CHAPTER 367

Probabilistic Risk Assessment of Beach Erosion at Pevensey Bay in England

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Abstract

This paper presents a comprehensive case study in which probabilistic methods were applied to assess the risk of damage to properties protected by a shingle beach on the south coast of England. Both the short term storm response and longer-term longshore drift effects were considered. The mathematical model was calibrated against data from an extensive series of physical model tests and was used to predict the shoreline evolution for a number of beach management design options. A full cost-benefit analysis was carried out based on the predicted damage probabilities. The general methodology developed is believed to be applicable to other situations with different beach material types and various design options.

Introduction

In recent years, the limitations of a conventional semi-probabilistic approach in coastline studies and scheme development have become more widely recognised. In studying beach processes, hydraulic parameters such as extreme waves, tides and surges are usually specified in terms of single parameter return periods or joint return periods. The safety of the structure, or the level of protection it provides, is ensured by selecting design conditions (generally waves and water levels) which, individually and/or in combination, have a sufficiently remote chance of occurring. No explicit reliability calculations are undertaken and the precise level of damages over the design life, due to overtopping, breaching and erosion, is unknown. Consequently, the standard of protection that coastal defence schemes may be expected to achieve

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can only be given in terms of the return periods of these input parameters rather than the damages which may be expected to occur. The success of such an approach would require that the return period of any damages is not lower than the return periods of the corresponding input parameters, a condition that can not be guaranteed *a priori* in a non-linear multi-parameter dynamic system such as a beach. By comparison with traditional methods, a direct technique which aims at evaluating the probabilities of occurrence of the beach processes that are actually responsible for the flood damages gives more meaningful design conditions. It also enables the evaluation of the variabilities and uncertainties in the damage estimates and provides a rational basis for cost-benefit assessment to be used as an integral part of scheme development.

The probabilistic design concept in coastal engineering is not new. It has been used in the design of breakwaters, seawalls and sand dunes as shown in a recent review on probabilistic design of flood defences by Vrijling (1990). Nearly all of the previous applications were restricted to dealing with the short term response of coastal defence structures under extreme forcing conditions, and the methodology used was largely based upon standard theories and techniques developed for the reliability of structures. Only very recently has some attention been paid to longshore processes. Vrijling and Swart (1992) presented a probability Level II method for berm breakwater design to evaluate the cumulative damage to the breakwater as the result of the longshore transport of rocks under extreme angular wave attack. Both Level II and Level III methods were employed by Vrijling and Meijer (1992) to assess long term shoreline evolution using a one-line shoreline model as the transfer function. Both the practical value of such approaches in engineering assessment and the uncertainties involved were highlighted by these workers.

The advantages of adopting a probabilistic approach and some important practical issues concerning its application in scheme development were presented by Riddell (1993). Probably, due to the lack of quality long term data and the perceived complexity of probability methods, the coastal engineering community are still showing signs of reluctance in adopting such methods in the design of beach management schemes. However, this situation is about to change in the UK with the introduction of new design guidelines from the Government which emphasise the need for rational cost-benefit analysis, the long term sustainability of engineering works and the need for all coastal works to be carefully evaluated in the light of global considerations.

The paper presents a comprehensive case study in which a probabilistic methodology was applied to assess the risk of damage to properties protected by a shingle beach on the south coast of England. Both the short term storm response and longer-term longshore drift effects were considered. The mathematical model was calibrated against data from an extensive series of physical model tests and was used to predict the shoreline evolution for a number of beach management design options. A full cost-benefit analysis was carried out based on the predicted damage probabilities. The general methodology developed is believed to be applicable to other situations with different beach material types and various design options.

