PROBABILITY DISTRIBUTIONS FOR LONG PERIOD RAINFALL: A SCOPING STUDY

R & D Technical Report W6-065/TR

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This report is the result of work jointly funded by the Environment Agency and the Natural Environment Research Council (NERC). The report offers a review of needs within and outside the Agency for long-duration rainfall frequency estimation, and identification of reliable consistent methodologies that could be developed to assess the severity of rainfall droughts. The information should be circulated amongst the Water Resources staff of the Environment Agency to ensure that the following research integrates all requirements.

Key Words
Meteorological drought; Drought orders/permit; Long-period rainfall; Severity assessment; Tabony tables; Standardized Precipitation Index; Drought Severity Index; Reed Drought Index; FORGEX; QdF.

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FOREWORD

This report presents the results of a project commissioned by the Environment Agency and the NERC Centre for Ecology and Hydrology, to scope methods of estimating long-period rainfall drought frequency to be developed in a potential follow-up project.

The original Environment Agency project leader was Tim Arkell of the Environment Agency Wales, but subsequently Tim Norton of the Southern Region took over.

The brief for the study was to identify users' needs for long-duration rainfall frequency estimation, to review existing methodologies and to assess the research needs for developing a consistent methodology that would provide an objective, soundly-based view of drought severity.

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EXECUTIVE SUMMARY

Staff of the Environment Agency and others often require estimates of the severity of long-duration (weeks to months) rainfall. This is primarily for the assessment of drought severity, although during recent wet winters such information is also required in order to determine the risk posed by prolonged rainfall on flooding. At present, the only convenient means of determining such information is the use of tables of rainfall deficit (or excess) for any particular duration in months. These Tabony tables were developed by the Met. Office many years ago (Tabony, 1977), and are both potentially rather out of date and rather difficult to get hold of.

In the present study, the needs of potential users for long-period rainfall frequency information are reviewed and a variety of means of re-analysing appropriate UK rainfall data are considered in order to provide an updated methodology. A number of approaches are considered and in each case, the advantages and disadvantages of each discussed. Seven potential replacements for the old Tabony tables are proposed and costed, of which updating the Tabony method is proposed as the first of these, work plan 1. It is suggested that updating the Tabony tables, but using more appropriate frequency distributions for drought periods, should be one of the first candidates for any subsequent studies.

Other potentially valuable indices are the regionalized standardized precipitation index and drought severity indices (work plans 2 to 4). The final three methods proposed are rather more demanding in terms of analytical inputs and also have a number of technical limitations in some instances.

Firm recommendations as to which of these seven potential methods may best be followed up are avoided. However, it is suggested that one or more from the first four proposed are likely to offer the best way forward.

Preliminary costs are given for the development of each of the seven potential methods and although these estimates are believed to be appropriate, there would be merit in the contractor and Environment Agency staff reviewing any of these that might be considered appropriate for further development.

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1. PROJECT DEFINITION

1.1. Background to the Study

Water Resources teams within the Environment Agency (Agency) require estimates of probability distributions of long-period rainfall for the assessment of drought severity. Derived figures from such analyses may be used in relation to Drought Management plans, the Agency's appraisal of water company Drought Contingency Plans, Water Resource license applications and other consultations for which Water Resource Management teams are responsible. Applications may include Drought Orders, Drought Permits, the implementation of spray irrigation restrictions, or other restrictions on any activity which may be water resource critical.

Droughts are complex phenomena that must be considered in a broad context. The diversity of the UK, particularly in terms of its climate, hydrogeology and patterns of water use, is such that water resource stress can vary greatly within the same region. This is the case even when rainfall across the region is broadly similar, e.g. the contrast in the summer of 1995 between those areas reliant on surface water resources and those dependant on groundwater is an obvious case in point; the reverse was the case (albeit less compellingly) in 1997. Some of the issues concerning the characterization and definition of droughts are provided in the second section of this report, and give an overview of some elements that must be considered when undertaking a drought study.

1.2. Research Needs and Objectives

At present the Water Resources staff estimate the drought severity using a range of methods, and there is no apparent prescribed or agreed consistent approach to this work across the Environment Agency. It is recognized that different assessment methods are known to return different results for the same base data. Such variability may leave the Agency at risk of treating actions based on these rainfall drought severity results in an inconsistent manner, e.g. Drought Contingency Plans.

The Agency needs Water Resources staff to have a consistent and scientifically sound method for determining return periods of long-duration rainfall drought which

i) Provides an objective, soundly-based view of drought severity; and

ii) Is robust enough to be used (and defended) when responding to/determining a Drought Permit/Drought Order application, including being used as evidence at a Public Inquiry.

The aim of this scoping study is to review the needs and requirements of potential users within (and outside) the Agency for a long-period rainfall frequency method, and to identify different methods or concepts already existing that could be developed at a national scale to obtain reliable and robust estimates of rainfall drought severity.

It is understood that the methodology to be developed in the research following this scoping study is aimed at water resources management, but it should be particularly designed to provide a robust assessment of the severity of droughts. To address this, the methodology review includes not only the Tabony tables (already in use across the Agency), and other traditional frequency estimations methods, but was also enlarged to cover alternatives such as non-parametric methods associated with various drought indices. These indices have been suggested as drought severity indicators, but do not necessarily rely on an estimate of return periods to define the severity. The selected methodologies reviewed do not incorporate the spatial factor when assessing the drought severity.

In the next section, the report gives a brief summary of the different issues surrounding drought severity assessment. This summary is designed to provide some background information useful to evaluate the strengths and weaknesses of methods assessing long-period rainfall frequency in the wider context of drought occurrence.

The four following sections identify major needs that users, within and outside the Agency, would have for a long-period frequency estimation method. This helps understand the key characteristics required for the new consistent methodology.

Following the above are a selection of models and methodologies that have been published. Six different methods are reviewed in detail and presented in this report:

- Two general methods for assessing the frequency of *d*-months accumulated rainfall totals;
- Two drought indices specifically designed to assess historical and current drought status;
- Two methods specific to extreme drought frequency analysis.

For each selected method, a short background and brief explanation precedes an assessment of the method with respect to the needs of the Agency, highlighting benefits and possible limitations. Finally, a proposed work plan of development is provided for each method, with a suggested timescale and cost for its uptake. To enhance the clarity of the description of each work plan, there is some overlap between the individual work plans (e.g. data selection and quality checking etc.). The costing of the work plans is not additive, i.e. a final method consisting of a combination of several work plans would have a lower cost than the total of the individual costs.

Conclusions and recommendations for future work are presented at the end of the report.

2. DROUGHT SEVERITY ASSESSMENT

2.1. Drought Definition

It is generally recognized that a drought is an extremely complex phenomenon that describes a deficit in water resources availability, but it has "*no universally accepted definition*" (Tate & Gustard, 2000). Drought severity depends not only on physical, natural factors such as the duration and intensity of water shortage, and the geographical extent, but also on the demands on water. Because of this complexity, Wilhite & Glantz (1985) suggest that a universal definition cannot (and should not) exist.

Usually droughts are divided into different categories that include: *meteorological droughts* (summary of the degree of dryness, mainly from rainfall records); *agricultural droughts* (reference to the water availability for crop production, often including temperature and evapotranspiration data); *hydrological droughts* (description of shortage in water availability in surface or sub-surface hydrology that can be characterized by low flow values); *groundwater droughts* (status of the groundwater levels and recharge); and *socio-economic or operational droughts* (representation of the combination of natural water shortages with the demand and the operational decisions).

A common factor for all droughts is that they originate from a deficiency of precipitation, resulting in water shortage for certain activities, e.g. plant growth, or for certain groups, e.g. farmers, water companies (Wilhite & Grantz, 1985). Mawdsley *et al*. (1994) identified four key indicators of drought severity amongst 13 potential environment indicators and six water resources indicators, namely, rainfall, reservoir storage, groundwater level, and river flow. These four indicators are all measures of natural conditions and do not include quantified elements of human influence.

2.2. Rainfall as Indicator for Drought Severity

Rainfall, by definition, is only proxy data for water resource availability, and thus does not provide an exact assessment of that availability. It is a less direct measure (some agricultural applications aside) of drought severity than either river flows or groundwater levels. However, the latter are affected by artificial influences across much of the UK, and flow measurements can be tricky in extreme droughts. Rainfall measurements over short periods (e.g. one month) take no account of initial ground conditions or seasonal evaporation variations, and so do not reflect true water availability in terms of natural storage or streamflow (Mawdlsey *et al*., 1994). This is particularly true in permeable regions, where rainfall totals accumulated over a short period of time are poor indicators of current water availability status of the water resources system. This is due to the importance of antecedent conditions in the recharge processes and associated groundwater levels. However, considering rainfall accumulation over periods of several months could provide some appreciation of these antecedent conditions, and thus may be more appropriate than short-duration rainfall averages in the assessment of droughts in permeable catchments.

The large spatial variability of rainfall may also bias drought assessment, especially during summer months when thunderstorm activity is greatest. Areal averages are sometimes recommended to reduce this bias (Mawdsley *et al*., 1994). Both individual raingauges and spatial aggregations are subject to measurement errors. Heterogeneity in areal precipitation time series is a serious issue - areal rainfall series are usually avoided in practice. Combined with the greater uncertainties relating to actual evaporation losses, this implies that the spatial integration provided by river flows (and, to a varying degree, by groundwater levels), will often provide the most meaningful index of drought severity, rather than rainfall alone.

In practice, the limitations of rainfall data are most evident in the English lowlands where annual rainfall totals can be less than annual PE totals. In water resources terms, the distribution of rainfall through the year can be critical, an above average summer will do little (apart from moderating demand) to reduce water resources stress.

The effective rainfall, which is the difference between actual rainfall and actual evapotranspiration, encapsulates some of the losses endured by the system that could be significant during low rainfall periods. Thus it constitutes a better descriptor of the status of the water resources than actual rainfall. This relatively simple means of assessing the effective precipitation can be useful, e.g. by using average monthly evaporation losses. However, effective rainfall is rarely considered as a drought indicator due to the lack of reliable long series data in the UK.

Despite all its inherent limitations, assessing droughts only from rainfall records is common practice in Britain. The justification for this is that in Britain, rainfall is the main influence on runoff and natural water resources, and thus can be considered as a primary factor of drought severity (Reed, 1995). Rainfall benefits from no artificial influence, such as land use, water abstraction or management policies, and thus presents the natural status of the system at a given time. In contrast, river streamflow or groundwater levels are subject to various external factors, and integrate the phenomenon over space and time. Rainfall deficits precede low flow and groundwater conditions and trigger major droughts. Consequently, they are useful indicators offering potential to anticipate a drought crisis before the system reaches critical threshold. This allows management procedures to be put in place, which may be more difficult from river flow or groundwater level monitoring.

Rainfall is a practical and versatile indicator amongst those suggested by Mawdsley *et al*. (1994). With a raingauge network larger and denser than that of any other water resource (river flow or groundwater levels), and which encompass long data series, the accuracy and robustness of frequency estimates of droughts derived from rainfall records is likely to be greater than if they were to be assessed from less extensive data sets. Moreover, rainfall requires less pre-processing of data than river flow data during drought periods.

Furthermore, the assessment of the severity of a drought, as legally requested under the Resources Act 1997 (ST73-81) for granting Drought Orders or Drought Permits, specifically stipulates that the Secretary of State has the power to make ordinary and emergency Drought Orders "*by reason of an exceptional shortage of rain*". Investing in a method of drought severity uniquely based on rainfall data is a compromise, but legitimately justified both by legal requirements, and the robustness and reliability of such an estimate.

2.3. Drought Characterisation

Droughts are non-instantaneous phenomena, controlled by a period of low rainfall, and can be seen as "*a condition relative to some long-term average condition of balance between rainfall and evapotranspiration in a particular area*" (Wilhite & Glantz, 1985). The duration and magnitude (or intensity) of the deficit are the two main characteristics that are often used to describe the severity of a drought, but some authors also consider the spatial extent of deficit-prone areas (Santos, 1983; Rossi *et al*., 1992; Hisdal *et al*., 2001; Santos *et al*., 2000).

Mawdsley *et al*., (1994) identified two crucial aspects of water deficiency which have to be addressed when assessing drought severity:

- The duration of the dry period;
- The region or location considered.

They suggested that environmental droughts should be defined as "*the accumulated monthly deficit relative to the mean of a standard period*", and classified according to their duration (short/long), frequency, and the date of start of the drought.

The vulnerability of a system to drought conditions depends not only on the severity of a drought, but also on its impact, e.g. for crop production, lack of resources at a particular moment during growth and rainfall shortages longer than three months may be disastrous. For groundwater droughts or reservoir management, it may be the accumulated deficit over a year. Reed (1995) suggested that drought severity assessment should include two independent analyses: (i) the low rainfall accumulation deficit; and (ii) the sensitivity of the water resource to low rainfall periods. The calculation of the severity of the drought should be based on current rainfall accumulation over periods of time shown to be most critical for the resource. Mawdsley *et al*. (1994) argue that "*the exact duration is less important than whether the drought lasts one summer or lasts several summers and include intervening winters*". They recommended considering two types of droughts: short droughts, lasting less than one season starting in autumn and long droughts, longer than one season.

However, defining a critical drought duration can be hazardous, and most authors do not commit to fixed durations classes, preferring to undertake an analysis on a complete range of durations from one up to sometimes 120 months. Such a detailed analysis guarantees provision of all information, but without justified guidance (and perhaps appropriate training) on how to interpret the results. As an operational tool, the overflow of information may lead to inefficient analysis that could be time- (and resource-) consuming. Moreover, depending on the length of the period over which the accumulated deficit is assessed, the rarity of the event may be variable. For example, the rainfall records of Oxford Radcliffe show that the 1976 drought was ranked the first lowest 12-month rainfall accumulation since 1767, but the second and 15th lowest were for six- and 24-month accumulation periods respectively (Marsh *et al*., 1994).

Appreciation of the rarity of the event for only one duration can therefore be misleading.

It is recommended that the main project should incorporate, in a first phase, the identification of a set of critical durations, at most six, for which the user will have to proceed to the drought assessment. Those durations should be representative of the majority of the systems that may require some Drought Orders, including agriculture, environment, water supply, and industry. It is expected that a range of durations may encapsulate all the various critical durations for most water resources systems, from short periods (e.g. a few months) for small reservoirs in impervious areas, to long or very long durations for large reservoirs, or groundwater systems (e.g. a year or multiple of years).

