for dep. (of upper Hs/WL) :  0.30
Starting point for mu21 (of upper Hs/WL) :  0.30
Starting point for mu22 (of upper Hs/WL) :  0.30
Starting point for sigma21 (upper Hs/WL) :  0.30
Starting point for sigma22 (upper Hs/WL) :  0.30
Starting point for constant for   (S/Hs) :  0.10
Starting point for coefficient of (S/Hs) :  0.10
Starting point for sigma^2 for    (S/Hs) :  0.30
Threshold prob-less-than-Hs for   (S/Hs) :  0.95


Information on GPD fitting of Hs
--------------------------------

csi1   = -0.158331
sigma1 =  0.611912
prob. of exceedance      =  0.049827
Hs at this probability   =  2.270000
Standard error of csi1   =  0.043258
Standard error of sigma1 =  0.038616


Information on GPD fitting of WL
--------------------------------

csi2   = -0.050147
sigma2 =  0.226524
prob. of exceedance      =  0.050043
WL at this probability   = 12.777000
Standard error of csi2   =  0.047554
Standard error of sigma2 =  0.015046
```

```
Information on fitting of two BVNs to Hs/WL
-------------------------------------------

mix prob =  0.063392
rho1     =  0.398190
rho2     =  0.022354
mu21     =  0.125176
mu22     = -0.782836
sigma21  =  0.319188
sigma22  =  0.852921

Standard error of prob =  0.058363
Standard error of rho1 =  0.085203
Standard error of rho2 =  0.022203
Standard error of mu21 =  0.530183
Standard error of mu22 =  0.173399
Standard error sigma21 =  0.085711
Standard error sigma21 =  0.211547


Information on fitting of S/Hs
------------------------------

cons (Hs/S)    = -0.148705
coef (Hs/S)    =  0.288735
sigma^2 (Hs/S) =  0.176975
standard error of cons    =   0.029305
standard error of coef    =   0.052234
standard error of sigma^2 =   0.011633
```

Appendix 5

Example questions and output files to *SIMBVN*

Appendix 5 Example questions and output files to *SIMBVN*

Example of input questions to *SIMBVN*

```
This program simulates Hs/WL data using the fitted Bivariate Normal distribution
 ------------------------------------------------------------------------------


 To choose the default values just hit return


 Give the name of the input data file with Hs/WL/Tm record  [default = datafile  ]  :
 Give the name of the input file containing BVN parameters  [default = transfer  ]  :
 And the name of the output file for the simulated records  [default = simdata   ]  :
 And the name of the output file for the extremes analysis  [default = marginals ]  :

 Reading input data from file named: datafile
 Title: North Wales data

 Number of points in the input file =  9272

 Reading GPD parameters for Hs from file: transfer
 Reading GPD parameters for WL from file: transfer
 Reading S/Hs dist. parameters from file: transfer

 Now give the parameters of the dependence model

 Threshold non-exceedance for dependence model of Hs/WL : between   0.00 and  0.99  [default =
0.90]  :
 Correlation coefficient for Hs/WL above this threshold : between  -0.50 and  0.80  [default =
0.10]  :

 Lower limit for wave steepness (2.0*pi*Hs) / (g*Tm*Tm) : between   0.00 and  0.04  [default =
0.02]  :

 Now some information about numbers of records

 Total number of events per year for this type of data  : between  10 and     8766  [default =
707]  : 662
 Number of output Hs/WL/Tm data records to synthesise   : between 100 and 70700000  [default
=707000]  : 662000

 Original marginal extremes of Hs and WL
 ---------------------------------------

 Return period   Wave height   Water level

      0.2           3.268       13.188
      0.5           3.655       13.372
      1.0           3.913       13.506
      2.0           4.144       13.636
      5.0           4.413       13.800
     10.0           4.592       13.920
     20.0           4.752       14.035
     50.0           4.939       14.181
    100.0           5.063       14.288
    200.0           5.174       14.391
    500.0           5.304       14.521
   1000.0           5.390       14.616
   2000.0           5.468       14.707
   5000.0           5.558       14.824
  10000.0           5.618       14.908

 Do you want to re-scale the extreme Hs values?  [default = n         ]  :
 Do you want to re-scale the extreme WL values?  [default = n         ]  :
```

```
Preparing equations ...