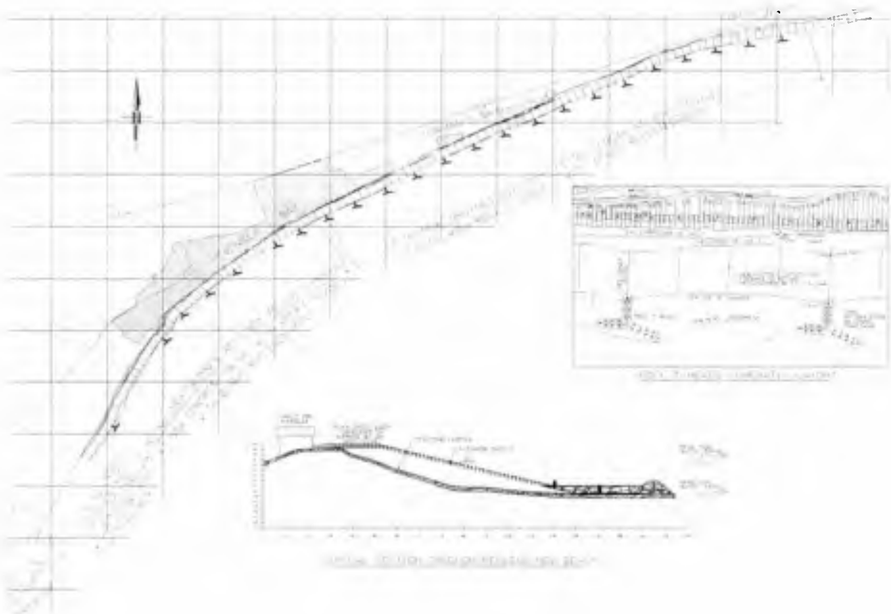

Figure 1 - Site Plan of Pevensey Bay

Site characteristics and design objectives

Pevensey Bay (Figure 1) has a shoreline 9km in length curving from a north/south alignment to east/west in a fairly classical bay configuration. Its beach is formed by shingle material above the mean water level grading rapidly to sand below this point. The shingle ridges, which are generally low and narrow, stand as a fragile

Figure 2

line of defence to the moderately well-developed low lying areas immediately behind the beach crest. Along several sections of the frontage, the beach has suffered from severe depletion of the mobile material and a large part of the existing timber groyne system has also been badly damaged, being, effectively, near the end of its useful life. Over the last twenty years extreme storms, combined with high tides, have, on a number of occasions, resulted in overtopping, beach crest recession and even small-scale breaching. These events have brought about considerable damages, not least of which were the costs of mobilising emergency services and carrying out rehabilitation measures to ensure some continued standard of protection. This situation can be best illustrated by an aerial view and a land-based photograph (Figure 2) of one of many critical locations showing the close proximity of housing to the crest of the shingle beach.

The threat of much larger breaching of the defences in the near future led the former National Rivers Authority (now part of the Environment Agency) to engage Babtie Group to carry out a comprehensive study of the Pevensey frontage lasting for a period of well over four years (1991-1995). During the first phase of this project, extensive data (both contemporary and historic) were collected and analysed with regard to waves, currents, sediment characteristics, beach profiles and past damages. Deterministic mathematical models were used to predict the beach response during extreme storm attack and the long term shoreline evolution over many years of average wave climate. These field data and predictions were used in an approximate cost-benefit analysis and for the preliminary design of a range of management options. During the second phase of the project, a detailed assessment of a limited number of potential scheme options was carried out, involving an extensive physical modelling programme and numerical model predictions.

Having realised the deficiencies of the deterministic methods that were used in the first phase, the decision was made to apply probabilistic techniques for both beach recession predictions and cost-benefit analysis. In this paper some of the work carried out in the second phase of the project is presented, with special emphasis on the use and validation of the probabilistic methods for beach recession predictions and cost-benefit analysis.

Methodology

General approach

The study methodology identified storm beach response as the primary process to be assessed in order to determine the type and severity of erosion, breach and levels of flooding. The probabilistic approach used for crest recession and overtopping was a simplified version of a full Level III approach with the erosion due to long-term longshore drift gradient being treated as an independent addition to the short-term crest recession.

Extensive physical model tests were carried out in the random wave flume and wave basin at HR Wallingford. The purpose of these tests was to assess the beach response under selected design storm waves and average morphological conditions over a period of 5 years. For the flume tests, 9 conditions were tested having estimated joint wave and water level return periods ranging from 1 in 1 year to 1 in 250 years. These tests were carried out on three profiles and two different gradings of beach material. Beach profile development for each test condition was recorded and used to calibrate a mathematical model. In the basin tests, one morphological condition and three (two for some cases) storm conditions were used. The full wave climate was represented by four equivalent wave spectra with increasing energy but decreasing probability of occurrence. The water levels were controlled to follow a predetermined tidal cycle. The data from the physical model tests were used to adjust the predictions made by the mathematical models. The return periods of overtopping and crest recession were calculated using a twenty year hindcast joint wave and water level time series, both including and excluding an allowance for long term sea level rise.

