Defra/Environment Agency
Flood and Coastal Defence R&D Programme

Environmental change indicators (including those related to climate change) relevant to flood management and coastal defence

R&D Technical Report

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Statement of Use
This technical report contains the results of a study to identify a range of environmental change indicators (ECIs), including those resulting from climate change, which might provide early warning of trends in fluvial flooding and coastal erosion. The study is aimed primarily at staff of the Environment Agency and others involved in planning and management of flood defences.

- Keywords

Environmental change indicators, Flooding, Coastal erosion, Sea levels, POT series.

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EXECUTIVE SUMMARY

Environmental change is important to the flood defence industry because it may alter the flood risk and intended level of protection that is being given. Inevitably public concern focuses on changes that are expected to increase the flood risk on river floodplains or coastal flats. However, where change is giving a greater margin of safety over the design life of the protection works, there could be a lower risk if a downward environmental trend can be detected and quantified.

This project has sought to identify a wide range of possible Environmental Change Indicators (ECIs) for England and Wales related to floods, to locate data series over sufficiently long periods to make the ECI calculations valid, to produce a small number of pilot indicators, and to discuss their implications for future use and expansion.

The team assembled to carry out this work came from senior levels in a range of research organisations serving the industry. An initial open workshop tested ideas for ECIs; a narrower range of queries was then put to flood defence specialists by telephone questionnaire; a literature review was produced to avoid duplication of work; an interim paper was delivered to the September 2002 Keele River and Coastal Engineers conference; and then trial ECI series were completed to illustrate some of the proposed indicators and to enable this report to be presented.

Here the 'environment' being examined is that of river and sea level, being the most direct measure of flood risk. Some districts suffer the slower but persistent risk of groundwater flooding, so aquifer levels have also been considered, as have those catchment characteristics that change with time, such as forest cover and urban spread, and which may affect flood response to rainfall.

One strong message that emerged from the project was the difficulty in locating good quality records of sufficient length to enable meaningful trends to be detected (and here we include ‘stationarity’, or no apparent change over time as a ‘trend’). Given natural climatic variability, we have suggested that any data series should ideally be over 70 years long, yet apart from a number of long term daily rainfall records, a small number of river level and flow stations, an equally small number of groundwater records, and one or two tide gauges, few environmental records of more than 30 to 40 years can be found. It is hoped that the Environment Agency and others will continue to monitor many of the necessary environmental variables at a sufficient number of ‘bench mark’ stations needed for this, and other purposes, to enable maintenance of the selected indicators.

A large number of potentially useful indicators of environmental change were identified during an initial workshop and during subsequent study. Some of these were rejected because of lack of suitable data. Another group of environmental indicators concerning land-use was also rejected from further consideration, in part because suitable data are hard to obtain, but primarily because there are in some cases still only poorly understood causative linkages between these land-use variables and flooding. It does not seem that this group of indicators can currently offer planners and decision makers any useful guidance.

Amongst the issues arising from the study was the suggestion that some indicators might be thought of as ‘headline’ indicators of prime importance to national decision

makers, and perhaps also the public, along the lines of the 'Central' England temperature record, whilst others might be aimed more at local or regional decision makers, such as those derived from analysis of a single record or regional group of data. There is a need for both types of indicator, but we have proposed a number of headline indicators to assist detection of possible environmental change impacts on flood risk:

- The frequency of daily rainfalls over 25 mm for 5 km grid squares representative of various parts of England and Wales. The gridded data are maintained by the Met Office.
- Time series of annual maximum and POT groundwater levels at selected sites having good quality long records.
- Time series of annual maximum and POT river levels at 16 sites identified by Garrad (2002).
- Time series and POT analysis of mean sea levels at the five benchmark sites monitored by POL.

(Details of the websites where these data sets are held are given in chapter 6 of the technical report)

A number of potential secondary indicators are being developed by the Met Office, and will be made available to the wider community via their websites and other published sources. Some of the more useful of these for FCD might include ongoing work to analyse tipping bucket rain gauge data, which should in time yield information on trends in high-intensity storm rainfall, as might analysis of thunderstorm activity, indexed through lightning activity. However, whist it is encouraging that such data are being collected and analysed, it is likely to be some considerable time before sufficient good quality, consistent data become available to enable their use as reliable environmental change indicators.

We do not believe that for most other indicators investigated there are sufficient data available in some cases, or that excessive computation would be involved with others, or finally, that the indicator can be displayed in an intuitive manner to lay readers. Thus for many other indicators, we recommend that no further action is justified at present.

Dissemination of results is an important issue, and it is proposed that the National Water Archive web site, run from CEH Wallingford, will instigate, on the publication of this report, an Environmental Change Indicators links page for Flood Risk Management (ECIFRiM). This will be complemented by a hard copy version of the same web addresses being published in the Monthly Hydrological Summary for the UK. The webmasters of Defra, the Agency, the Met Office and POL will be asked to add links from their Flood Management pages to this master ECIFRiM links page.

Finally, the National Flood Forum has been approached to give a link from its web page to this same set of ECIFRiM sources, (links are generally preferred to copied material so that everyone sees concurrently the same updated Indicators).

It is suggested that these indicators be reviewed on a 3 to 5 year. This would ensure that the usefulness of all indicators is regularly re-examined by a panel of stakeholders to enable indicators of little perceived value to be discontinued, and also to identify any gaps in the indicator series.

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1. BACKGROUND

1.1 Introduction

The study was aimed at identifying, defining and selecting an appropriate range of indicators that would be likely to be representative of changes to environmental factors that will impact on, and give early warning of, changes in risk of flooding or coastal erosion. The indicators should seek to identify the changes in flood and coastal erosion risk due to a range of drivers in order to support policy development and implementation. Such indicators should be of value to those responsible for risk reduction and with managing and planning flood defence systems. Thus, potential users of the indicators might be government departments, local government planners, flood and coastal defence engineers, the insurance industry and local authorities amongst others.

A useful environmental indicator should be one that provides quantifiable information that measures environmental change, and should:

- be scientifically valid,
- be simple to understand,
- be sensitive, in that changes in flood risk are easily detected,
- enable temporal or spatial trends to be detected,
- provide early warnings to planners and decision makers of significant changes,
- be cost effective and maintainable using existing resources, and
- be based upon good quality data.

Indicators of value to flood and coastal defence engineers should concentrate on both identification of drivers of possible change, such as increases in temperatures, extreme rainfall, wind strength, falling land levels and so on, but also upon the consequences of such changes, on river and groundwater levels, upon relative sea levels, and upon waves and storm surges. As far as sea levels are concerned, what is of significance to coastal engineers is not simply changing absolute sea level, but rather changes in relative sea level. Thus for many parts of southern Britain, the absolute sea level is rising in response to global warming, but at the same time land levels are falling due to post-glacial recovery. Coastal defence must take account of both effects, and flood defences set accordingly.

It was intended that preference should be given to indicators based on readily available historical records enabling conclusions to be drawn during the project. However, should a need for a new indicator be established for which data do not at present exist, recommendations have been made as to what data are required and to who should collect such data. Such recommendations are supported by a broad assessment of the potential value of the proposed data collection activity.

It was intended that the study should then develop mechanisms for monitoring, analysing and interpreting the findings.

Some indicators should be ‘headline’ indicators aimed at national decision makers, and be analogous to the familiar Central England Temperature record (see Figure 3.1), whereas other indicators might be aimed more at regional or local decision makers, such as those derived from analysis of a single record or regional group of data. There may be a need for both types of indicator.

1.2 Objectives

The scientific objectives of the study were defined as:

1. To identify and define a broad range of indicators relevant to flood and coastal defence that are able to represent the impacts of environmental changes. The review will include: defining the types of indicators, reviewing and developing best-practice in the analysis and interpretation of environmental indicators, and identifying relevant indicators that are already collected.

2. To identify the data requirements for each of these indicators and who might be responsible for collecting the relevant data and maintaining the indicators.

3. To demonstrate the construction and usefulness of the more important of these indicators by utilising a limited amount of historic data from sample sites.

4. To establish sustainable means of disseminating the results.

5. To make recommendations for a review mechanism after a period of years.

The study has been led and managed by the Centre for Ecology and Hydrology at Wallingford (CEH-W) who were supported by Frank Law, who acted as project director and external referee on behalf of Defra and the EA.

The main contractor, CEH-W, was supported by inputs from staff of the Proudman Oceanographic Laboratory (POL), an associated component body within the Natural Environment Research Council (NERC). POL advised on all aspects relating to sea level changes and storm surges and their consequent impact upon coastal erosion and flooding. Further support was provided by HR Wallingford, who contributed primarily on wave effects on coastal erosion and flooding, and by the Meteorological Office, who contributed on climate, and particularly aspects of precipitation and its possible impact upon flooding and erosion.

2. BROAD APPROACH

The aim was to seek indicators which the flood defence industry could identify with and trust, and ones that were straightforward to define and robust when taken up separately by others. To those ends we have sought to carry out the project as publicly as possible, adopting five thrusts:

- An initial workshop of representative parties;
- A telephone questionnaire;
- A paper to the 2002 Defra Keele conference of river and coastal engineers;
- Public domain data usage, with no proprietary ownership of final indicators;
- Evaluation of a number of prospective indicators in this first phase work as examples of potentially useful indicators, but leaving wider regional development of any success to a subsequent phase.

Experience has taught us to recognise that there are human factors involved in the take-up of any indicator. Each user has his or her own responsibilities and career experience. So no one is likely to express huge enthusiasm for an indicator, however powerful, if it does not relate to his or her working life (or home situation). Nor will a user take readily to an untried indicator if it bears no relation to prior expectation; in such cases it is hoped that time will bring growing confidence.

By their nature indicators are trying to uncover:

- Possible trends in means of chosen extremes, and in variability affecting these;
- Any quasi-periodicity of those extremes;
- Any clustering rhythm and related 'strength' in rare events;
- Detection of any step change in the chosen phenomenon.

It is obvious that although indicators of this type may have a medium to long-term fore-sighting function, they cannot have a shorter-term forecasting function. Rather they can steady the nerve of anyone pressed to over-react to a current 'rare' event; or they may act as a wake-up call where there may be a temptation to reduce flood defence expenditure in a 'quiet' epoch for floods in the region (or nation). They should also answer insistent queries about the extent to which climate change has already taken effect. Finally, although it is suggested that the indicators be used to detect ‘trends’, there is equally merit in maintaining indicators that show no evidence of trend. Such evidence of ‘stability’ is every bit as valuable as early warning of increasing flood risk.

We consider that any 'good' indicator can readily be interpreted by eye once an appropriate graphical framework is made available. Sometimes this is a matter of scale, or labelling; at other times it may need a strong contrast between the blur of raw statistics and a line of fit. Any indicator that cannot be given a short-form headline title is unlikely to be of much use.

Government has differentiated between primary, or headline indicators, and those associated with them as secondary indicators of less immediate relevance to a wide audience, but valued by specialists. We support that outlook, and commend any hierarchy of indicators in which the user can dig down below the headline graph to those which are successively more targeted and specialist. This approach is evident in the sphere of national economics, but only since the work of the Sustainability Round Table has it come into the environmental sector of which flood defence is a key part.

3. DISCUSSION OF PREVIOUS WORK

3.1 The Central England Temperature Index

One model of success, and failure, is the Central England Temperature sequence (see Figure 3.1), so well known for bringing global warming down to a sub-national indicator on which politicians can base major treaty obligations and associated taxation. Its success is its wide usage by a broad range of official and NGO groups, and the clarity with which it shows that, long after the Western European industrial revolution, the sheer growth in the carbon emissions from an accelerating global population has in the last 50 years given rise to well-nigh uncheckable atmospheric warming. The 'failure' relates to the few people who realise that the warming is largely attributable to higher night-time temperatures than to any perceptible daytime change. If the indicator were published as a pair of lines, one for 'daytime max' and the other for 'daytime min' there would be more truth, but less headline impact.

So the dilemma remains. Should we seek out the diurnal or monthly or seasonal indicator that shows change at its largest, or should we concentrate on the simplest of indicators that may be reassuring for too long, or mask a subtlety that engineers, insurers and others could act upon? The approach of this project is to look initially very widely, but then to rapidly narrow down the options to those on which our stakeholders can respond.

Although this indicator bears little direct relationship to flood severity, it is mentioned here because it is probably the best-known indicator of climate change in the public mind. It can be found tabled on the web at:
http://www.met-office.gov.uk/research/hadleycentre/CR_data/Monthly/HadCET_act.txt
and in graphical form at:
http://www.Defra.gov.uk/environment/statistics/des/globatmos/gafg01.htm

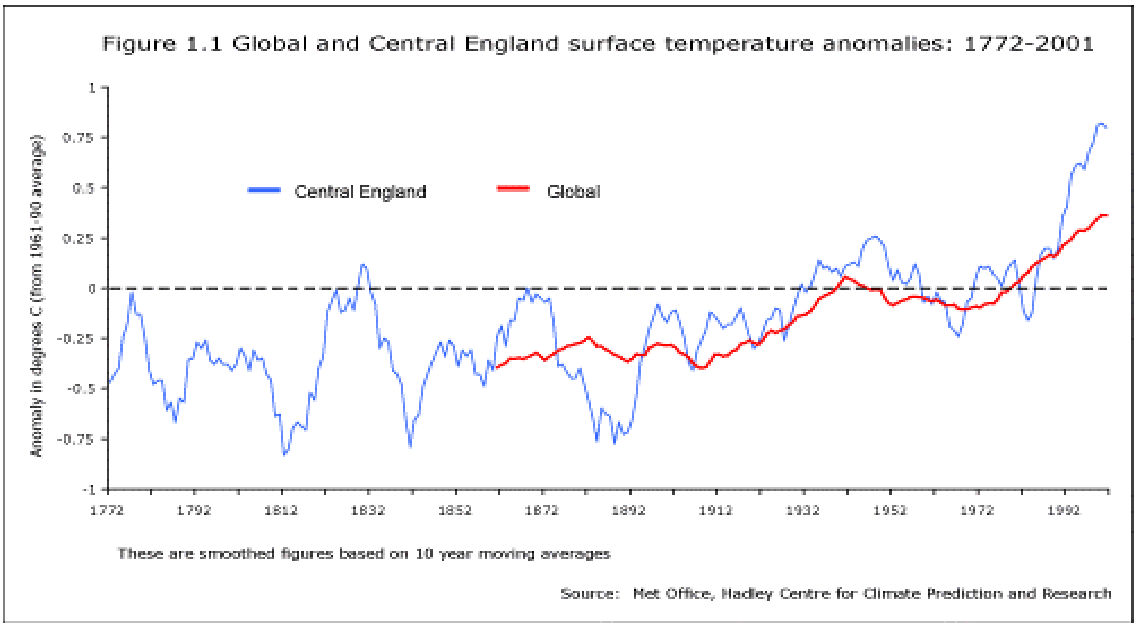


Figure 3.1 Global and Central England surface temperature anomalies: 1772-2001

The series is maintained by the Hadley Centre, but it owes its definition to the late Professor Gordon Manley (1974), who put together disparate sources to make a monthly mean dataset from 1659 to 1973; Parker *et al* (1992) updated and refined that work, covering in a daily form, 1772 to 1991. The dataset represents a broad region of England's mid-latitudes, and is the local manifestation of the global rise in air temperatures due to the atmospheric emissions of a burgeoning world population over the past century. However, its very success masks the detail that the rise in temperature is largely a night-time phenomenon, and so has a smaller impact of evaporation loss and soil moisture deficit than might be first thought. It does however have an immediate consequence of causing ocean water expansion and hence sea level rise, exacerbated by glacier melt, and hence has a gradual, direct impact on coastal flooding.

3.2 Oceanography and Coastal Processes

In most parts of the world, including the UK, mean sea level (MSL) is rising and has been rising for a century or more. Projections by IPCC indicate that this rise will continue and accelerate. Consequently, there is increasing public concern that coastal flooding may occur more often and affect areas not presently seen as vulnerable to its effects. For flood prevention and UK coastal defence, Defra, the Environment Agency (EA) and coastal engineers require "best" estimates of sea level trends and extremes to ensure that defence standards are maintained, or at least that changes in the level of protection can be quantified.

Sea level variations occur on a wide range of time scales and arise from several mechanisms. It is useful to consider these separate contributions, expressed as

$$\text{Sea level} = \text{tide} + \text{storm surge} + \text{MSL} - \text{land movement},$$

and to summarise the mechanisms and processes involved.

<u>*Tides*</u> are generated primarily in the deep oceans by astronomical forcing arising from the varying gravitational attraction of the Sun and Moon. They propagate as long waves round the ocean basins and onto continental shelves where their energy is dissipated in the shallow water. Tidal behaviour near coasts is affected by, amongst other things, resonance producing large tidal range in areas which have natural frequencies of oscillation close to those of the forcing, the Bristol Channel being a good example. Non-linear processes cause interactions with storm surges and other motions. On short (hourly) time scales, tides dominate most UK sea level records

<u>*Storm Surges*</u> are generated by wind stress acting over shallow seas and by variations in surface atmospheric pressure (P_{msl}). Large surges result from storms; near UK coasts from mid-latitude depressions. The best known event occurred 50 years ago, on 31 January - 1 February 1953, causing widespread flooding and considerable loss of life on the east coast of England, in the Thames Estuary and in the Netherlands. Surges are weather dependent and so there are links with effects of climate change and possibly with some climate indicators. The frequency of occurrence and magnitude of surges and their extremes are affected by changes in "storminess", the track, frequency of occurrence and intensity of atmospheric storms, which may result from climatic change. Coastal flooding is threatened typically when a large storm surge coincides with a high

spring tide. Sometimes, however, a modest surge event can cause problems if it coincides closely with high water of a very large tide. On the other hand, an extreme surge may pass with no threat of flooding if it occurs near tidal low water.

Land movements. Coastal floods depend on the sea level relative to the land level. In the UK, changes in the level of the land, known as *land movements*, are mainly caused by "glacial isostatic adjustment" following the melting of glaciers covering much of the country during the Holocene. The result is land uplift in Scotland and submergence in SE England. Other more local effects also contribute e.g. sediment compaction and subsidence due to ground water extraction.

Mean sea level, MSL, (averaged over months, years or longer periods) includes contributions from tides and storm surges. For example, storm surges, averaged over months or seasons, can alter MSL by a few cm in some shelf and coastal areas. However, important contributions arise on larger scales from variations in circulation and total volume ("eustatic changes") of the nearby (and global) ocean, and locally from river inputs, modifying water density, and wave setup. Global and regional MSL change, density effects (thermal expansion) etc. are discussed and estimated by IPCC.

3.3 Flood Occurrence Trends

The Flood Estimation Handbook (Vol. 2 Fig 7.2) showed that a daily rainfall of at least 25 mm/day occurs almost every other year (RMED) over the bulk of the country. Fig 20.1 from that Handbook, reproduced here as Figure 3.2 below, summarised fluctuations in the number of floods per year over the longer period from the late 1930s. It also shows in smoothed dimensionless form how annual flow maxima have varied over that period. No trend emerges but the marked variability, particularly in flood magnitude, does.

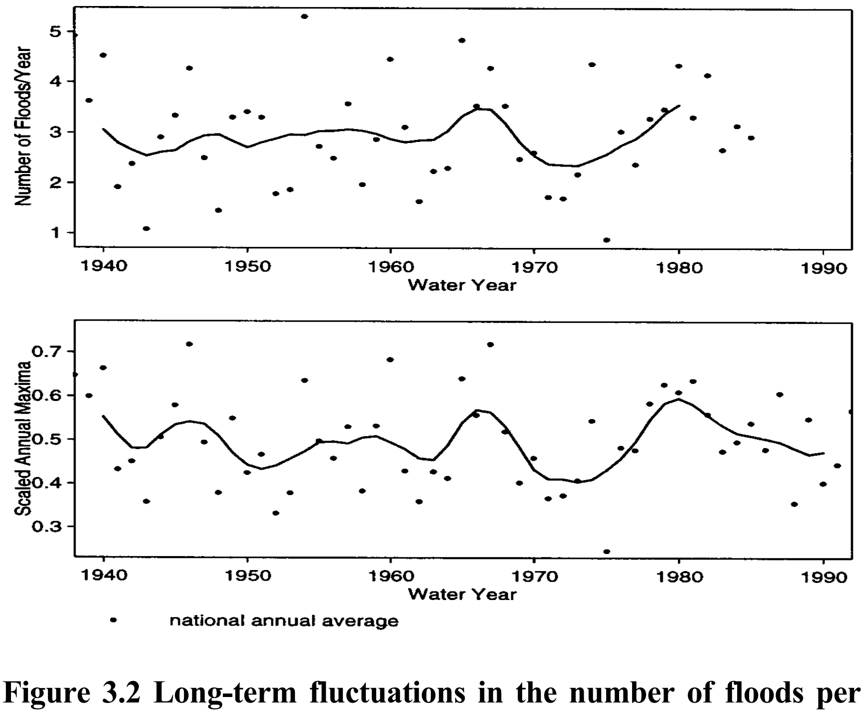


Figure 3.2 Long-term fluctuations in the number of floods per year and in annual maxima. Points show national averages and a smoothed curve is fitted.
(Note: A Water Year runs from 1st October in year N to 30th September in year N+1)

On trends in UK flood peaks the Handbook concluded:

- No significant trends were found in the annual count of peaks-over-threshold events for 1941-80 and annual maxima for 1941 to 1990;
- the confounding effects of natural climatic variation means trends associated with land-use change can neither be easily identified nor readily dismissed.

It is unfortunate that the data used in the FEH extends only to the early 1990s, particularly given the very severe flooding in recent years throughout England and Wales (e.g. Easter 2000, the winter of 2000/01 and the recent flooding in December 2002). However, until the current HiFlows updating project is completed, no more recent trend analysis is possible. HiFlows is a project being undertaken on behalf of Defra and the Agency funded out of the Capital Modernisation Fund, which is updating the database of good quality, checked, flood levels and flows data used in the Flood Estimation Handbook. Data are being collected from all hydrometric agencies through a series of consultancies.

3.4 Flood Levels

Garrad (2001, 2002) has recently completed an important project entitled "Identification of Flood Indicators". It sets out to *"produce an indicator for analysing patterns of flood behaviour in England and Wales to add to the Agency's suite of environmental indicators."* This included a search for an aggregated indicator from different regional catchments. That work utilised the digital hydrometric datasets to the fullest extent possible, but was necessarily affected by the length of time EA Regions had been producing digital data, or had moved to transfer records to digital formats. Further work was done on Peaks over Threshold (POT) extraction, enabling some record lengths to be doubled. Floods were not analysed in relation to their damage impacts.

Garrad (2002) was able to recommend the use of 16 flow gauging stations, with between 11 and 45 years of digital records, and between 33 and 79 years of POT records. We note the finding that *"The increase in the size of floods (Annual Maximum series) does not appear to exhibit a significant trend at 14 of the 16 stations."* This mirrors the work of Robson and Reed (1996, 1999). However *"Positive regression gradients exist for the number of flood peaks per year....The regression gradients are less steep at stations with longer records....".* Our comment here is that the number of flood peaks per year should not be allowed to colour views on the trends (if any) in the extreme floods that cause damage to community health and property. Crooks (1994) identified for the long Thames records that post-WW2 years had seen more frequent flood spates but less frequent damaging outlier events. It remains a key finding of this report that conclusions will only be found where long records, preferably of 70 years or more, are used. Alternatively shorter records can be displayed but with a background context of a related indicator that is known for a longer period.

The Garrad report is very well illustrated, and this makes plain that the number of hours per year for which a POT is sustained can rise over a 25 year window e.g. Bewdley between 1970 and 2000. This is not general everywhere, and may just be a local feature.

This indicator of flood duration is not generally as critical as the repetition of flood damage after a first clean-up has taken place. So, while hydrologically exact in both definition of separate POT events and durations, this suggested indicator is not pursued here.

Garrad examines the number of flood peaks per year above the median annual flood (QMED), the flood observed in 50% of years. This was done for 6 stations, although only one runs from 1936, the full set being available from 1968. The averaging of the number of such floods per year looks to have real promise for identifying years of flood management stress. Perhaps coincidentally those years which exceed 2.5 floods per year (1938/1947/1979/2000) are memorable years for flood damage. 1968 scores less highly, but then the flood extremes were more localised (e.g. Bristol/Surrey). Garrad says:

"The use of the number of floods per year above QMED could therefore meet the overall objective of producing an indicator for analysing patterns of flood behaviour in England and Wales to add to the Agency's suite of environmental indicators. It is easy to calculate using existing summary data files and will be easier to update in the future. The previous preference for use of river level rather than flow as the basis for an indicator, due to errors to or inaccuracies in ratings, is not overcome. However QMED is in the middle of most ratings where inaccuracies are smaller, and the flooding indicator is based on the frequency above this level – whether flows or levels are used is immaterial."