2.4. Assessing the Suitability of Selected Methodologies

The suitability of the proposal agreed following this scoping study will depend on how well it meets the needs of the users – and in particular responds to the Agency's needs – while incorporating elements that are critical for drought severity assessment. These theoretical elements are summarized here, and can be compared to the characteristics of the different work plans suggested in the following sections:

- Regional analysis. Past analyses often had the tendency to select "worst case" raingauge accumulations to support Drought Order applications, with a potential for causing mischief. When possible, the definition of "target regions", that represent the regional water resource, should be favoured. It is anticipated that spatial averages would then provide a more objective picture than local analysis. It is important to determine the drought stress in relation to the resource itself, i.e. if the resource is integrated regionally, the drought should also be assessed regionally;
- Seasonality. The impact of a rainfall deficit on the water resource is very dependant on the season considered. The method should be able to distinguish seasonality, and differences between winter and summer droughts;
- Flexible duration. Considering *n*-day rather than *n*-month accumulations would provide a more complete and accurate picture of drought stress, helpful for general application including agricultural purposes. In recent years (1990 and 1995 especially), the deterioration of the water resources outlook has been rapid through the spring. Water managers and policy makers would be assisted if the severity of a range of durations (e.g. 20-, 40-, and 60-day duration) could be made available;
- Critical duration. Not all the water resources have the same sensitivity to drought duration. There is thus a need for further research to guide the selection of *n*-month/day rainfall accumulations appropriate to a variety of drought impacts (e.g. groundwater-fed wetlands, single reservoir resource, and integrated regional resource – surface and groundwater). Guidance on which duration(s) to consider must be provided;
- Multi-duration analysis. Single duration analysis restricts the assessment to an individual specific condition that may not reflect the whole reality. Multi-duration analysis has the advantage of incorporating the temporal dimension of droughts (e.g. different weights given to the timing within the drought period or

on the vulnerability to the system), thus providing a more objective picture of the reality. Analysis of the frequency of a drought duration (drought being defined as the period of time for which the rainfall is continuously under a certain threshold) is another technique recommended in low flow analysis (Tate *et al*., 2000);

- Robustness. The method has to have an unambiguous, robust definition of droughts, i.e. slight variations in the drought definitions should not have a large impact on the final severity assessment;
- Vulnerability. Potential for specific vulnerability analysis would help the water managers to objectively assess the droughts for various water resources systems and regions of the UK;
- Severity scale. Classes referring to various degrees of severity (e.g. similar to the Richter scale) would help form a quick, objective and consistent assessment of the drought stress that would be understood by the general public. These classes should be based on frequency, duration and impact of the drought on the water resource. Several classes for various systems should be provided;
- Ease of use. Tables of return periods, such as those derived by Tabony, are tools most Agency staff are familiar with. Providing sets of similar tables would ensure the best usability of the final output. Improvement of the output tables, with a product referenced by the end of the period concerned. Flexible dates (e.g. end-of-month and mid-month) could be envisaged.

The characteristics of each proposed work plan will be summarized according to the critical elements listed above.

3. USERS' REQUIREMENTS - THE AGENCY

The Agency's role is defined in the Environment Act 1995 and includes the long-term planning of resources to cope with future demands as well as having the responsibility for managing resources during droughts. The Agency has consultative responsibility in assessing the severity of droughts prior to granting statutory amendments defined in the Water Resources Act 1991, Section 73-81. It also has legal responsibility for the granting of Drought Permits.

3.1. Drought Order

Drought Orders are special legal amendments that enable the Agency and water utilities to temporarily change or be relieved of their statutory obligations during times of drought. This includes (Gustard *et al*., 1987):

- Reducing the compensation flow to be discharged from any particular reservoir;
- Altering conditions of abstraction licenses;
- Restricting the use of water.

Drought Orders can only be justified by "*a serious deficiency of supplies of water*", and are made by the Secretary of State for the Environment at the request of the Agency (for itself or a third party) or a water company.

When applications for Drought Orders are received, it is the responsibility of the Agency to consider the application and objections, to establish if an exceptional shortage of rainfall has occurred and to make a recommendation to the Secretary of State. The Agency also responds to requests from the Secretary of State for an assessment of the current status and future prospects for water resources and supply. In particular, the Agency is charged to examine the balance between drought measures and drought severity, i.e. "*the scale of natural drought severity against the current and forecast level of deterioration in the availability of public water supply resources if the drought continues*". The Agency should be able to audit arrangements which may need to change if the drought conditions change.

Drought Orders provide power to the applicant to abstract, discharge, prohibit or limit abstractions and water uses which would seriously affect supply (specified by the Secretary of State), and to modify conditions of abstraction, discharge, supply of water and water treatment. Emergency Drought Orders can also prohibit or limit use of water at the discretion of the Secretary of State of Environment. Orders can affect inland navigation (WRA 1991 S77).

Technical requirements

There is no specific technical requirement to assess, if the shortage of rainfall is exceptional or not in the legislation.

Specific indicators can be used, that could be defined by region on the basis of local knowledge by regional Agency staff, but rainfall is the primary driver for any request. It is proposed by the Agency that the frequency with which Drought Orders or Permits are issued for a given place is one in twenty years (Environment Agency, 1997).

3.1.1. Ordinary Drought Orders (WRA 1991 S73/75; Envt Act 1995 Sch 22(139))

Ordinary Drought Orders are granted by the Secretary of State if by "*exceptional shortage of rain, a serious deficiency of supplies of water exists or is threatened*" (WRA 1991 S73(1)) or "*a deficiency in the flow or level of water in any inland waters as to pose a serious threat to any of the flora or fauna which are dependent upon those waters*" (Envt Act 1995 Sch 22(139)). The Secretary of State can change ordinary Drought Orders restricting water use.

Ordinary Drought Orders have an initial duration of six months, with a possible six month extension.

3.1.2. Emergency Drought Orders (WRA 1991 S75(1))

Emergency Drought Orders are granted by the Secretary of State if an "*exceptional shortage of rain, a serious deficiency of supply [is] likely to impair social and economical well being*". They can only be requested by the Agency or a water company, and the Secretary of State can specify the manner in which emergency drought order powers are exercised.

Emergency Drought Orders have an initial duration of three months, with a possible two-month extension.

3.1.3. Environmental Drought Orders (WRA 1991 S74(1); Envt Act 1995 Sch 22)

The Agency alone may apply for Environmental Drought Orders, and the request will be granted if "*by reason of an exceptional shortage of rain, there exists or is threatened a serious deficiency of supplies of water in any area, or such a deficiency in the flow or level of water in any inland waters as to pose a serious threat to any of the flora or fauna which are dependant on those waters*". When granted, the Agency may restrict abstractions by water companies.

Environment Drought Orders have an initial duration of 6 months, with a possible 6 month extension.

3.1.4. Winter Drought Orders

The Agency may also seek water companies to apply for Drought Orders in the winter if it reduces the number of Drought Orders the following summer, when more environmental damage would occur.

The Agency has a policy to encourage water companies to apply for Drought Orders in the winter, if this alleviates the risk of Drought Orders being sought the following summer.

3.2. Spray Irrigation (WRA 1991 S57)

The Agency may restrict or ban spray irrigation surface licenses "*by reason of exceptional shortage of rain or other emergency*". As for the Drought Orders, there is no legal specification of how to assess the exceptionality of the rainfall deficit.

3.3. Drought Permits (Envt Act 1995 Sch 22 (140))

Drought Permits are issued to water undertakers in case of "*exceptional shortage of rain*" by the Agency (not the Secretary of State) when "*such provision as appears to the Agency to be expedient with a view to meeting the deficiencies of supplies*". It is an emergency measure only conditioned by shortage of rain.

Drought Permits may either authorize unlicensed abstractions, or modify license conditions.

Drought Permits expire after six months, but can be extended to a year in exceptional circumstances.

3.4. Post Drought Frequency Analysis

Some analysis of droughts is sometimes requested by the public when they have perceived that exceptional conditions have occurred, e.g. if fish population or the environment have suffered. In this case, the analysis is often done after the drought has occurred.

4. USERS' REQUIREMENTS - WATER COMPANY

The water companies' duties and powers follow the Water Industry Act 1991. However, under the Water Resources Act 1991, they can apply for emergency measures in the case of a severe drought to the Secretary of State for the Environment, or apply some restrictions at their own discretion.

4.1. Drought Order (WRA 1991 S73/75)

Ordinary and Emergency Drought Orders can be requested from the Secretary of State for the Environment by a water company in the case of "*exceptional shortage of rainfall*" (see previous section), based on the water company's assessment of the severity of the drought and adequacy of supplies.

Support from the Environment Agency will be sought when a water company requests a Drought Order.

4.2. Drought Permits (Envt Act 1995 Sch 22)

Drought Permits are requested by a water company and issued by the Agency (see previous section). They give the right to abstraction from a specified source and modify or suspend obligations.

4.3. Restriction of Use (Ordinary) Order (WRA 1991 S73 S73/76)

Water companies can apply to obtain a Restriction of Use Order, which will be granted for "*exceptional shortage of rain and threatened or actual deficiency of supply"*. If granted, they can prohibit or limit particular non-domestic use of water, following the DEFRA guidance.

Restriction of Use Orders have an initial duration of six months, with a possible six-month extension.

4.4. Drought Contingency Plan

These are proposed by a water company and agreed with the Agency, and should be on a scenario basis including a "*worst drought scenario*". The Agency can ask a water company to clearly identify in its plan, the environmental impact a Drought Order or Drought Permit would have, should a "*worse case drought*" occur.

4.5. Hosepipe Bans (WIA 1991 S76)

Water companies can impose hosepipe bans under the Water Industry Act 1991 when it considers "*a serious deficiency of water available for supply exists or is threatened*". Such a ban is decided at the discretion of individual water companies.

5. OTHER USERS' REQUIREMENTS

5.1. National Water Archive (CEH)

The **Hydrological Summary** is produced monthly and disseminated amongst about 160 various water-related bodies, including the Agency and SEPA, various water companies, academia, registered charities, governmental departments and consultants. The Agency, SEPA and DEFRA contribute a large proportion of the production cost of the summary. Since its launch in the winter of 1988-1989, the Hydrological Summary has experienced dramatic increase of interest, in particular during severe drought periods. At present, this is confirmed by electronic dissemination, and the introduction of summary tables and maps, which are publicly available on the internet at: www.nercwallingford.ac.uk/ih/nrfa/water_watch/hydrological_summaries.htm.

It is therefore important that a designed technique is established to provide the best assessment of the climatic conditions.

The Hydrological Summaries provide an overview of hydrological and water resource conditions throughout the UK. Rainfall accumulations are presented over timespans relevant to any prevailing hydrological stress on a regional basis in the form of tables and maps, e.g. including the preceding winter when the groundwater levels and flows in spring-fed rivers are depressed. The frequency of the accumulated rainfall is calculated from the Tabony tables derived using data covering the period 1911-1970. The most recent extreme events (droughts or floods) have not been considered in the frequency estimation, and thus the return periods stated in the summary are only indicative. In addition, return periods are not estimated above 200 years (all appear as '> 200 years'). The return periods are based on fixed start months to respect the seasonality, as much lower return period may be derived if 'any start month' analysis were employed. The maps provide a quick assessment of the resources, in colour-coded severity thresholds (see Table 4.1).

Table 4.1: Severity classes used in the hydrological summary.

Accumulated rainfall anomalies		
Colour	**Return period**	**Severity**
Black	*Above 20 years*	Very wet
Dark blue	*Between 8 and 20 years*	Substantially above average
Blue	*Between 3 and 8 years*	Above average
Green	*Below 3 years*	Normal average
Yellow	*Between 3 and 8 years*	Below average
Orange	*Between 8 and 20 years*	Substantially below average
Red	*Above 20 years*	Exceptionally low rainfall

Although not used operationally by the Environment Agency, it is an important document that could be used in policy making under the statutory requirement to provide assessment of water resources (Water Resource Act, 1963) and as a means of distributing information to the general public, with CEH acting as an independent party in providing this information (Appendix II.1).

Technical requirements

The most recent variations in rainfall should be taken into account in the estimation of the rainfall frequency. A regional method, with homogenized rainfall data would be useful, ideally based on hydrological rather than administrative regions. Fixed-length durations, rather than calendar months, would better reflect the current conditions. For example, a 64-day or 92-day accumulated rainfall would be a better indicator for groundwater resources than one calendar month.

5.2. The Met. Office

5.2.1. Tabony Tables

The Tabony tables (Tabony, 1977) were developed at the Met. Office and are still the standard way for estimating return periods of monthly rainfall totals. The current tables have been derived from coefficients obtained using more recent data than the original series used by Tabony, but the methodology itself has remained unchanged. While providing adequate estimates for the majority of rare events, at present its use in the analysis of very extreme events is being called into question (Hollis, personal communication).

5.2.2. Monthly Climatic Summary

Monthly climatic assessments, including rainfall, are produced by the Met. Office and are available on the internet at http://www.meto.gov.uk/climate/2002. Maps of rainfall totals, anomalies relative to the 1961-1990 average and estimated return periods are shown, and results are summarized in tables on a regional basis (except for return periods) (Appendix II.2).

5.3. Farmers

There is a demand from farmers managing large irrigation schemes to anticipate or evaluate severe drought conditions, so that they can respond appropriately to minimize potential damage to crop.

6. THE TABONY TABLES

6.1. Background

The "Tabony tables" provide regional and national correspondence between monthly rainfall deficit (or excess) and a return period. They were developed and published by Tabony in 1977, and have ever since been used routinely to assess the rainfall conditions in the UK. Examples of use include the Hydrological Summary (see Appendix I.1) and the national maps of monthly climate statistics (Met. Office, see Appendix I.2).

The method is a combination of parametric distributions and empirical formulae that are used to define regional parameters for estimated frequency distributions for rainfall accumulations of a specific duration and starting month. These estimates are expressed as a percentage of a long-term average: the 1911-1970 average was the original long-term value chosen when first published. Associated return periods are derived from the curves, and express the rarity of either excess or deficit rainfall totals.

The original tables were derived from records of 90 raingauges across Britain with data from 1911 to 1970. A number of different tables are provided, corresponding to a rainfall duration of one to up to 120 months for a given starting date (see Appendix I.3). They are either calculated locally, or derived from regional estimates to provide catchment or regional tables. Tables for "any start date" are also available.

In the context of climate change, the assumption that the rainfall is static is sometimes hard to justify, and there are some concerns that estimates based on ancient data may no longer be representative of the current climatic regime. In 1994, a study was undertaken by Hough to assess the representativeness of the Tabony tables on three long series records in Kent (Hough, 1994). The author concluded that despite an apparent decline of the average monthly rainfall from 1911-1970 to 1931-1990, the variability of the rainfall remained much the same, and thus, the method was still valid if associated with the most recent long-term average. However, the results are only based on three sites, and the spatial properties used in the regionalization of the method were not verified.

6.2. Methodology

The method, as described by Tabony (1977), adheres to the following assumptions:

(i) The rainfall deficit/excess (compared to the long-term mean) of *d*-month duration starting month *m* follows a modified log-normal distribution;

(ii) The parameters of the distribution can be defined using regional estimates of the coefficient of variation (C_v) and coefficient of skewness (C_s) of the series of *d*-month total rainfall starting month *m*;

(iii) Regional estimates of C_v and C_s for any *d*-month can be deduced from local estimates of C_v and C_s for one month using areal reduction coefficients and averaging. These are dependent on the region and on the season, but are independent of the duration.

Using various empirical formulae and data for the 90 sites over the UK for the 60-year period 1911-1970, Tabony produced maps of C_v, C_s and areal reduction factors for Britain. These were later used to produce the tables consisting of anomalies (in percentage of the long-term average rainfall) associated with their return periods.