Starting simulation ...

    10%
    20%
    30%
    40%
    50%
    60%
    70%
    80%
    90%
    100%

Collecting data in file ...

662000 Hs/Tm/WL records written to output file
representing  1000 years of data @ 662 per year

Average wave steepness over the S/Hs model threshold = 0.030
```

Example output from *SIMBVN* - *marginals* file

```
JOIN-SEA Version 1.0

North Wales data

 Original marginal extremes of Hs and WL
 ---------------------------------------

 Return period   Wave height   Water level

      0.2           3.268        13.188
      0.5           3.655        13.372
      1.0           3.913        13.506
      2.0           4.144        13.636
      5.0           4.413        13.800
     10.0           4.592        13.920
     20.0           4.752        14.035
     50.0           4.939        14.181
    100.0           5.063        14.288
    200.0           5.174        14.391
    500.0           5.304        14.521
   1000.0           5.390        14.616
   2000.0           5.468        14.707
   5000.0           5.558        14.824
  10000.0           5.618        14.908

 Average wave steepness over the S/Hs model threshold = 0.030
```

Example output from *SIMBVN* (input to *ANALYSIS*)– *simdata* file

```
JOIN-SEA Version 1.0

North Wales data

      662 | Number of events per year (of a total of 662)
   662000 | Number of records in file
     1000 | Number of years in sample

  Wave    Wave    Water
 height  period   level
 1.2800  5.6818 11.5740
 0.5300  2.7823 12.1230
 0.4800  3.9207 12.8610
 1.0500  4.9827 11.4210
 0.3200  2.7101 12.1790
 0.5700  2.9700 12.0390
 0.2600  2.6103 11.7770
 0.8200  3.6091 11.4780
 1.0700  5.2292 11.2600
 0.2500  2.3171 10.6090
 0.7900  4.9265 11.4530
 0.6300  3.9178 10.5890
 2.6310  7.5779 10.0890
 1.2700  5.5719 12.4890
 0.4700  3.1327 11.1190
 0.5200  3.7003 11.2190
 0.6900  3.5687 10.3890
 0.2700  2.8781 11.2190
 1.0000  4.0927 12.1740
 1.0400  5.7711 11.0890
 1.2900  5.9516 12.8950
 0.4200  2.7844 10.9040
 0.8300  4.8381 13.0137
 0.9100  4.3500 11.2790
 1.6100  6.7358 12.0890
 0.9600  5.5447 12.6290
 0.3500  2.5872 12.0690
 2.2700  7.3681 12.6590
 1.7900  6.5845 12.2990
 0.3600  2.4713 11.6350
 0.2900  2.5213 11.4790
 0.4800  3.4700 10.3870
 1.1200  5.0500 12.3360
 0.2000  1.8878 11.1490
 0.5400  4.1373 10.5060
 0.5500  2.7727 12.4970
 1.0300  5.7433 10.7220
 0.6200  3.3786 11.1470
 0.1900  2.3297 10.0810
```

Appendix 6

Example questions from *SIMMIX*

Appendix 6 Example questions from *SIMMIX*

Example questions from *SIMMIX*

```
This program simulates Hs/WL data using the fitted mixture of BVN distributions
 ------------------------------------------------------------------------------


 To choose the default values just hit return


 Give the name of the input data file with Hs/WL/Tm record  [default = datafile  ]  :
 Give the name of the input file containing MIX parameters  [default = transfer  ]  :
 And the name of the output file for the simulated records  [default = simdata   ]  :
 And the name of the output file for the extremes analysis  [default = marginals ]  :

 Reading input data from file named: datafile
 Title: North Wales data

 Number of points in the input file =  9272

 Reading GPD parameters for Hs from file: transfer
 Reading GPD parameters for WL from file: transfer
 Reading mixture of BVN parameters  from: transfer
 Reading S/Hs dist. parameters from file: transfer


 Lower limit for wave steepness Hs/Lm : between   0.00 and  0.04  [default =  0.02]  :

 Now some information about numbers of records

 Total number of data events per year: between  10 and 8766  [default =   707]  : 662
 Number of data records to synthesise: between 100 and 70700000[default=707000]:662000