We feel that Garrad's view offers real promise and deserves wider testing. The strength of this view lies in the ability of a wider range of users to become readily acquainted with it.

4. POSSIBLE NEW INDICATORS

4.1 Introduction

The project has considered a wide range of indicators, some of which are maintained already, that may have an impact in some way on flood and coastal defence and management (FCD). The plan has been to consider a broad range of indicators covering the hydrological cycle from what may be termed 'drivers', such as temperature, rainfall and winds through to receptors, such as river and groundwater levels, relative sea levels and waves, that are of relevance to FCD.

A preliminary set of indicators were primarily identified during the initial workshop held at CEH Wallingford in February 2002, although some additional indicators have been identified during the project.

The study suggests that for any indicator to be useful in the long-term to those involved in FCD that:

- Any indicator should be rigorously and straightforwardly defined so that values can be replicated by any interested party.
- All data are analysed for the year beginning July 1st. In that way a single slowly-changing flood event is highly unlikely to produce two values at the changeover date (which might well occur if calendar years were specified).
- Generally no more than three significant figures should be quoted for an Indicator. Units are of no great concern as dimensionless trends, or their absence, are being sought. Cluster rhythms may also be observed but in that case it is timing that is all important.
- Record gaps of complete years are permissible, but should be noted. Missing days or months of record may be inferred (say by a persuasive correlation with nearby sites) but only to show that the annual maximum, or all countable peaks, exist in measured form.
- It is difficult to make any case for trying to draw up indicators for any phenomenon where less than 20 full years of data exists. We recommend that the period 1970-89 (1/7/1970 to 30/6/1990) be used as the base reference period, as this represents a period of relative data abundance as far as groundwater and river level/flow records are concerned.

4.2 Meteorological Indicators

4.2.1 Large-scale meteorological indicators

SSTs / SLPs, temperature gradients in the North Atlantic

As part of the MAFF (now Defra) funded project examining the autumn 2000 floods, carried out jointly by CEH and the Met Office, an attempt was made to analyse the meteorological conditions that resulted in the series of depressions that passed over Britain (in a more southerly storm track than usual) during October and November 2000. These floods were very significant causing widespread flooding across the UK and, from a hydrological point of view, were of note for the prolonged nature of the rainfall. This period of flooding is therefore considered to be a useful case study for this research project. The reader is referred to Defra report FD2304 for further information (CEH and Met Office, 2001).

Two key meteorological indicators that were identified as significant in the autumn 2000 floods were sea surface temperature (SST) anomalies across the northern Atlantic and sea level pressure (SLP) anomalies. Using data held by the Met Office's Hadley Centre it was possible to compare the mean SST and SLP for the month of October and the month of November in 2000 with 120 previous Octobers and Novembers over the UK and the Atlantic. Analysis of the mean SLPs indicated the pressure over the UK in October and November 2000 was very low on average, having approximate return periods of occurrence of 3 to 20 years for October and 20 to in excess of 100 years for November. Analysis of the SSTs indicated a steep temperature gradient in the north Atlantic prevalent for both October and November 2000, which was undoubtedly linked to the generation of cyclones in the Atlantic and the heavy rainfall over the UK during this period. The steep temperature gradient was a result of cold air to the north being situated close to much warmer air in the south, as shown in Figure 4.1.

However, while analysis of these weather features is of real interest to those concerned with flood producing rainfall, it is regarded as unwise or misleading to assign return periods to the anomalies in north Atlantic SSTs and SLPs over the UK for two reasons. Firstly, the pattern, extent and location of the anomalies are never the same for different periods and so any comparison with former anomaly plots is not strictly comparing like with like. Secondly, to assign return periods is relatively misleading, as it is not *necessarily* high SST gradients which cause heavy rainfall over the UK, though this may be a major causative factor. Specifically, it is the position and strength of the SST gradient which is important. Much will depend on exactly *where* a cyclone deposits its associated rainfall – i.e. the precise track of the cyclone as it passes across the UK. For example, the cyclone which affected the country on 30/10/00 resulted in extremely strong winds and severe weather over the North Sea late on 30th October. If this weather had occurred over the UK mainland, damage from high winds and flooding would have been considerably worse than it was.

The link between mean SLP and rainfall is closer, however, particularly since the rainfall in October and November 2000 was almost entirely derived from cyclonic activity. Mean pressures over the UK in October 2000 had a probability of occurrence of approximately 5 to 30% (return periods of 3 and 20 years) and in November had a probability of occurrence of 5 to 1% (return periods of 20 to 100 years). In the north east of England the mean SLP for November 2000 was found to be in excess of 3 standard deviations below the mean, i.e. with a return period in excess of 100 years. This indicates that SLP was extremely low in these two months, particularly so in November, implying that it was the repetitive effect of a series of low pressure cells moving across the country which was particularly rare.

However, it is interesting to note that the rarity of the mean pressure anomaly was significantly less in October than it was in November, whilst the rarity of the rainfall totals over the UK over these two months does not reflect this difference. This implies that analysis of the link between SLP anomaly and UK rainfall should be treated with caution.

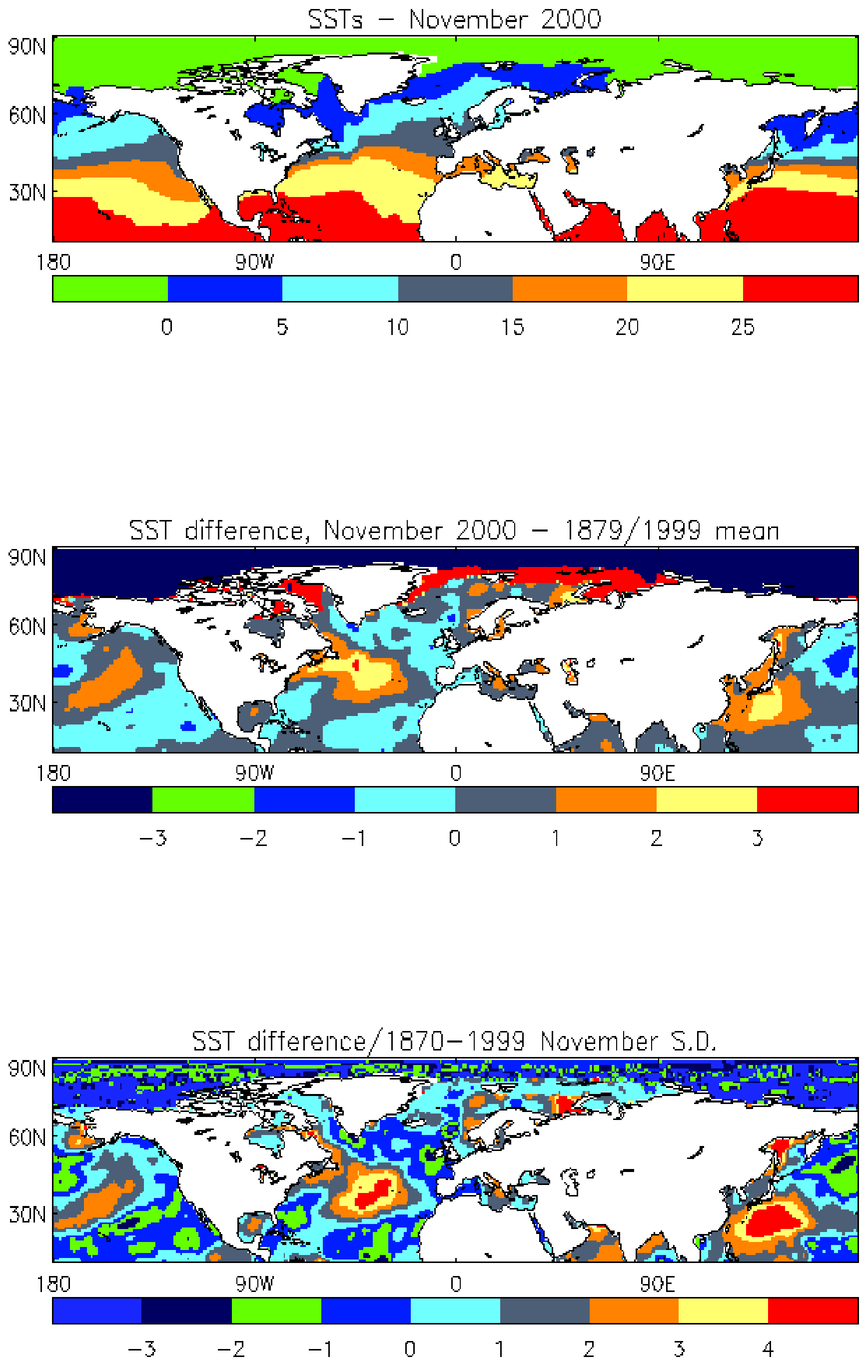


Figure 4.1 Mean sea surface temperature for November 2000 and anomaly – the top image shows mean SST values in degrees centigrade, the middle image SST variance in November 2000 from the 1879-1999 mean and the bottom image shows this difference in standard deviations

In summary, then, it is considered that monitoring of the steepness and position of the SST gradient in the north Atlantic and of mean SLP across the UK is useful for assessing meteorological conditions favourable to the creation of depression systems that can result (and have resulted) in serious flooding in the UK.

Monthly SSTs for the period 1903-1994 (GISST2.2) and 1871 to present (GISST2.3b) generated at the Hadley Centre (Met Office) are held in the British Atmospheric Data Centre. The new version of GISST (also known as HadISST) is planned to be available from the Met Office web site by the end of the year. This will be 1-degree globally complete sea surface temperature data from 1870.

Monthly SLPs from 1949 are also generated at the Hadley Centre and can be accessed at the BADC.

Changing patterns of cyclonic activity over the UK

Work is currently underway at the Hadley Centre looking at depression tracks across the Atlantic, from where most of the UK's weather originates. Low pressure areas were identified and tracked using the pressure fields from the high resolution global model, HadAM3H. A weather system with its lowest pressure below 1000hPa was classed as a depression. It was found that the number of all such depressions crossing the UK in an average winter increases from about five for the present climate to about eight for the Medium-high Emissions scenario by the 2080s. This is illustrated in Figure 4.2. This is mainly due to a shifting southward of the depression tracks from their current position. The probability of an individual low pressure system being a 'deep' depression (central pressure less than 970 hPa) is not predicted to change by the 2080s, but since there are more depressions overall, there would be more frequent deep depressions. Such 'deep' depressions are predicted to increase in frequency in winter by about 40% for the medium-high scenario in the 2080s. In the summer, however, the pattern is reversed with depressions over the UK in the 2080s falling, on average, from five to four per season. There is little significant change predicted in depression frequency or intensity in autumn or spring. These findings are presented in the UKCIP02 Scientific Report (2002.)

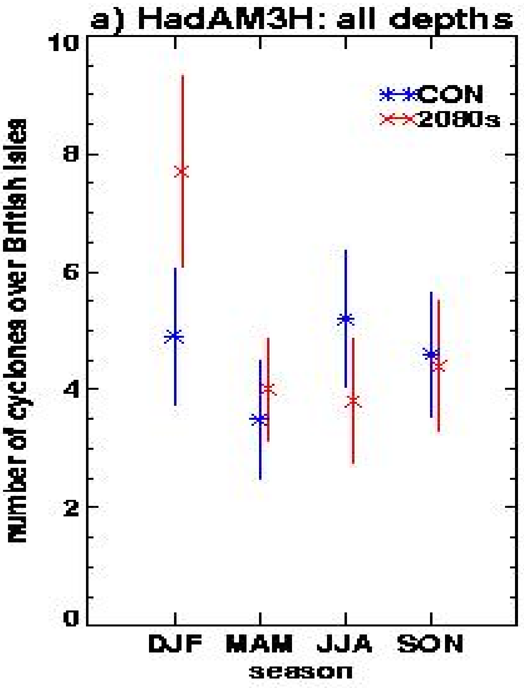


Figure 4.2 Average absolute number of depressions per season across the British Isles for the baseline period (blue (plotted on left for each quarter) : 1961-1990) and for the medium-high scenario by the 2080s (red (plotted to right)). Crosses are the 30 year average and the bars show one standard deviation either side of the average. (Figure created by Ruth McDonald, Hadley Centre, Met Office and reproduced in UKCIP02 Scientific Report as Figure 52)

To improve the confidence in predictions of changes in mid-latitude variability we need to both improve the simulation of present day climate and to better understand the processes leading to the changes. The horizontal and vertical resolution of the atmospheric model used in these experiments is relatively high compared to most coupled models used for long climate integrations, but may still be insufficient to correctly simulate the development and tracks of storms and relatively large systematic errors remain and improvements may be achieved through increased horizontal and vertical resolution as well as improvements in model physics. The use of data with an increased temporal resolution may also improve the tracking of the storms.

The North Atlantic Oscillation (NAO) is related to the storm track behaviour over the North Atlantic and British Isles. The NAO is an oscillation in the pressure gradient between the Azores and Iceland and hence its strength is a measure of the 'westerliness' of winter weather, where a high NAO index indicates a mild but wet winter, such as that of 2000/2001 in the UK. A graphical representation of the NAO over the last 125 years in shown in Figure 4.3. For the medium-high scenario the future trend is for an increase in the NAO index, although the year-to-year variability is large. This increase in the decadal NAO index becomes significant, or greater than 'natural' variability, by the 2050s.

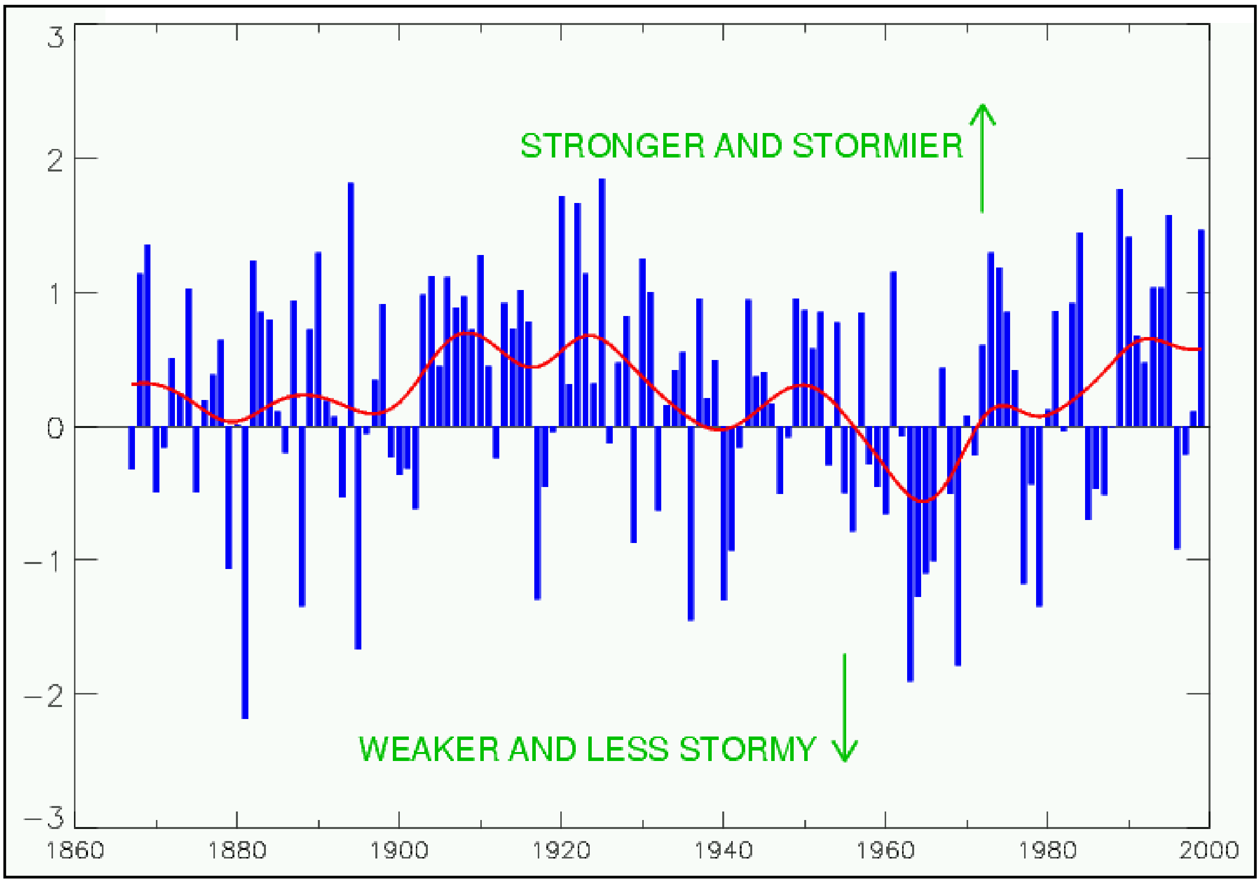


Figure 4.3 North Atlantic Oscillation over the last 125 years, indicating the variability in observations of wetter, milder and windier winters opposed to colder, and less stormy winters. (y-axis is a standardised index).

4.2.2 Precipitation indicators

Daily rainfalls over 25 mm

A rainfall of this magnitude is likely to cause flooding, the severity of which will depend on:

- the duration and intensity (e.g. 1 hour) of the rain within the day for small and urban catchments;
- the extent to which an entire large basin (e.g. 1000 km^2 upwards) receives this fall;
- the antecedent saturation state of the catchment.

The recent UKCIP report (Hedger *et al*, 2000), and at: http://www.ukcip.org.uk/scenarios/sci_report/sci_report.html included a discussion of rainfall intensity, stating that there are now:

- "more intense rainfall events over many Northern Hemisphere mid-to-high latitude land areas", and that;

- “a larger proportion of winter precipitation in all regions now falls on heavy rainfall days than was the case 50 years ago”.

However, it took as a baseline 1961-90, which we believe may be insufficiently long to form a pattern of trend. Nevertheless, the frequency of such events is clearly a valuable indicator of a catchment’s tendency to ‘floodiness’.

Rain gauge recording in the Met Office

The Met Office has recently made changes to its rain gauge network, using modern technology to further automate rain gauges. Recently, an enhanced version of the Windows NT-based Semi-automatic Meteorological Observing System (SAMOS) has been made operational. This is capable of being used on sites where manual observations had previously been thought essential. Two systems were deployed for trial at Hemsby and Manston in May 2000 and a second phase of the trial was begun at Hemsby and Aviemore in November, with additional snow-depth and icing sensors. More significantly, these systems employ a software-based algorithm which uses all available data to produce a better representation of current conditions than that from the present weather sensors alone. Towards the end of the year, the system was further developed to produce observations every ten minutes. The successful completion of the trial at the end of March 2001 will allow the automation of surface observing on a number of sites, particularly the dual function radiosonde sites. They can thus be completely ‘de-manned’ with a corresponding efficiency gain. In parallel with the development of the enhanced automatic SAMOS, the Windows NT interactive version was accepted by operators and rolled out to approximately half of the 108 sites which already have DOS-based systems.

As well as annual, seasonal, monthly, daily or sub-daily rainfall records for stations across the UK the Met Office has produced gridded data records of rainfall at 5km resolution for annual and monthly rainfall (these records are listed in section 6.1) and annual and monthly 5km grids of :

- Days with rainfall of 0.2mm or more
- Days with rainfall of 1mm or more
- Days with rainfall of 10mm or more

Analysis of indices such as these could help detect trends of changing patterns and intensities of rainfall over time in a way that analysis of rain gauge records directly could not.

Collation of tipping bucket rain gauge data.

Tipping bucket rain gauge data from 73 rain gauge sites were made available in October 2002 by the Met Office in a software tool designed specifically for the urban drainage modeller. This allows the user to access all the available data from any of these 73 gauges (which have between 1 and 14 years continuous record) to extract ‘storm’ data required; hence all rainfall events above a specified rainfall depth and rainfall intensity can be extracted from each record.

This tool could be of use in providing an indicator of how rainfall intensities are changing. The gauge data runs back to 1987 in many cases and is to be updated annually with most recent data, after quality control has taken place.

Engineers are concerned that flooding in urban environments in the UK may have been exacerbated by increased rainfall intensities and the only way to analyse this (apart from using radar data) is to analyse rain gauge records which have high temporal resolution. As a tipping bucket rain gauge records the time of each tip the rainfall can be accumulated over a short period, 5 minutes in the case of this Met Office tool. Hence analysis of these time series of data could allow rainfall intensity to be monitored and trends detected.

Although there is clearly value in this indicator, the current data sets may be too short at present to provide real indications of change. Any apparent trends may just be due to the effects of normal climatic variability, and it may be some time before sufficient data are available for this indicator to be really useful. Nevertheless, we welcome the Met Office's efforts in maintaining this data set, and hope that its value for FCD, particularly for urban drainage, may be easier to judge in a few years' time.

Monitoring thunderstorm activity

A method of measuring the incidence of thunderstorm activity over the UK – which results in flooding in flashy (very responsive) catchments and often urban, highly paved environments – may be to monitor lightning. A warming of the atmosphere from climate change predicted for the 21st century would lead to more energy in the atmosphere and an expected increase in convection and thunderstorm development.

However, a feasibility study to explore whether such sub-grid scale analysis is possible (requested by UKCIP) found, during the medium-high scenario, that lightning flash rate in summer in a convective event is expected to more than double over parts of south-western England, while the number of thunderstorms over the UK as a whole is expected to decrease by half. Such work is in its infancy and there are no published results (other than reference to this in the UKCIP02 Scientific Report).Climate modellers involved in this work are keen to emphasise that the findings were a first attempt and there is only low confidence in the projections that were produced.

Clearly further work is required in this area before we have confidence in the relationships between lightning and heavy rainfall. If this is possible, however, monitoring lightning incidence could be an effective way to record thunderstorm occurrence and location across the UK. In this way the effects of climate change could be noticed through changing frequency and location of thunderstorms over the UK.

In order to monitor lightning, the Met Office has developed an Arrival Time Difference (ATD) lightning location system. In March 2000 this system was significantly improved when a new computer took control over the network of seven ATD outstations. Previously limited to fixing the location of just 400 lightning flashes per hour, the capability has increased to a rate of 8,000 per hour. The increased automation provided by this new control station has led to improved reliability, much appreciated by users of the ATD information. The maximum rate achieved to date has been greater than 4,500 fixes in one hour. In the future, it is expected to include extra features such as the determination of the flash strength, polarity, type (cloud to ground strike, or cloud to cloud) and multiplicity (number of strikes per flash).

Analysing and assessing climate observations

The system for producing gridded values of meteorological elements at the Met Office, based on data from station values, has recently been updated. Gridding permits the production of consistent and high-quality contours and areal averages, minimising the impact of changes to the station network and its spatial inhomogeneities. The previous system has been migrated to the ARCVIEW geographical information system. During the migration several innovations have been introduced, although the process remains fundamentally the same.

Changes include:

- The introduction of detailed land-use data to better quantify the impact of water and urban areas upon local climates;
- the calculation of areal statistics over a wider range of areas, including post codes; the ability to choose from three different local surface fitting methods;
- the ability for non-technical users to construct regression equations, used in generating a global surface fit to the input station data.

Figures 4.4 and 4.5 are contoured maps of October 2000 rainfall and the percentage of long-term average created using this new system.

In addition, the new system gives improved means for assessing how representative of the local area current and proposed observing sites are. These are:

- 3D visualisation of topography giving enhanced perspectives on station locations;
- versatile combined analysis of topography and land-use data to identify areas which are representative of the local area;
- contoured maps showing the mean spacing between stations.