From wave refraction analysis and inshore monitoring results, it was found that the inshore wave climate exhibits considerable change from one end of the frontage to the other. In order to account for this variation, the use of different design wave conditions at different sections of frontage, for the purpose of cross-shore process analysis, was necessary. Due to these longshore changes of wave climate, as well as the change in shoreline orientation, large gradients in littoral drift exist at a number of sections of the shoreline. The effect of this was confirmed by observations that these beaches were known to be prone to erosion and required continuous maintenance. Therefore, longshore structural erosion was included in the overall risk analysis.

In developing design options, the probability of various levels of damage was determined for each beach management scenario, and these probabilities were then used to carry out a comprehensive cost-benefit analysis. This methodology is summarised in Box 1.

Transfer functions

A key element in the design methodology is the transfer function which determines the response of the system for a given set of input parameters. In coastal engineering, the transfer functions are usually in the form of empirical equations or models or process-based mathematical models. Deterministic beach profile responses during storms have been parameterised by Dean (1972), Van der Meer (1991) and Powell (1991). Among these models the **B**each **P**rofile **P**rediction **M**odel by Powell was developed specifically for shingle beaches based on extensive physical model tests and validated against a certain amount of (mainly UK) field data. This was therefore selected for the present work.

In order to limit the number of random variables that have to be considered, the model parameters were treated as deterministic and adjustable to give the best fit to the site specific data from the flume tests. In the case of Pevensey Bay such adjustments were required for only one of the three profiles considered. This was largely due to the influence of the limited thickness of the shingle layer at the location of this profile. It should be pointed out that the relationship as described by the BPPM model, between the equilibrium profile shapes and the input wave and water-level parameters, is highly non-linear and dependent upon the characteristics of the initial profile. Therefore, the predicted probability distribution of crest recession for different profiles could be quite different not just in terms of numeric values but also in the shape of the overall distribution.

APPROACH

Response of beach to specific storm events

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Generalisation to cover complete wave climate

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Application to joint wave and water level series

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Probability of crest recession, overtopping and breach

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Probability of damages

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Preferred Design

Box 1

Input Data

The input data can be classified into two main types: hydraulic data and morphological data. The hydraulic data consisted of a twenty year inshore joint wave and high water level time series, obtained by transferring a hindcast offshore time series to a number of inshore locations using a spectral back-tracking model (OUTRAY by HR Wallingford). The hindcasting model was calibrated against one year of offshore directional wave data obtained at the site during the study period. The refraction model was calibrated against simultaneous inshore records obtained at two locations.

The morphological data consists of surveyed beach profiles, sediment sizes and shoreline positions. Cross-sections at 150m intervals of this and adjacent frontages had been taken annually for a period of twenty years and were used for the detailed assessment of recent shoreline evolution and sediment budget considerations. For simplicity of modelling, the morphological inputs were treated as deterministic. The appropriate mean values and variations for these morphological input data were derived using historical charts and the long term beach survey data.

Prediction procedures

When considering cross-shore processes, it is important to preserve the essential correlation in the wave and water time series. This rules out a probability Level II method which assumes the parameters to be independent and to follow Gaussian distributions. All the wave and water level records in the time series, apart from some small waves deemed to be insignificant, were directly input into the calibrated BPPM model to obtain a single time series for the beach crest movement. The predicted beach movements were then ranked and fitted with appropriate logarithmic distributions. The same calculations were performed for each of the three profiles, taken as being representative of sections of frontage, using the appropriate time series for different inshore points.

Longshore processes are more difficult to deal with, because they essentially have two time scales; one for long-term average movements of sediment and the other for short-term storm effects. Although the techniques of Vrijling and Swart (1992) could, at least in principle, be adopted for predicting the probability of long term average shoreline changes, difficulties arise when trying to combine the two sets of recession probabilities from cross-shore and alongshore calculations. The short-term effects due to oblique storm waves on the coastline development would also need to be determined separately.