 Original marginal extremes of Hs and WL
 ---------------------------------------

 Return period   Wave height   Water level

      0.2           3.298       13.201
      0.5           3.681       13.385
      1.0           3.936       13.519
      2.0           4.164       13.648
      5.0           4.431       13.812
     10.0           4.608       13.931
     20.0           4.766       14.046
     50.0           4.951       14.192
    100.0           5.074       14.298
    200.0           5.184       14.400
    500.0           5.313       14.530
   1000.0           5.398       14.625
   2000.0           5.475       14.716
   5000.0           5.564       14.832
  10000.0           5.623       14.916

 Do you want to re-scale the extreme Hs values?  [default = n         ]  :
 Do you want to re-scale the extreme WL values?  [default = n         ]  :

 Preparing equations ...
```

```
Starting simulation ...

    10%
    20%
    30%
    40%
    50%
    60%
    70%
    80%
    90%
    100%

Collecting data in file ...


662000 Hs/Tm/WL records written to output file
representing  1000 years of data @ 662 per year

Average wave steepness over the S/Hs model threshold = 0.030
```

Appendix 7

Example questions and output from *ANALYSIS*

Appendix 7 Example questions and output from *ANALYSIS*

<u>Example of questions from *ANALYSIS*</u>

```
Give name of the input file of synthetic data   [default = simdata   ]  :
Give the output file for the extremes analysis  [default = extremes  ]  :

Reading input data from file named: simdata
Title: North Wales data
Containing:  662000 simulated records
Representing:  1000.00 years of data:
Records are assumed to be Hs(m)/Tm(s)/WL(m)


There are several types of extremes analysis
available, although they are intended only for
demonstration purposes and not for final design

Respond "y" or "Y" to any that you want to try

Do you want to analyse the marginal extremes?  [default = n         ]  :
Do you want analysis of the joint extremes?    [default = n         ]  : y

Give seven water levels at which to derive Hs

13.0 13.2 13.4 13.6 13.8 14.0 14.2

Give seven wave heights at which to derive WL

3.0 3.25 3.5 3.75 4.0 4.25 4.5

Do you want analysis of extreme overtopping?   [default = n         ]  : y

Give overtopping parameter "a": between  0.007 and   1.000 [default =  0.0192]  :
Give overtopping parameter "b": between  4.800 and  65.200 [default = 46.9600]  :
Give the sea wall crest level : between  0.000 and 100.000 [default = 5.0000]   :14.5
Give the wall slope roughness : between  0.500 and   1.000 [default =  1.0000]  :
Give toe elevation at sea wall: between -99.00 and  10.000 [default =-50.0000]  :

Do you want analysis of the extreme forces?    [default = n         ]  : y

Give toe elevation at sea wall : between -99.000 and  10.000  [default =-50.0000]  :

Do you want to analyse the extreme run-up?     [default = n         ]  : y

Give sea wall slope (1 in ??)  : between   1.000 and  20.000  [default =  2.0000]  :
Give toe elevation at sea wall : between -99.000 and  10.000  [default =-50.0000]  :

Do you want analysis of likely armour size?    [default = n         ]  : y

Give sea wall slope (1 in ??)  : between   1.000 and  20.000  [default =  2.0000]  :
Give toe elevation at sea wall : between -99.000 and  10.000  [default =-50.0000]  :
Give stone permeability factor : between   0.100 and   0.600  [default =  0.6000]  :
Give stone damage level factor : between   2.000 and  17.000  [default =  3.0000]  :
```

Example output from *ANALYSIS– extremes* file

```
JOIN-SEA Version 1.0

North Wales data

 Analysing:  662000 simulated records
 Representing:  1000.00 years of data


Estimates of extreme wave height Hs (m)
---------------------------------------

       Return    Wave
       period   height

          0.1    2.949
          0.2    3.272
          0.5    3.657
          1.0    3.912
          2.0    4.130
          5.0    4.395
         10.0    4.558
         20.0    4.742
         50.0    4.921
        100.0    5.024
        200.0    5.120
        500.0    5.288