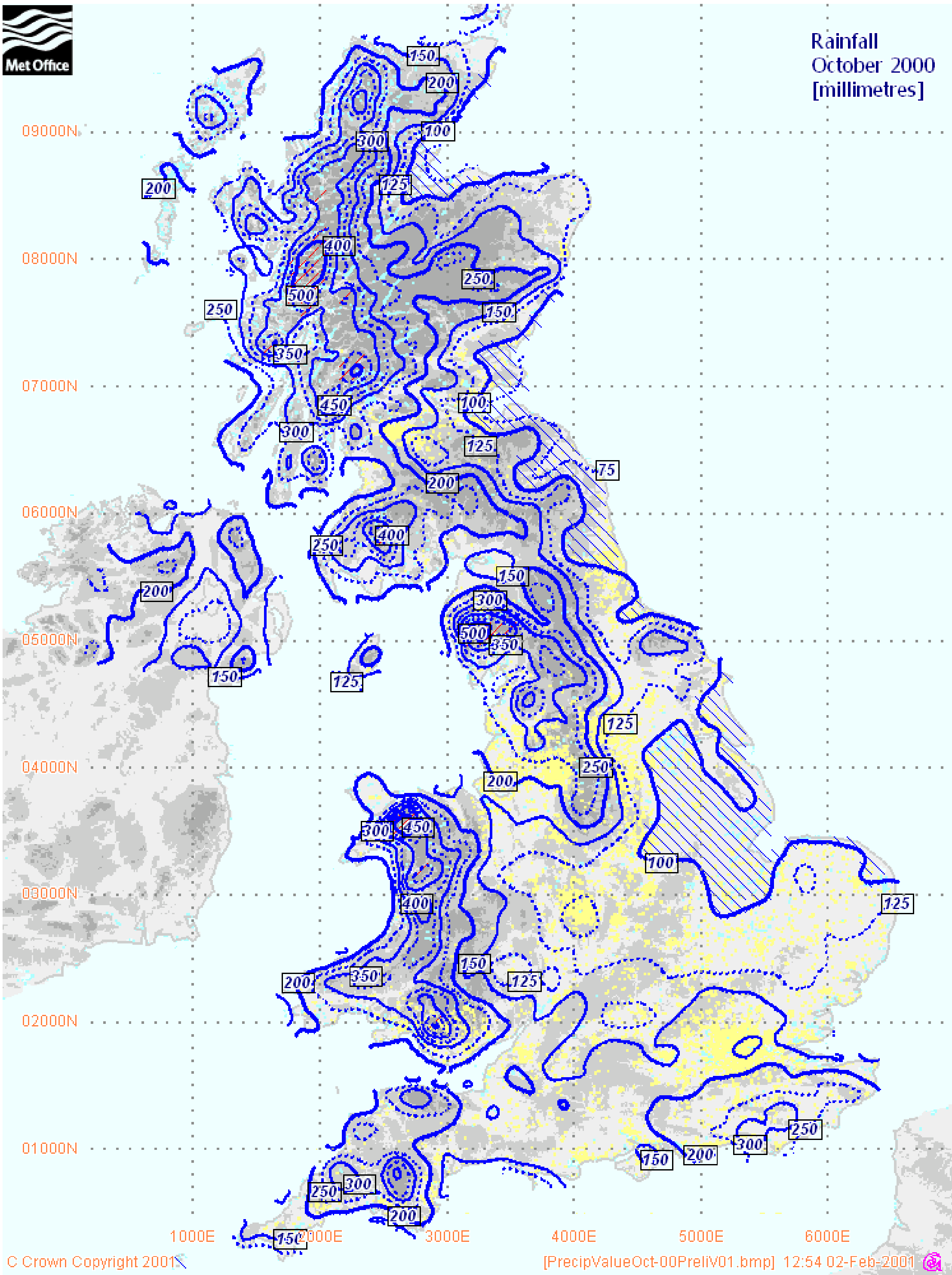


Figure 4.4 Total rainfall over the UK for October 2000 (from 650 gauges)

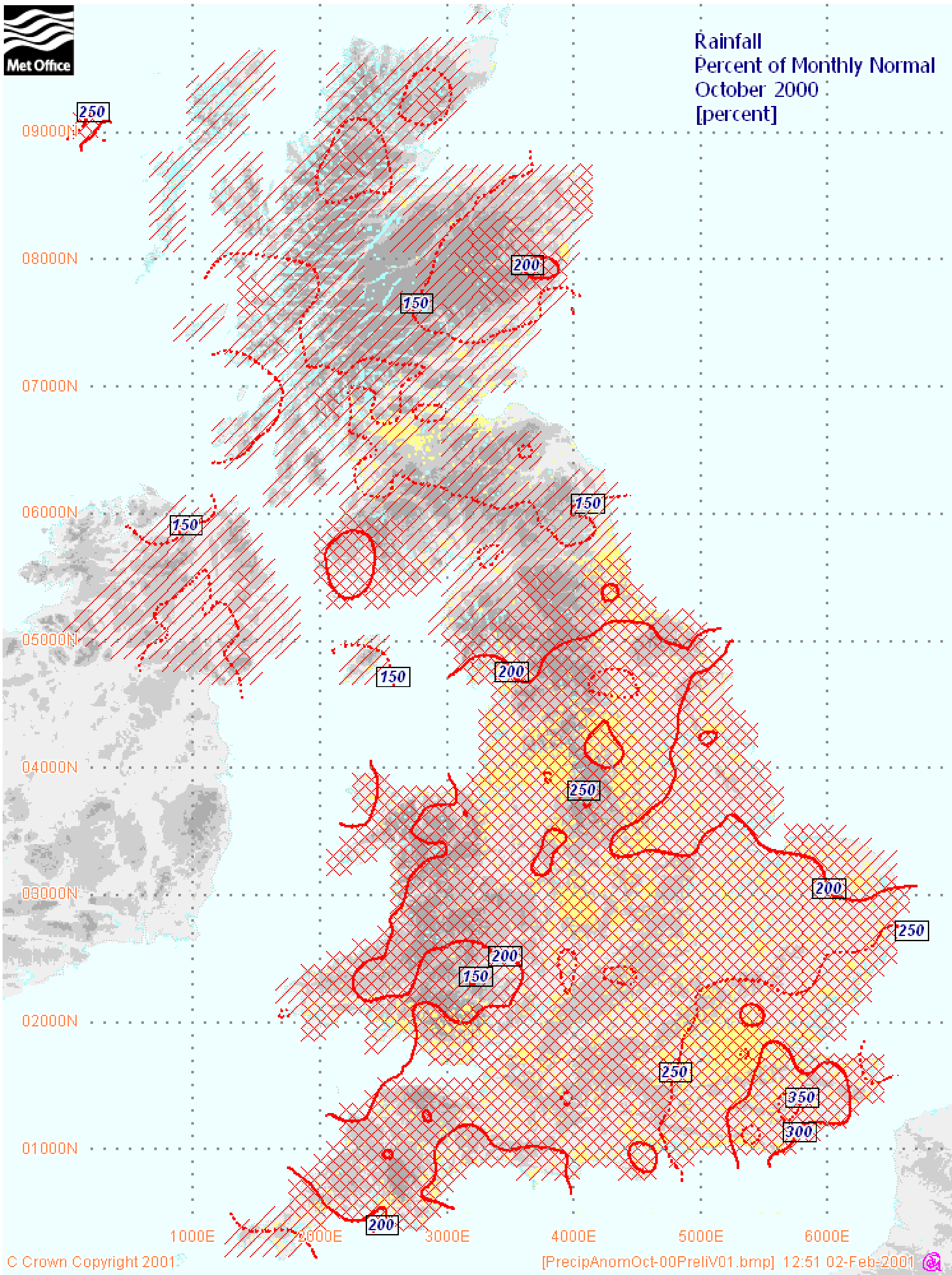
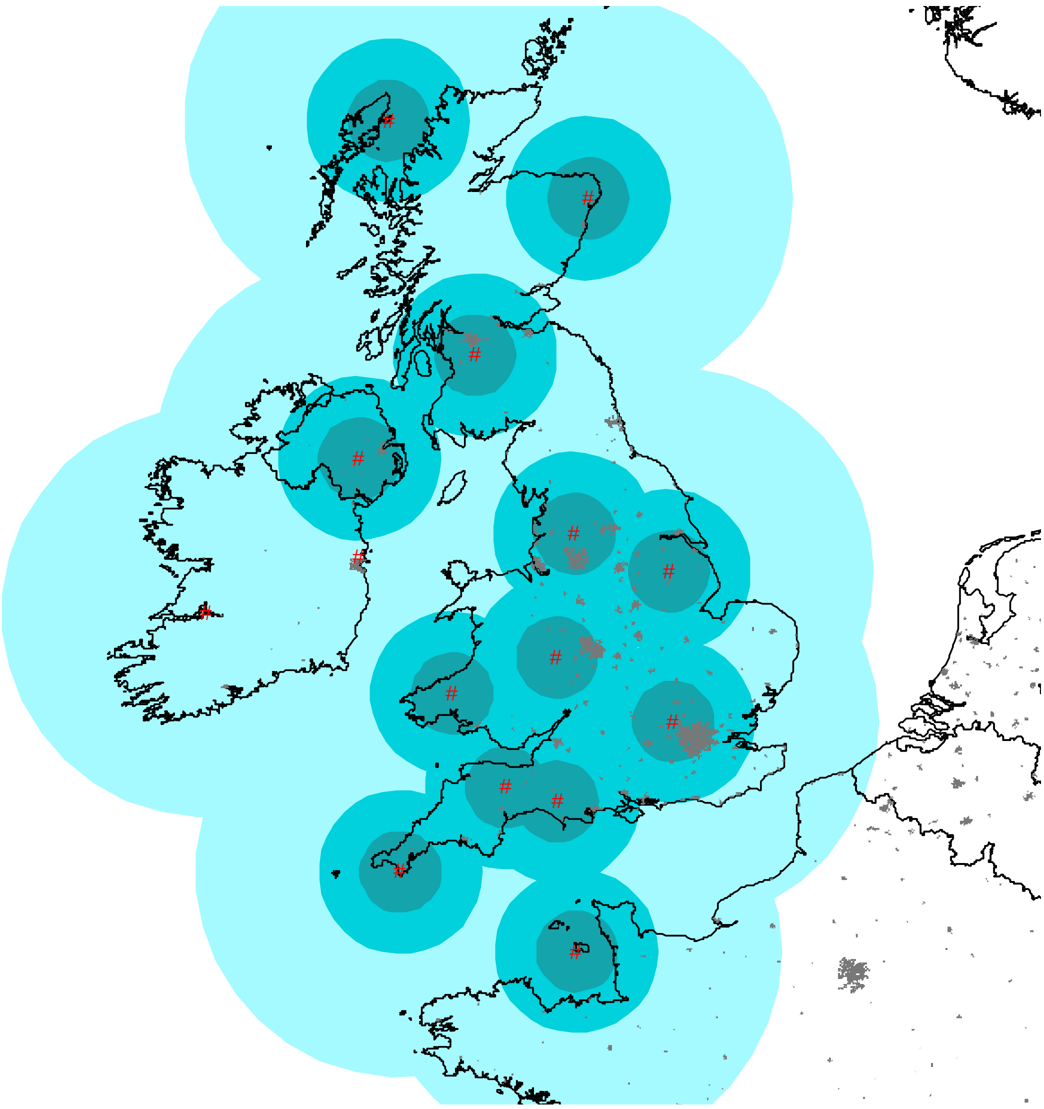


Figure 4.5 Percentage of long-term average rainfall over the UK for October 2000 (from 650 gauges)

Radar data

The replacement of the weather radar data processing systems, combined with upgrading of the communications links with the radar sites, has enabled the coverage and resolution of radar data to be improved. Figure 4.6 shows the extent of radar coverage as of August 2002. The main benefits are the large area of contiguous 2 km resolution coverage over England and Wales, and 1 km coverage of several conurbations.



Key

- Location of radars
- Radar coverage at 5km resolution
- Major towns and cities
- 2km resolution coverage
- 1km resolution coverage

Figure 4.6 UK radar network coverage as at August 2002

Evidence for the improvement in accuracy of radar in recent years is shown in Figure 4.7, where a time series of the root mean square fractional difference between hourly rain gauge accumulations and integrations of radar data in collocated pixels is presented. The radar data have been subject to quality control and correction within the Nimrod system. All gauges within the area of radar coverage in the UK have been included in the statistics. A threshold of 1 mm has been adopted to ensure that the statistics are representative of hydrologically significant rainfall. The monthly average statistics show considerable variability month-to-month, but a 12-month running mean of the monthly values shows a fairly steady downward trend over the last five years. This improving trend in radar data quality is ascribed to developments in the radar hardware and in the correction procedures in Nimrod.

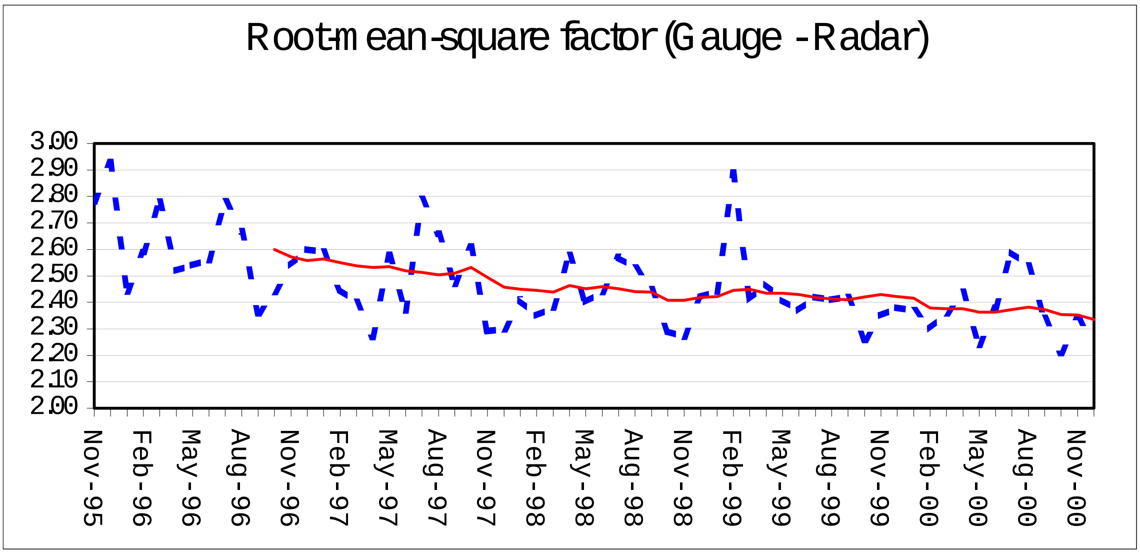


Figure 4.7 Time series of monthly Root mean square factor differences between hourly gauge and radar rainfall (dashed line). The solid line is a running 12-month mean formed from the monthly values

Other precipitation-based indicators

Prior to the production of the UKCIP02 work, a number of possible climatological indicators were highlighted by the Hadley Centre. These included two indicators relevant to this project:

HadFFI – A 'Flash Flood Indicator', describing the short-term heavy bursts of convective rain, disruptive to drainage and sewage systems – it was indicated that this might require sub-grid scale modelling, as well as sub-daily observations.
HadFRI – A 'Flood Risk Indicator', describing the accumulated risk of a prolonged wet spell which could eventually lead to regional flooding. Would be based on accumulated daily totals of heavy precipitation events (exceeding 5-10mm/day).

Neither of these indicators were selected by the team of scientists at UEA / UKCIP for inclusion in the final list of indicators (from which datasets considered relevant to this project are listed later). According to UKCIP, the main limitation on deriving the indices was the amount of time required as quality controlling, then interpolating station data took considerably longer than anticipated. Also, certain indicators had to be dropped because of feasibility (e.g. maximum wind speed) (ref. Email from Iain Brown of UKCIP to Murray Dale on 24/10/02.) It should also be borne in mind that the UKCIP02 scenarios were not designed as indicators and the observed data (1961-2000) were intended to be matched with future scenario data (out to 2080s). The observed data were therefore a compromise between what the demands were from users against what could sensibly be extracted from climate models. (ref. email from Mike Hulme of UEA to Murray Dale on 24/10/02).

4.2.3 Wind indicators

While wind is not directly responsible for flooding it has an indirect effect by causing sea waves and by being one of the factors causing surges. It can also be responsible for dam overtopping inland, for which there are design guidelines in the ICE Floods and Reservoir Safety guide (1996). Often the type of weather system associated with strong winds (typically cyclones in the UK) is also responsible for significant precipitation.

Analysis of wind speed records over time can be a useful tool to support analysis of storminess and changes in wave height. The UKCIP02 Scientific Report indicates that the largest increases in average wind speed predicted in the UK occur along the south coast of England. According to the Hadley Centre model the average wind speed in winter is predicted to increase by 4 to 10 per cent by the 2080s.

The only available gridded wind data records are monthly mean wind speed for the UK which has been converted to a grid of 5km resolution. However, daily wind information for the UK, known as Jenkinson Indices, is freely available at daily timescales from 1881. The indices use adjusted daily mean sea level pressure values to calculate the strength of the geostrophic wind flow and vorticity which can be used to obtain a gale index. They are updated automatically each month and appear on the Met Office's public ftp. It should be noted, however, that this information is on a large scale and will generally not be able to resolve small, intense cyclonic systems. In addition, interpretation of the data is a non-trivial process, and at present the study cannot see how a simple and informative indicator can be developed from the Jenkinson Indices, and hence no indicator is proposed.

4.3 Groundwater and Catchment Indicators

4.3.1 Soil moisture deficits

The Met Office has two models which can be used to estimate catchment wetness, one calculating a soil moisture deficit (SMD) and the other estimating runoff directly. The former is MORECS (Met Office Rainfall and Evaporation Calculation System), now over 20 years old, though still being used and with a considerable archive of historic data that has been extended back to 1961. The latter is a new system the Met Office has developed, MOSES, and, in conjunction with work at the Joint Centre for Hydrometeorological Research at Wallingford, has a method for determining runoff in millimetres at hourly resolution. The two models are described below, with examples of their use.

MORECS calculates evaporation and soil moisture either for 40 x 40 km squares on a weekly operational basis, or at individual weather recording sites for hindsight studies. MORECS has some distinct advantages over the direct methods. Firstly, it gives a consistent nationwide assessment of the general soil moisture status over an area for those who need to know national or regional moisture status. Secondly, a long-period record can be generated instantaneously for a particular site, enabling extremes, averages and return periods to be calculated. To do either task by direct measurement would be both costly and laborious.

MORECS produces an estimate of soil moisture and hydrologically effective rainfall (HER) for the whole country each week. For the autumn 2000 floods an analysis of SMD was carried out and the example of an area in Kent is given below.

The autumn 2000 floods began with a wet spring and early summer (approximately weeks 10 to 22) which severely hampered the drying out of the soils. This can be seen in Figure 4.8, where the soil moisture deficit (SMD) represents the amount of rainfall needed to bring the soil to a saturation level; the higher the SMD, the drier the soil. 2000 has been compared with average and the year with the lowest SMD's on record.

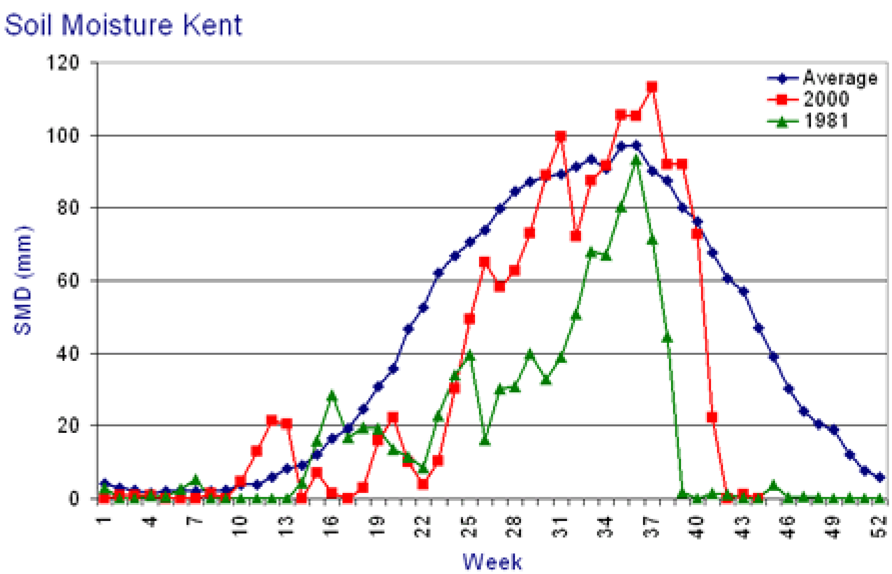


Figure 4.8 Soil moisture deficit for Kent during 2000 (figures derived from MORECS)

Noticeable in Figure 4.8 is the manner in which a substantial SMD is reduced abruptly to zero by the autumn rainfall (weeks 38 to 42) which is considered to be unusual in comparison to SMD records back to 1961.

The rain that brought the speedy return to saturation has continued and become 'hydrologically effective'. MORECS cannot differentiate between aquifer recharge and runoff to rivers, and this must be appreciated when considering Figure 4.9, which compares HER in autumn 2000 with average and other wet years.

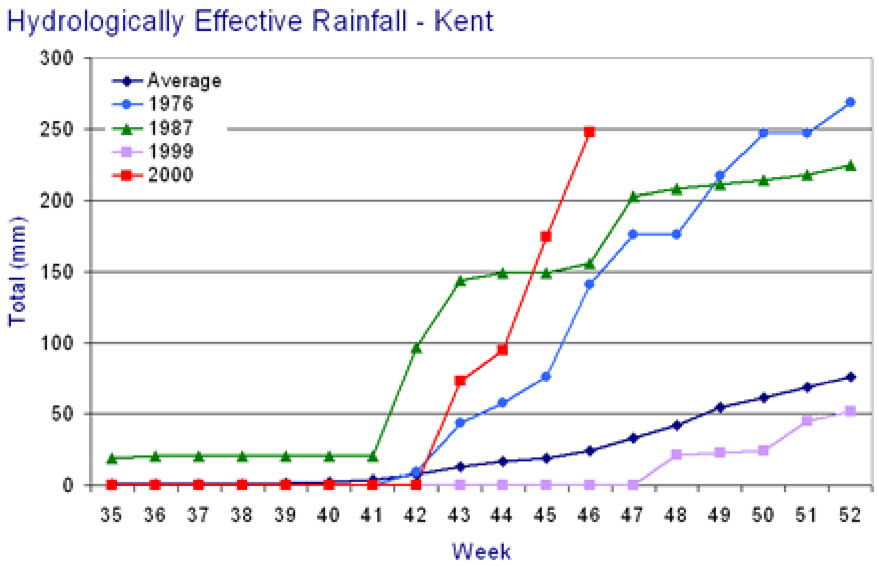


Figure 4.9 Hydrologically effective rainfall (HER) for Kent in 2000 (figures derived from MORECS)

While MORECS has a single-layer soil moisture store and makes no allowance for the energy involved in the phase changes of the water within the soil, the newer MOSES scheme addresses both of these deficiencies by introducing four soil layers for both temperature and moisture, and includes a treatment of the energy associated with the phase change of the water. In addition, MOSES also explicitly parameterises the influence of atmospheric variables, such as temperature, humidity and radiation, on the stomatal resistance of vegetation. The previous scheme had geographically varying stomatal resistance, but no temporal variation.

Some comparisons have been made between MORECS and the latest version of the MOSES model for one MOSES 5 km square that lies within MORECS square 157 for the year 2001. This MORECS square includes Bristol and surrounding areas. The MOSES model was run with the leaf areas, rooting depths and crop heights equal to those used in MORECS. The comparison shown in Figure 4.10 is for the median SMD developed for the mix of land uses (in MOSES SMDs for individual land uses are not available). The comparison is of course strongly affected by the soil conditions for the particular MOSES square which has been used. It is not easy to define a field capacity in MOSES and in effect the graph shows, for this MOSES square, a field capacity which corresponds to an SMD of about 20 mm. In summer the MOSES SMDs are within about 20 mm of the MORECS values. In autumn the MORECS SMD falls faster than in MOSES because there is no calculation of surface runoff in MORECS.