Short of using a 3D or quasi-3D model as a transfer function, further assumptions on the potential correlation between short- and long-term processes and between cross-shore and longshore effects have to be made. Due to the lack of research concerning the above problems, longshore processes were treated as deterministic. As a result, the crest recession probabilities would be invariant although the reference shoreline position would change with time as predicted by a one-line model. The corrections to the reference shoreline position were introduced in the design assessment based on the basin test results.

Predictions of crest recession

Model calibration

In order to ensure that the transfer function used was reliable the numerical model (BPPM) was firstly calibrated against the crest recession data from the flume tests. It was found that the model predictions agreed well with the measurements from Profiles 2 and 3 but some adjustment was necessary for Profile 1 in order to achieve best overall fit. Similarly the one-line model predictions were also compared with the actual shoreline positions determined from the annual surveys for the same data period (20 years). To achieve best agreement, it was found that the transport parameter in the CERC formula 'K' should be about 0.04 assuming the existing groynes are virtually ineffective.

Cross-shore beach crest recession

Assuming that an equilibrium beach profile can be established over the period of one tidal cycle, under given wave and water level conditions, the time series of crest recession and overtopping rates can be calculated for a given beach configuration. The exceedance probability and the return periods of crest recession can then be determined using ranking statistics. Some of the results are shown in Figures 3 and 4. It can be seen that the active crest tends to establish seaward of the initial crest for most wave conditions during the twenty year record period whilst crest retreat takes place during only a small number of severe events. In order to determine the extreme crest recession, a logarithmic curve was fitted to the computational data. The crest recessions for the more extreme events such as 1 in 250 year, can be obtained by extrapolation of the fitted recession curves.

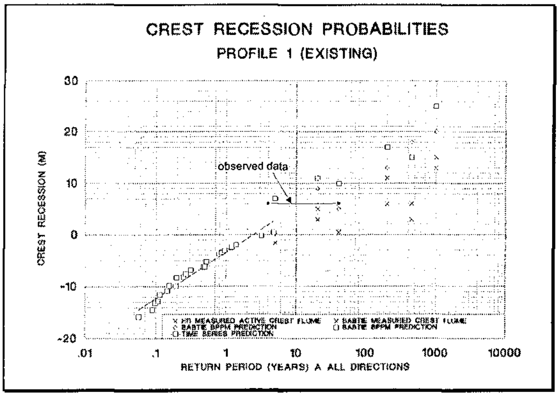

Figure 3

The above method is more easy to apply than a more conventional approach which involves extrapolating the joint probability density of wave and water level and then calculating the overtopping and crest recession for the extended records. This is due to the fact that the joint probability density function is very irregular at small values, and it is difficult to find a sensible surface to fit to these values. Whatever probability distributions is assumed, large errors are unavoidable in extrapolation.

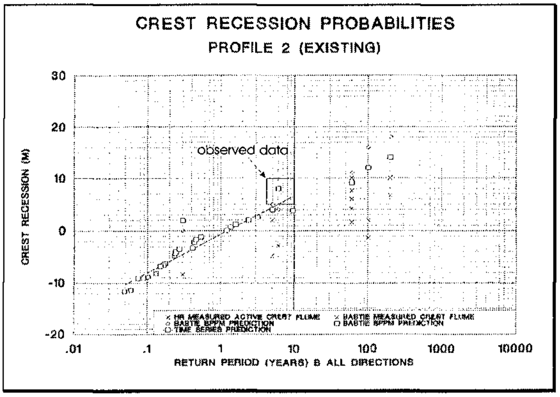

Figure 4

In general, the accuracy of the simpler method has been shown to depend on the data length, regularity of crest movement and the transfer functions adopted. From the model tests it was found that the beach can be 'washed off' by overtopping when its crest is very thin. This means that extrapolation of the predicted recession probability can not be extended indefinitely because the crest movement can change from progressive erosion to wash-out with only a very small change of input hydraulic conditions. A minimum crest width has been assumed on the basis of the model tests which represents this change of mode of beach damage. A 250 year return period was determined to be the upper cut-off limit for the extrapolation of beach processes at the study frontage.