6.3. Comments on the Tables

6.3.1. Advantages

The tables offer the user simplicity and relative ease of use, providing a way of rapidly assessing the rarity of the rainfall total, expressed in terms of return period, for any season and any region of Britain. This simplicity made them very popular in the past, and they could be considered as almost a standard method to assess frequency of long-duration rainfall in the UK. Widely-distributed across the Agency, the Water Resources staff are familiar with its use and limitations, which will not be the case for any other method developed during the second phase of this project. The results of the Hough study (Hough, 1994), while not necessarily representative of the rest of Britain, placed some degree of confidence in the use of the Tabony tables.

6.3.2. Limitations

Table layout and outputs

The Tabony tables are formed by an extensive number of tables (one for each combination of duration and starting month); too large for an objective and practical assessment of drought severity. They are designed to refer to a fixed starting month, and thus they establish the frequency of a particular deficit to occur at intervals of whole numbers of years. While maintaining seasonal characteristics of the rainfall regime, they do not permit an assessment of the risk of a similar drought occurring at any time of the year. Moreover, the rarity of the event is likely to be overrated (Marsh *et al.*, 1994). Reed (1995) adds that considering deficits of a fixed number of months at a fixed starting date "*is of limited value for drought severity assessment*" and should be avoided.

Without guidance, misinterpretation of the tables will result in inconsistent overestimates. Recommendations are likely to include the analysis of a limited number of durations only.

Methodology

The method described by Tabony does not include the analysis of extreme events, but considers accumulated rainfall over certain durations, mixing both periods of wetness and dryness. Moreover, the same distribution is used to estimate the frequency of the dry episodes (accumulation lower than the average) and of the wet episodes (accumulation greater than the average). There is a risk of bias in the estimation of the frequency of extreme events such as droughts.

The regionalization of the method is based on areal reduction factors estimated from empirical formulae derived from data up to 1970. However, since then, research on regionalization has burgeoned and robust methods have been developed, particularly for flood frequency estimation (e.g. reviews by GREHYS, 1996 and Ouarda *et al*., 1999). Although a verification of Tabony's regional method is required, investigating new regionalization techniques would guarantee the best possible results.

The monthly series used to derive the tables (60 years long) are too short to provide reliable estimates of large return periods (Robson & Reed, 1999) and yet estimates are given up to 1000 years, including for 120-months accumulated rainfall series derived from very few independent samples. Extreme care must be taken in the interpretation of return periods greater than 200 years, and we recommend that the new methodology should not provide estimates in excess of 200 years.

6.4. Data Requirements

The Tabony methodology and derived tables necessitate long series of monthly rainfall from a network of raingauges across Britain. Originally derived from 60-year data, the analysis would benefit from even longer series.

6.5. Work Plan 1: New Tabony Tables

6.5.1. Details

The proposed work plan is (i) to verify the assumptions used by Tabony; and (ii) to update the methodology. The method will still consider rainfall anomalies for fixed dates, but clear guidance on the durations to analyze will be given so that the user will undertake the analysis within a consistent framework. Extraction following a fixed ending date, rather than fixed starting date, is proposed, as it simplifies the operational assessment of current droughts.

3 motnhs	(i)	Identify two representative raingauge networks: a benchmark set, with at least 80 years of records - ideally, this network will be identical to that used by Tabony; an additional set, with at least 50 years of records, selected to complement the benchmark set in areas with poor density. This includes data quality check, regional comparison, verification of consistency of different data bases, and reformatting;
2-3.5 momnths	(ii)	Define *n* different durations for which to define the new tables (e.g. short, medium, long, and very long). The set of durations should encompass the various drought lengths to which most of the water resources systems are sensitive (it is anticipated that a few selected systems will be analyzed). Guidance on durations to analyze for different applications will be provided. Extra analysis for flexible duration (*n*-day accumulation) are optional;

3 months	(iii)	Fit appropriate distributions to the *d*-duration accumulated rainfall series of same ending month for the *n* selected durations *d*. Several distributions will be considered, including log-normal, Pearson-3 and Gamma distributions. The frequency distributions will not be extrapolated above a 200-year return period;
2 months	(iv)	Verify the hypothesis that the distribution parameters of *d*-duration series can be deduced from those of the one-month series;
3 months	(v)	Assess the regional procedure suggested by Tabony. Investigations of different regionalization methods may also be considered;
2 months	(vi)	Apply the regional method to all the benchmark gauges, and produce final codes and outputs, including tables of rainfall accumulation anomalies and corresponding return periods estimated from each distribution;
2 months	(vii)	Production of final technical report and guidance for users.

6.5.2. Outputs

The outputs of this work plan will be:

- A revised methodology for frequency estimation of rainfall anomalies accumulated over several months;
- A set of new regional tables for return periods up to 200 years for selected durations, and homogeneous regions to which they correspond;
- A code of fitted distributions and parameters;
- Software implementation;
- Guidelines on which method to use for a particular application's requirements.

6.5.3. Characteristics of the work plan

A checklist of the specifications for drought severity assessment suggested in the second section is summarized in Table 6.1 for a quick assessment of the methodology proposed.

Table 6.1: Summary of characteristics of work plan 1.

Specifications	
Regional analysis	✓
Seasonality	✓
Flexible duration	(✓)
Critical duration	✓
Multi-duration analysis	
Robustness	
Vulnerability	
Severity scale	
Ease of use	✓

6.5.4. Implementation

Work plan 1 is intended to be developed over 28 months. Staff cost estimates are shown but no dissemination of the cost is included. They will be agreed later with the Agency in conjunction with the development strategy.

Table 6.2: Summary of work plan 1 implementation.

	Year 1	Year 2	Year 3	Cost
(i) Data selection/preparation	______			£18k
(ii) Critical duration definition	______ _			£12k-21k
(iii) Frequency distributions analysis	________			£18k
(iv) Duration analysis		_____		£13k
(v) Regional analysis		__________		£18.5k
(vi) Final validation and application		____		£13k
(vii) Technical reports			____	£13k
TOTAL				£105.5k-114.5k

7. THE STANDARDIZED PRECIPITATION INDEX

7.1. Background

The Standardized Precipitation Index (SPI) was developed in the early 1990s by McKee *et al*. (1993, 1995) to provide a representation of wetness or dryness from rainfall series data. Review of recent literature show its growing popularity amongst scientists (e.g. Guttman, 1998, 1999; Hayes *et al*., 1999; Wu *et al*., 2001; Lana *et al*., 2001) and water managers (Vogt & Somma (Eds), 2000).

The drought index is "*simple, spatially consistent in its interpretation, probabilistic so that it can be used in risk and decision analyses, and can be tailored to time periods of a user's interest*" (Guttman, 1998) and has replaced the popular Palmer Drought Severity Index for drought assessment for agriculture management in USA and worldwide (Wilhite *et al*., 2000).

The SPI represents "*the number of standard deviations that the observed value would deviate from the long-term mean if it was a normally distributed random variable*" (Hayes, 2001). It can be used as a monitoring tool to assess both wet and dry conditions, and is now provided as part of the climatic assessment of the U.S. National Drought Mitigation Center NDMC and Western Regional Climate Center (please refer to the web addresses below).

The SPI is actually an alternative to the Tabony tables, where the original frequency distribution is transformed to express the deficits or excesses in normal scores rather than in return periods. This procedure was suggested because the accumulated rainfall series are not normally distributed.

7.2. Methodology

The SPI can be calculated for a range of lengths: 1, 2, 3, 6, 9, 12, and 24 months (WRCC, 2002). Longer periods of accumulated rainfall would need series over 100 years long to provide reliable estimates of extreme events, and are not recommended (Guttman, 1999).

(i) The *d*-month accumulation series is derived for the site. Running averages are not recommended to respect independency of the elements of the series;

(ii) The values for all ending months are extracted, and a probability distribution fitted to each of the 12 series to maintain seasonal characteristics. Guttman recommends using the Pearson-3 distribution, while McKee used the Gamma distribution. Tabony uses a log-normal distribution;

(iii) The corresponding cumulative distribution is transformed using equal probability to a normal distribution with a mean of zero and a standard deviation of one. The SPI value corresponding to an x-rainfall accumulation is the standardized Gaussian value (or normal score value) of probability p, where p is the probability associated to x in the fitted cumulative distribution;

(vi) The SPI series are derived for each duration and plotted;

(vii) The magnitude of a drought is defined by McKee as the number of months during which the SPI is negative. Severe droughts are defined as the period for which the SPI is constantly lower than -1 (see Figure 7.1).

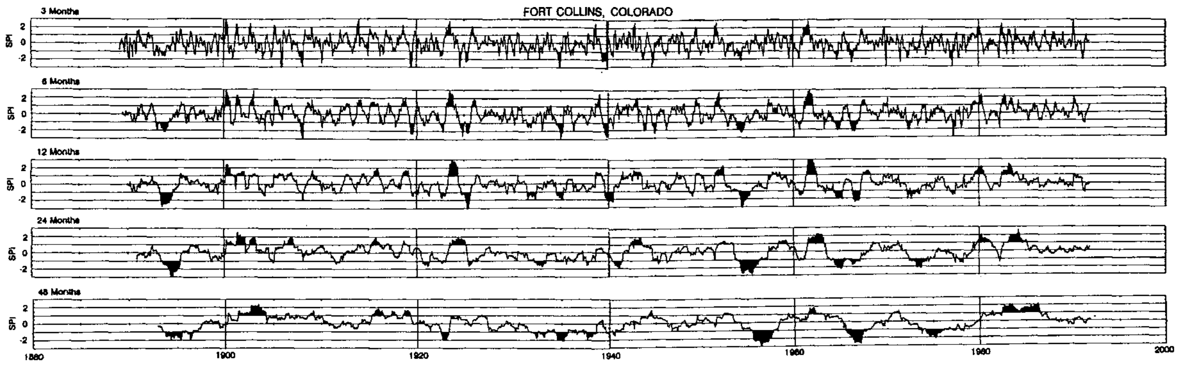


Figure 7.1: Example of Standardized Precipitation Index series (After McKee et al., 1993).

Classification of events is done according to their SPI values, such as that used by the WRCC (Table 7.1). Thresholds in mm (or in % of the long-term average) of rainfall accumulated during the given length can be defined for each site from the SPI classes and the cumulative density probability.

Table 7.1: SPI classification.
(http://www.wrcc.sage.dri.edu/monitor/wdccomn.html**)**

SPI values		
SPI value	**Frequency**	**Severity**
3.0 and above	*Less than 2 times per 1000 years*	Know how to swim?
2.0 to 2.99	*2-3 times per100 to 1000 years*	Extremely wet
1.25 to 1.99	*Between 10 and 2 times per 100 years*	Very wet
0.75 to 1.24	*Between 22 and 10 times per 100 years*	Moderately wet
-0.74 to 0.74		Near normal
-1.24 to -0.75	*Between 22 and 10 times per 100 years*	Moderately dry
-1.99 to -1.25	*Between 10 and 2 times per 100 years*	Severely dry
-2.99 to -2.00	*2-3 times per 100 to 1000 years*	Extremely dry
-3.00 and less	*2-3 times per 1000 years*	Where's the nearest oasis?

7.3. Comments on the Method

7.3.1. Advantages

The method is extremely similar to that of the Tabony tables, but does not attempt the regionalization proposed by Tabony. Owing to the simple definition, calculation and classification, it gives a rapid, consistent and accurate assessment of a given local situation in relation to historical records, and provides ideal drought monitoring capacity. The SPI is becoming a standard in agricultural drought assessment. Tables similar to the Tabony tables can be derived locally. A very simple, straight-forward classification of drought severity is suggested, which is not given with the original Tabony tables. A "return-period free" assessment has the advantage of avoiding possible misinterpretation.

McKee defines severe droughts as the period of time when the SPI index is below a certain threshold (-1 was suggested), and the drought magnitude as the duration of this period. It is envisaged that the project will address the problem of assessing the frequency of long-lasting droughts by undertaking frequency analyses on drought durations as suggested by Tate *et al*. (2000). This therefore enables a multi-duration assessment, a procedure not possible with the Tabony method.

An objective and clear methodology has been published by Guttman (1999) with a code which is publicly available, allowing analyses over several durations and inter-site comparisons.

7.3.2. Limitations

Similar to the Tabony method, the analysis considers accumulated rainfall over a certain duration without focusing on extremes, and provides a single distribution to the frequency of the dry and wet episodes. There is a risk of bias in the estimation of the frequency of extreme events such as droughts.

To maintain the independence of the sampled events, running averages are not recommended for long-period accumulation, and a maximum 24-month period is suggested as an operational limit (Guttman, 1999). The Tabony method does not have such a limitation, *a priori*, because the long-duration distributions are deduced from the original one-month distribution. However, it is not clear how this propriety was verified with the limited 120-months accumulated independent series (derived from only 60 years of records). The seasonality of rainfall is addressed in the same way as in the Tabony tables, with different distributions for fixed starting/ending month periods.

The drought probability is only estimated locally, and the method cannot identify regions that may be more "drought-prone" than others. However, it enables inter-comparison of the status of a region at a given time compared to its respective historical values. Regions with, on average, very low rainfall totals may produce unreliable SPIs for short duration accumulations (one to three months). However, this is unlikely to be a problem in the UK, where the average one-month accumulation rainfall is rarely nil.

The SPI method has been designed as a monitoring tool, and thus SPIs series are calculated locally from averaged series for each duration. Generalizing and regionalizing the method must be investigated, for instance in deriving seasonal or annual SPIs (i.e. *d*-months) from one-month SPIs (Lana *et al.*, 2001). We recommend only developing a regional method that would be more robust than a local one.

7.3.3. Useful Websites

The U.S. National Drought Mitigation Center drought watch:
http://enso.unl.edu/ndmc/watch/watch.htm

The Western Regional Climate Center:
http://www.wrcc.sage.dri.edu/monitor/wdccmon.html

7.4. Data Requirements

The Standardized Precipitation Index necessitates monthly rainfall for a network of raingauges across Britain with data series without missing data and that are as long as possible.

The work plan suggested is to develop a regional method of estimation of regional SPI (work plan 2).

7.5. Work Plan 2: Regional Standardized Precipitation Index

7.5.1. Details

The proposed work plan is to develop a regional method for the Standardized Precipitation Index for the UK. The method will use a set of benchmark raingauges with at least 80-years of data, plus a set of raingauges with shorter records (around 50-years). This will allow better regionalization in areas where the density of gauges with long records is poor.