Average wave steepness over the S/Hs model threshold = 0.030


Estimates of extreme water level (m)
-----------------------------------

       Return    Water
       period    level

          0.1   13.044
          0.2   13.194
          0.5   13.384
          1.0   13.519
          2.0   13.649
          5.0   13.821
         10.0   13.937
         20.0   14.017
         50.0   14.142
        100.0   14.216
        200.0   14.266
        500.0   14.475
```

Estimates of extreme wave height (m)

for a water level of above 13.00 (m)

Return period	Wave height
1.0	2.270
2.0	2.699
5.0	3.221
10.0	3.549
20.0	3.755
50.0	4.052
100.0	4.314
200.0	4.426
500.0	4.837

Estimates of extreme wave height (m)

for a water level of above 13.20 (m)

Return period	Wave height
1.0	1.670
2.0	2.110
5.0	2.743
10.0	3.108
20.0	3.472
50.0	3.821
100.0	4.067
200.0	4.426
500.0	4.837

Estimates of extreme wave height (m)

for a water level of above 13.40 (m)

Return period	Wave height
1.0	0.910
2.0	1.490
5.0	2.110
10.0	2.625
20.0	2.942
50.0	3.404
100.0	3.697
200.0	3.926
500.0	4.676

Estimates of extreme wave height (m)

for a water level of above 13.60 (m)

Return period	Wave height
2.0	0.550
5.0	1.450
10.0	1.990
20.0	2.577
50.0	3.044
100.0	3.404
200.0	3.809
500.0	4.426

Estimates of extreme wave height (m)

for a water level of above 13.80 (m)

Return period	Wave height
5.0	0.400
10.0	1.120
20.0	1.750
50.0	2.595
100.0	2.875
200.0	3.218
500.0	3.809

Estimates of extreme wave height (m)

for a water level of above 14.00 (m)

Return period	Wave height
20.0	0.610
50.0	1.450
100.0	2.304
200.0	2.595
500.0	2.959

Estimates of extreme wave height (m)

for a water level of above 14.20 (m)

Return period	Wave height
100.0	0.520
200.0	1.380
500.0	1.610

Estimates of extreme water level (m)

for a wave height of above 3.00 (m)

Return period	Water level
1.0	12.671
2.0	12.871
5.0	13.081
10.0	13.248
20.0	13.353
50.0	13.606
100.0	13.742
200.0	13.908
500.0	13.941

Estimates of extreme water level (m)

for a wave height of above 3.25 (m)

Return period	Water level
1.0	12.479
2.0	12.729
5.0	12.989
10.0	13.125
20.0	13.280
50.0	13.480
100.0	13.729
200.0	13.765
500.0	13.941

Estimates of extreme water level (m)

for a wave height of above 3.50 (m)

Return period	Water level
1.0	12.123
2.0	12.529
5.0	12.839
10.0	13.025
20.0	13.186
50.0	13.357
100.0	13.499
200.0	13.694
500.0	13.926

Estimates of extreme water level (m)

for a wave height of above 3.75 (m)

Return period	Water level
1.0	11.574
2.0	12.184
5.0	12.640
10.0	12.839
20.0	13.015
50.0	13.257
100.0	13.353
200.0	13.640
500.0	13.926

Estimates of extreme water level (m)

for a wave height of above 4.00 (m)

Return period	Water level
2.0	11.549
5.0	12.302
10.0	12.640
20.0	12.833
50.0	13.081
100.0	13.257
200.0	13.357
500.0	13.754

Estimates of extreme water level (m)

for a wave height of above 4.25 (m)

Return period	Water level