Figures 3 and 4 also show the observed recession ranges during previous observed storms. Although the data are rather limited, and the quality of these data is far from ideal, it was quite satisfying to note that the predictions were consistent with the field data on all three profiles. Since the numerical model was only calibrated against data from the physical model, and for only a limited number of extreme storm conditions, the predictions obtained are considered to be remarkably good.

Effects Of Long Term Shoreline Evolution

Although the storm response of the beach is dominant in the determination of the level of risk at any particular point in time, the long-term shoreline evolution trend must be taken into account if the true risk level of a particular section of the

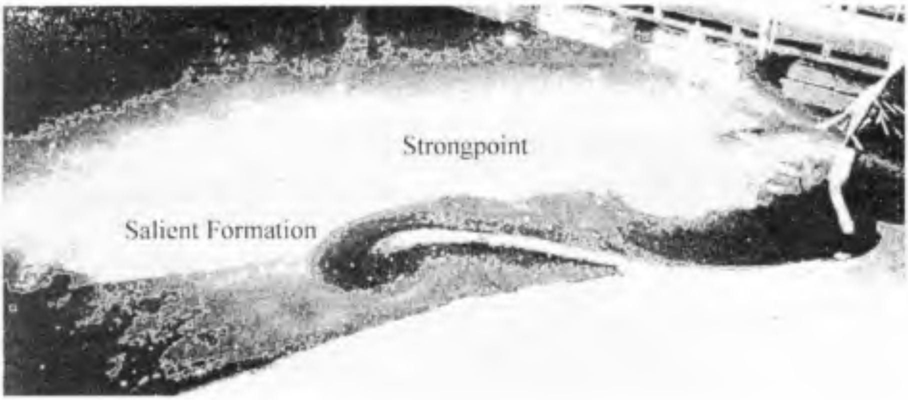

Figure 5, Strongpoint Basin Test in Progress

coastline, over a significant length of time, is to be established. For an open beach, the long term erosion due to the longshore transport gradient is usually fairly regular at a given site, depending, primarily, on the average wave climate, the supply of material and local shoreline orientation. The mean erosion rates for the Pevensey Bay frontage were calculated using a standard one-line model. In order to account for variability in the predictions of wave climate and sediment supply, the average shoreline position was determined for 5, 10, 20 and 50 year periods. The storm wave response probability was assumed to be invariant at any time within the design life of the defence. Although it is possible to introduce a higher level of probabilistic representation for the shoreline position than that used, such an approach was rejected on the grounds that the transfer function would have become too complicated to be practicable and no suitable method was found which was capable of dealing with the correlation between longshore and cross-shore processes in a consistent and robust way.

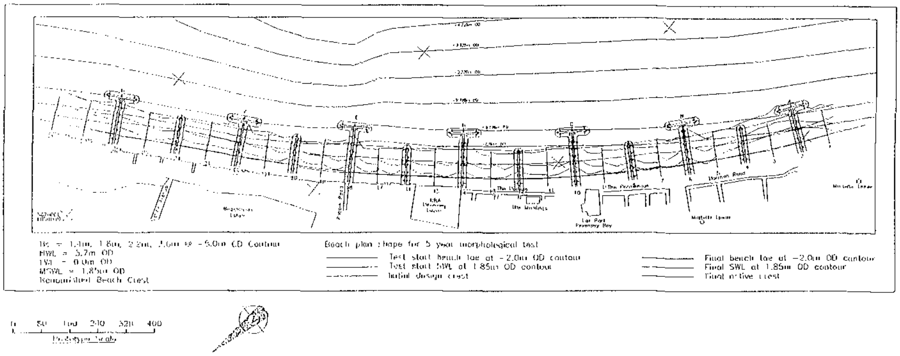

Figure 6 - Basin Test Results for mixed Rock T-head and Groyne Scheme

In developing the scheme options a number of beach management scenarios, ranging from timber groynes to large shore-attached rock structures, were tested in the wave basin. The crest movements under morphological and extreme storm conditions were obtained. Using similar techniques as described for the open beach case, the crest recession probabilities for each of the beach management options were estimated, taking into account the effects of the longshore gradient of drift rates during storm events. An example of a test in progress is shown in Figure 5 and an example of scheme test results in Figure 6. A comparison of the effect of different