3 months	(i) Identify two representative raingauge networks: a benchmark set, with at least 80 years of records; an additional set, with at least 50 years of records, selected to complement the benchmark set in areas with poor density and to be used for the SPI relative to short duration. This includes data quality check, regional comparison, verification of consistency of different data bases, and reformatting;
2-3.5months	(ii) Define *n* different durations for which to estimate the SPI (e.g. short, medium, long and very long). The set of durations should encompass the various drought lengths to which most of the water resources systems are sensitive (it is anticipated that a few selected systems will be analyzed). Guidance on durations to analyze for different applications will be provided. Extra analysis for flexible duration (*n*-day accumulation) are optional;

3 months	(iii) Fit appropriate distributions to the *d*-duration accumulated rainfall series of same ending month for the *n* selected durations. Several distributions will be considered, including log-normal, Pearson-3 and Gamma distributions; (iv) Transform each fitted cumulative distribution by an inverse-normal function (one for each site and each duration);
3 months	(v) Calculate the SPI series of duration *d* from the 12 transformed distributions. The SPI value of a given month is the normal score given by the transformed distribution for the corresponding rainfall anomalies. Extract drought magnitude series, defined as the number of consecutive months when the SPI is below -1; (vi) Fit appropriate distribution to the drought magnitude series;
4 months	(vii) Assess and develop a regional method for estimating the SPIs and drought magnitude frequency. Methods to consider include regionalization of the distribution parameters for homogeneous regions (either parameters of the rainfall accumulation distributions, or on the drought duration distributions), and regionalization of the SPI values (e.g. Lana *et al.*, 2001). Use of shorter series will be considered to improve the regionalization.
2 months	(viii) Apply the method to all the benchmark gauges, and produce final codes and outputs, including tables of *d*-duration SPI thresholds and frequency distributions of drought magnitudes. The classifications used by the Drought Mitigation Centre (USA) will be considered for the SPIs thresholds;
2 months	(ix) Production of final technical report and guidance for users.

7.5.2. Outputs

The outputs of this work plan will be:

- A new methodology for regional Standardized Precipitation Index method;
- A set of regional SPI tables classifying events from moderate, severe to extremely severe for selected durations, along with corresponding regions;
- A set of regional drought magnitude frequency distributions;
- A code for deriving all the regional distributions, SPIs and drought magnitude frequency Summary tables;
- Software implementation;

- Guidelines on which method to use for a particular application's requirements.

7.5.3. Characteristics of the Work Plan

A checklist of the specifications for drought severity assessment suggested in the second section is summarized in Table 7.2 for a quick assessment of the methodology proposed.

Table 7.2: Summary of characteristics of work plan 2.

Specifications	
Regional analysis	✓
Seasonality	✓
Flexible duration	(✓)
Critical duration	✓
Multi-duration analysis	✓
Robustness	
Vulnerability	
Severity scale	✓
Ease of use	✓

7.5.4. Implementation

Work plan 2 is intended to be developed over 34 months. Staff cost estimates are shown but no dissemination of the cost is included. They will be agreed later with the Agency with the development strategy.

Table 7.3: Summary of work plan 2 implementation.

	Year 1	Year 2	Year 3	Cost
(i) Data selection/preparation				£18k
(ii) Critical duration definition				£12k-21k
(iii/iv) Frequency distributions analysis				£18k
(v/vi) Magnitude frequency analysis				£18k
(vii) Regional analysis				£24.5
(viii) Final validation and application				£13k
(ix) Technical reports				£13k
TOTAL				£116.5k-125.5k

8. THE DROUGHT SEVERITY INDEX

8.1. Background

The assessment of drought severity is often carried out using indices that have been defined to summarize the status of rainfall deficits. The use of an index has the great advantage of providing a simple way for comparisons to be made, and potential for monitoring the state of the system. Several drought indices were included in this report because they were derived from extreme events only, and thus provide more reliable estimates of drought rarity than more general methods such as Tabony or SPI.

The Drought Severity Index has been suggested by Mawdsley *et al*. (1994) to characterize an **environment drought**, as a measure of the significance of drought for those who are directly affected by rainfall shortage. The droughts are assessed by length and intensity from a simple classification that enables rapid evaluation of the type of drought.

8.2. The Rainfall Deficiency Index

The Drought Severity Index needs to be calculated from an intermediate series, referred to as the Rainfall Deficiency Index series by Mawdsley *et al*. (1994). The Rainfall Deficiency Index (RDI) is calculated from the accumulated monthly rainfall deficit relative to the mean of a standard period. Its concept is described by Bryant *et al*. (1992, after Mawdsley *et al*., 1994) and used in Marsh *et al.* (1994) to assess the drought severity of 1988-1992.

A RDI series is a transformation of a monthly rainfall series into a partial series that only contains information relative to droughts. If the month considered endures conditions of a drought, its rainfall deficit is calculated. If it is considered not to be under drought conditions, the value of the series for this month is set to zero.

A drought starts when the one-month accumulated rainfall is lower than the long-term average. It stops when the rainfall total of the three preceding months exceeds the corresponding three-month long-term mean, i.e. the three-month zero-threshold rule (Mawdsley *et al*., 1994). For long duration events, they suggest an *x*-threshold excess (RDI value is set to zero if three-month total exceeds more than *x* % of the long-term average three-month total). Marsh *et al.* (1994) prefer a six-month criterion arguing that it is of greater relevance to groundwater droughts.

The chosen termination rule is crucial for the resulting drought assessment, and remains a severe weakness in the method.

8.3. The Drought Severity Index

A drought is defined as an episode of non-zero RDI values. For each drought, a Drought Severity Index (DSI) is estimated, whose length is the number of months of the drought, and magnitude the last RDI value of the drought, i.e. largest accumulated deficit.

The DSI is classified according to the drought's length, and the drought magnitude. Two categories are suggested:

- Short droughts, lasting less than one season starting in October;
- Long droughts, lasting more than one season.

For each category, the intensity of the drought is given depending on the frequency of the drought magnitude: moderate, if between five- and 20-year return period; serious, if between 20- and 50-year return period; and severe, if rarer than a 50-year return period.

8.4. Methodology

8.4.1. The Rainfall Deficiency Index

The method describes the derivation of the RDI series from monthly rainfall series for the general case of *x*-excess *m*-month termination criterion.

(i) The long-term average for each individual month and *m*-month total is calculated for a standard period. These values serve as a reference;

(ii) The departure between the monthly record and the long-term average of the corresponding month is calculated. If it is negative (deficit), then (iii). If it is positive, or if the total rainfall of the *m* preceding months is greater than the *x*-excess threshold, the index is set to zero (Figure 8.1);

(iii) The accumulated monthly rainfall deficit from the previous non-zero index corresponds to the RDI of that month.

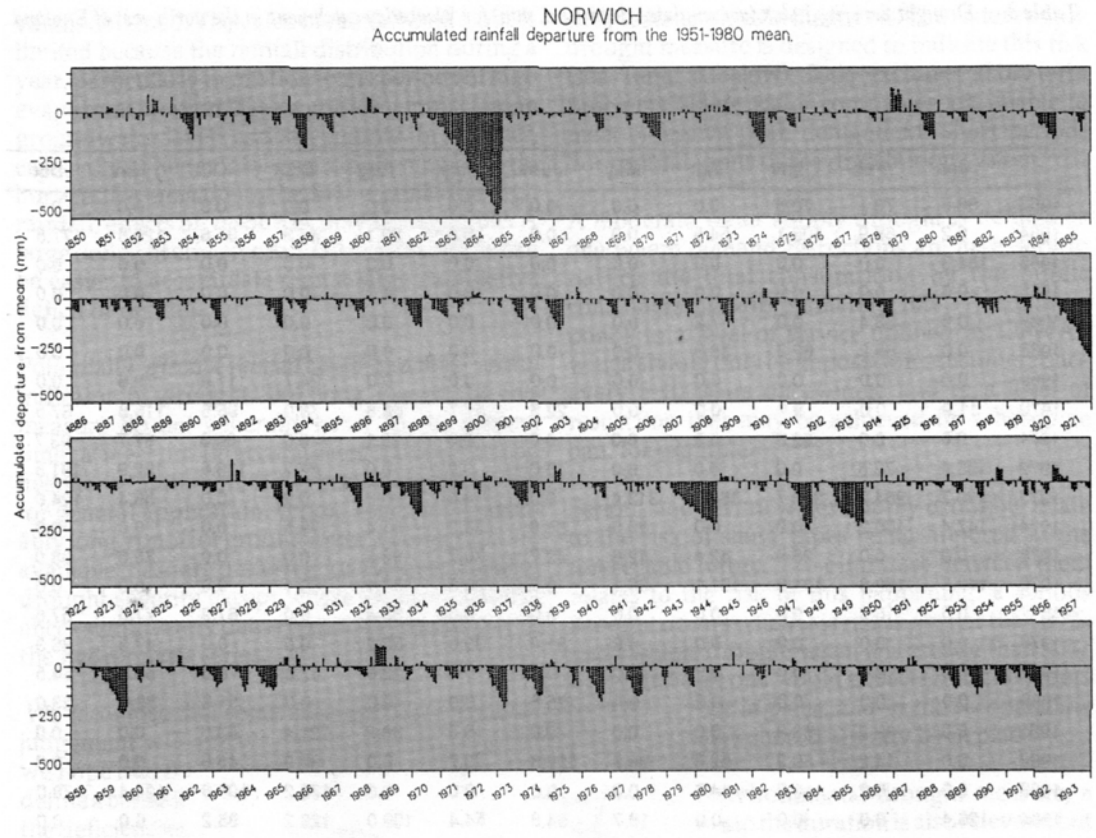


Figure 8.1: Example of Rainfall Deficiency Index (*after Marsh et al., 1994*).

8.4.2. The Drought Severity Index

The droughts are defined in a further three-step procedure, that must be repeated for each site of interest.

(i) The Rainfall Deficiency Index value is assessed using long-term averages following the zero-excess 3-month termination criterion;

(ii) The deficit threshold corresponding to a 5, 20 and 50-year return period is defined from the same historical series;

(i) The drought is classified in duration and intensity to provide a Drought Severity Index value (see Table 8.1). A colour code is suggested for easy interpretation.

Table 8.1: A classification of environmental drought (*After Mawdsley et al., 1994*).

Class of drought	Duration	Return Period	Start of drought
1- Yellow (moderate)	Short	5-20 years	After October*
	Long	5-20 years	> one season
1- Amber (serious)	Short	5-20 years	After October*
	Long	5-20 years	> one season
1- Red (severe)	Short	5-20 years	After October*
	Long	5-20 years	> one season
		*October of the previous year	

8.5. Comments on the Method

8.5.1. Advantages

The DSI focuses only on periods of rainfall deficits, and thus provides a more targeted assessment of the drought rarity than more general methods (such as Tabony or the Standardized Precipitation Index) that include all wet and dry *d*-month accumulation, i.e. not only extreme events.

The Rainfall Deficiency Index series and the subsequent Drought Severity Index have simple, clear definitions, and can be easily computed from monthly means.

With a simple threshold classification, the DSI offers a very effective and rapid assessment of drought conditions, and is thus very appropriate for engineers or Agency staff. Such a classification of droughts has operational advantages, and would be worth considering for any method of drought severity assessment.

The DSI was originally designed as a regional method, but it would be possible to undertake similar analysis on averaged rainfall series representative of a region. However, using an averaged series needs to be considered with caution, and the compromise between homogeneity (i.e. derived from the same set of gauges) and the length of the record must be clearly assessed. The alternative is to define some class thresholds from long raingauge series, taken as representative of the rainfall regime of the (homogeneous) regions.

8.5.2. Limitations

As mentioned earlier in the section, the termination rule defining the “end-of-drought” criterion is **extremely subjective**, and needs to be carefully established when analyzing droughts. At the moment, the method does not appear to provide sufficient evidence for using a particular criterion, and further research would be necessary to provide the users with a set of justified rules. It is possible, for example, that during a long-lasting drought, an intermediate month has excess rainfall compared to the long-term average. In this case, the RDI will be set back to zero, and the duration of the drought shortened.

The concept of short and long droughts is very useful in the operational and engineering context. However, the loose definition suggested by Mawdsley *et al*. (1994) of "*longer than one season*" makes the frequency assessment of long droughts complex. In effect, long droughts could incorporate durations from six months to several years, and the frequency of the ensemble of the durations is not straight forward.

For the DSI to be used as a standard drought assessment technique across the Agency regions, a consistent method for frequency estimation of drought events must be implemented. Mawdsley *et al*. (1994) do not specify any particular technique, and so the use of parametric or non-parametric methods must be investigated.

8.6. Data Requirements

To be derived nationally, the Drought Severity Index method necessitates long monthly/daily rainfall series for a network of raingauges across Britain, including possible nationally and regionally averaged series. These benchmark raingauges will serve as a basis for defining the frequency threshold levels at the origin of the intensity classes.

Because of the difficulty in assessing the frequency of events defined using different durations, it is proposed to define DSI estimates from a fixed set of durations, selected for their critical importance for various water resource systems. For a drought of length m, the intensity of DSI of duration d ($m>d$) will be assessed from the frequency distribution of the d^{th} RDI value of all droughts of duration greater than d.

Two work plans are suggested for the main project: derivation of a local Drought Severity Index (work plan 3), and development of a modified regional method (work plan 4).

8.7. Work Plan 3: Local Drought Severity Index

This work plan details a methodology to derive local DSI for a set of selected benchmarks. The severity of a current drought on these benchmark gauges will be taken as representative of the severity of the current drought in a region.

8.7.1. Details

3 months

(i) Identify two representative raingauge networks: a benchmark set, with at least 80 years of records; an additional set, with at least 50-years of records selected to complement the benchmark set in areas with poor density. The latter to be used for the SPI relative to short duration. This includes data quality check, regional comparison, verification of consistency of different data bases, and reformatting;

2-3.5 months	(ii) Define *n* different durations for which to estimate the DSI (e.g. short, medium, long and very long). The set of durations should encompass the various drought lengths to which most of the water resources systems are sensitive (it is anticipated that a few selected systems will be analyzed). Guidance on durations to analyze for different applications will be provided. The DSI will not be defined for the totality of the drought (i.e. between two zero-value RDI), but for droughts longer than the duration *d* as the greatest *d*-duration deficit;
3 months	(iii) Define a "termination rule". It is possible that different termination rules may be defined for different regions, e.g. permeable regions will have a longer termination excess rule than impervious areas. Guidance on how and when to apply those rules will be justified;
3 months	(iv) Derive the RDI series for the benchmark raingauges. Extract series of *d*-duration accumulated deficits. Different series will be produced for different ending dates. These will constitute the reference series; (v) Fit appropriate distributions to the accumulated rainfall series of same ending date. Several distributions will be considered, including Log-normal, Pearson-3 and Gamma distribution;
2 months	(vi) Estimate the 5-, 20-, and 50-year return period deficits for each duration *d* for all selected sites. They will be expressed as percentage of the total *d*-month long-term rainfall accumulation. Different estimates may be given for different ending dates;
2 months	(vii) Production of final technical report and guidance for users.

8.7.2. Outputs

The outputs of this work plan will be:

- A clear methodology for deriving the Drought Severity Index, respecting seasonality;
- A set of local accumulated thresholds (in % of long term average) classifying events from moderate, serious and severe for selected durations for each benchmark site, taken as representative of the region. Threshold may differ with the ending month;
- A code for deriving the frequency distributions – summary tables;
- Software implementation;
- Guidelines on which method to use for a particular application's requirements.

8.7.3. Characteristics of the Work Plan

A checklist of the specifications for drought severity assessment suggested in the second section is summarized in Table 8.2 for a quick assessment of the methodology proposed.