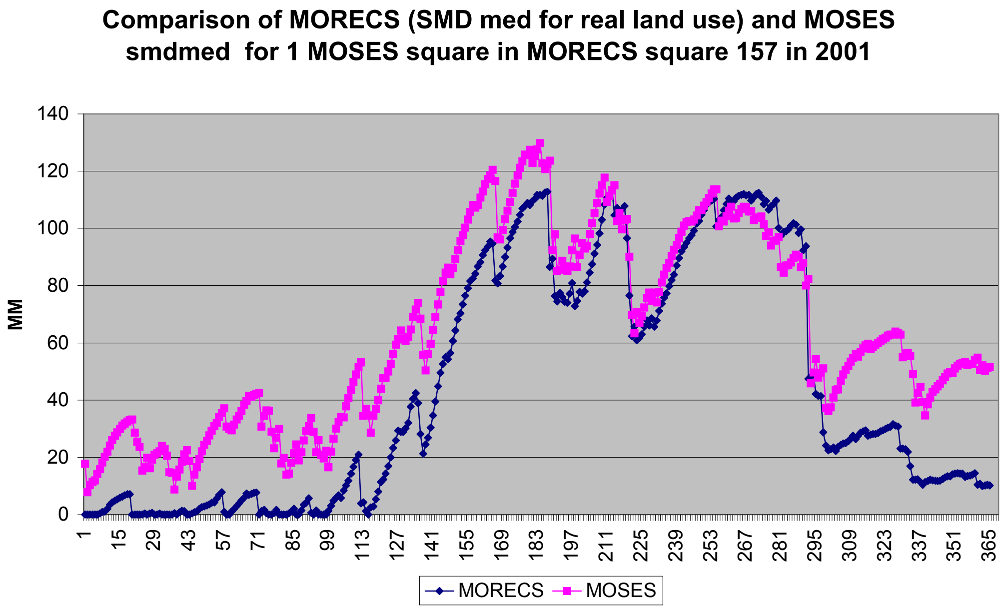


Figure 4.10 MOSES – MORECS comparison of median SMD data (smdmed) (x-axis scale is in days) **(MOSES line predominantly to top of graph)**

The above example is just a small part of on-going research to assess the degree of variance in MORECS and MOSES and to indicate any regional differences. At this stage, we would emphasise that the findings given above should be treated with caution and are not representative of the country as a whole.

However, due to the comparison work currently being undertaken, a continuous record of soil moisture and catchment conditions can be used as an indicator of catchment wetness. A pseudo-archive of MOSES data extending back 40 years to 1962 is to be developed as part of this work.

Emerging indicators of soil moisture deficit are valuable aids to determining the probable duration of the winter flood season to some extent, and any emerging pattern will be valuable to FCD engineers. It is hoped that the work proposed by the Met Office on soil moisture deficits will be published shortly.

Two of the most useful indicators might be:

- The median SMD for each calendar month displayed as a running mean for each of those series, again with 1970-89 forming the base. The median is proposed because of the bias otherwise introduced by zero SMD months.
- The annual duration of zero SMD each year, noting the starting month of such events each year. Any trend away from the 1970-89 mean will have implications for fluvial flood likelihood and contingency.

4.3.2 Groundwater levels

Persistent flooding due to high groundwater levels has been a feature of the winters 2000/01 and, to a lesser extent 2002/03. Although such flooding is generally less ‘dramatic’ and widespread than fluvial flooding, it is often far more disruptive to those affected as the inundation may last for weeks or months rather than days. With climatologists predicting wetter winters, such flooding may become more prevalent in the future.

The longest continuous record of groundwater level in the world runs from 1836 in the chalk aquifer at Chilgrove, near Chichester, in Sussex. Privately owned, readings are now maintained by the Environment Agency, who recently upgraded the site. It has a surface reference level of 77.2 m Newlyn OD, and at that level water can on rare occasions spill from the surface casing as the local water table rises to intersect the valley bottom topography around the site. That water then flows down the normally dry side valley to join the main River Lavant with its bourne head varying widely in position all the way from Chichester (in dry summers) to a point above Singleton in wet winters.

The Chilgrove well readings are sensitive to each winter's recharge of the South Downs in that locality. Soils are very thin and land use is a mix of deciduous woodland and hedgerows, sheep grazing and arable cropping. Despite considerable interest in, and research into, these levels over the years (Thompson, 1938, 1956, Limbrick, 2002, Law *et al*, 2002) no-one has yet been able to show that changed land use has disturbed that recharge pattern. Similarly, despite a major abstraction of groundwater from the Lavant unit by Portsmouth Water Company, its impact appears only to be felt in the valley below East Dean and down through Lavant village, not up the Chilgrove side valley. Consequently there is a presumption of a 'clean' record at this site.

The mean annual level range (1836-1990) is 25.57 m, with a maximum annual range of 47.3m and a minimum of 0.9m. The record used here has been quality controlled by first the observing authority at the time, and more recently by BGS staff at the National Groundwater Archive, Wallingford. A wall poster has been issued by them of the graphical version of the readings, with a legend outlining the observation intervals (normally about monthly) and other details.

It is an outstanding indicator of the risk of the Lavant going overbank in the City of Chichester, particularly in the area near the Hornet where it is a partially culverted stream along an un-natural alignment, probably created by the Romans to service their urban settlement there. Once total groundwater flows exceed about 4 $m^3 sec^{-1}$ at Greylingwell, roughly coinciding with the Chilgrove well going artesian, flooding is initiated. This occurred in 1993, when the escaping water took a route across the A27 dual carriageway, halting traffic for some days. A flood diversion scheme has now been constructed which formalises that diversion route by allowing excess flow to spill to Pagham Rife via local gravel pit attenuation.

The occasions when Chilgrove well has spilled vary in character between:

Type A: the serious long season of excess groundwater, and

Type B: brief excursions to such high levels, which are less of a problem.

Type A events have occurred in: 1865/6, 1882/3, 1903/04, 1960 and 1993
Type B events have occurred in: 1871, 1873, 1900, 1939, 1947, 1951 and 2000
Limbrick (2002) has used Locally-weighted Regression Smoothing (LOESS), (Kundzewicz and Robson, 2000) to examine whether any trend exists in this major dataset. Figure 4.11 shows selected extracts from his thesis, and Figure 4.11(a), the annual rainfall for the period 1834-1997, shows a marked rise until WW1, but general stability thereafter. Figure 4.11(b) presents the annual mean groundwater level for 1836-2000, which is also very stable at close to 50 mOD, although there is a slight rise of about 3 metres over the period of rising annual rainfall shown on Figure 4.11(a).

Figure 4.11(c) presents the average winter (Nov - Apr) groundwater levels, which lie close to 53 m NOD, having been nearer 50 m NOD when the measurements first began. The pattern is very similar to that shown in the two previous figures. Perhaps Figure 4.11(d) is the most informative, showing the April, 'end of winter recharge', levels. There appears to be a distinct, and accelerating, positive trend, which may indicate an increasing risk of flooding due to high groundwater levels, although it may be dangerous to place too much emphasis on this one plot.

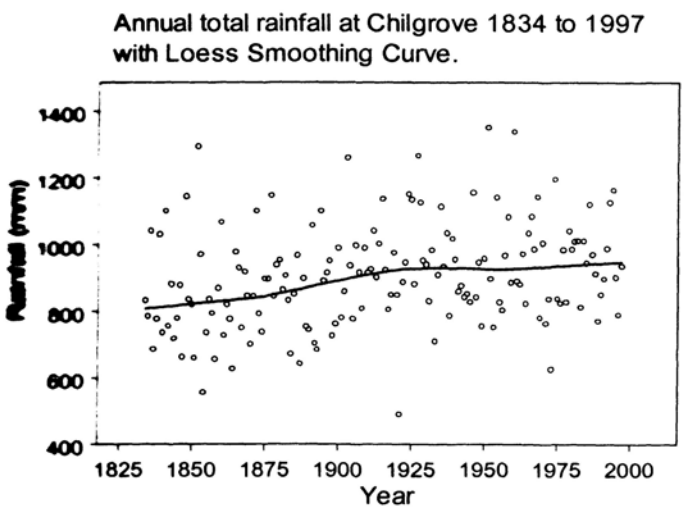


Figure 4.11(a)

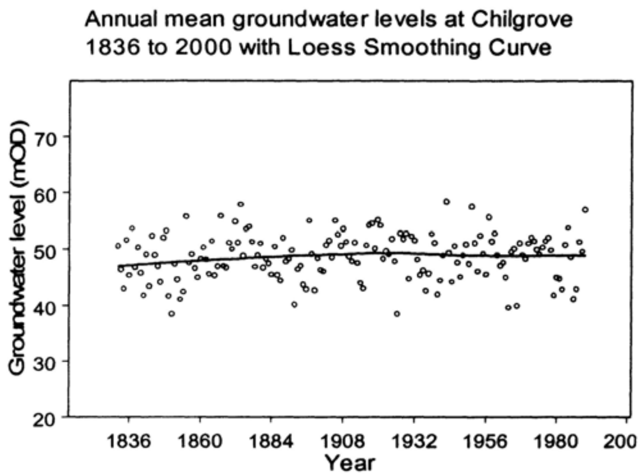


Figure 4.11(b)

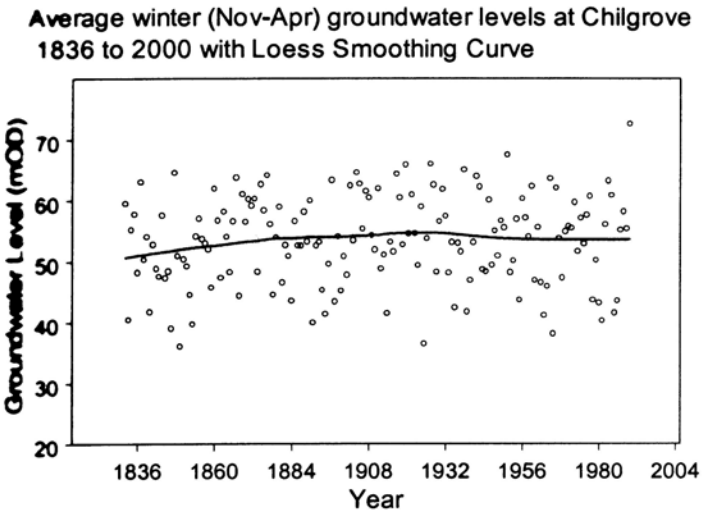


Figure 4.11(c)

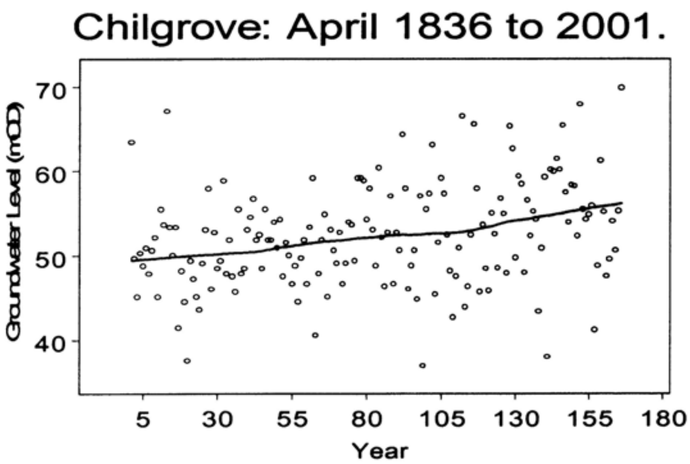


Figure 4.11(d)

Figure 4.11 Selected extracts from Limbrick (2002) showing Chilgrove rainfall and groundwater levels.

For both the Chilgrove groundwater level, and also a number of subsequent indicators, time series have been analysed using the 'peaks over threshold' (POT) technique (Robson and Reed, 1999, Vol. 3, Section 12.3) on the grounds that flood damage costs are not always limited to a single event in a year. The threshold passed by 1,2,3,4, and 5 events per year have been calculated to see if the profile created from those five definitions reveals more than a single arbitrary choice. The flood year has been taken as July 1st to June 30th rather than the calendar year; this is particularly important for localities that suffer clusters of floods when a wet winter season has waterlogged a catchment.

A base period of 1970 to 1989 has been suggested so that ECI movement away from that common base can be evaluated. However, we stress that many flood rich eras have come and gone in the past, and will do so in the future. In climatological terms it is doubtful if quasi-stability can be found in mean statistics for Britain without averaging over at least 70 years; this is due to its dependence on maritime influences, especially, but not solely, those of the North Atlantic. The North Atlantic Oscillation Index

(NAOI), being the pressure difference between the Azores and Iceland, is available from 1823 and gives the best coarse understanding of the westerly influences that bring large basin 'winter' flooding to this country. It deserves to be better known by flood defence staff, although it is unlikely ever to be a predictor of next season's risks.

The report commends a flexible understanding of seasonal risks, because saturated soil conditions can persist right through a 'summer' in years like 1968. Groundwater seasonality is more regular for our major aquifers, and summer-to-autumn underground water storage space softens the potential impact of storm rainfall sequences in those areas.

POT analysis of Chilgrove groundwater levels

The Chilgrove data have been subjected to a peaks over threshold (POT) analysis, and POT1, POT3 and POT5 are shown in Figures 4.12 to 4.14.

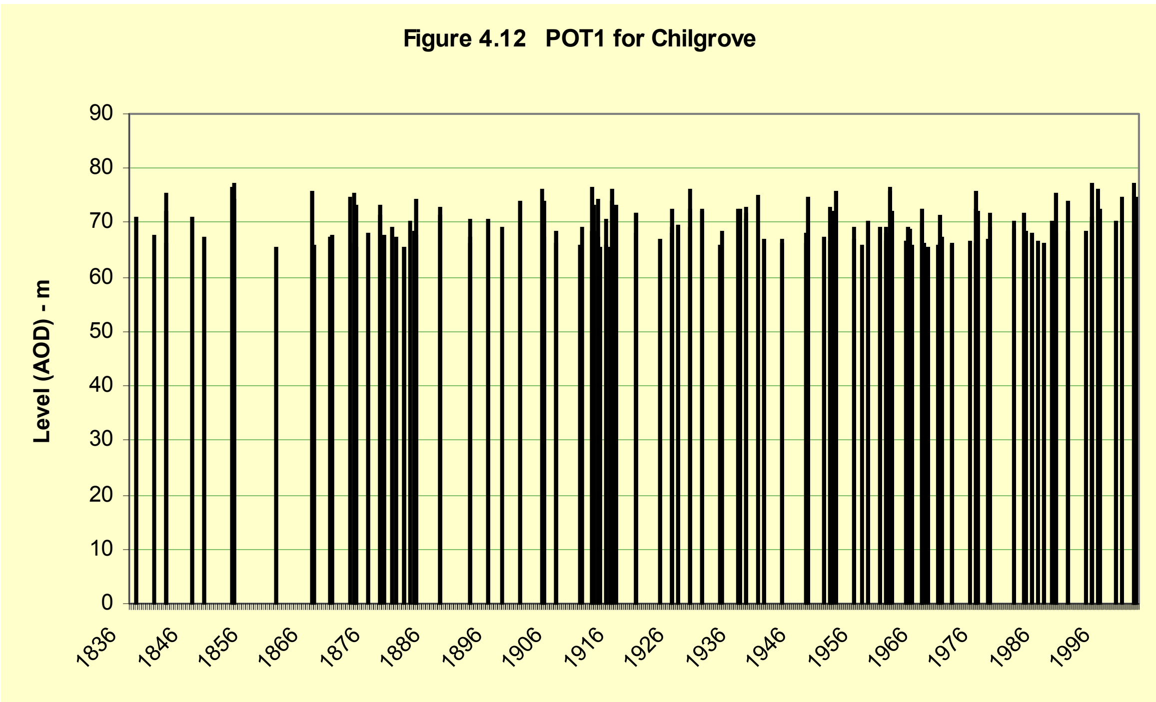


Figure 4.12 POT1 for Chilgrove

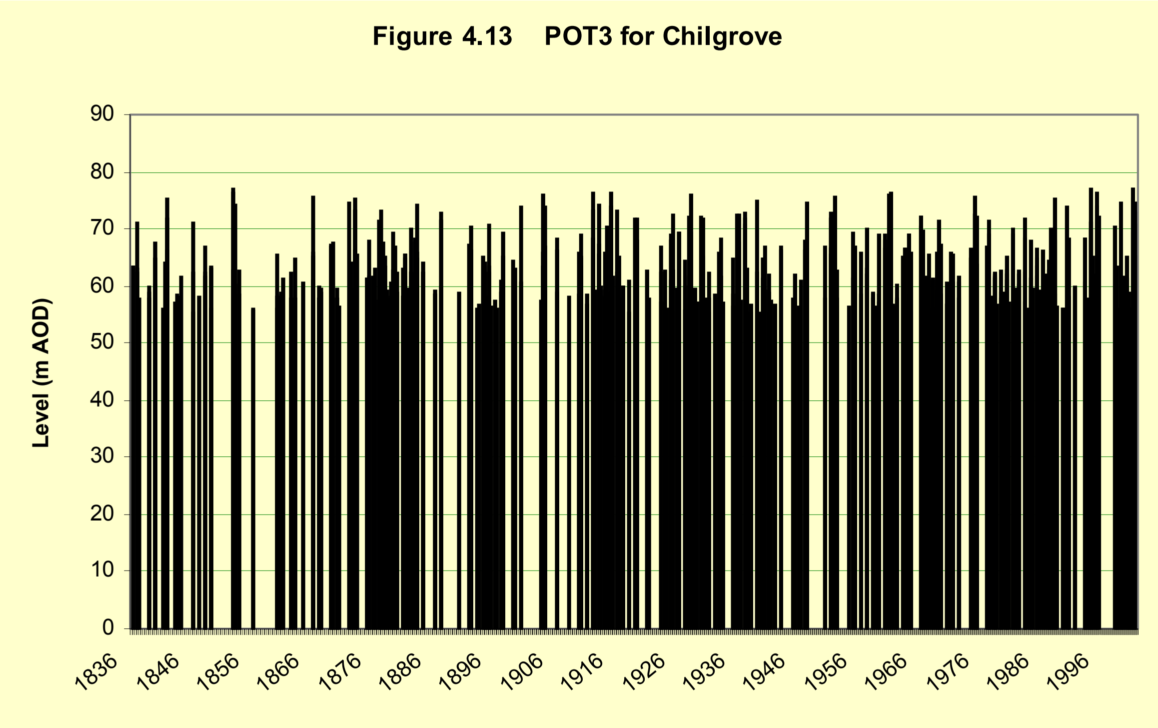


Figure 4.13 POT3 for Chilgrove

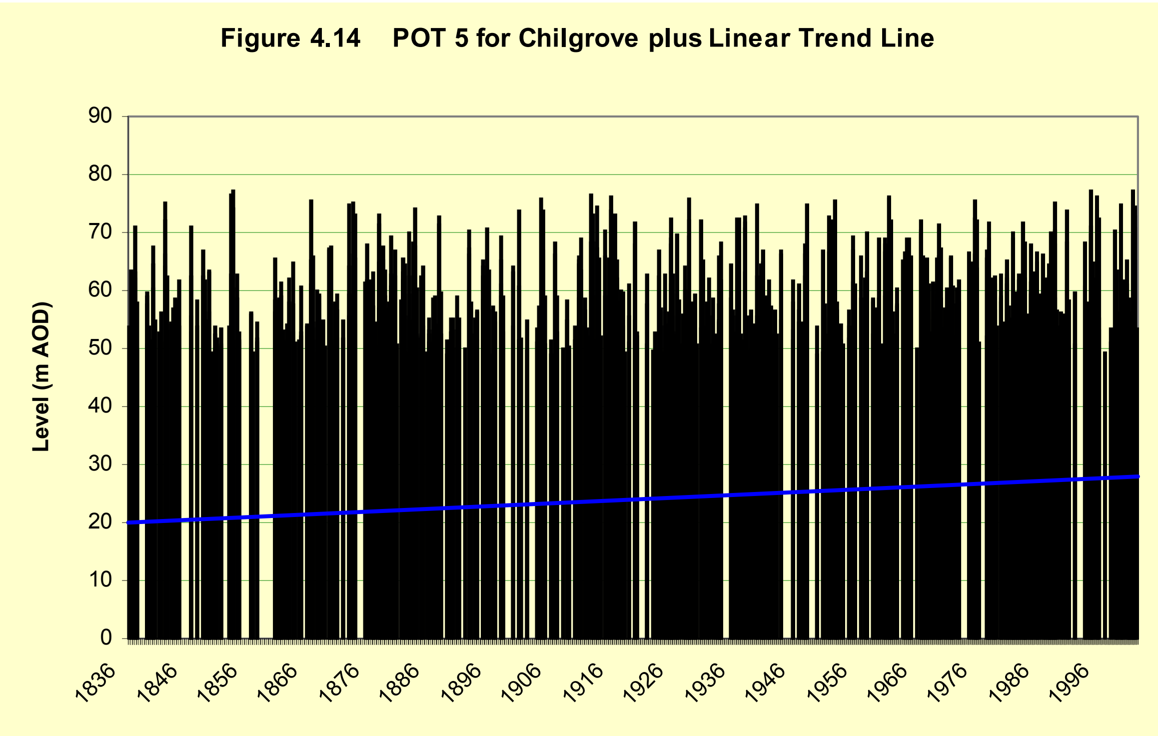


Figure 4.14 POT5 for Chilgrove plus linear trend line

Overall the record matches the climate change scenarios that speak of higher winter recharge and longer drier summers that give the same low water table condition (generally speaking) each October.

The record has also been examined to see if aquifer storage is such that persistent flood conditions can be expected in a run of years after each high water table state occurs.

There is only weak evidence of this at Chilgrove; what provides a larger feature is the recent range of extremes of the past decade, seen most strongly in the January level series. An indicator could be constructed to illustrate this characteristic of the recent British climate; however, it would not produce an absolute value that could be used, so it has not been pursued. Similar reasoning has prevented us from analysing the National Groundwater Archive series of regional aquifer annual recharge estimates; however if these gain more acceptance for general use in catchment flood modelling, this decision should be re-visited.

The POT5 series (Figure 4.14) has a fitted linear trend line, which shows a positive trend. However, this trend, developed using Microsoft Excel, should be considered as suspect as it the statistical routines in Excel are somewhat suspect. Nevertheless, there is evidence in the POT1 to POT5 series of increasing exceedences towards the end of the record, and hence the apparent trend line is probably an indication of increased frequency of high groundwater level rather than increased magnitude, and the trendline may not be indicating the pattern that the casual reader would interpret. It is suggested that such trend lines be omitted from any presentation of POT results, since although it may be indicating a true change in flood regime, the change may be in frequency rather than magnitude, and could easily be misinterpreted.

4.3.3 Land-use change

Land use change may have a direct impact upon a catchment's flood response, and are hence of primary interest to fluvial flooding. Increasing urbanisation for example will increase runoff volumes and reduce response times unless developers implement appropriate mitigation measures. Similarly changing forest cover may increase a catchment's propensity to flood (due to deforestation), or may reduce it (increased forest cover). We consider below a number of possible land use indicators that may impact upon fluvial flooding, although a recurring theme to many of the possible indicators is the difficulty of obtaining good quality, consistent, long records.

Woodland cover

Smith (Undated), of the Forestry Commission, has not only summarised recent surveys of tree cover in the British landscape, but has been able to add to that picture some historic values to give a longer perspective (Figure 4.15). Of particular interest is the result from examining data given in the Domesday Book from the 11th century. This produces an approximation to a baseline condition (assuming that we overlook the extensive woodland clearance in Neolithic times as agricultural change began on a serious scale). The Government's Environment Statistics volumes have given breakdowns of woodland cover as between conifer plantations and native deciduous woods. Conifer cropping began as a response to the national need for timber, and rural employment, in the early 20th century. However, the use of fuelwood timber for home heating is known to have continued in country areas until the Depression of the 1920s was over. Since then a gradual but distinct recovery in overall tree cover has taken place. It is expected that tree cover will continue to grow at a steady , if slow, pace due to:

- The establishment of various National Forests, bringing mixed deciduous woodland back to industrial regeneration areas;
- Re-establishment of hedgerow trees as part of Defra initiatives to reverse past bio-diversity losses;
- EU grants for a range of countryside measures to counteract past excesses in agricultural crop subsidy impacts.

Fig 4.15(a) shows the total forest cover as a percentage of total land area in England and Wales from 1870 to 2000, and Figure 4.15(b) tentatively does the same over the last millennium. The overall picture is clear; forest decline was halted some 80-90 years ago following the First World War and at present rates of net planting could perhaps ultimately return to Domesday Book proportions by the end of the 21st century. What should be said about Figure 4.15(b) however is that a simple linear extrapolation from the Domesday book cover of 15% to the first census figure of 5% in 1870 has been assumed, and this simplification is shown as a dashed line. It is likely that the real decline in woodland cover was non-linear and much of the decline may well not have occurred until the industrial revolution.