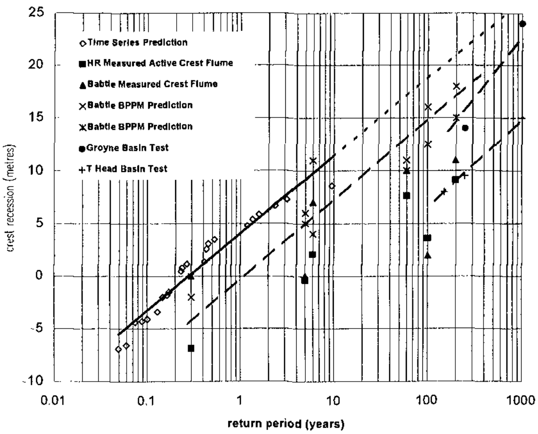

Figure 7 - Crest Recessions for various schemes

management options on the probability distribution of crest recession is shown in Figure 7.

Cost Benefit Analysis

The ultimate aim of all the preceding analyses is to generate damage probability graphs for all kinds of damage/loss considered. A typical graph for an open beach 'do-nothing' option is shown in Figure 8. In developing various design options, losses due to erosion, overtopping and breaching were all included wherever appropriate. The damage cost was assessed for each year during a nominal 50 year design life using appropriate discount factors. Since the total loss for any area is not always the simple sum of all probable losses, depending on the physical characteristics and economic values of the shoreline and hinterlands, and the interaction between them, care must be taken in deriving the total losses/damages.

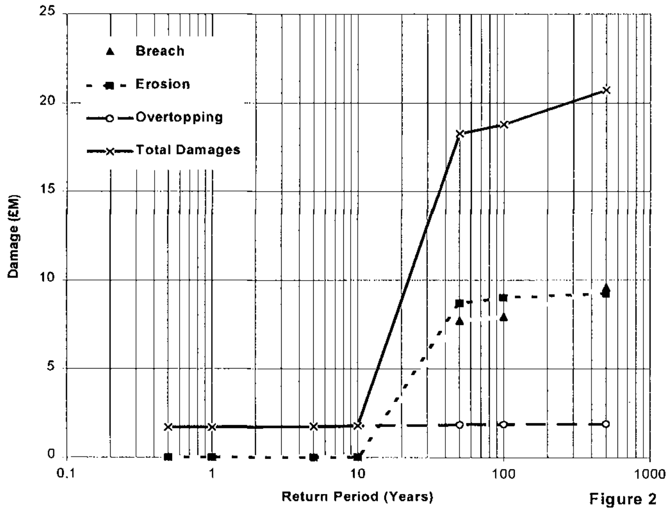

Figure 8 - Damage / Probability Profile

Discussion And Conclusions

A probabilistic design methodology has been developed which can be applied to shoreline studies, scheme design and the selection of management options. It provides a rational basis for the assessment of flooding risk and the standard of protection.

As long as the joint time series of wave and water level can be made available, it is straightforward to calculate the probability of run-up, overtopping and breaching using either empirical formulae or mathematical models. Physical modelling significant confidence to the results of the above and is essential for the consideration of non-standard situations.

Beach response is not just dependent on waves and water levels. Many other parameters are important such as the initial beach profile, material variability and storm duration and sequencing. A true probabilistic design methodology needs to take into account all of these parameters on a physical basis including systematic sensitivity assessments.

The transfer functions which provide the link between hydraulic parameters and beach processes are dependent on the configuration of the beach and detailed material properties. Great care must be taken when applying a transfer function developed for one type of beach condition to another.

Based on this study the following conclusions can be drawn

1. Predicted erosion probabilities are consistent with experimental data and some limited field observations.

2. The probabilistic method is no more difficult to apply than a conventional method, although it does require more long-term data and is therefore more time consuming.

3. Predictions are site dependent and sensitive to changes in the parameters characterising the beach and within the numerical model transfer function.

4. The damage modes treated in this study were limited and many other damage modes such as scouring, abrasion and offshore loss of beach material could be important at other beaches. Hence, design decisions made at one site should not be transferred to another site despite apparently similar features.

5. It has been found to be virtually impossible to deal with both long term and short term processes using the same high level of probabilistic techniques and within the prediction framework adopted. Research in this area is urgently required.

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