Table 8.2: Summary of characteristics of work plan 3.

Specifications	
Regional analysis	
Seasonality	✓
Flexible duration	(✓)
Critical duration	✓
Multi-duration analysis	
Robustness	
Vulnerability	
Severity scale	✓
Ease of use	✓

8.7.4. Implementation

Work plan 3 is intended to be developed over 22 months. Staff cost estimates are shown but no dissemination of the cost is included. They will be agreed later with the Agency with the development strategy.

Table 8.3: Summary of work plan 3 implementation.

	Year 1	Year 2	Year 3	Cost
(i) Data selection/preparation	_______			£18k
(ii) Critical duration definition	______ _ _			£12k-21k
(iii) Termination rule	_______			£18k
(iv/v) Frequency distribution analysis		________		£18k
(vi) Final validation and application		_____		£13k
(vii) Technical reports			_____	£13k
TOTAL				£92k-101k

8.8. Work Plan 4 : Modified Drought Severity Index

The original Drought Severity Index is difficult to calculate because it mixes deficits accumulated over different durations (less or more than one season). Analysis of fixed duration, such as the Local DSI described previously, has the disadvantage of ignoring the real length of a drought.

An *x*-% deficit will not have the same impact on the system if it occurs after a wet period or after a prolonged dry spell. The Modified Deficiency Index is a deficit accumulation calculation that gives greater weight to a deficit occurring at the end than at the beginning of the drought. A strict termination rule must apply when deriving the MDI.

The suggested Modified Deficiency Index is calculated as follow:

$$Modified\ Deficiency\ Index = \sum_{i=1}^{n} Deficit_i \cdot \lambda_i$$

with	Deficit	monthly rainfall departure from long-term average of that month;
	λ_i	weight to impose on each monthly deficit, increasing with rank, and satisfying the condition: $\sum_{i=1}^{n} \lambda_i = 1$;
	i	rank of the month in the drought period;
	n	number of months of the drought, i.e. between two monthly deficits set to zero.

The MDI is a weighted average of the monthly accumulated deficit observed during the whole drought. The corresponding Modified Drought Severity Index (MDSI) is derived in the same way as the DSI, but using MDI as basic information and not RDI.

8.8.1. Details

Work plan 4 will follow the same steps as work plan 3, but the analysis will only be undertaken once, rather than for the *n* selected durations:

3 months	(i) Identify two representative raingauge networks: a benchmark set, with at least 80 years of records; an additional set, with at least 50 years of records selected to complement the benchmark set in areas with poor density. The latter is to be used for the SPI relative to short duration. This includes data quality check, regional comparison, verification of consistency of different data bases, and reformatting;
3 months	(ii) Define a "termination rule". It is possible that different termination rules may be defined for different regions, e.g. permeable regions will have longer termination excess rule than impervious areas. Guidance on how and when to apply those rules will be justified;
4 months	(iii) Define the weight function, derive the MDI series for the benchmark raingauges, and extract all the non-zero MDI for the same ending date (a total of 12 distributions will be fitted). These will constitute the reference series; (iv) Fit appropriate distributions to all the non-zero MDI of same ending date. Several distributions will be considered, including log-normal, Pearson-3 and Gamma distributions;
4 months	(v) Assess and develop a regional method for estimating the MDSI frequency. Methods to consider include regionalization of the local parameters from local characteristics, and regional estimation of the distribution for defined homogeneous regions. Use of shorter series will be considered to improve the regionalization;

2 months	(vi) Estimate the 5-, 20-, and 50-year return period deficits for all selected sites. They will be expressed as a percentage of the 1-month long-term rainfall accumulation. Different estimates may be given for different ending dates. They will serve as the basis to define the MDSI status, i.e. if the drought is moderate, serious or severe;
2 months	(vii) Production of final technical report and guidance for users.

8.8.2. Outputs

The outputs of this work plan will be:

- A new methodology for deriving a regional multi-duration drought Index: the Modified Drought Index (MDI);
- A set of regional MDI accumulated thresholds (in % of long term average) classifying the MDSI events from moderate, serious and severe for selected durations, along with corresponding regions. Threshold may differ with the ending month;
- Codes for deriving frequency distributions – summary tables;
- Software implementation;
- Guidelines on which method to use for a particular application requirements.

8.8.3. Characteristics of the Work Plan

A check list of the specifications for drought severity assessment suggested in the second section is summarized in table 8.4 for a quick assessment of the methodology proposed.

Table 8.4: Summary of characteristics of work plan 5.

Specifications	
Regional analysis	✓
Seasonality	✓
Flexible duration	✓
Critical duration	✓
Multi-duration analysis	✓
Robustness	
Vulnerability	
Severity scale	✓
Ease of use	✓

8.8.4. Implementation

Work plan 4 is intended to be developed over 28 months. Staff cost estimates are shown but no dissemination of the cost is included. They will be agreed later with the Agency with the development strategy.

Table 8.5: Summary of work plan 4 implementation.

	Year 1	Year 2	Year 3	Cost
(i) Data selection/preparation	___			£18k
(ii) Critical duration definition	___			£18k
(iii/iv) Frequency distribution analysis	___	___		£24k
(v) Regional analysis		___		£24.5k
(vi) Final validation and application		___		£13k
(vii) Technical reports			___	£13k
TOTAL				£110.5k

9. THE REED METHOD

9.1. Background

Reed (1995) claims that methods such as the Drought Severity Index or the Tabony tables do not provide an objective methodology to assess the severity of droughts. He doubts the results, stating that the methods are often misleading and overestimate the real severity. On the basis that different resource systems have different sensitivities to droughts (a small, local storage will be more sensitive to intense summer droughts than a regional system based on large storage) the notion of risk in assessing the drought severity would permit a more accurate assessment. This notion of risk is also encouraged by Moore *et al*. (1989) for monitoring drought for real-time reservoir management.

The severity of a drought can be defined by the combination of the actual "hazard" (or the rainfall rarity) with the "vulnerability" of the system of interest.

The Reed Drought Index is derived from a three-step methodology:

(i) The rainfall drought is identified "*simply and objectively*" as a period of low rainfall. The greatest rainfall deficits in record for periods of different durations (e.g. from 1 to 49 months) are extracted and ranked (rank = 1 for the lowest accumulation) (see Figure 9.1a);

(ii) The sensitivity of the system (reservoir, aquifer etc…) to droughts of different durations is explored through simulation, and the probability of failure modelled. Weights are given to droughts (of a given duration) according to their impact on the system: highest weights for duration causing most frequent failures (see Figure 9.1b);

(iii) The rarity of the ongoing drought is depicted by looking at the current rainfall event of duration relevant to the storage characteristics, with particular attention to durations most critical to the system (Figure 9.1c). The Reed Drought Index is given by:

$$Reed\ Drought\ Index = \sum_{d=d_i}^{n} rank_d \cdot weight_d$$

with d_i duration identified in step (ii) as critical to the system;
n number of critical durations;
$rank_d$ rank of drought of duration d currently observed relative to the worse historical droughts (step (i));
$weight_d$ weight to give to drought of duration d, estimated in step (ii).

Finally the Reed Drought Index is calculated for all the severe droughts filtered for critical durations (Figure 9.1d).

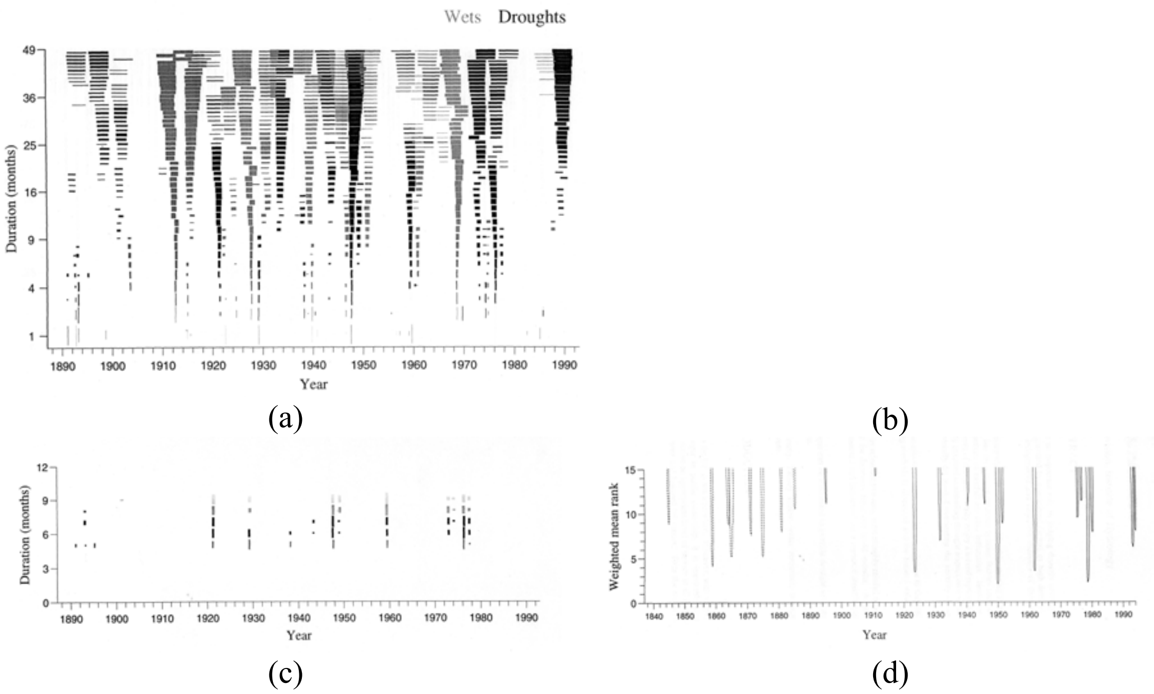


Figure 9.1: Example of calculation of the Reed Drought Index (*after Reed, 1995*).

(a) The 10 greatest accumulated deficits (grey) and excesses (black) over 1 to 50 months; (b) Empirical and modelled probability of durations causing failure; (c) Extracted relevant drought events causing historical failures; (d) Month-by-month evaluation of the Reed Drought Index (with back calculations).

9.2. Comments on the Method

9.2.1. Advantages

Reed proposes to take into account the vulnerability of the water resource system in the assessment of the severity of a drought. This concept, as simple as it is, is rarely used, but offers great scope for an efficient, unbiased drought estimation. A multi-duration approach enables the incorporation of the elements of drought duration, known to be extremely important. A single final value is produced, allowing an unbiased and consistent final assessment more difficult when several index values have to be considered. Moreover, the definition of the index is clear and simple to implement when critical durations and corresponding weights are known. Default weights, representative of a type of water resource system, could be proposed for a basic assessment when local series are not available or are limited.

The method focuses on the most extreme drought events, and follows a technique similar to the well-acclaimed Peak-Over-Threshold abstraction in flood estimation, where only the lowest rainfall accumulations of *d*-months duration are abstracted and considered. This technique has proved its robustness for hydrological drought definition, and is recommended by scientists for low flow assessment (Hisdal *et al.*, 2001). The use of daily (rather than monthly) original rainfall series is preferred for small storage systems, but monthly series can also be used. Intermediate graphical, easy-to-interpret display of the Peak-Under-Threshold series (PUT) allows one to visualize and integrate the duration of droughts in the historic analysis.

The Reed Drought Index does not make any reference to a given frequency or return period when assessing the measure, and thus does not, in the strictest sense, fit the Agency's quest for a "*probability distribution for long-duration rainfall*". However, the vulnerability approach suggested offers scope for independent, reliable drought assessment, and thus was included in the review.

9.2.2. Limitations

A general and consistent use of the Reed Drought Index would require sets of rules not provided in the original publications. These include:

- Independence criterion for sampling the most extreme droughts;
- Size of the historical sample, which conditions the value of the final derived index. Reed uses 50 events, a target difficult to obtain when considering long-period rainfall totals and original rainfall series shorter than 100 years;
- Threshold values that the Reed Drought Index would reach for a drought to be classified as severe;
- Guidance to define the failure of the water resource system.

The method is local, and to be repeated for all sites of interest, and must be generalized before becoming routinely operational. Originally demonstrated for reservoir storage, it also needs to be verified on other water resources systems, provided that long monitored or simulated series of key representative systems (including range of reservoir types, groundwater aquifers and catchments) are available.

The method is based on the vulnerability assessment of the system, and requires definition of the joint probability between the drought events and the failure events. The stochastic empirical approach suggested by Reed requires further validation before complete generalization. Stochastic modelling has the advantage of simplicity compared to implementing detailed modelling methodology such as proposed by Moore *et al.* (1986, 1989) for assessing and managing drought risk.

The project relies heavily on obtaining long data series from representative resource systems. There is some risk that the inability of obtaining relevant data would jeopardize the project outputs.

9.3. Data Requirements

The Reed Drought Index requires long term rainfall and streamflow series, and groundwater and reservoir levels that are representative of most systems existing in the UK. Around 20 representative benchmark sites will be defined and will include the mean to obtain long rainfall series and for monitoring (or potential for modelling) various water resources system. Additional long rainfall series will be included for better regional assessment.

9.4. Work Plan 5: The Reed Drought Index for Representative Key Systems

9.4.1. Details

3 months	(i) Define a set of key systems (around 20) representative of the majority of the UK water resource systems, including range of reservoir types (small to large), aquifers (chalk and permo-triassic), and catchment areas. The key systems should be representative of various climatic regimes;
3 months	(ii) Identify a set of benchmark raingauges with at least 80 years of records. They will be used to provide the user with a Peaks-under-threshold (PUT) series that will serve as a regional indicator of the current and historic climatic conditions. Daily will be preferred to monthly data series. A subset of "representative" raingauges will also be selected for their proximity to the selected key systems. If necessary, gauges with shorter records will also be considered. This includes data quality check, regional comparison, verification of consistency of different data bases, and reformatting;
2 months	(iii) Define strict independence rules for defining different drought events, and thresholds for system failures. Different threshold failures may be defined for different system types;
1 month	(iv) Extract PUT series (i.e. minimum rainfall accumulated over a duration of *d*-duration, or partial series) from the benchmark raingauge network and the representative network for durations up to 50 months;
5 months	(v) Model each of the systems to produce long series of daily values (e.g. reservoir levels, groundwater levels). Derive records of major failures in the system for each key site following the failure threshold defined at stage (iii);
6 months	(vi) Undertake stochastic modelling of the failures from the drought series. For each site, empirical distribution between the frequency of failure and the drought durations will be derived. The frequency of failure for a given duration will be the weight attached to that duration;
2 months	(vii) Undertake a sensitivity analysis of the Index on the size of the PUT sample and the number of durations considered to estimate the Index;

2 months	(viii) Define threshold Drought Index values for various drought classification (moderate, serious, and severe, for instance);
2 months	(ix) Validation of the previously defined weights on the validation set of water system data. These weights will be used as representative of each system in the UK;
4 months	(x) Production of software;
2 months	(xi) Production of final technical report and guidance for users.