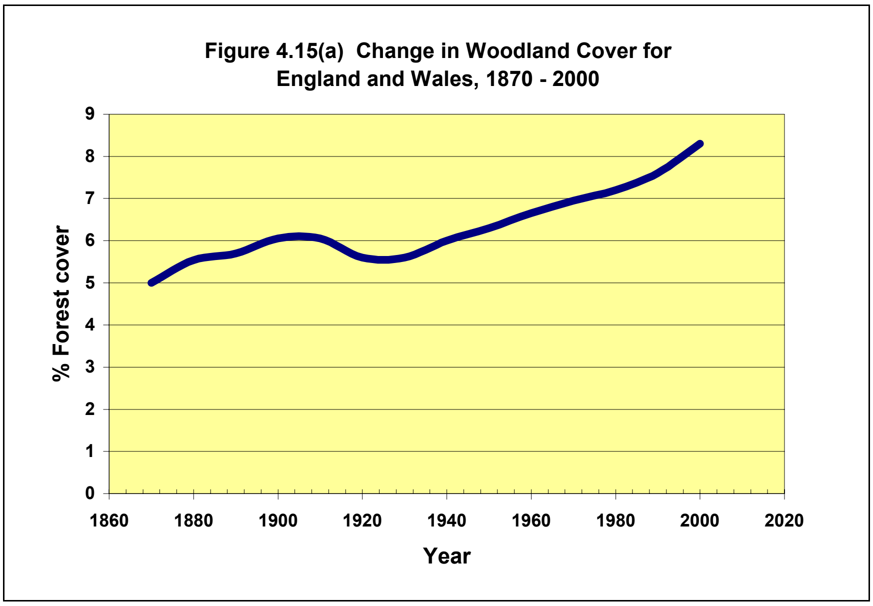


Figure 4.15(a) Change in woodland cover for England and Wales, 1870-2000

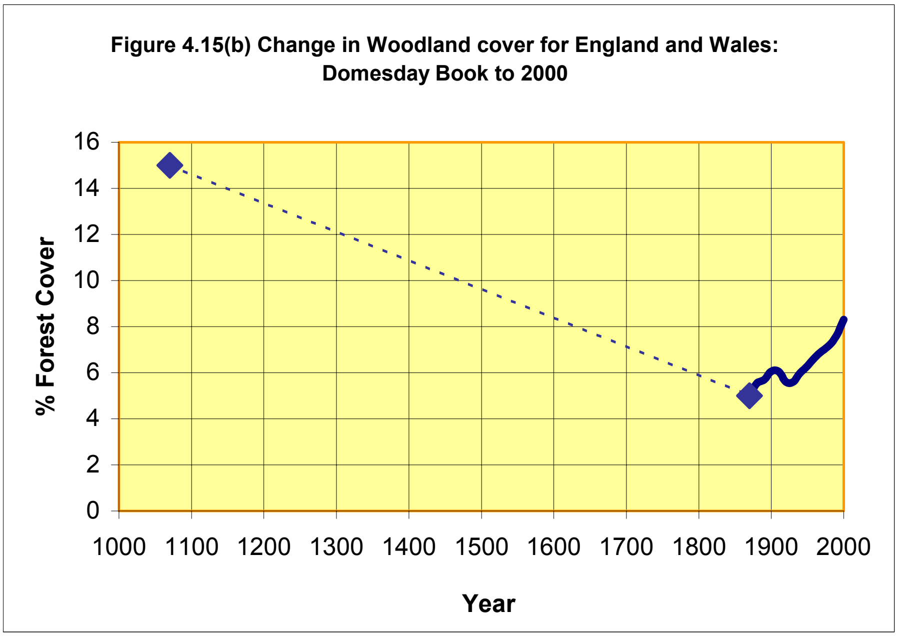


Figure 4.15(b) Implied change in woodland cover for England and Wales – Domesday Book to 2000

In the Flood Estimation Handbook this issue is not covered explicitly, although if the afforestation leads to an area reaching the criterion for being a 'permeable catchment' the relevant adjustment procedure should possibly be used.

However, it needs to be remembered that one of the most difficult factors to predict is whether flood debris dislodged by high run-off depths/velocities, or by under-cutting of a stream bank, or by landslide, will lead to a bridge logjam downstream. In the August 1967 Forest of Bowland flood trees 'torn' from the River Wray banks floated down to the main River Lune, successively causing the collapse of bridges en route. Several hundred were observed floating past the Lune Valley Water Board intake at Caton.

Land use cover

The Digest of Environmental Statistics has given in various formats the breakdown year-by-year of urban, forest and arable land, albeit with changing detail over time.

The percentage of the land area of England and Wales that is down to arable for the July to June year for which the farm returns were made to MAFF (Defra's predecessor) might provide useful data. The Countryside Information System (CIS) does not yet hold a long time series of arable area at a 1 sq. km. grid. However where it is known locally that change has been evident in farming practice it is recommended that the catchment average for arable be calculated as a times series of potential future value.

However, in view of the uncertain linkages between land cover and flood response, it is suggested that no work be undertaken on these indicators until better data become available and until the cause-and-effect linkages have been established. This supports the findings of the Flood Estimation Handbook (Robson and Reed, 1999) that natural climatic variability masks any trends that might result from land use changes, such that any such trends can neither be detected, nor readily dismissed. It may be worth re-examining the possible effects of land use once full results from the HiFlows data collection project are available.

4.4 River Indicators

4.4.1 Peak river levels

Garrad (2001, 2002) has already made the case for use of peaks over threshold (POT) river levels, and some comments on his work were presented in Chapter 3. However, one of Garrad's comments was the difficulty of finding long records with good quality data from catchments that have not undergone significant land use or drainage changes. It is hoped that the current HiFlows project, that is extending and quality controlling existing POT data for the country will in time held to address this problem.

To illustrate the topic further we have analysed data from two stations with long records. Unfortunately, both of these are in the wetter south-west, one in Devon, and the other in Wales. Some work was also carried on out a station in East Anglia, and one in the north-east, but there were excessive gaps in the record in one case, and a suspected discontinuity in the data in the other, meaning that both were rejected.

The River Taw at Umberleigh

The Taw is located in north Devon and has a continuous and homogeneous level record from 1958 (Institute of Hydrology, 1993). A rock step downstream gives level control and, although by-passing of flow begins at a stage of about 3.7m on the right bank, a good cableway rating accommodates this (See Plate 4.1, which illustrates the by-passing during the winter of 2000).

Plate 4.1 Taw at Umberleigh, view from downstream of the gauging station during the winter 2000 flood. (Source: Anna Branthwaite, Express and Echo, Exeter)

This rural catchment is dominated by Dartmoor granites on the south, and Exmoor Devonian shales and sandstones on the north; the central lower-lying farmland (grade 3 and 4 soils) is underlain by Culm shales and sandstones. The basin has little or no protection from westerly Atlantic storms. Barnstaple lies at the mouth of its estuary, where it meets the River Torridge flowing in from the west. It has a catchment of 826 km^2 and can be regarded as representative of many flood responsive larger basins in western England and Wales. Its flood of record had been 650 m^3s^{-1} for many years, having been set on December 4th, 1960***;*** however this was surpassed by about 0.3 m on 30th October 2000, when a Severe Flood Warning came to fruition and property damage occurred from flooding in Umberleigh itself. A peak flood level of just over 5 m was reached and initially assessed by the EA as a 50 to 100 year event. (Environment Agency, 2001, Table 5.4) A £300k flood protection scheme is planned for the Umberleigh community, with work expected to start in 2003; its influence on the level record series at high stage is not yet known.

It is known that major floods took place in the lower Taw in 1586 and autumn 1894, the latter being the highest for about 50 years. Lesser floods are reported from 1900 and 1909. If the Exe and Tamar are any guide then other big floods, on the scale of 1960 and 2000, may have occurred in 1625, 1786, 1800, and 1809, with a lesser one in July 1847, but this remains to be confirmed for the Taw (Law *et al*, 2002).

Figs 4.16 to 4.18 show the POT1, POT3 and POT5 series for the River Taw at Umberleigh.

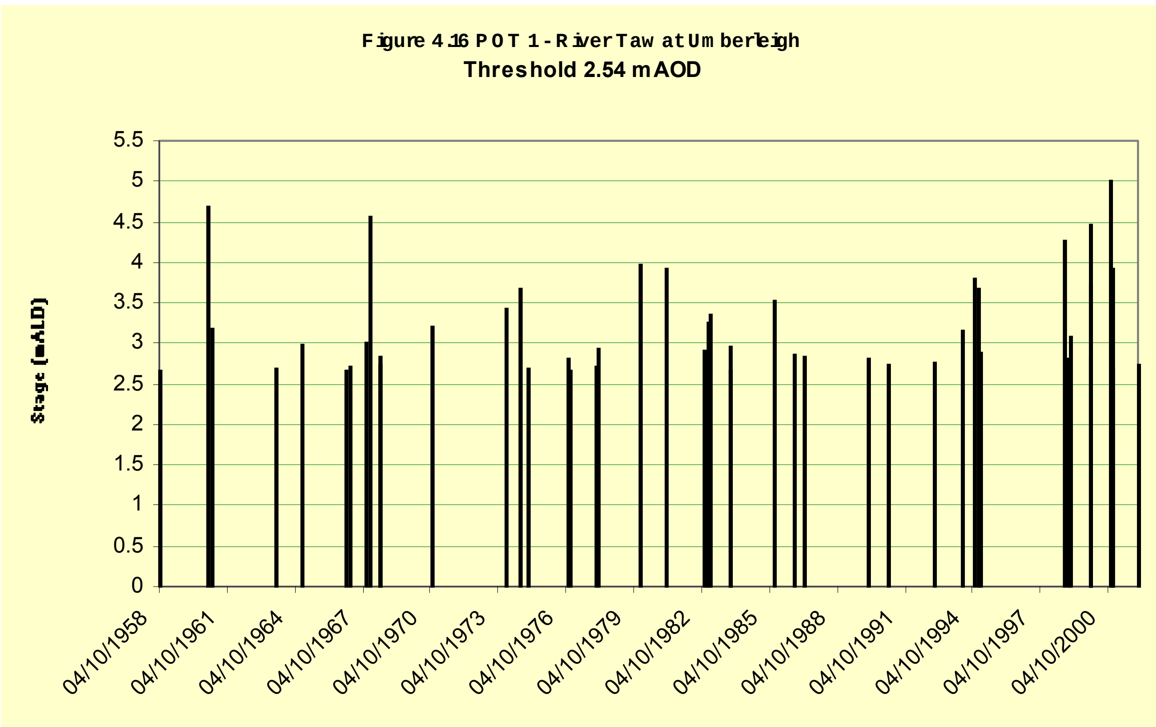


Figure 4.16 POT1 for the River Taw at Umberleigh

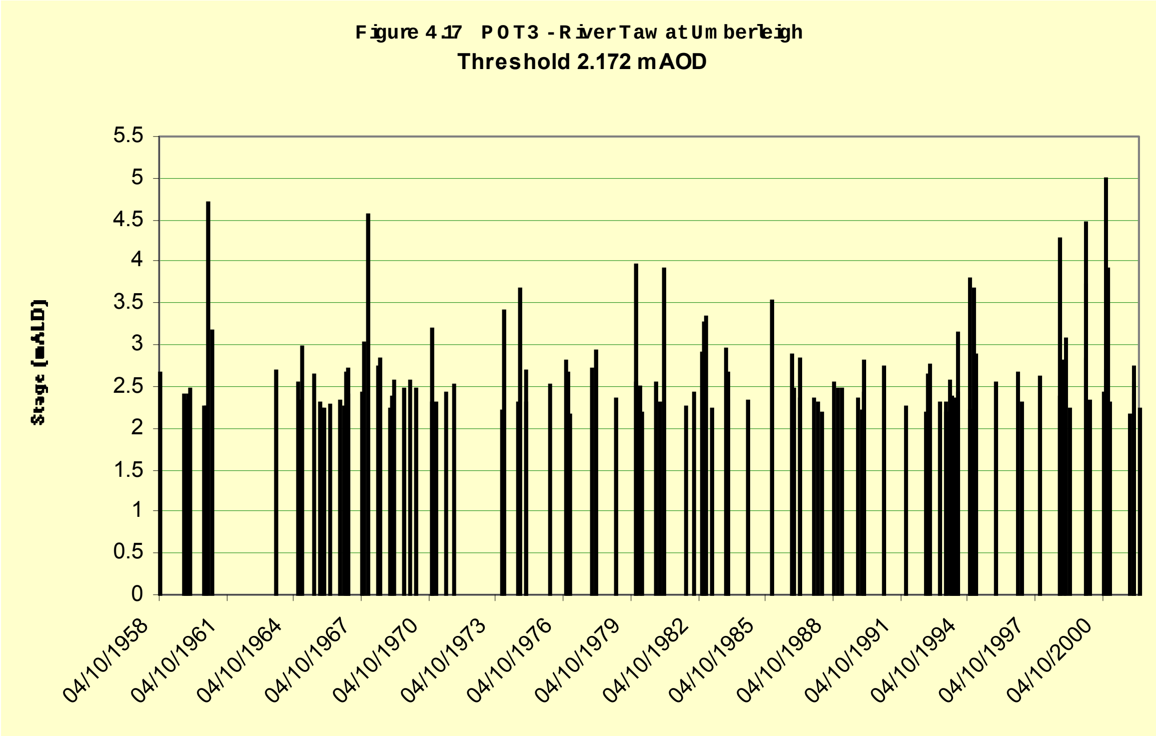


Figure 4.17 POT3 for the River Taw at Umberleigh

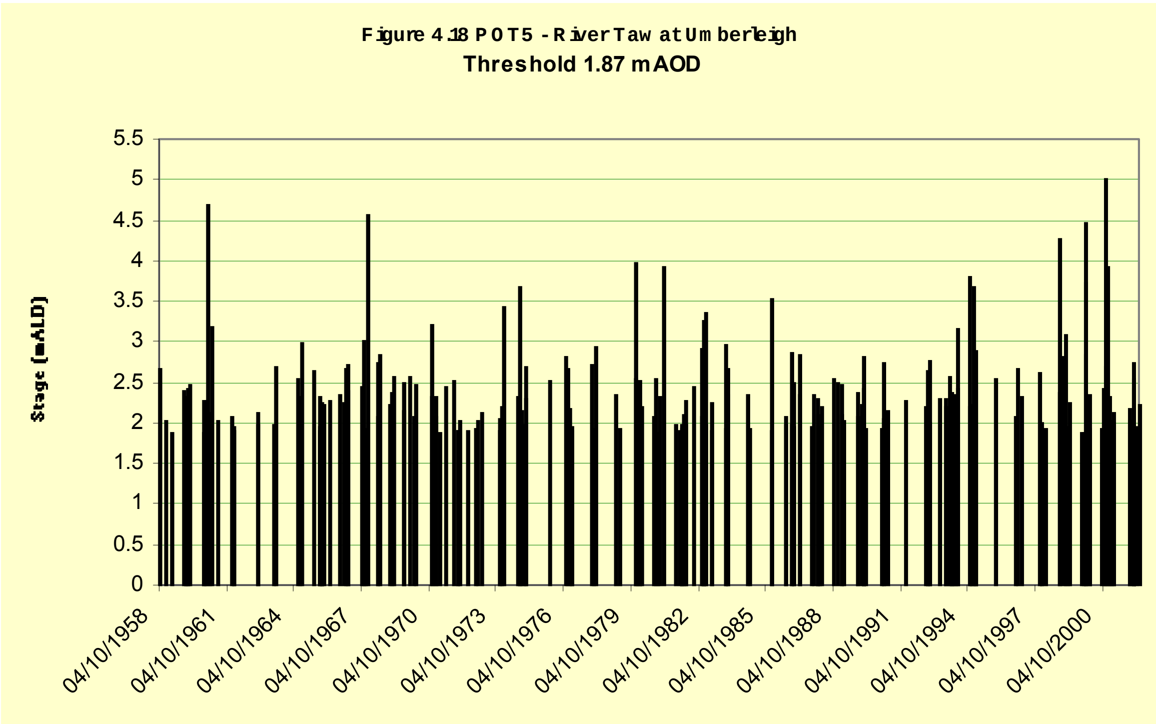


Figure 4.18 POT5 for the River Taw at Umberleigh

No clear trend is evident to the eye from any of the graphs, whether taking in only the extremes or from the generality of spates above 2 mALD. The profile of thresholds for the entire record is as follows:

Table 4.1 POT thresholds for the River Taw at Umberleigh

Average number of excedences per year	Level above local datum (m) (mALD)	Increment (m) (POT4 – POT5 etc.)
5, (POT5)	1.87	
4, (POT4)	1.97	0.10
3, (POT3)	2.17	0.20
2, (POT2)	2.34	0.17
1, (POT1)	2.54	0.20

These seem reasonable but cover only a narrow range compared with the elevations reached by Q10+ floods. So for Umberleigh it is satisfactory to work only from the POT1 graph.

Of the five largest floods on the EA record, 2 fell in the 1960s and the other three came in 1999/2000, a reminder of the difficulty for Emergency Work Force sizing and planning. Gaps of 4 or 5 consecutive years without any flood of note have always been present intermittently. Another way of looking at the data is to look at the number of peaks exceeding the POT5 threshold of 1.87 m in each decade, as shown in Figure 4.19, where no significant pattern emerges.

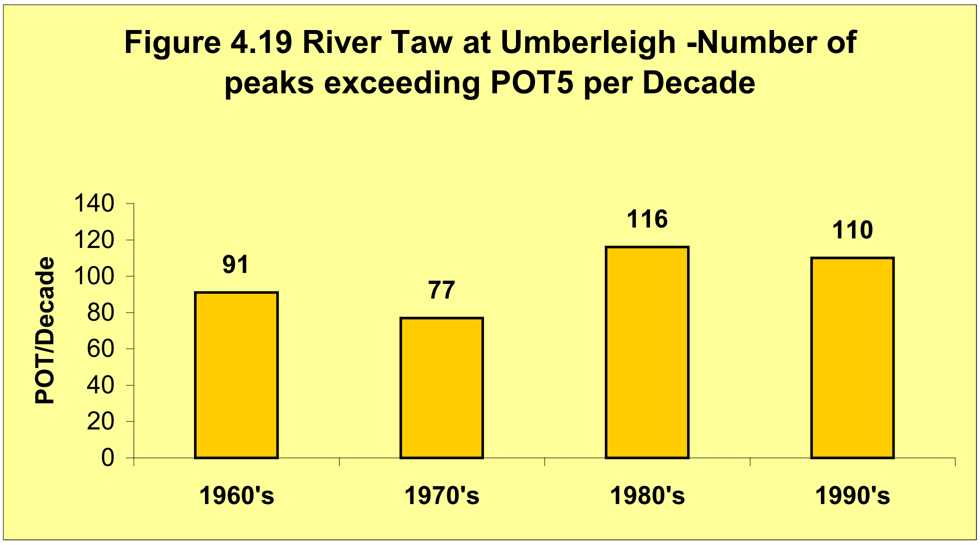


Figure 4.19 River Taw at Umberleigh – Number of peaks exceeding POT5 per decade

In the broadest of terms the upper envelope of flood level fell from 1960 to 1992 and has since risen again, Researchers have suggested looking to links to the North Atlantic Oscillation Index. (Limbrick (2002) showed that January riverflow volumes are correlated to this index most strongly in the west but decreasingly across towards the east of England -- on a Cornwall/Kent transect. However, for Umberleigh flood peaks the NAOI might lead one to conclude that they should have risen in size from the early 1960s until the mid 1990s, but as we have seen that is not borne out by the record for the Taw.

The Usk at Chain Bridge

The Usk in Gwent has a continuous level record from 1957 but it is only possible to work on a homogeneous one since 1972 (Institute of Hydrology, 1993). This hilly catchment is mainly underlain by Old Red Sandstone. Newport, with its huge tidal range, lies at the mouth of the Usk, but Chain Bridge lies well inland , between the towns of Abergavenny and Usk. It has a catchment of 912 km^2, about 3% of which is under conifer plantations; there are three water supply reservoirs that reduce downstream flood potential marginally. Brecon is the only case of a well known local flood protection scheme in the catchment.

The Chain Bridge record can represent basins that lie in the lee of a mountain barrier, albeit well to the west of the nation as a whole. Its measured flood of record is 945 m^3sec^{-1} set during the major S Wales storm of 27 December 1979; this was not surpassed by the 2000/01 floods, notable though they were in parts of southern Wales (Environment Agency, 2001a). Major floods of over 600 m^3sec^{-1} were recorded in December 1960 and October 1967, with other flood peaks over 500 m^3sec^{-1} in December 1965, February 1967, March 1981, February 1990, December 1992 and autumn 1998. Summer floods do not feature in this list; decadal gaps between outstanding events do occur, even in such a generally wet climate, 1969-1978 being an example.

Pre 1957 floods became better known due to research before Brecon's flood alleviation scheme (Hutchinson and Smith, 1986). Major floods came in 1528, (1772), 1795, (1840), 1853, 1873, (July 1875), October 1876, (1877), (May 1886), 1924, 1931 and 1960 (some uncertainties exist for those floods in brackets). Of the floods listed, that of 1795 has been described as 'catastrophic' (Hutchinson and Smith, 1986), and the 1853 peak was a little higher than 1979 at Brecon, halfway down the basin. With such a succession of damaging events it could be said that there is little scope for any indicator to identify growth (or decline) in the number of floods. However, few of those past floods can yet be quantified adequately to be as sure about flood magnitude stability.

Figs 4.20 to 4.21 show the POT1 to POT5 series for Chain Bridge.