5.0	11.635
10.0	12.199
20.0	12.589
50.0	12.888
100.0	13.090
200.0	13.327
500.0	13.754

Estimates of extreme water level (m)
----
for a wave height of above 4.50 (m)

Return period	Water level
10.0	11.269
20.0	12.107
50.0	12.640
100.0	12.797
200.0	12.898
500.0	13.480

Average wave steepness over the S/Hs model threshold = 0.030

Summary of joint probability extremes

Joint return (years)	Water level (m)	Wave height (m)
1.0	0.00	3.91
1.0	11.57	3.75
1.0	12.12	3.50
1.0	12.48	3.25
1.0	12.67	3.00
1.0	13.00	2.27
1.0	13.20	1.67
1.0	13.40	0.91
1.0	13.52	0.00
2.0	0.00	4.13
2.0	11.55	4.00
2.0	12.18	3.75
2.0	12.53	3.50
2.0	12.73	3.25
2.0	12.87	3.00
2.0	13.00	2.70
2.0	13.20	2.11
2.0	13.40	1.49
2.0	13.60	0.55
2.0	13.65	0.00
5.0	0.00	4.39
5.0	11.64	4.25
5.0	12.30	4.00
5.0	12.64	3.75
5.0	12.84	3.50
5.0	12.99	3.25
5.0	13.00	3.22
5.0	13.08	3.00
5.0	13.20	2.74
5.0	13.40	2.11
5.0	13.60	1.45
5.0	13.80	0.40
5.0	13.82	0.00
10.0	0.00	4.56
10.0	11.27	4.50
10.0	12.20	4.25
10.0	12.64	4.00
10.0	12.84	3.75

10.0	13.00	3.55
10.0	13.03	3.50
10.0	13.12	3.25
10.0	13.20	3.11
10.0	13.25	3.00
10.0	13.40	2.63
10.0	13.60	1.99
10.0	13.80	1.12
10.0	13.94	0.00
20.0	0.00	4.74
20.0	12.11	4.50
20.0	12.59	4.25
20.0	12.83	4.00
20.0	13.00	3.76
20.0	13.01	3.75
20.0	13.19	3.50
20.0	13.20	3.47
20.0	13.28	3.25
20.0	13.35	3.00
20.0	13.40	2.94
20.0	13.60	2.58
20.0	13.80	1.75
20.0	14.00	0.61
20.0	14.02	0.00
50.0	0.00	4.92
50.0	12.64	4.50
50.0	12.89	4.25
50.0	13.00	4.05
50.0	13.08	4.00
50.0	13.20	3.82
50.0	13.26	3.75
50.0	13.36	3.50
50.0	13.40	3.40
50.0	13.48	3.25
50.0	13.60	3.04
50.0	13.61	3.00
50.0	13.80	2.60
50.0	14.00	1.45
50.0	14.14	0.00
100.0	0.00	5.02
100.0	12.80	4.50
100.0	13.00	4.31
100.0	13.09	4.25
100.0	13.20	4.07
100.0	13.26	4.00
100.0	13.35	3.75
100.0	13.40	3.70
100.0	13.50	3.50
100.0	13.60	3.40
100.0	13.73	3.25
100.0	13.74	3.00
100.0	13.80	2.87
100.0	14.00	2.30
100.0	14.20	0.52
100.0	14.22	0.00
200.0	0.00	5.12
200.0	12.90	4.50
200.0	13.00	4.43
200.0	13.20	4.43
200.0	13.33	4.25
200.0	13.36	4.00
200.0	13.40	3.93
200.0	13.60	3.81

200.0	13.64	3.75
200.0	13.69	3.50
200.0	13.77	3.25
200.0	13.80	3.22
200.0	13.91	3.00
200.0	14.00	2.60
200.0	14.20	1.38
200.0	14.27	0.00
500.0	0.00	5.29
500.0	13.00	4.84
500.0	13.20	4.84
500.0	13.40	4.68
500.0	13.48	4.50
500.0	13.60	4.43
500.0	13.75	4.00
500.0	13.75	4.25
500.0	13.80	3.81
500.0	13.93	3.50
500.0	13.93	3.75
500.0	13.94	3.00
500.0	13.94	3.25
500.0	14.00	2.96
500.0	14.20	1.61
500.0	14.47	0.00

Estimates of extreme overtopping rate (m3/m/s)

Return period	Overtopping rate
0.1	0.311
0.2	0.501
0.5	0.808
1.0	1.073
2.0	1.342
5.0	1.739
10.0	2.062
20.0	2.359
50.0	2.743
100.0	3.247
200.0	3.848
500.0	4.793

```
 0.0192 | overtopping parameter "a"
 46.960 | overtopping parameter "b"
 14.500 | sea wall crest elevation
  1.000 | sea wall slope roughness
 -50.00 | toe elevation at sea wall
   5.00 | approach slope (1 in ???)
```