9.4.2. Outputs

The outputs of this work plan will be:

- A methodology for generalizing the Reed Drought Index method;
- Classification of the severity of the drought from Reed Drought Index values thresholds. Different thresholds may be provided for different water resources systems and end of drought dates;
- Set of weights for each key water system, and critical drought durations;
- PUT threshold series for the benchmark raingauges network for all the durations identified as critical for any water resources system. The PUT will be expressed as percentage of the long-term average. They will serve to derive a local Index assumed representative of the region;
- Software implementation;
- Guidelines on which method to use for a particular application's requirements.

9.4.3. Characteristics of the Work Plan

A checklist of the specifications for drought severity assessment suggested in the second section is summarized in Table 9.1 for a quick assessment of the methodology proposed.

Table 9.1: Summary of characteristics of work plan 6.

Specifications	
Regional analysis	
Seasonality	
Flexible duration	✓
Critical duration	✓
Multi-duration analysis	✓
Robustness	✓
Vulnerability	✓
Severity scale	✓
Ease of use	

9.4.4. Implementation

Work plan 5 is intended to be developed over 32 months. Staff cost estimates are shown but no dissemination of the cost is included. They will be agreed later with the Agency with the development strategy.

Table 9.2 Summary of work plan 6 implementation

	Year 1	Year 2	Year 3	Cost
(i/ii) Data selection/preparation				£38k
(iii) Independence and failure criterion				£12.5k
(iv/v) Data processing				£40k
(vi) Failure stochastic modeling				£29k
(vii) Sensitivity analysis				£13.5k
(viii) Drought classification analysis				£13.5k
(ix) Final validation and application				£13.5k
(x) Technical reports and software				£40.5k
TOTAL				£200.5k

10. THE FORGEX METHOD ADAPTED TO DROUGHTS

10.1. Background

The FOcused Rainfall Growth Extension (FORGEX) method is an empirical method that has been developed for the Flood Estimation Handbook to provide a way of estimating extreme (high) rainfall frequency in any part of Great Britain, including where no recorded rainfall is available (Faulkner, 1999). It was developed to update the outdated rainfall method of the Flood Study Report (NERC, 1975).

FORGEX is the combination of a regionally-estimated growth factor, and a local rainfall index. The rainfall growth curves (dimensionless) are focused on a subject site by incorporating the largest events from successive hierarchical networks of gauges surrounding the focal point (Reed *et al.*, 1999) (see Figure 10.1). The extracted network maxima must be standardized by the index to allow inter-site comparison. The original method used the median of the recorded annual maxima as the standardization index.

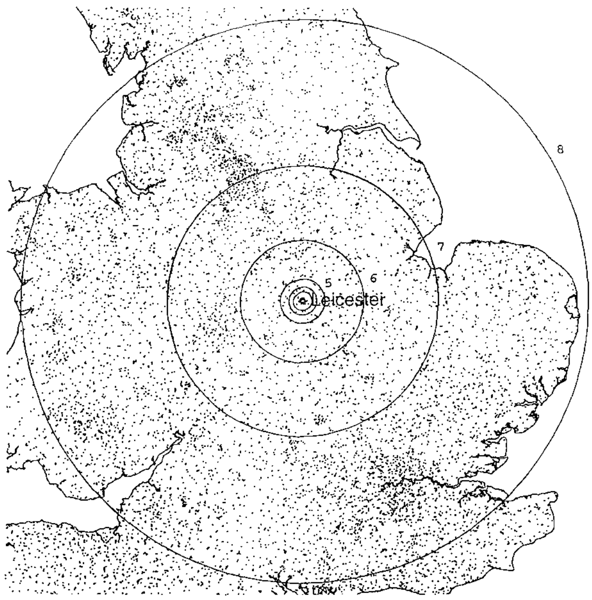


Figure 10.1: Example of hierarchical network used in the FORGEX method (*After Faulkner, 1999*).

The growth curve is derived empirically from a non-parametric method, and can be calculated for various durations (see Figure 10.2). A local index for the same duration must then be used to transform the regional growth curve into the local rainfall depth curve.

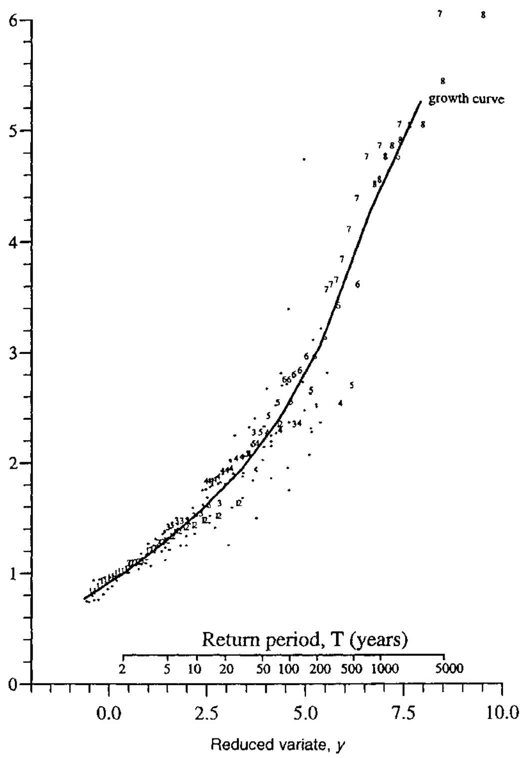


Figure 10.2: Example of FORGEX growth curve (*after Faulkner, 1999*).

A similar methodology could be adapted to *d*-day total rainfall minima to provide robust rainfall drought frequency estimates consistent across all of Great Britain, including in areas with only little information or short rainfall series.

10.2. Comments on the Method

10.2.1. Advantages

The FORGEX method (and the following Intensity-duration Flow (IdF) low flow) are sophisticated drought frequency assessment methods, focusing on the most extreme drought events. They are not providing the same information as the drought indices, but allow robust, accurate estimation of the frequency of the largest deficit accumulations. Local or regional assessment of the drought frequency with these methods could serve as the basis of the class threshold concept used in some droughts indices.

The FORGEX method has been developed to exploit the spatial dependence of rainfall, and to use regional information to improve the robustness and accuracy of long-return period estimates. Such spatial dependence is well known for low rainfall periods and it is legitimate to test the same concept for rainfall droughts. The take up of FORGEX as part of the Flood Estimation Handbook encourages us to envisage enlarging the methodology to low rainfall. With no formal assumption on the underlying distribution, the method is not as restrictive as other parametric methods. Its regionalization depends on the estimation of the standardized index, which can be difficult in sparsely gauged areas such as the highlands of Scotland. However, these regions are unlikely to require assessment of the drought severity, as they are also usually sparsely populated and thus artificial strains on the system virtually non-existent.

10.2.2. Limitations

FORGEX is based on an empirical formulation that describes the spatial dependence of rainfall extremes. The concept and its formulation must be formally validated for low-rainfall. The treatment of zero-rainfall events in probability distributions is non-trivial and must be addressed, even if it is unlikely to arise for durations longer than one month in the UK. Being non-parametric, the method requires large amounts of data, and does not respect seasonality unless specific seasonal extraction is undertaken. FORGEX estimation is local, and must be repeated for each critical duration.

The development of the FORGEX method for extreme high rainfall has been a major task within the Flood Estimation Handbook project and its adaptation to drought rainfall is anticipated to require significant investment.

10.3. Data Requirements

The FORGEX method requires data from an extensive network. Short series are to be included in the analysis to improve regional assessment. Ideally daily series are needed, but monthly data could also be used.

10.4. Work plan 6 : Low Rainfall FORGEX

10.4.1. Details

5.5 months	(i) Data acquisition, formatting and minima extraction for different durations, chosen to be representative of various drought types. The network considered will be as extensive as possible, ideally incorporating all good quality rainfall records available in the UK. The acquisition of long-term rainfall series is a necessity. This includes data quality check, regional comparison, verification of consistency of different databases, and reformatting;
2-3.5 months	(ii) Define *n* different durations for which to assess the drought severity (e.g. short, medium, long and very long). The set of durations should encompass the various drought lengths to which most of the water resources systems are sensitive (it is anticipated that a few selected systems will be analyzed). Guidance on durations to analyze for different applications will be provided. Extra analysis for flexible duration (*n*-day accumulation) is optional;
2 months	(iii) Evaluation and adaptation of the empirical formula for spatial dependence for low rainfall for the different durations;

6 months	(iv) Selection of the standardization index and development of an interpolation method for its national estimation. Derivation of a 1-km grid map of the index (for each duration of interest) for the whole of the UK;
3 months	(v) Production of code to derive growth curves focused on any point in the UK. The current *d*-duration accumulated deficit will be compared to the distributions of the worst historical *d*-duration deficits to assess the return period current drought;
2 months	(vi) Production of final technical report and guidance for users.

10.4.2. Outputs

The outputs of this work plan will be:

- A detailed methodology presenting the technical aspects of low rainfall FORGEX;
- A corresponding code to be run in Windows environment;
- A CD-ROM containing the partial series of all sites of interest along with their coordinates in NGR, the national estimates of the standardization index, and the code that generates the regional growth curves;
- Software implementation;
- Guidelines on which method to use for a particular application's requirements.

10.4.3. Characteristics of the Work Plan

A checklist of the specifications for drought severity assessment suggested in the second section is summarized in Table 10.1, for a quick assessment of the methodology proposed.

Table 10.1: Summary of characteristics of work plan 6.

Specifications	
Regional analysis	
Seasonality	
Flexible duration	✓
Critical duration	✓
Multi-duration analysis	
Robustness	✓
Vulnerability	
Severity scale	
Ease of use	

10.4.4. Implementation

Work plan 6 is intended to be developed over 36 months. Staff cost estimates are shown but no dissemination of the cost is included. They will be agreed later with the Agency with the development strategy.

Table 10.2: Summary of work plan 6 implementation.

	Year 1	Year 2	Year 3	Cost
(i) Data acquisition/preparation				£47k-56.5k
(ii) Critical duration definition				£21k
(iii) Spatial empirical formulation				£12k
(iv) Standardization index estimation				£36.5k
(v) Final validation, production code				£18.5k
(vi) Technical reports				£13k
TOTAL				£148k-157.5k

11. THE FLOOD-DURATION-FREQUENCY (QDF) METHOD ADAPTED TO RAINFALL DROUGHTS

11.1. Background

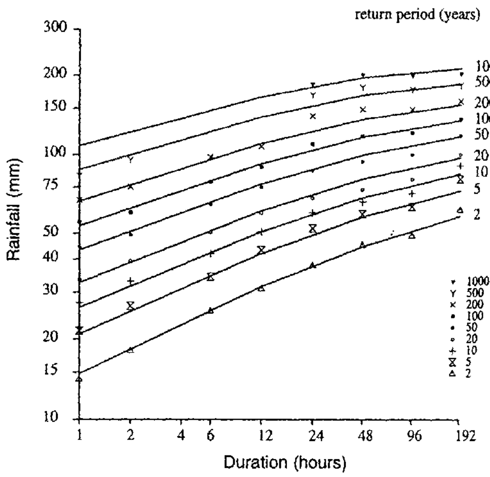
The Flood-duration-Frequency (QdF) approach was developed in France in the 1980s and 1990s to provide a management tool that enables the estimation of the rarity of flood volume quantiles, defined for any duration up to 30 days in any catchment (Galéa & Prudhomme, 1997). The approach links the frequency distributions of different durations by a single formulation, and is derived from a former concept named Intensity-duration Frequency (IdF) specific to high rainfall extremes. The QdF method has been recently generalized in a single form whose parameters must be defined locally (Javelle *et al*., 2000), or assessed regionally (Javelle *et al*., 2002), and successfully validated for different flood regimes (Meunier, 2001). A more empirical technique was developed specifically for rainfall for the Flood Estimation Handbook named Depth-Duration-Frequency (DDF), (Faulkner, 1999). This technique fits locally a set of parameters to FORGEX growth curves estimated over different durations (see Figure 11.1).

The QdF concept has been recently extended to low flows for durations up to 30 days (Galéa *et al*., 1999, Galéa *et al*., 2000). It uses the empirically observed property that all frequency distributions of minimum flow volumes converge towards the same focal point. These minumum flow volumes can be defined over different durations, but are found to have the same theoretical distribution. The general formulation (based on the log-normal distribution) requires three local parameters and provides frequency estimates of minima volumes or threshold discharge never-exceeded during a period of time (see Figure 11.2). The generalization of the parameters, successfully achieved for flood regimes, has not yet been investigated for the low flow case. The importance of estimating low flow quantiles for different durations for hydrological drought assessment has also been noted by Zaidman *et al*. (2002) who developed a method of low flow frequency estimation. However, they did not attempt to generalize the formulation over several durations nor to regionalize their model, nor did they encouraged the use of a single distribution nationally.

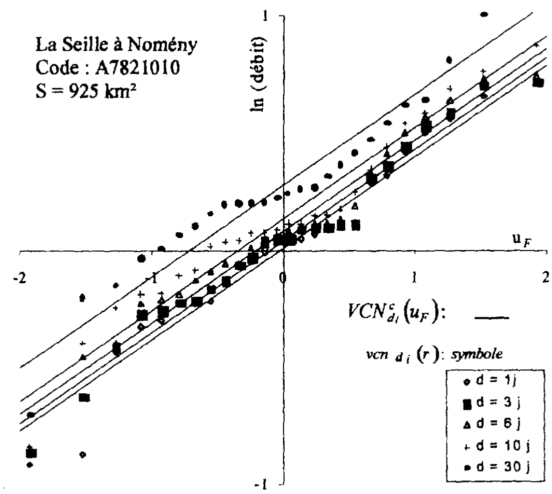
There is thus scope for applying a similar concept to low flow rainfall estimates, in order to provide a robust method that assesses the frequency of low flow extremes for a range of durations. This could be named low Intensity-duration-Frequency.

The FORGEX method is non-parametric, and thus necessitates a complete analysis on a case-by-case basis and for any duration of interest. Methods such as the QdF or DDF enable a much faster complete frequency analysis of low flow quantiles using a set of regional parameters.

The low rainfall IdF approach will provide fast reliable estimates of extreme drought events at any location in the UK. It will be designed as an operational tool useful for calculating reservoir dimensions and efficient drought management planning.



(11.1)



(11.2)

Figures 11.1 and 11.2: Example of DDF (11.1) (after Faulkner, 1999) and QdF (11.2) curves (after Galéa *et al.*, 2000).

11.2. Comments on the Method

11.2.1. Advantages

QdF/IdF focuses on the most extreme drought events, providing a more accurate and robust estimation of the rarity of a drought than a more general method which would involve analyzing all accumulated long-period rainfall totals.

The QdF approach has proved to be efficient for both floods and low flows. It offers scope for a fast, reliable and robust estimation of low rainfall frequency at any location in Britain from a set of parameters for any location in Britain. Moreover the parameters can determined from local data or regional estimates. This versatility and ease of use makes it an efficient engineering tool.