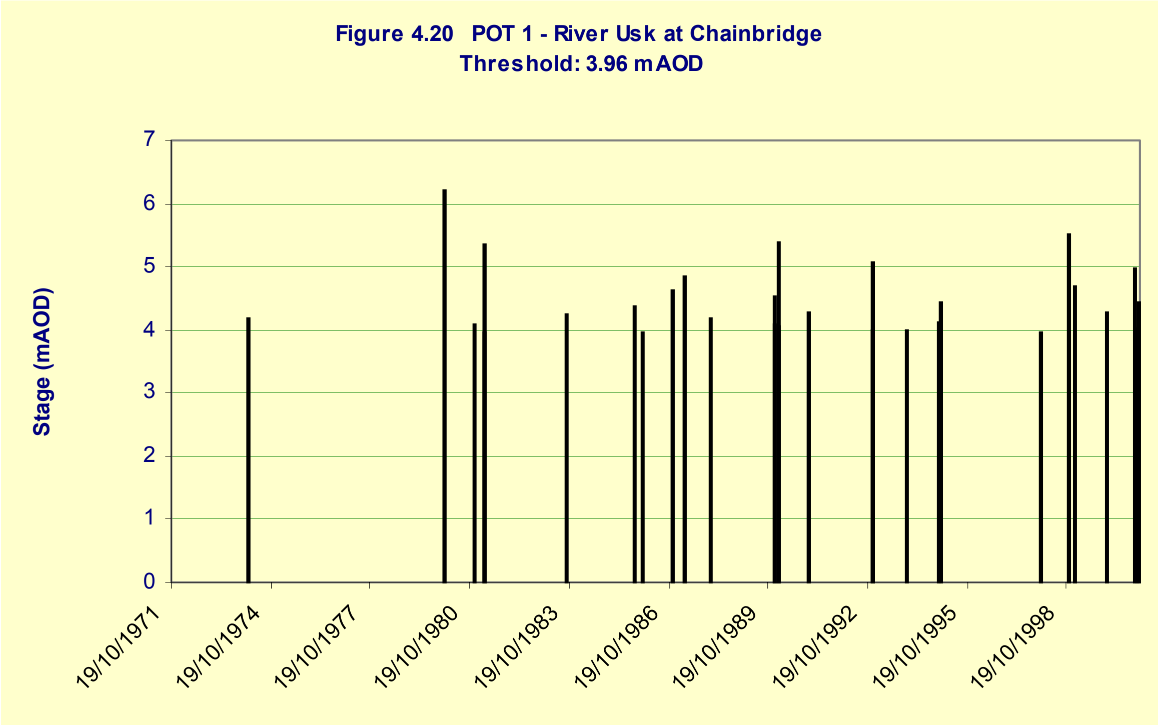


Figure 4.20 POT1 for the River Usk at Chain Bridge

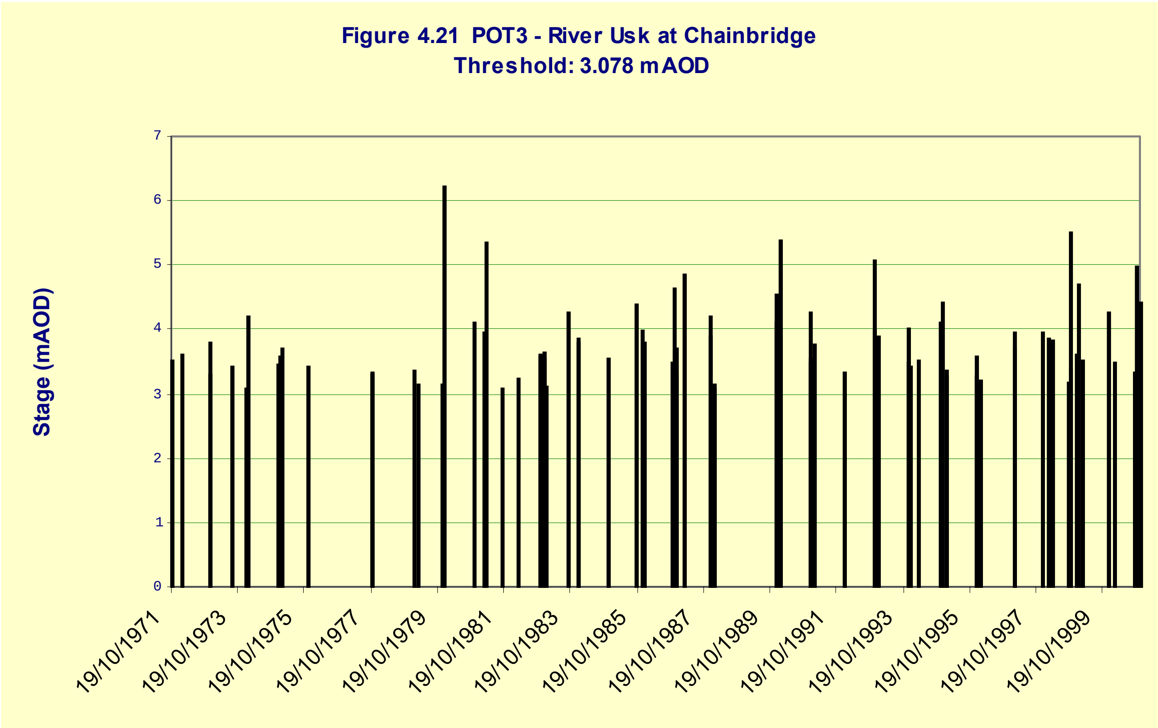


Figure 4.21 POT3 for the River Usk at Chain Bridge

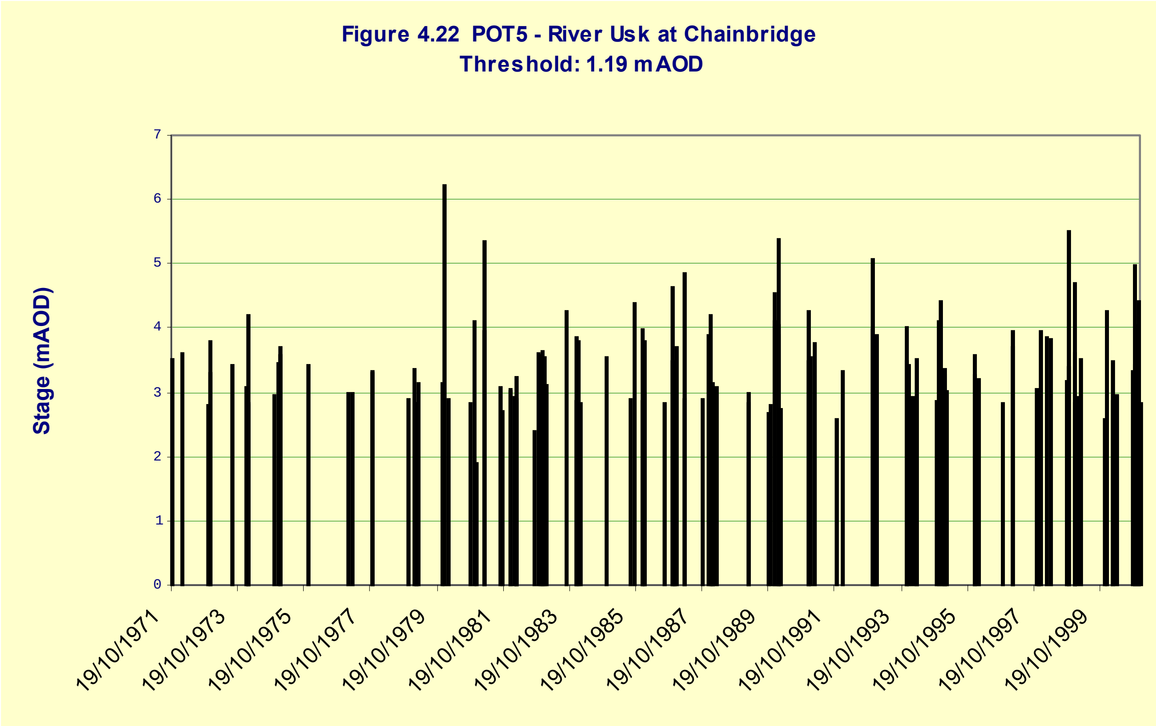


Figure 4.22 POT5 for the River Usk at Chain Bridge

No clear trend is evident once the outstanding 1979 flood and the preceding dry years are set to one side, whether taking in only the extremes or from the generality of spates above 2.0 mALD.

The profile of thresholds for the entire record is as given in Table 4.2.

Table 4.2 POT thresholds for the River Usk at Chain Bridge

Average number of excedences per year	Level above local datum (m) (mALD)	Increment (m) (POT4 – POT5 etc.)
5, (POT5)	1.19	
4, (POT4)	2.85	1.66
3, (POT3)	3.08	0.23
2, (POT2)	3.48	0.30
1, (POT1)	3.96	0.48

For Chain Bridge it is most satisfactory to work from the POT3 graph (on the principle of 'least data to give clearest truthful impact'). The upper envelope suggests flood intensification every 10 or 12 years, with perhaps two significant events clustering together within 1 to 2 years.

Comparison is possible with the flood chronology published for the smaller Tawe basin, which has a catchment area of 269 km^2, (Walshe *et al*, 1982). The authors claimed " Both floods and heavy daily rainfalls have increased dramatically since the late 1920s. Of 17 major floods since 1875, 14 occurred from 1929 to 1981 and only 3 during the

1875 - 1928 period..." The same was claimed for the Ebbw valley for 1908-78 (ref 7.8), even closer to the Usk, changes that "correlate well with previous findings for the Wye" (Halton Thompson, 1938). Additionally Walsh *et al* noted "that floods have tended to occur in groups within the 1929-81 period"; these flood-rich bursts down the Tawe were in 1929-33; 1958-67 and 1979-81. They discuss whether the observed rise in flood magnitude and frequency could be due to:

- Afforestation
- Field drainage
- Urbanisation
- Industrialisation

They show that forest expansion was modest and too late to explain changes, that formal drainage schemes were very limited in the Tawe area, that urbanisation pre-dated the period largely, as did most industrialisation.

However, correlation in flood rankings for the Tawe and Usk is not good, presumably because of their windward/leeward contrast in dominant winter rainstorm sequences. Hence it would not be appropriate to transfer any finding by Walsh *et al* immediately to the Usk basin.

Again, the number of exceedences per decade has been plotted and is shown in Figure 4.23.

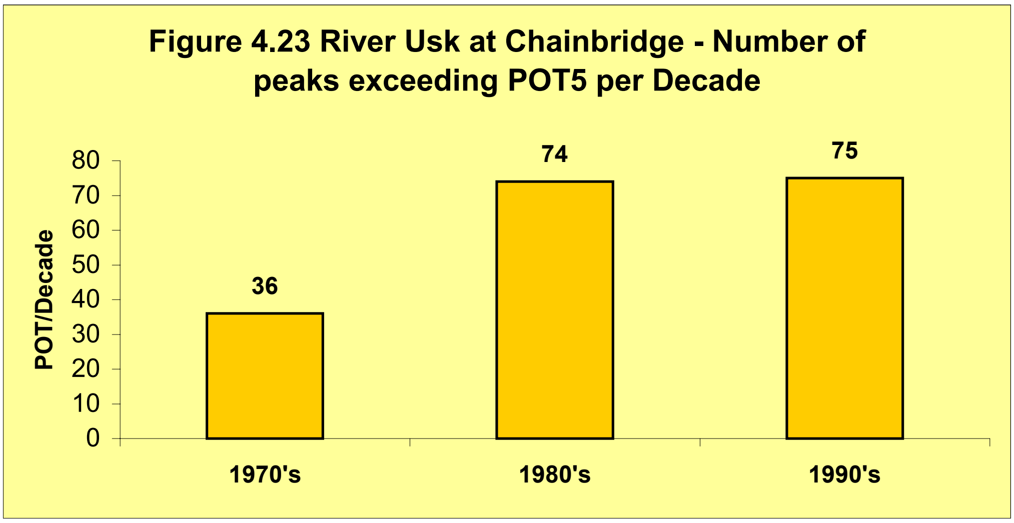


Figure 4.23 River Usk at Chain Bridge – Number of peaks exceeding POT5 per decade

There is some suggestion that flooding was less common in the 1970s than of late, but it is unwise to read too much into this analysis.

Records for both the Tawe and Usk are of lengths typical on many gauging stations in England and Wales, and the earlier suggestion that indicators be related to a base period of 1970-89 has not been tested for this particular indicator as insufficient data are available.

4.5 Oceanographic Indicators

4.5.1 Introduction

Most useful indicators for sea level and storm surges are derived from data from the National Tide Gauge network, as available from NTSLF, and from PSMSL data.

- Maximum (and minimum) sea level

NTSLF extracts monthly values of maximum and minimum sea level for each station on the National Network. These are stored in an ORACLE tables for easy access for the last 10+ years. Earlier values are stored in other tables.

- Maximum (and minimum) storm surge elevations

NTSLF also extract and tabulate monthly maximum and minimum storm surge elevations. As noted in the background section on storm surges, surge maxima do not in general coincide with water level maxima, so in themselves are not a direct indicator of but contribute to flood risk.

- Extreme sea levels

Professor Jonathan Tawn, together with POL researchers, has done extensive work on methods to estimate extreme sea levels (see Dixon and Tawn, 1994, 1995 and 1997). The methods developed aim to make best use of all available data (hourly, annual maxima and mean sea level) from the National Tide Gauge Network, combined with outputs from POL surge models, to provide values not only at tide gauge sites but along the whole coastline of England and Wales. Trends can be estimated and allowed for in the extreme estimates. Techniques include joint probability methods which treat tide and surge components separately, so storm surges are directly relevant here.

- Mean sea level indicators

A review of the British Isles MSL data set from tide gauges can be found in Woodworth et al. (1999). Several UK records are approximately 100 years long and show clear evidence for rising levels, implying "absolute" sea level trends for the last century of about 1 mm/year, or 10 cm for the century (see Figure 4.24(a)). The Aberdeen and Liverpool time series are composites constructed as described in the paper. The North Shields, Sheerness and Newlyn records are from the PSMSL dataset. This trend is consistent with but at the lower end of the range of uncertainty of 10-20 cm of the estimates of global change by the IPCC.

An even longer sea level record for the period 1700 to 1925 is available for Amsterdam, and is shown in Figure 4.24(b). It is apparent that sea levels were relatively stable at this site during the 18th and early part of the 19th centuries, but that they have risen by almost 150 mm between 1820 and 1925, a somewhat higher annual increase that UK equivalents.

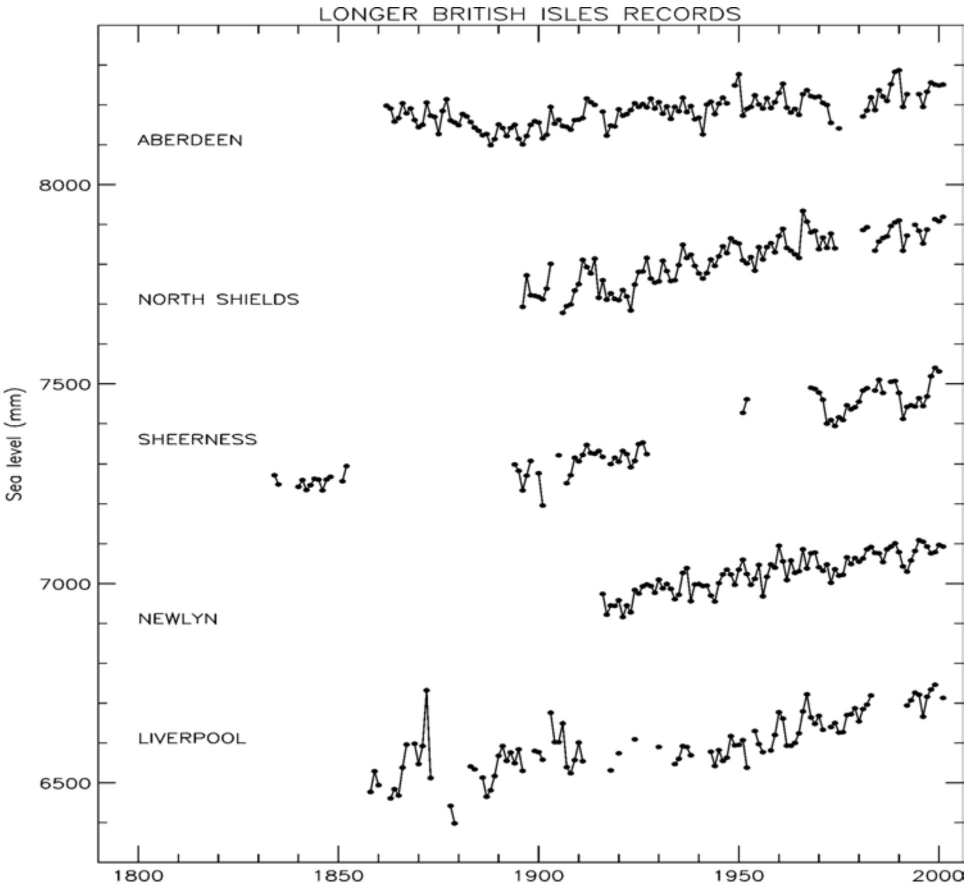


Figure 4.24(a) Long British Isles records of annual MSL spanning the last and present centuries. Each record has been offset for presentation purposes.

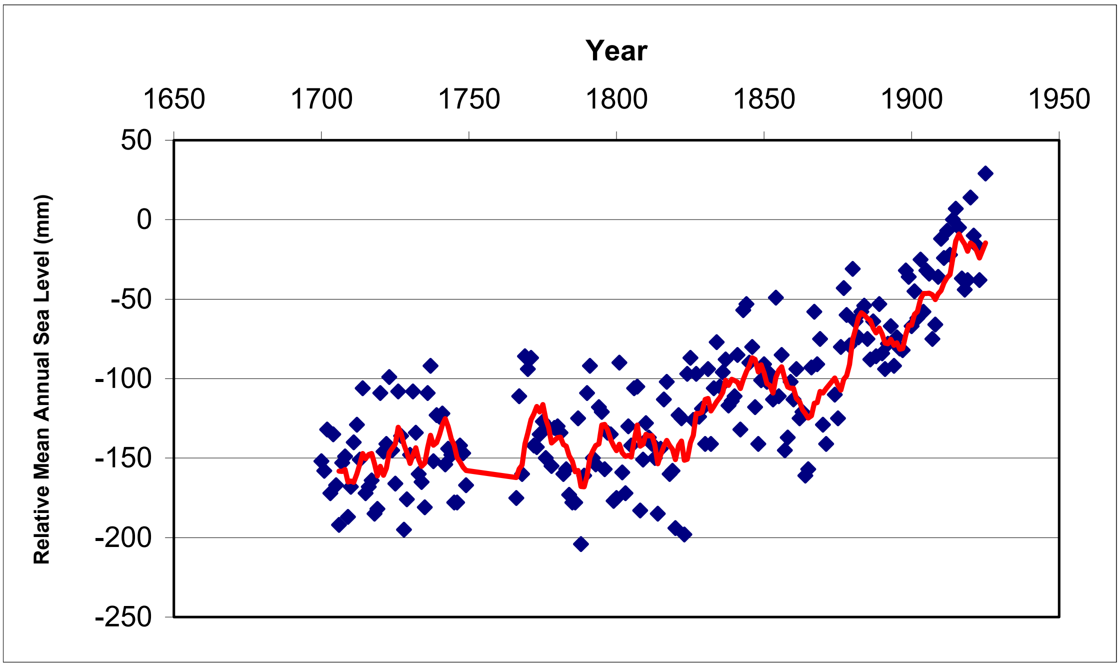


Figure 4.24(b) Long-term relative sea level for Amsterdam for 1700 – 1925 with 7 year moving average (solid line)

Sea level changes also show a small "sea level acceleration" component, which is consistent with being the result of an acceleration towards the second half of the 19th century, as well as considerable inter-annual and inter-decadal variability. A UK sea level index for the twentieth century (Figure 4.25) computed from MSL data from 5 stations (Aberdeen, North Shields, Sheerness, Newlyn and Liverpool) provides a useful indicator of these variations. Each record has been de-trended over the period 1921-1990 and the de-trended values averaged. Standard deviations of de-trended values about the average are shown by the error bars.

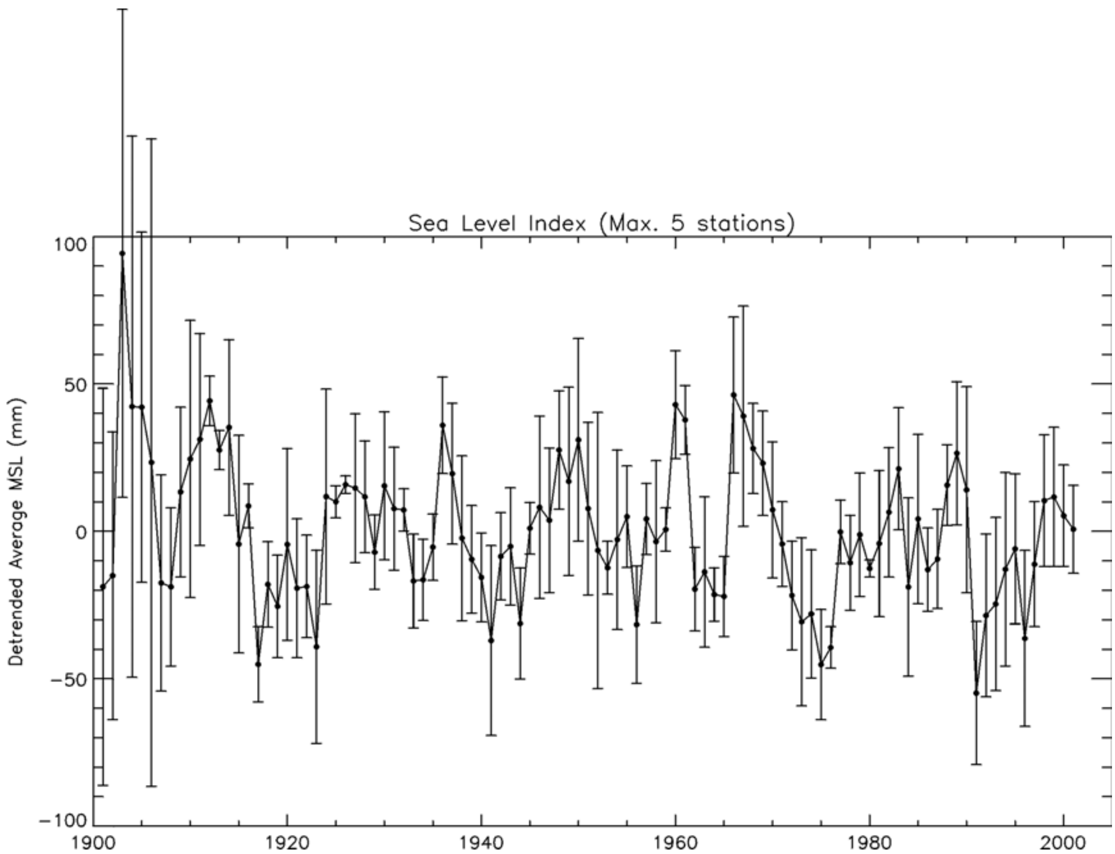


Figure 4.25 A UK sea level index for the twentieth century computed from MSL data from 5 stations

Such UK MSL indices will be maintained at http://www.pol.ac.uk/ntslf/products.html

POT applied to sea level records

Peak over threshold (POT) analyses have been carried out for 3 tide gauge sites (Newlyn, Dover and Lowestoft) of the National Network with a sufficiently long period of records. The Flood Estimation Handbook methodology (Robson and Reed, 1999), Fig 11.1 of Volume 3 for POT peak series was adopted. This approach is not generally applied to observed sea levels because of their cyclical nature, but can be useful in the present context. Figures 4.26, 4.27 and 4.28 show results for Newlyn, Dover and Lowestoft, respectively.

The procedure is to first, extract all values above an "abstraction threshold", shown on the left plots as the lowest (red) line. All values for above this are plotted as dots. The green lines indicate POT values for the whole data set; i.e. POT1 (the threshold above which there is, on average, one extreme event per year) to POT5 (threshold exceeded by, on average, five events per year). In some individual years, more than one event exceeds this overall POT1 threshold, indicating a more than average flood risk in that year. In other years, no value may exceed the overall POT5, indicating low flood risk in that year.

The right plots show fitted 20-year running averages of the POT1 to POT5 levels in each individual year (plotted at the mid-point of each 20 year interval). This shows for Newlyn, which has the longest record, a clear upward trend with some variability (Figure 4.26(b)). At Dover, with a shorter record, there are apparent trends in the 20 year mean POT2-POT5 series, but POT1 has a step around 1985 (Figure 4.27(b)). The trend for Lowestoft, which has the shortest record, is less clear. Using a shorter averaging period than 20 years might reveal more usefully the variability or trends in shorter records.

On the basis of this brief study of POT techniques applied to sea level data, we conclude that it has some potential as an indicator of sea level extremes and trends and of variations of flood risk.

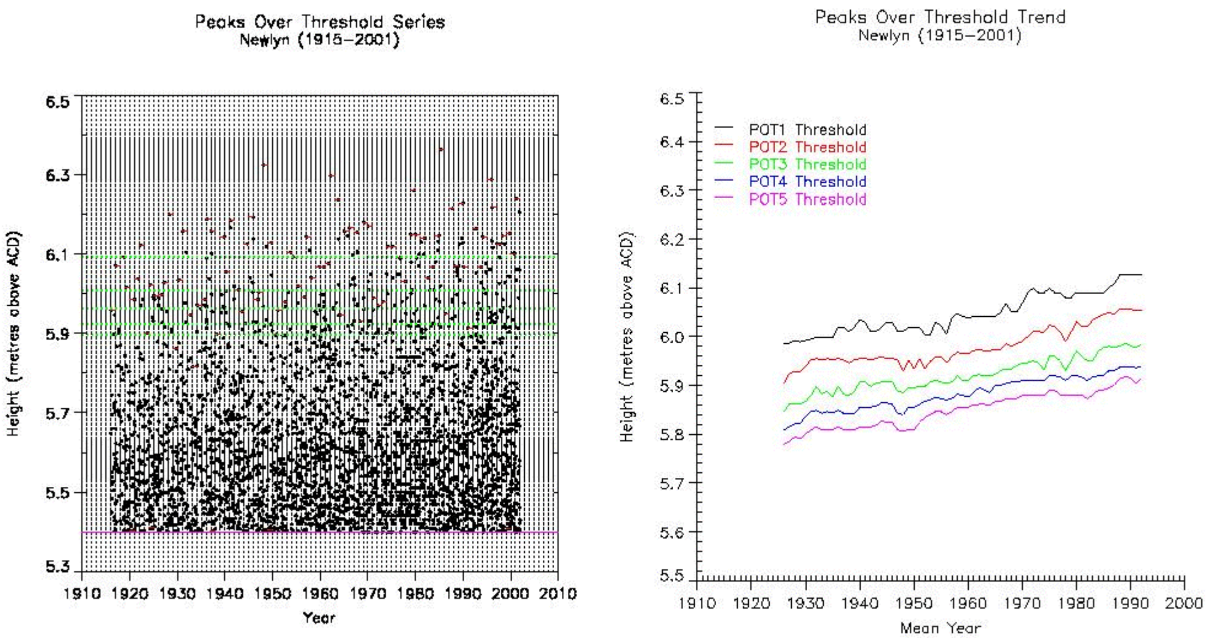


Figure 4.26 (a) POT levels for Newlyn plotted against year, and (b) fitted trends of 20-year running averages of POT1 to POT5

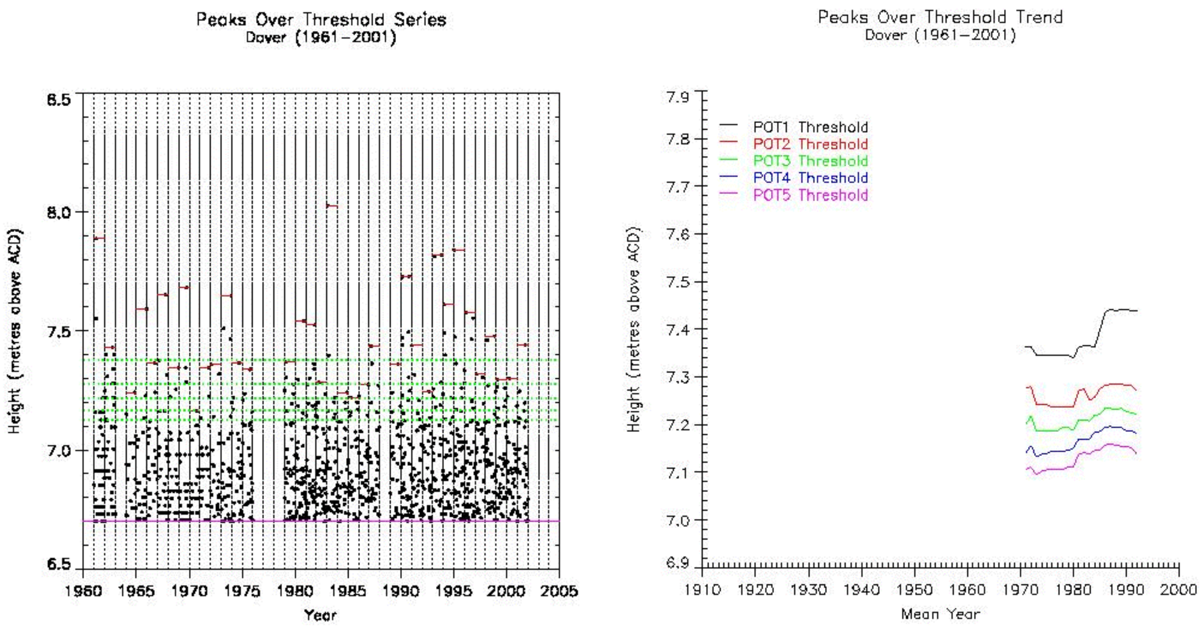


Figure 4.27 As Figure 4.26 but for Dover.

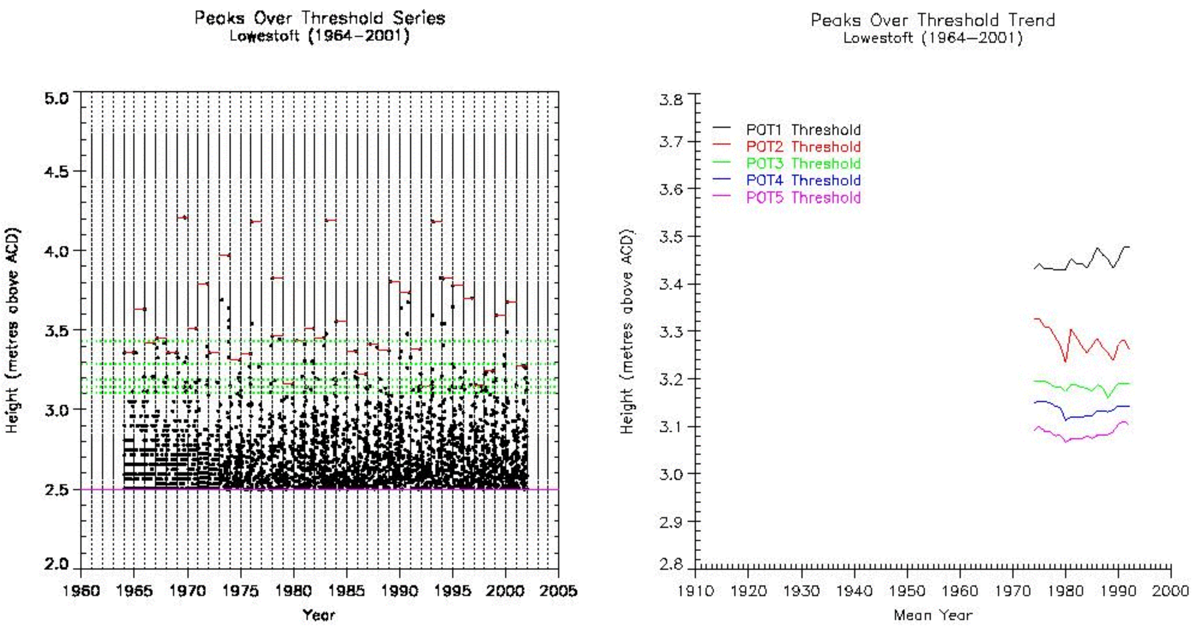


Figure 4.28 As Figure 4.26 but for Lowestoft.

4.5.2 Storm surges

Storm surges are temporary increases in sea level, above the level of astronomical tide, caused by low atmospheric pressure and strong winds. As indicated in the UKCIP02 Scientific Report, future changes in the extreme sea levels associated with storm surges will occur if there are changes in the number, location, or strength of storms. In addition, increases in mean sea level mean that, in future, a lower (and more frequent) surge may cause the same extreme water level as a larger and less frequent surge does today.

Surge and tide forecasts are produced operationally by the Met Office, although, to date, only a short period has been archived. Longer periods have been simulated using winds and pressures from climate models. Regional climate models cannot yet produce simulations of storm surge height directly because they do not have an ocean component, although a project has recently begun in the Hadley Centre to develop a coupled regional climate model. Therefore, the atmospheric winds and pressure from the RCM are used to drive a separate high resolution (30 km) model produced by Proudman Oceanographic Laboratory (POL) of the shelf seas around the UK. This model has allowed future changes in the 50-year return period storm surge heights to be estimated. The geographical pattern of simulated surges around the coastline for present-day climate compares well with observations from tide gauges and provides some confidence in the model simulations.

Despite the belief that current and future modelling work by the Hadley Centre and POL will in time suggest how storm surges may change under the driver of a changing climate, it does not seem that any useful indicator on storm surge can be developed. The matter of storm surges is also complicated as stated earlier in that a modest surge on top of a high spring tide may result in flooding, whereas a much more severe surge on a smaller high tide, or during the low tide period, will be of no consequence to coastal engineers.

We suggest that storm surges remain an operational issue for the time being, as it is difficult to see how any simple indicator could be produced to enable meaningful inferences on changing storm surge regime to be drawn. A significant amount of analysis is required to abstract storm surge data, and whilst a trend in surges may be significant, the possible impacts on coastal flooding and erosion are difficult to predict; timing is all-important.

4.5.3 Wave Climate

Changes in wind conditions, as discussed in section 4.2.3, will inevitably have an impact on wave conditions around the coastlines of the UK, hence affecting beaches and coastal defences. Even if the statistical distribution of mean hourly wind speeds remains unchanged, differences in the duration of wind conditions (e.g. more storms but of shorter duration) or in wind directions can have marked consequences on waves that cannot be easily deduced.

While wave conditions around the UK coastline are almost entirely a consequence of wind conditions, at any given point and time, the correlation between the two parameters can be small. The earliest wave recording experiments showed that waves approaching the UK coastline could have been generated not only locally and in the eastern North Atlantic Ocean, but also from the Gulf of Mexico and even the Southern Hemisphere in the vicinity of the Falkland Islands. The complicated relationship between wind and wave conditions therefore makes direct measurements of the wave climate worthwhile, as demonstrated by past and present expenditure on wave monitoring.

Some indication of the importance of future changes in wave conditions can be obtained by reference to recent events, since a general increase in wave heights around the whole of the UK in recent decades has been a cause of considerable concern to coastal managers and engineers. In deep water, companies involved in supplying oil and gas from offshore fields have been concerned by greater risks to platforms and pipelines and disruption to routine operations. At the coastline, larger waves can damage seawalls, cause coastal flooding and lead to increased rates of erosion of "soft" coastlines such as the glacial till cliffs in East Anglia and Yorkshire. However, it is by no means true that an increase in wave heights is necessarily an indication of increased coastal flood risk. An increase in cliff erosion rates at one location, for example, could provide a greater volume of sediment that would add to the beaches fronting low-lying land elsewhere.

There are specific concerns about changes in the "wave climate" around the UK, and a requirement to estimate such changes, for example when designing new coastal defence structures. The monitoring of waves for use in the design of coastal and offshore structures may also provide as source of information on climatic changes.

Review of wave monitoring around the UK coast

It must be remembered, in the following discussion, that the measurement of waves is a relatively recent development, with only very crude instruments available prior to about 1955. Compared to many other countries, the UK has a poor record of long-term wave recording. In the 1960's and 1970's National Institute of Oceanography equipped a number of lightships around the coastline with ship-borne wave-recorders which used pressure fluctuations to provide information on wave heights and periods (but not directions). Inevitably, these recorders were in areas of the sea where water depths were not uniform, and therefore the measurements of waves, at these from some directions, would have been affected by the reefs or sandbanks that the lightship marked.

In these early days, the main emphasis was on providing some information for as many locations around the coastline as possible, and thus the recorders were typically only deployed at each site for 1-2 years. The main exception to this pattern was the recorder on the Sevenstones LV, between Scilly and Land's End, which eventually provided one of the longest wave records from UK waters.

Pressure-type wave recorders were eventually replaced by wave-rider buoys, which were more versatile and could be deployed without the need for a fixed "platform" on which to mount them. However, the mooring systems, the buoys themselves and the data transmission systems used were far from robust, and regular servicing/ repairs were needed to obtain a high data recovery rate. By the late 1970's, most wave recording was being carried out using wave-rider buoys, but there was no national programme or funding to carry out such monitoring on a strategic basis. Rather, wave measurements were made in connection with specific projects, for example the possible construction of an airport on Maplin Sands in the Thames Estuary. The cost of deploying and maintaining a wave-rider buoy was (and remains) considerable and as projects came to an end, there was no funding to continue wave measurements. Wave-rider buoys that could also measure wave directions were being deployed routinely in the 1980's and are now the preferred option for most coastal wave recording exercises.

The offshore industry was able to develop alternative methods of wave recording, by taking advantage of the fixed "platforms", and instruments such as wave "staffs" or downward-pointing acoustic or radar recorders are all used to monitor wave conditions. However, as with the lightships, there is the possibility that waves from some directions may be affected by the presence of the installation itself. Overall, it is more likely that these recorders operate for longer periods than those in coastal waters, although the instruments at any particular location are changed from time to time, partly in the light of improved technology.

One of the consequences of this rather *ad hoc* approach to wave recording has been that much of the information gathered is subject to varying degrees of confidentiality. That collected in connection with coastal defence schemes has usually been funded by central Government, and is therefore usually available, while that collected by the offshore oil/ gas companies is often confidential.

Even when the data is not confidential, the existing arrangements for checking, analysing, storing and collating it are at best informal, and often non-existent. Hence simply obtaining those wave records that have been made for use in climatological studies will often pose considerable problems.

Use of coastal wave data

In this section, we consider the potential use of <u>coastal</u> wave data as potentially useful indicators of climatic change, and have assumed such data is collected in water depths of 20m or less, and within about 20m of the shoreline. There are a number of factors that militate against the use of such data as a reliable indicator of climatic change, namely:

- The generally short period for which most wave recording has been carried out in the past;
- The restricted range of directions which can reach many coastal sites;
- The changes undergone by waves as they travel through shallow water to a coastal site.

These points are discussed next.

<u>The generally short period for which most wave recording has been carried out</u>

The relatively short periods of wave recording so far undertaken seem unlikely to reveal more than short-term changes in the atmospheric conditions over the UK, e.g. fluctuations in the NAO, or the changes in wind speed deduced in the North Sea, e.g. Jenkinson (1977), Weiss and Lamb (1979). Much longer wave data series will probably be needed to detect an underlying trend that might indicate a climate change caused by global warming.

<u>The restricted range of directions which can reach a coastal site</u>

Most coastal locations will only "receive" waves from a 180° range of directions, and in some cases (as for the recorders at Whitstable/ Herne Bay) from a much smaller sector than this. As a consequence, a hypothetical small shift in wind direction due to climate change might have a considerably more dramatic effect on wave conditions at that recording site.

<u>The changes undergone by waves as they travel through shallow water to a coastal site</u>

Waves measured close to a coast (e.g. on the 5m depth contour at low tide) will have undergone substantial changes as they travelled through shallow water. A good example would be where the coastline (and measurement site) was protected by offshore sandbanks, as found over much of the southern North Sea. Such banks will alter the waves, for example by causing them to break, and the resulting near-shore wave conditions will have been "filtered" to some extent by the seabed bathymetry. Long-term changes in wave conditions relative to changes in the climate may be masked by this process, or be due as much to changes in the seabed bathymetry as to any change in the wind conditions that generated the waves.

The latter two points also indicate that such nearshore wave recording may not only fail to clearly identify changes in the "deep water" wave climate, but also may produce conclusions on such changes that only relate to that particular site. Along some parts of the UK coastline, wave conditions vary dramatically within 10km, so any indications of changes in wave climate that were obtained would only be applicable to a very limited frontage. It follows that such recordings will therefore not provide a reliable indicator of a widespread (i.e. regional) change in the climate.

Use of offshore wave data

While the problem of the short periods of wave measurements at offshore locations still remains, data collected from offshore structures such as oil platforms is rather more likely to be suitable as an ECI than coastal wave measurements. Indeed, the offshore energy industry has contributed more to studies of wave climate changes than the coastal management community in recent years.

The principal problems with this type of measurement lie in the difficulty in obtaining the privately collected information, and the likelihood that as individual platforms cease to operate, so the wave measurements will be discontinued.

Use of wave data collected by satellites

At present, the use of "remote sensing" methods to collect wave data is probably the most promising source of information in wave climate changes, at least in open-ocean areas. As with all other sources of wave data, there is presently only a short historical record. Additional problems relate to:

- The limited description of wave conditions that can be obtained from a satellite (i.e. good estimates of wave height, but wave periods and directions are much more difficult to measure);

- The rapid development of instruments that may cast doubt on the consistency of data recorded by different "platforms"; and

- The accuracy of wave conditions measured close to the shoreline, thus limiting the direct applicability of the data to coastal managers.

Use of wave data collected by WaveNet

The newly introduced national programme of long-term wave recording in intermediate water depths, i.e. about 20m-50m, to be funded by Defra is an important a valuable initiative. An important part of the justification for this programme was the intention to provide information on changes in the wave climate off various parts of the UK coastline (see http://www.cefas.co.uk/wavenet/). While some use of historical data may be possibly used to extend the length of the wave records at the proposed recorder sites, it will clearly be a considerable time (over 10 years) before these new measurements will provide direct evidence of climatic change. However, it is gratifying to see that a clear intent by government to the collection and archiving of wave data. It is hoped that analysis of the data will be valuable in a few years' time once sufficient good quality data are available.

4.5.4 Coastal Erosion

Cliff edge recession

Estimates of rates of cliff edge recession due to erosion along the eastern coastline may be estimated by studying surveyed maps over time. Such datasets are available in digital form from Landmark, and should provide a suitable dataset for derivation of a suitable indicator. (It is understood that some work has been undertaken already by Halcrow, but details are not yet available to the project). This is one indicator that may be of value to coastal engineers and one that could usefully be developed from available data sources. However, within the timescale of the current project, no work has been undertaken.

Longshore drift

This may be a useful indicator of changing coastal erosion. The best data may come from records of volumes of material transported back along a coastline through "beach re-cycling", (e.g. schemes at Dungeness, Seaford and Shoreham). Some local authorities have undertaken regular, or intermittent, cross-sectional surveys of beaches, often associated with beach re-cycling schemes (and consequently may be of limited value). Although such indicators would be imprecise, they may provide some directional indication of changing rates of erosion.

However, although coastal erosion and longshore drift are important issues, no work has been attempted on these matters during the current study.

4.6 Discussion On Selection Of Suitable Indicators

Considering the possible indicators described above, some are already being maintained and have direct relevance to flood and coastal defence, whilst others may be of only general scientific relevance, and others, although showing clearly significant environmental changes, have little obvious direct linkage to flood risk.

What is required is some means of categorising potential indicators so that valuable indicators can be identified and others abandoned.

Criteria for selecting a useful indicator were discussed earlier in the report, and may be summarised as:

- A proven causative linkage between the indicator and flood risk,
- Ready availability of good quality data for a sufficiently long period of time to enable trends to be detected,
- Existence of a 'champion' organisation who will take on responsibility for development, maintenance and publication of the indicator,
- Headline indicators should be simple to understand by the lay reader, yet be capable of revealing more detail to the professional through access to more complex, underlying indicators or data series.

One means of identifying suitable indicators is to develop a semi-subjective scoring framework as shown in Table 4.3 below. The number of stars, from one (low) to five (high) is an indication of the indicator's score in any particular category, and the overall score is a subjective assessment of the overall pattern.

The star markings of these indicators may appear a little arbitrary in some cases. Thus in the data availability column, what has been scored is not only absolute data availability, but also whether data are readily available in a suitable format. Thus where data are available, but only after a significant data processing exercise, an indicator has been given a lower 'score' than might at first glance seem sensible. Thus, although cliff edge recession data are undoubtedly available from Landmark or analysis of old maps, no readily available digital data source currently exists.

In some other cases, scores have been marked down because the data has changed over time due to changes in methods of computation, as is the case with soil moisture deficit data. Although it is potentially a valuable flood risk indicator, in the absence of a consistent long duration data series, we can see no immediate value in the indicator for the current project.

Table 4.3 Proposed indicator selection framework

Indicator	Data Avail.	Record Length	Data Quality	Relevance to FCD	Champion	Easy to visualise	Overall
1. Meteorological indicators							
1.1 Sea surface temps	****	*****	****	**	**** (1)	*	**
1.2 Sea level pressure	****	****	****	*	**** (1)	*	**
1.3 Cyclonic activity	***	***	***	***	**** (1)	****	***
1.4 Daily rainfalls > 25 mm	****	****	***	****	**** (1)	****	****
1.5 Tipping bucket data	**	**	****	****	**** (1)	**	**
1.6 Thunderstorms	**	**	***	***	**** (1)	***	**
1.7 HadFFi and HadFRI (See page 20)	***	***	****	****	**** (1)	***	** (complex)
1.8 Wind indicators	****	*****	****	*	**** (1)	*	** (complex)
2. Groundwater and catchment							
2.1 Soil moisture deficits	***	****	****	****	**** (1)	**	** (methods changed over time)
2.2 Groundwater levels (POT)	***	****	****	****	**** (2), (4)	****	****
2.3 Woodland cover	****	****	***	**	**** (5)	***	**
2.4 Land use cover	***	***	***	**	*** (various)	***	*
3. River Indicators							
3.1 POT of river levels	***	***	****	*****	***** (2), (4)	****	****
3.2 Annual maxima	****	****	****	*****	***** (2), (4)	****	****
3.3 Flood volumes	***	****	***	***	***** (2), (4)	***	**
4. Oceanographic indicators							
4.1 Mean sea level	****	****	***	*****	***** (3)	*****	*****
4.2 POT of MSL	***	***	***	****	*** (3)	****	***
4.3 Storm surges	**	**	***	***	*** (1), (3)	**	**
5. Wave data	*	**	**	***	** (various)	*	*
6. Coastal erosion							
6.1 Cliff edge recession	**	***	**	***	*** (OS)	**	**
6.2 Longshore drift	*	*	*	**	* (various)	*	*

(1) Met Office
(2) Environment Agency
(3) Proudman Oceanographic Laboratory
(4) CEH Wallingford
(5) Forestry Commission

What is suggested from the table is that of the meteorological indicators, cyclonic activity may be a useful indicator, although the frequency of days having more than 25 mm rainfall for various regions of the country is potentially the most valuable indicator.

Of the other suggested meteorological indicators, some result from model output only rather than from observations, and hence their derivation over time is likely to change, making interpretation of any apparent trend dangerous. In other cases, visualising the indicator is difficult, and involves a great deal of computation. Whilst the Met Office may be willing to undertake this computation at present, it is not certain that the indicator will exist in its present form for a number of years in the future. Many of the indicators described in Section 4.2 are therefore not thought to be suitable outputs from the current study.

Indicators of groundwater levels are certainly valuable as there have been several instances of properties being affected by prolonged flooding resulting from high groundwater levels. Some of Limbrick's plots using the Loess smoothing technique (Limbrick, 2002) provide a very visual means of interpreting highly variable year-to-year annual or monthly maximum water levels (See Figure 4.11). However, the POT5 analysis of the data for Chilgrove, as shown in Figure 4.14 also suggests a 'clustering' of high groundwater levels during the 1880s, the late 1930s and particularly the early 1980s. There are fortunately a number of good quality, long groundwater records throughout the country, and continued monitoring of these by the EA is essential.

Garrad (2001,2002) has identified POT analysis of river level data as a valuable indicator, and we fully support this. However, it is difficult to find sufficient river flow stations with stable data over a sufficiently long time period to enable reliable detection of trends. Work on extraction of suitable data from river level records is currently being undertaken by consultants as part of the HiFlows project, and in view of the importance of such data to flood estimation, it is likely that such data will continue to be extracted for those using the Flood Estimation Handbook, and eventually probably by CEH Wallingford so that the FEH can be updated.

It is clear that mean sea level will continue to be monitored by POL, and that the long-term graph of MSL against time will be maintained by them. This plot, and the associated POT analysis of the data provide a graphical means by which the pattern over time can be very easily identified.

5. PROCESSES REJECTED FOR INDICATOR DEVELOPMENT

5.1 Bank Height Changes

Whether the concern is fluvial or coastal flooding, it is important to maintain checks on the defence level that obtains. Many manmade banks subside or erode with time for a variety of reasons; intermittently bank heights are raised, and just occasionally lowered. It would be preferable if time series were available for key defence bank levels to compare with flood level chronologies and real time flood level observations. However the reality is that there is no tradition of recording data in that form. Flood alleviation scheme surveys, and subsequent defence works drawings, show pre- and post-construction information, but it soon gets lost to view of all but the best of EA drawing office or map archive staff. Asset condition surveys have the potential to add to the time series of defence levels but are generally directed at prioritising works and investment.

We have had to conclude that the next step forward is for the Agency to publish 'defended floodplain' maps, appropriately qualified by the degree of defence. There will then be a wider interest by the lay public in defence level time series.

5.2 River Sediment Dredgings

There are key sites where the channel must be dredged at intervals in order to maintain navigation and/or flood conveyance. It is not easy to infer where these localities are without close knowledge of EA operations. Reaches known to us include the lower Rivers Severn and Thames, the confluence of the Dane and Weaver [for which annual reports of the Navigation Engineer gives tonnages of sand taken out], and sensitive localities such as the link channel between Derwentwater and Bassenthwaite, which can threaten Keswick residents if left too long. Occasionally commercial gravel dredging companies have had an influence as on the River Tyne, quantified in one doctoral thesis in the 1960s at Newcastle University Engineering Dept.

However we have concluded that it would be more appropriate for Defra/EA to commission research to draw together the published papers, and unpublished data sources, into a single document so that present and past practice is better understood by EA staff and their consultants. Only later might an ECI, perhaps expressed as annual tonnage of sediment removed converted to equivalent riverbed depth change over the reach concerned, be developed.

5.3 Barrier Operations

Analysis of the frequency of barrier operations may at first sight provide an indication of changing storm surge risk. However, there is a risk that other factors, such as operating rules, or embankment heights, may have changed over time. Certainly the operating rules for the Thames Barrier have changed in recent years such that the barrier is now often raised to prevent tidal ingress to the lower Thames, thus assisting drainage of the river into the Pool of London. Thus the original purpose of the barrier, exclusion of high tides and storm surges, has been supplemented by a desire to improve fluvial drainage. Consequently any analysis of the frequency of barrier operations might well lead to very misleading impressions of trends in levels of storm surges in the southern North Sea.

5.4 Wave Heights

Direct measurements of waves, whether offshore (e.g. from satellites, oil platforms or deep-water wave-rider buoys) or closer inshore are undoubtedly valuable from the viewpoint of understanding and designing against coastal flooding risks. However, the use of wave measurements as an ECI is not presently seen as promising. The main reasons for this are:

- The lack of long-term historical data sets at present;
- The complicated linkages between waves and the winds that caused them;
- Difficulties in deducing regional changes in the climate from wave data from a specific location;
- Lack of direct linkage between increased wave heights and an increased flood risk.