A Peak-Under-Threshold approach is recommended for the QdF/IdF for a better assessment of the extremes, but annual minima sampling could also be used. Annual minima sampling would avoid the definition of independence criterion for sampling the worst drought events. The model links together a set of frequency distributions through the duration of the rainfall period, avoiding any contradiction between durations and return periods that may occur under independent analysis. The properties of invariability of the distributions when standardized, observed for both floods (Javelle *et al.*, 2002) and low flows (Galéa *et al.*, 2000; Zaidman *et al.*, 2002), consolidates the estimation of the parameters of the local distribution for a more robust fit (see Figure 11.3).

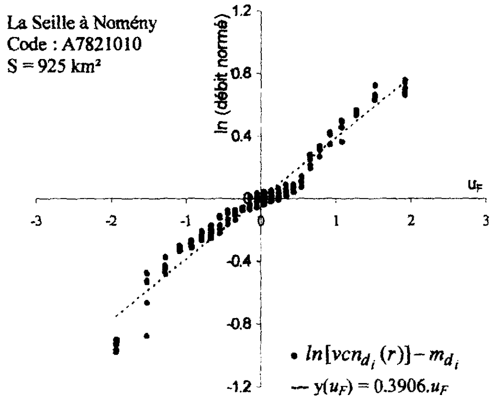


Figure 11.3: The consolidated Low flow QdF curves (after Galéa et al., 2000).

Once the model is developed and it's parameters known, the estimation of the frequency of an event of duration *d* (*d* within the model boundary conditions) becomes rapid, without extensive analysis or data. Regionalization of the concept has already proved successful for flood regimes, and is expected to be possible for low rainfall, whose regional character is already well known.

11.2.2. Limitations

The original models, QdF and DDF, have both been developed for short durations (up to eight days for DDF, up to 30 days for QdF). Validation of the concept for longer durations (up to several years) on local data must be done before the models can be tested for generalization.

The DDF, more than the QdF/IdF approach, requires local fitting of the model parameters. For the parameters to be known nationally, extensive complete FORGEX analysis is required at each cell of the final grid. Different methods of regionalization of the parameters have to be investigated and tested before the model can be satisfactorily generalized. Over-parameterization and extrapolation at very large return periods of the DDF model have already been questioned (Babtie Group *et al.*, 2000). With less parameters, the QdF/IdF concept is unlikely to suffer from over-parameterization, but it still requires generalization of the parameters nationally to enable consistent use. It is not expected to provide estimates over 200 years return period. Because it is derived only from a regional analysis rather than an extensive local analysis, QdF/IdF may not follow local features as closely as the DDF model would.

Generalization of the frequency distribution implies that a single distribution/ formulation will describe the low rainfall regime of the whole of the UK. This may enforce smoothing that is avoided with the local fitting practiced within FORGEX. Additional smoothing will again be overlaid when the regionalizing procedure is put in place. The magnitude of the subsequent errors must be assessed and quantified for an objective assessment of the method.

11.3. Data and Work Requirements

The low rainfall QdF/IdF method appears less computing intensive than the DDF approach, and thus is suggested here. It requires data from a network of (preferably) daily rainfall gauges representative of the different rainfall regimes of the country, with records as long as possible and geographical characteristics data for its generalization. A set of benchmark raingauges with long rainfall data series will serve as the basis to define the model. It will be complemented by a network of gauges with shorter series, which will be used to improve regionalization in low gauge density areas, and for validation of the methodology.

11.4. Work Plan 7 : Regional Low Rainfall IdF Model

3 months	(i) Identify a set of benchmark raingauges with at least 80 years of record. They will be used to provide the user with PUT series that will serve as a regional indicator of the current and historic climatic conditions. Daily will be preferred to monthly data series. This includes data quality check, regional comparison, verification of consistency of different data bases, and reformatting;
2-3.5 months	(ii) Define *n* different durations for which to assess the drought severity (e.g. short, medium, long and very long). The set of durations should encompass the various drought lengths to which most of the water resources systems are sensitive (it is anticipated that a few selected systems will be analyzed). Guidance on durations to analyze for different applications will be provided. Extra analysis for flexible duration (*n*-day accumulation) are optional;
3.5 months	(iii) Define independence criterion for the drought sampling. If no independence rule can be identified, an annual minimal sampling will be undertaken rather than a Peak-Under-Threshold sampling. Definition of the occurrence law; (iv) Extract Peak-Under-Threshold/annual minimum series of rainfall totals accumulated over a range of long durations (from one month to several years) for the benchmark raingauges and the complementary network;
4 months	(v) Select an "index" to standardize the frequency distribution (growth curve). The median of the 30-day annual minima may for example be considered; (vi) Develop a methodology to estimate the index at any point of the country. The use of multi-variable statistical analysis, (empirical orthogonal functions, EOF) or an interpolation method such as kriging will be considered;
2 months	(vii) Undertake a frequency analysis on all standardized PUT series, using a range of different frequency distributions. The distribution that is appropriate for most sites will be selected as the national representative;

2 months	(viii) Validate the concept of local convergent QdF model on sub-selection of gauges, for long-duration rainfall minima series;
3 months	(ix) Regionalize the model from the benchmark data set. Two options will be investigated: the estimation of the local parameters from local characteristics (elevation, geographical characteristics); and the definition of homogeneous regions for which pooled regional distributions will be fitted (the “FEH flood method”);
2 months	(x) Validation of the regionalized/ generalized model on the complementary data set;
2 months	(xi) Production of final technical report and guidance for users.

11.4.1. Outputs

The outputs of this work plan will be:

- A detailed methodology detailing the technical aspects of low rainfall IdF;
- A corresponding code to be run in Windows environment – summary tables;
- Software implementation;
- Guidelines on which method to use for a particular application’s requirements.

11.4.2. Characteristics of the work plan

A checklist of the specifications for drought severity assessment suggested in the second section is summarized in Table 11.1 for a quick assessment of the methodology proposed.

Table 11.1: Summary of characteristics of work plan 7.

Specifications	
Regional analysis	✓
Seasonality	(✓)
Flexible duration	✓
Critical duration	✓
Multi-duration analysis	(✓)
Robustness	✓
Vulnerability	
Severity scale	✓
Ease of use	✓

11.4.3. Implementation

Work plan 7 is intended to be developed over 40 months. Staff cost estimates are shown but no dissemination cost is included. They will be agreed later with the Agency with the development strategy.

Table 11.2: Summary of work plan 8 implementation.

	Year 1	Year 2	Year 3	Year 4	Cost
(i) Data selection/preparation	______				£18k
(ii) Critical duration definition	_____ _				£12k-21k
(iii/iv) Independence criterion & processing	_____				£21k
(v/vi) Index estimation	___	__________			£26k
(vii) Frequency analysis			_____		£13k
(viii) Validation concept			_____		£13k
(ix) Regional analysis			____	___	£20k
(vi) Final validation and application				___	£13k
(vii) Technical reports				___	£13k
TOTAL					£149k-158k

12. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

This report presents the first phase of a project aiming to provide the Environment Agency with a consistent and scientifically sound method for determining return periods of long-duration rainfall drought which

(i) provides an objective, soundly-based view of drought severity;
(ii) is robust enough to be used (and defended) when responding to/determining a Drought Permit/Drought Order application, including being used as evidence at Public Inquiry.

The scoping study presented some of the applications that such a method would be used for, within and outside the Agency.

A literature review of various methods published to assess the severity of a drought in Britain and elsewhere was conducted. A selection is presented in this report, consisting of eight proposals that represent possible different work plans for adapting existing methodologies for drought severity assessment. Each of them has been discussed in detail, with background information on the methodology and potential applications, along with some limitations and data requirements for their update.

A number of analyses are common to all work plans, such as data acquisition and formatting, definition of critical drought durations, and planning for future updating of the method. They reflect the key elements that are necessary for providing the most efficient and reliable drought severity assessment method and were identified at the beginning of the report. Not all the methodologies described are unique or specific to a given work plan, and there is some overlap between each of them. This has been deliberate, to allow the reader who is only interested in a particular technique to quickly establish how it could be implemented.

The characteristics of each proposed work plan are summarized in a summary table (see Table 12.1). This table is a guide for the Agency designed to quickly assess what can, and cannot, be provided by the different work plans. Following this report, the final preferred option will have to be agreed between the Environment Agency and the research team, to meet as many requirements as possible within the Agency. It is possible that the final option will be a mixture of several work plans, so that the most appropriate methodology, in the Agency's view, can be implemented. It is anticipated, though, that the constraints of the resource and data availability will force a compromised option close to one of the presented proposals.

To guarantee the best usability of the output, it is suggested that summary tables will be provided as output (where possible), in addition to some simple codes. This is because it is perceived that the Agency staff are familiar with tables such as Tabony's, and thus would prefer outputs of similar form. Sophisticated software could also be provided for most work plans at additional cost.

12.1. Data Requirements

Most of the proposed methods assess the drought severity of a current event in relation to historical records, and not in terms of absolute magnitude. This is because it is expected that only the most unusual events will cause management problems, and that the water resource is efficiently managed for "normal" conditions, whatever they are. In these conditions, the severity of a drought is directly linked to its rarity, and to some extent to the magnitude of its departure from normal conditions. The underlying assumption is that of a stationary climate. It is anticipated that the impact of using different periods of measurement will be investigated, to account for potential change in the variability of the climate. It is envisaged that the proposed method should be updated at regular intervals – every 10 years for example, to account for possible trends in the regime. Guidance on updating procedures will be given.

The development of a new operational method for assessing the rainfall drought severity thus requires rainfall records that are as long as possible, and representative of the climatic variability observed across England and Wales. Daily series are preferred, but monthly values would be acceptable alternatives.

Results will depend on a thorough quality check of rainfall data. The various project plans do not cater for careful quality control, but this problem must be stressed as an important criterion in the quality of the results and robustness of the developed methodology. This must be tackled for the UK to benefit from top-quality data – the potential is there. Additional costs towards the improvement of a rainfall series database would benefit this project and all subsequent projects in the field of water resources.

Averaged rainfall series, produced by the University of East Anglia Climatic Research Unit and the Hadley Centre, may also be considered.

12.2. Definition of a Critical Drought Duration

The review of the various drought definitions identified a key characteristic of a drought in its duration: the vulnerability of a given water resource system to drought conditions will depend on its duration, and on the time of the year the "below normal" conditions occur. It is therefore essential to invest some time at the beginning of the project to identify key durations to which the range of water resource systems of the UK are the most sensitive.

The project will identify, from a literature review or empirical analysis, sets of critical durations that any drought analysis should consider. The selection of all the durations must be fully justified, including for which system they are most critical, and how to interpret the results.

Multi-month durations are usually chosen for defining droughts. However, there is a need for further research to guide the selection of critical durations (*n*-month or *n*-day) to provide a selection of *n*-duration rainfall accumulation appropriate to a variety of drought impacts. This could be incorporated in any method, as an optional extra.

The issue of drought termination criteria will be carefully examined if the chosen work plan request such termination to be defined. The final criterion should be as robust and representative as possible.

12.3. Work Plans Characteristics

For an easier assessment of each proposed work plan, a table summarising the various characteristics is given (Table 12.1).

Table 12.1: Summary of work plans characteristics.

	Focus on extremes	Multi-duration	Seasonality	Return period	Regional	Vulnerability analysis	Robustness	Drought severity classification	Repeated each time	Fast assessment	Code	Tables	Guidance for duration	Risk of project failure	Project cost (max)
WP 1 Tabony			✓	✓	✓					✓		✓	✓	L	£114.5k
WP 2 Regional SPI		✓	✓	✓	✓			✓		✓	✓	✓	✓	L	£125.5k
WP 3 Local DSI	(✓)		✓	✓				✓		✓		✓	✓	M	£101k
WP 4 Modified DSI	(✓)	✓	✓	✓	✓			✓		✓		✓	✓	M	£110.5k
WP 5 Reed DI	✓	✓				✓						✓	✓	H	£200.5k
WP 6 FORGEX	✓		(✓)	✓			✓		✓		✓		✓	M	£157.5k
WP 7 Low rain IdF	✓		(✓)	✓	✓		✓			✓	✓		✓	M	£158k

One of the requirements of the scoping study was to review methods for assessing the return period of long-period rainfall. Amongst the eight proposed work plans, one of them does not provide a way of estimating the return period of a drought, namely the Reed Drought Index (work plan 5). The method has been proposed because it is based on a vulnerability assessment of the system to droughts of different durations. This approach, unique amongst the reviewed methodologies, presents an alternative to drought management and planning that would offer real operational consistency, despite perhaps the difficult practical implementation. Derivation of the return period estimate associated with this index would require extra analysis not budgeted in the WP5.

Two methods enable a multi-duration analysis: the Modified Drought Severity Index, that defines a drought as the weighted-average of the monthly rainfall deficits; and the Reed Drought Index, discussed above. It is suggested that the Standardized Precipitation Index could be supplemented by a frequency analysis of the drought "magnitude" defined by a severity threshold, i.e. length of the period of time during which the SPI is below the severity threshold. The rarity of the duration of the drought is assessed with this approach, but the magnitude of the maximum deficit is not depicted. This criterion could be expressed for example as a return period threshold, or by a combination of magnitude and duration. However, there is much concern about the robustness of the termination rule used in the MDSI (and its sibling the Drought Severity Index) that must be borne in mind when applying this method.

The existence of a simple criterion that classifies drought severity enables a fast, robust assessment from an approach that can be used consistently and objectively across the country. Formal drought classifications are suggested by two original methods (the Drought Severity Index, and the Standardized Precipitation Index). Similar criteria could also be defined for most of the presented methods, if the Agency declared a need for it. Expert analysis, ensuring that the proposed criterion describes critical conditions objectively, would certainly be requested for defining these thresholds.

It has been long argued that flood studies should be undertaken on a limited subset of river flow measurements, focusing on high streamflow values. This enables the inclusion of events that are assumed to be the result of the same processes in the analysis, and for it to belong to the same "population". Such assumptions allow one to undertake statistical analyses and to deduce estimates from historical records, i.e. the historical average recurrence of extreme events will remain the same in the (near) future. A similar argument can be given when analysing rainfall drought events and assessing the severity of droughts. Methods focusing only on the worst of the rainfall deficits, rather than rainfall totals averaged over fixed durations, should be favoured because they are more robust (Reed Drought Index, FORGEX, low rain IdF). For example, methods such as that suggested by Tabony or McKee (i.e. the SPI), provide a first assessment of the current status of a rainfall total, relative to an average situation, and not relative to the worst of the observed situations. Respect of the seasonal characteristics of the rainfall regime may also be found to be important in water resource management. Water demand does not have the same stress at different periods of the year, and has to be considered in the development of a new methodology.

Regional, rather than local, methods have the advantage of providing potential for estimation in any location in the country, and not just on sites where long records are available. However, rainfall regimes, especially during dry spells, are known to usually show a large spatial consistency. Local estimates, not too far from the site of interest, could be used as surrogate if no local information is available, or when statistical analysis is difficult or not recommended.

12.4. Work Plans Implementation

Table 12.2 presents a summary of the probable timescale for each of the proposed work plans, excluding any dissemination strategy.

It has been suggested that the project output should include codes and table outputs, as well as a technical report and guidelines for the application of the methodology. It is not intended, however, that sophisticated software would be produced. If there were a need for such tools, extra implementation cost would have to be added to the original estimation.