Although it is suggested that analysis of wave height be excluded from further consideration at present due a lack of data, the situation may improve over the coming years as increasing volumes of data become available from WaveNet. However, such data will be of limited value as an indicator of change for at least the next 10 to 15 years.

6. DATA SOURCES

Data sets are increasingly being made available to interested users via the Internet, and a number of such sources of suitable environmental data have been referred to throughout the report. However, it is envisaged that the vast majority of ECIs finally selected will be maintained and disseminated by an appropriate government agency, such as the EA, possibly Defra, or perhaps the Met Office, UKCIP or BODC. Thus, for most potential users of identified ECIs, the primary interest will be in published indicators rather than in the background data itself.

Nevertheless, it is possible that some useful indicators may be taken up by agencies other than those responsible for collection of the under-pinning data. In such cases, those adopting such ex-governmental ECIs will require access to the necessary raw environmental data.

Much of the data required for computation and maintenance of ECIs will be available from a small number of sources:

- The Met Office for rainfall and SMD data.
- The EA, either from the National Centre for Environmental Data and Surveillance at Twerton, or perhaps increasingly from the new HARP (Hydrometric Analysis Replacement Project) national database in Leeds.
- The National River Flow and Groundwater Archives maintained by CEH-W and BGS at Wallingford.
- However, past climatological data is also obtainable from the University of East Anglia's Climate Research Unit, who work closely with the Met Office, Tyndall Centre and others, and who maintain long-term climatological records which may be of interest.
- The British Oceanographic Data Centre (BODC) maintained by POL is increasingly the primary source of data on tides and sea levels.

6.1 Data Available from the Met Office

Data that are considered useful for this project for which the Met Office has existing databases are shown below. These have been separated into four temporal scales: sub-daily, daily, monthly and annual.

Sub-daily data

Mentioned in section 4.2.2, the Met Office has recently made available nearly 700 years of 5-minute resolution rainfall data for the UK, primarily for urban drainage engineers. This encompasses continuous, quality controlled data from 73 gauges around the UK, an average of approximately 7 years per gauge, many of which go back to 1987. It is anticipated that this dataset will be increased by including records from more tipping bucket rain gauges.

Model surge and wave heights would be available on sub-daily time scales if some of the research work mentioned later were to be funded.

Daily data sets

Daily rainfall data is available for the stations across the UK shown in Figure 6.1.

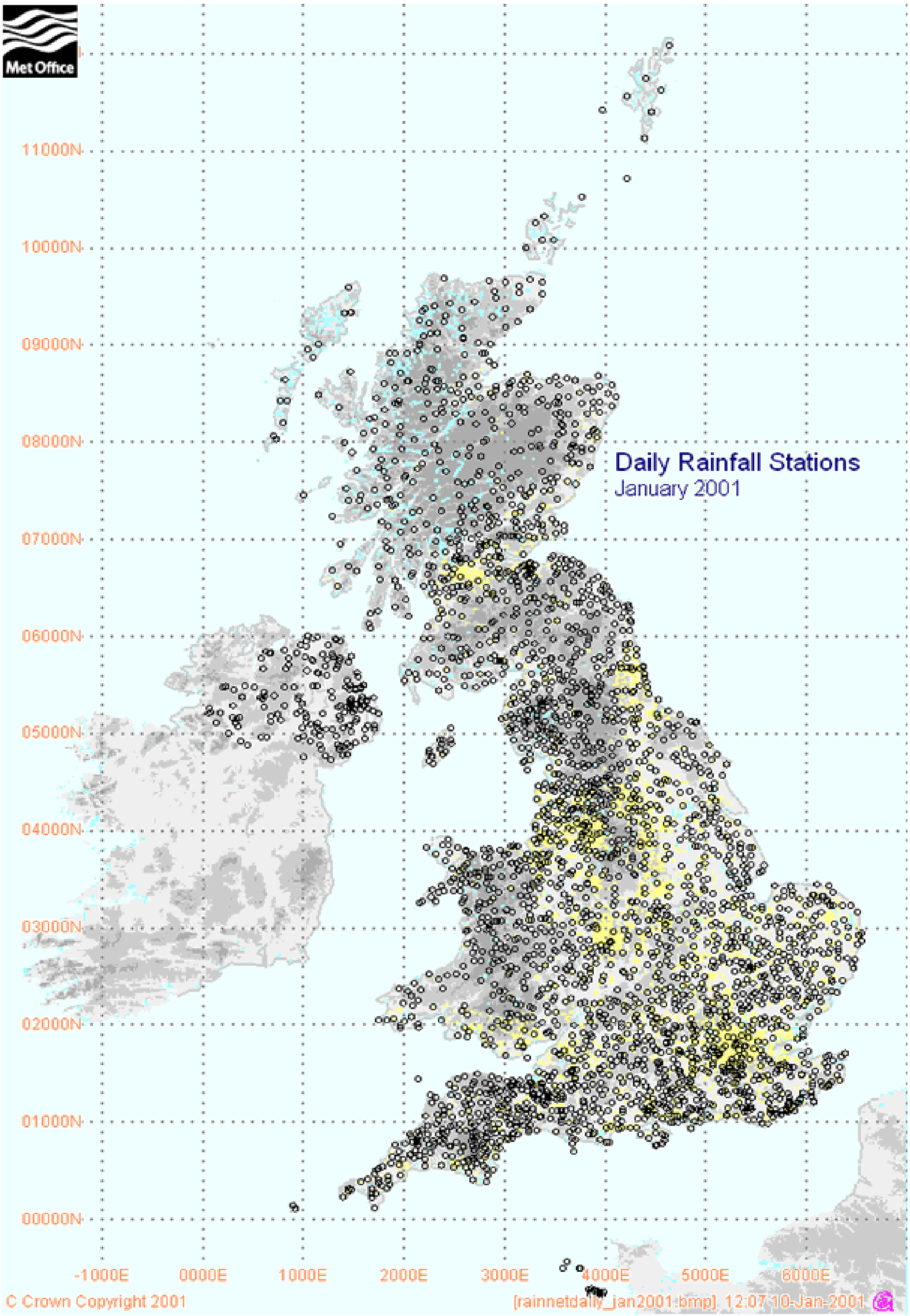


Figure 6.1 Daily rainfall stations in the UK

Monthly datasets

Monthly data are in 10-year blocks and are available for the period 1961 to 2000. These files are available from the Met Office web site at: http://www.hadleycentre.com/research/hadleycentre/obsdata/ukcip/index.html. The list of available parameters is given below:

- Number of days of ground frost
- Mean monthly sea level pressure (hPa)
- Mean monthly vapour pressure (hPa)
- Mean monthly wind speed (knots)
- Mean monthly cloud cover (%)
- Number of days per month having a rainfall >= 1 mm (Rain Days)
- Number of days per month having a rainfall >= 10 mm (Wet Days)
- Number of days per month with snow falling (Snow Fall)
- Number of days per month with snow cover > 50%
- Total monthly precipitation (mm)

Yearly datasets

Yearly data are stored as single 40 year blocks and are also available from the Met Office web site. The list of available parameters is given below:

- Maximum number of consecutive dry days (days with less than 1 mm of rain) in a year
- Greatest five day precipitation total in a year (mm)
- Wet/dry rainfall intensity (annual total of wet days (> 1 mm of rain) / number of days giving a wet day rainfall)

Quality Control

Rigorous quality control procedures are undertaken on all Met Office archived observed data. This includes initial checks for consistency and correctness and then areal checks that compare data with other nearby data using a bespoke computer program. If erroneous or spurious values are identified these may be adjusted or replaced as necessary. It is up to the quality controller to look at all the available information, consider the queried value and come to a reasoned decision supported by the evidence available.

6.2 River Flow and Groundwater Data

National archives of river flows and groundwater levels are maintained at Wallingford by CEH-W and BGS. The National Water Archive data are collated, quality controlled, and maintained as an archive available to any interested user. The data were originally published in the form of yearbooks and a five-yearly register of stations and summary statistics, but are now available on the web.

Details of the archives can be found at the main National Water Archive website:
http://www.nerc-wallingford.ac.uk/ih/nwa/index.htm
with the river flow archive being accessed through:
http://www.nerc-wallingford.ac.uk/ih/nrfa/index.htm
and the groundwater archive through:
http://www.nerc-wallingford.ac.uk/ih/nrfa/groundwater/index.htm

Details of data availability and data retrieval are available through the websites shown above.

It should be noted that neither CEH-W nor BGS collect the vast majority of data available through the National Water Archive, but are the archivists for data collected primarily, but not solely by, the EA, SEPA and DANI.

6.3 Sea Level and Tidal Data

Tide gauges

The UK has a national network of 44 tide gauges (Figure 6.2), operated by the National Tidal and Sea Level Facility (NTSLF) at POL on behalf of Defra. The NTSLF is responsible for modernising and maintaining this network of gauges and telemetry links.

Figure 6.2 The UK National Network of 44 tide gauges

The objective is to obtain high quality sea level information for operational use in the coastal flood warning systems operated by the Environment Agency and the Storm Tide Forecasting Service at the Met Office. The data are also used for research, specifically in scientific studies of coastal processes such as tidal response, storm surge behaviour and sea level rise. NTSLF quality controls and archives the 15 minute or hourly values of sea surface elevation collected by the network and provides data to users. Table 6.1 indicates the periods of data availability.

The NTSLF at POL also maintains South Atlantic gauges which are the UK's contribution to the Global Sea Level Observing System (GLOSS), and hosts the Permanent Service for Mean Sea Level (PSMSL), the global data bank for MSL records.

Satellite altimetry

The value of satellite radar altimetry measurements for sea level research was recognised from the mid-1970s. Analysis techniques developed since then provide powerful tools for extracting global and large scale sea level variations and tides, making major contributions in these areas of study. In particular, time series of MSL offshore from Topex-Poseidon altimetry agree closely with those derived from coastal tide gauges. Limitations are that measurements are unreliable within a few kilometres of land as the satellite tracks across the coast. For storm surges, typically affecting small areas of shelf seas, the usefulness of satellite data is limited by the frequency with which observations are collected from the same location. Orbits are such as to repeat the pattern of measurements once every 10-30 days, so that effects of a single storm may be completely missed. Future developments in swath altimetry will improve coverage of shelf seas.

GPS and absolute gravity

New advanced geodetic techniques using GPS and measurement of changes in gravity using absolute gravimeters (AGs) provide methods of directly measuring present day vertical land movements. A long-term monitoring programme funded by Defra is under way to improve estimates at tide gauge sites and provide local variations.

Table 6.1 Availability of data from the National Tide Gauge Network

Tide Gauge	Data Availability
Aberdeen	1930-36, 1946-58, 1960-62, 1964-65, 1967-75,1980 onwards
Avonmouth	1961-62, 1972-76, 1979-84, 1986 onwards
Bangor	1994 onwards
Barmouth	1987, 1991 onwards
Bournemouth	1996 onwards
Cromer	1973-74, 1976, 1982, 1988 onwards
Devonport	1961-62, 1967-68, 1987, 1991 onwards
Dover	1924, 1926, 1928, 1930, 1934-36, 1938,1958 onwards
Felixstowe	1982, 1984, 1986 onwards
Fishguard	1963-71, 1973 onwards
Heysham	1964-69, 1971 onwards
Hinkley	1990 onwards
Holyhead	1964-73, 1977-85, 1987-91, 1995 onwards
Immingham	1953, 1956-58, 1963 onwards
Ilfracombe	1968-71, 1977 onwards
Jersey	1992 onwards
Kinlochbervie	1991 onwards
Leith	1981, 1989 onwards
Lerwick	1959-78, 1980 onwards
Liverpool	1927, 1963-1983, 1986, 1991 onwards
Llandudno	1971, 1994 onwards
Lowestoft	1964 onwards
Milford Haven	1953-54, 1961-62, 1964-65, 1967 onwards
Millport	1978, 1981-83, 1985 onwards
Moray Firth	1994 onwards
Mumbles	1989-93, 1997 onwards
Newhaven	1982-87, 1991 onwards
Newlyn	1915 onwards
Newport	1993 onwards
North Shields	1946-47, 1949-56, 1961, 1965-75, 1978 onwards
Port Ellen, Islay	1979-80, 1991 onwards
Port Erin, Isle of Man	1992-95, 1998 onwards
Portpatrick	1968 onwards
Portrush	1995 onwards
Portsmouth	1991 onwards
Sheerness	1952, 1958, 1965-75, 1980 onwards
Stornaway	1976, 1978-81, 1983, 1985 onwards
St. Mary's	1994 onwards
Tobermory	1990 onwards
Ullapool	1966-68, 1970-72, 1974-80, 1981, 1983,1985 onwards
Weymouth	1989, 1991 onwards
Whitby	1980 onwards
Wick	1965-70, 1972 onwards
Workington	1992 onwards

From http://www.bodc.ac.uk/ links "On-line Data Systems" & "UK Tide Gauge Network"

6.4 Wave Conditions

A discussed in Section 4.5.3, development of wave condition data into useful ECIs is constrained by the limited data available. The longest periods of wave measurements, at a consistent location around the UK coastline, are believed to be as follows:

Coastal wave data

- Off the North Kent coast (1979-1998 off Whitstable, 1996 to present off Herne Bay)
- Tees Bay (1988-present)
- Perranporth (1975 – 1986)

Offshore wave data

- Sevenstones Light Vessel (1962-1988)
- Forties Field (1974-present)
- Frigg QP (1979-present)
- Ekofisk Field (1980-present)

Some of these data have been analysed to investigate trends in wave conditions over the recording periods, and have shown considerable inter-annual variability and some significant trends in height. The paper by Carter and Draper (1988), based on the records from the Sevenstones LV, gave rise to considerable debate on the long-term changes in wave conditions in the north-east Atlantic. They found an underlying trend for an increase in wave heights, triggering fears that global warming might be causing increased "storminess" and threatening greater problems of erosion and flooding along the coastlines of the UK.

The trend observed at the Sevenstones Light Vessel seemed to have persisted into the early 1990's at least, although recent winters have suggested a levelling off, or perhaps the beginning of a decreasing trend. In the years since the paper by Carter and Draper was published, further research has indicated a link between wave intensity around the UK coastline and the North Atlantic Oscillation (NAO), e.g. Bacon and Carter (1993). Given that waves are strongly related to wind conditions, particularly their strength and persistence, this link with the north-south atmospheric pressure gradient over the North Atlantic is hardly surprising.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

One strong message that emerged from the project was the difficulty in locating good quality records of sufficient length to enable meaningful trends to be detected (and here we include 'stationarity', or no apparent change over time as a 'trend'). Given natural climatic variability, we have suggested that any data series should ideally be over 70 years long, yet apart from a number of long term daily rainfall records, a small number of river level and flow stations, an equally small number of groundwater records, and one or two tide gauges, few environmental records of more than 30 to 40 years can be found. It is hoped that the Environment Agency and others will continue to monitor many of the necessary environmental variables at a sufficient number of 'bench mark' stations needed for this, and other purposes, to enable maintenance of the selected indicators.

On this point, Garrad (2002) noted the shortness of digital flow/level records for the Thames Region. This could be rapidly overcome in large measure by converting the mainframe datasets (held at CEH Wallingford) of weir headwater and tailwater records (Crooks, 1994). This would have the advantage of making 110 year long records available for any subsequent phase of this study, as well as for the wider interests of the Agency. Less than a man-month would be required to achieve this objective, although bringing the records up-to-date in a routine manner would take somewhat longer.

A large number of potentially useful indicators of environmental change were identified during the initial workshop and during subsequent study. Some of these were rejected because of lack of suitable data, and a number were discussed in Chapter 5. Another group of environmental indicators that has been rejected from further consideration are those concerning land-use. There are two reasons for not including such indicators in our recommended final set. One is that suitable data are hard to obtain, but the main reason is that there are in some cases still only poorly understood causative linkages between these land-use variables and flooding. It does not seem that this group of indicators will currently offer planners and decision makers any useful guidance.

Amongst the issues arising from the study was the suggestion that some indicators might be thought of as 'headline' indicators of prime importance to national decision makers, and perhaps also the public, along the lines of the 'Central' England temperature record, whilst others might be aimed more at local or regional decision makers, such as those derived from analysis of a single record or regional group of data. There is a need for both types of indicator.

The final section of Chapter 4 attempted to 'score' prospective indicators, albeit using a semi-subjective scheme, and from this analysis we recommend that the main headline indicators should be:

- The frequency of daily rainfalls over 25 mm.
- Time series of annual maximum and POT groundwater levels at selected sites.
- Time series of annual maximum and POT river levels at sites identified by Garrad.

- Time series and POT analysis of mean sea levels at the five benchmark sites monitored by POL.

A number of potential secondary indicators are being developed by the Met Office, and will be made available to the wider community via their websites and other published sources. Some of the more useful of these for FCD might include ongoing work to analyse tipping bucket rain gauge data, which should in time yield information on trends in high-intensity storm rainfall, as might analysis of thunderstorm activity, indexed through lightning activity. However, whist it is encouraging that such data are being collected and analysed, it is likely to be some considerable time before sufficient good quality, consistent data become available to enable their use as reliable environmental change indicators.

We do not believe that for most other indicators investigated there are sufficient data available in some cases, or that excessive computation would be involved with others, or finally, that the indicator can be displayed in an intuitive manner to lay readers. Thus for many other indicators, we recommend that no further action is justified at the present time.

7.2 Dissemination of results

The Indicators that we are proposing can be treated either as key national examples, or as samples that can be followed by others with datasets local to the stakeholders concerned. We believe the latter idea will catch on if champions of those indicators we have recommended in this report are willing to update them regularly on their web sites. However, it is always possible for good information to be lost among many other competing messages that major organisations need to put out. We therefore plan that the National Water Archive web site, run from CEH Wallingford, will instigate, on the publication of this report, an Environmental Change Indicators links page for Flood Risk Management (ECIFRiM). This will be complemented by a hard copy version of the same web addresses being published in the Monthly Hydrological Summary for the UK. The webmasters of DEFRA and the Agency are asked to add links from their Flood Management pages to this master ECIFRiM links page.

The National Flood Forum has been approached to give a link from its web page to this same set of ECIFRiM sources, (links are generally preferred to copied material so that everyone sees concurrently the same updated Indicators). The logical extension of this approach to dissemination is to ask local Flood Action Groups if they will use our methodology to create a matching indicator of direct relevance to the community it represents. The Bewdley Flood Action Group is being approached with the aim of it taking the lead in this type of local initiative, using River Severn peak stage data.

So that the profession is made aware of the point that this project has reached, we are asking the River and Coastal Panel of the Chartered Institution of Water and Environmental Management (CIWEM) if its newsletter will give its members, who are the bulk of the professional users of our ECIs, the set of web addresses to be given on the National Water Archive site.

The Press Release to accompany this report can be helpful if it gives that same set of addresses to the appropriate range of editors, besides the 'story' of the project. In an ideal world we might hope that the weather section of national, and regional newspapers might carry one or more of the indicator graphs once a year. However this has not yet happened for even the Central England Temperature series, which editors have covered in special update articles rather than as a routine.

In summary the successful dissemination of Indicators begins with action by the following:

- Met. Office: Time series graph of the frequency of daily rainfalls over 25 mm, using the 1961- 2002 5 km gridded dataset for representative areas of England and Wales. The first of these should be the "Berkshire" square of 2500 sq km as illustrated in the UKCIP studies (Hulme *et al*, 2002, Fig 57) as it covers sufficient of the Thames basin to make correlations with the 1883-2002 Thames rainfalls dataset kept by the Agency and its predecessors.

- Environment Agency Sussex Area office, backed by the National Groundwater Archive run by British Geological Survey Wallingford: Time series from representative long records of aquifer level in both the Chalk limestone and Permo-triassic sandstone. The first of these should be the Chilgrove Chalk well water levels, taken as both annual maximum and POT1 series from 1836, preferably using LOESS smoothing to identify trend.

- Environment Agency, backed by the National River Flow Archive at CEH-W, who will need level data in addition to the daily flow data that they now receive from Agency offices: Time series of both annual maximum river levels as well as POT peak levels at the 16 sites identified by Garrad (2002) but augmented by additional sites with longer records. This report has used the Usk (Chain Bridge) and the Taw (Umberleigh) for illustrative purposes, but it will be desirable to bring the Thames weir tailwater level series from 1883, now in old format on the CEH mainframe computer, into a modern database format. The Severn at Bewdley, and Trent at Colwick should also receive early attention because of their importance as indicators to many 'at risk' communities.

- British Oceanographic Data Centre, at NERC Proudman Oceanographic Laboratory, Liverpool University: POT1 analysis of sea level, and creation of the consequent time series for the full available record at Newlyn and three other benchmark sites, North Shields, Sheerness and Liverpool. We further propose that a year from now we will check progress in dissemination. If there are impediments, or changes required, we will then make a further proposal to DEFRA/EA for the necessary funding to widen access. By that date the parallel project by Atkins entitled "Position Review of data and information issues within Flood and Coastal defence" will be available. A welcome outcome could be the removal of the current impediments to availability of climatological information of use to flood managers and floodplain stakeholders.

7.3 Proposed follow-up work

An outline proposal entitled *"Detailed study of Environmental Indicators, with guidance for medium / long term decision making relevant to both flood risk management and climate change adaptation"* has been submitted to Defra.

The objectives of this project would be:

- To extend trial environmental indicators and trend analysis techniques to two regions of England and Wales that have markedly different hydrologic regimes;
- To produce an associated Guidance Note for the operational staff in flood defence, together with other interested users of indicators;
- To ensure that all useful indicators are published in such a way as to be readily available to all those interested. We have suggested that all headline indicators be maintained by the appropriate originating agency, and regular (annual updates) posted on their respective websites.

This is best done as a first phase that would eventually be extended to cover the whole country. A little over one year is required to carry through this project phase.

Analysis of UK rainfall, river and sea level data beyond that achievable in current Theme 5 projects would be worthwhile. Once identified, each technique needs to be packaged in a way that respects the source data, the IT system in which it is embedded, and the graphical indicator form (embodying trend analysis) in which it should be made available to the widest possible user group. As the flood management community is already preparing for adapting to a future changed environment, they need a guidance with reduced (and quantified) uncertainty to support medium / long term decision-making. Delivery of results can be staged while also providing guidance and interpretation of rate and direction of change. Initially testing and interpretation will be for two regions with different climatic, hydro-geological and topographical conditions. The Guidelines will also specify by who and how it is to be used.

In addition, this project should aim to establish a suitable review mechanism whereby the usefulness of all indicators is examined by a panel of stakeholders such that indicators of little perceived value may be discontinued, and where obvious gaps in the indicator series can be identified. It is suggested that such reviews be undertaken every 3 to 5 years, and should be led by staff of Defra and the Agency, supported by key research contractors and consultants.

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GLOSSARY

BGS	British Geological Survey
BADC	British Atmospheric Data Centre
BODC	British Oceanographic Data Centre
CEH-W	Centre for Ecology and Hydrology, Wallingford
CIWEM	Chartered Institution of Water and Environmental Management
DANI	Department of Agriculture, Northern Ireland
Defra	Department for the Environment, Food and Rural Affairs
EA	Environment Agency
ECIs	Environmental Change Indicators
ECIFRiM	Environmental Change Indicators links page for Flood Risk Management
FEH	Flood Estimation Handbook
FCD	Flood and Coastal Defence and Management
GPS	Global Positioning System
H_s	Significant wave Height
IPCC	Inter-governmental Panel on Climate Change
LV	Light Vessel
mALD	Metres Above Local Datum
mOD	Metres above Ordnance Datum
MSL	Mean Sea Level
NAOI	North Atlantic Oscillation Index
NGO	Non-Governmental Organisation
O.D.	Ordanance Datum
OS	Ordanance Survey
OFWAT	Office of Water Regulation
POL	Proudman Oceanographic Laboratory
POT	Peaks over a Threshold
POT1 etc.	Threshold Peaks exceeded once, twice …five times a year on average
QMED	Median Annual Maximum Flood flow
RMED	Median one day maximum Rainfall
SEPA	Scottish Environmental Protection Agency
SMD	Soil Moisture Deficit
SLP	Sea Level Pressure
SST	Sea Surface Temperature
UKCIP	United Kingdom Climate Change Impact Programme