It is envisaged that the method should be regularly updated, to account for any possible change in the climatic regime, either due to long-term cycles, or as a repercussion of a greenhouse-gas enriched atmosphere. A 10 year update should be enough to account for major changes in the different rainfall conditions.

Table 12.2: Summary of work plans implementation.

	Year1	Year2	Year3	Year4	Cost
WP 1 Tabony					
WP 2 Regional SPI					
WP 3 Local DSI					
WP 4 Modified DSI					
WP 5 Reed DI					
WP 6 FORGEX					
WP 7 Low rain IdF					

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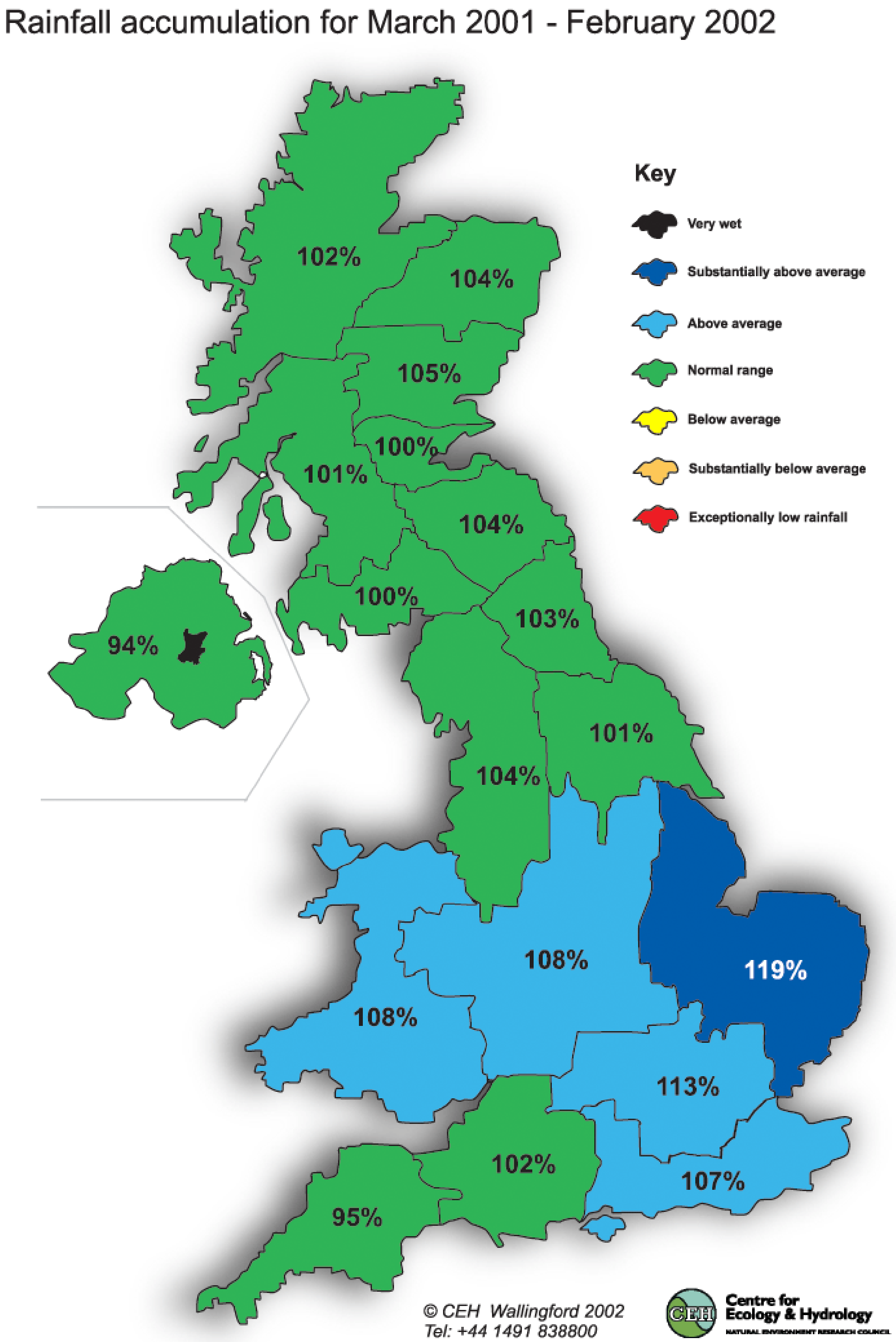
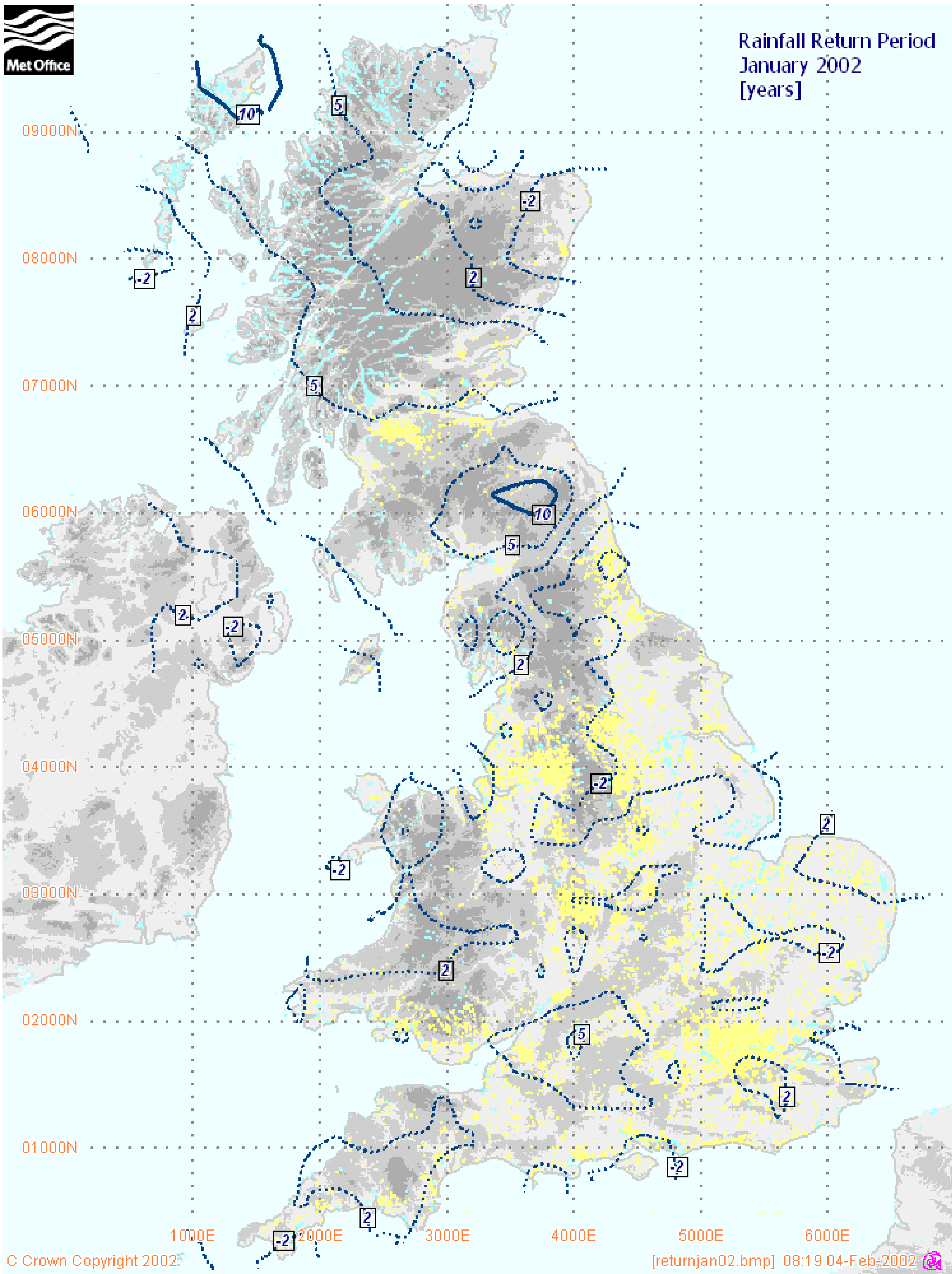
APPENDICES

APPENDIX I Examples of use of the Tabony tables

Appendix I.1 The National Water Archive Hydrological Summary



Appendix I.2 the Monthly rainfall assessment status (Met. Office)



Appendix I.3 Examples of the Tabony tables

AREA PERIMETER DEFINED BY D-MAC TRACE SCOTLAND 1911 TO 1970

PERCENTAGE OF AVERAGE RAINFALL CORRESPONDING TO GIVEN RETURN PERIODS

RAINFALL SUMMED OVER A NUMBER OF MONTHS STARTING IN A GIVEN MONTH

NUMBER OF MONTHS

QUANTILE	1	2	3	4	5	6	7	8	9	10	11	12	14	16	18	20	RETURN PERIOD
0.99900	223.6	185.7	169.6	160.0	153.5	148.9	145.2	142.3	139.9	137.8	136.1	134.6	132.0	130.0	128.3	126.8	1000
0.99800	214.0	179.3	164.4	155.6	149.7	145.3	142.0	139.3	137.0	135.1	133.5	132.1	129.7	127.8	126.3	124.9	500
0.99500	200.4	170.2	157.1	149.3	144.1	140.3	137.3	134.9	133.0	131.3	129.8	128.6	126.5	124.8	123.4	122.2	200
0.99000	189.6	162.8	151.2	144.3	139.7	136.2	133.6	131.4	129.6	128.1	126.8	125.7	123.8	122.3	121.1	120.0	100
0.98000	177.9	154.8	144.8	138.8	134.8	131.8	129.5	127.6	126.0	124.7	123.6	122.6	121.0	119.6	118.5	117.6	50
0.95000	160.9	143.2	135.4	130.7	127.5	125.2	123.4	121.9	120.7	119.6	118.7	118.0	116.7	115.6	114.8	114.0	20
0.90000	146.4	133.1	127.2	123.7	121.2	119.4	118.0	116.9	116.0	115.2	114.5	113.9	112.9	112.1	111.4	110.9	10
0.80000	129.3	121.2	117.5	115.2	113.7	112.6	111.7	111.0	110.4	109.8	109.4	109.0	108.4	107.9	107.4	107.1	5
0.50000	98.5	99.2	99.5	99.6	99.7	99.7	99.8	99.8	99.8	99.8	99.8	99.9	99.9	99.9	99.9	99.9	2
0.20000	69.8	78.4	82.2	84.5	86.1	87.3	88.2	88.9	89.5	90.1	90.5	90.9	91.5	92.1	92.5	92.9	5
0.10000	55.6	67.9	73.5	76.9	79.2	80.9	82.3	83.4	84.3	85.0	85.7	86.3	87.2	88.0	88.7	89.2	10
0.05000	44.4	59.5	66.5	70.7	73.6	75.7	77.4	78.8	80.0	80.9	81.8	82.5	83.7	84.7	85.6	86.3	20
0.02000	32.1	50.2	58.6	63.8	67.4	70.0	72.1	73.8	75.2	76.4	77.4	78.3	79.8	81.1	82.1	83.0	50
0.01000	24.6	44.2	53.6	59.3	63.3	66.3	68.6	70.5	72.1	73.4	74.6	75.6	77.3	78.6	79.8	80.8	100
0.00500	18.6	38.7	48.9	55.2	59.6	62.9	65.4	67.5	69.2	70.7	71.9	73.0	74.9	76.4	77.7	78.7	200
0.00200	12.8	32.3	43.5	50.4	55.1	58.7	61.5	63.8	65.7	67.3	68.8	70.0	72.1	73.8	75.2	76.4	500
0.00100	9.5	28.0	39.6	47.0	52.1	55.9	58.9	61.3	63.3	65.1	66.6	67.9	70.1	71.9	73.4	74.7	1000
CV	0.355	0.254	0.209	0.182	0.164	0.150	0.139	0.131	0.124	0.118	0.112	0.108	0.100	0.094	0.089	0.084	
SKEW	0.262	0.188	0.155	0.135	0.121	0.111	0.103	0.097	0.091	0.087	0.083	0.080	0.074	0.069	0.066	0.062	

QUANTILE	22	24	27	30	33	36	42	48	54	60	72	84	96	108	120	RETURN PERIOD
0.99900	125.6	124.5	123.1	122.0	120.9	120.1	118.6	117.4	116.5	115.6	114.3	113.3	112.4	111.8	111.2	1000
0.99800	123.8	122.8	121.5	120.4	119.5	118.7	117.3	116.2	115.3	114.5	113.3	112.3	111.6	110.9	110.4	500
0.99500	121.2	120.3	119.2	118.2	117.4	116.7	115.5	114.5	113.7	113.0	111.9	111.0	110.3	109.8	109.3	200
0.99000	119.1	118.3	117.3	116.4	115.7	115.0	113.9	113.1	112.3	[illegible]	110.7	109.9	109.3	108.8	108.4	100
0.98000	116.8	116.1	115.2	114.5	113.8	113.2	112.3	111.5	110.9	110.3	109.5	108.8	108.2	107.8	107.4	50
0.95000	113.4	112.8	112.1	111.5	111.0	110.6	109.8	109.2	108.7	108.2	107.5	107.0	106.6	106.2	105.9	20
0.90000	110.4	110.0	109.4	108.9	108.5	108.2	107.6	107.1	106.7	106.4	105.9	105.4	105.1	104.8	104.6	10
0.80000	106.8	106.5	106.1	105.8	105.6	105.3	105.0	104.7	104.4	104.2	103.8	103.6	103.3	103.2	103.0	5
0.50000	99.9	99.9	99.9	99.9	99.9	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	2
0.20000	93.2	93.5	93.8	94.1	94.4	94.6	95.0	95.3	95.6	95.8	96.2	96.4	96.6	96.8	97.0	5
0.10000	89.7	90.1	90.7	91.1	91.5	91.9	92.5	92.9	93.3	93.6	94.2	94.6	94.9	95.2	95.4	10
0.05000	85.9	87.4	88.1	88.7	89.2	89.6	90.4	90.9	91.4	91.9	92.5	93.1	93.5	93.9	94.2	20
0.02000	83.7	84.4	85.2	85.9	86.6	87.1	88.0	88.8	89.4	89.9	90.7	91.4	91.9	92.3	92.7	50
0.01000	81.6	82.3	83.3	84.1	84.8	85.4	86.4	87.3	88.0	88.5	89.5	90.2	90.8	91.3	91.8	100
0.00500	79.7	80.5	81.5	82.4	83.2	83.9	85.0	85.9	86.7	87.3	88.4	89.2	89.9	90.4	90.9	200
0.00200	77.4	78.3	79.5	80.5	81.3	82.1	83.3	84.3	85.2	85.9	87.1	88.0	88.7	89.3	89.8	500
0.00100	75.8	76.7	78.0	79.0	80.0	80.8	82.1	83.2	84.1	84.9	86.1	87.1	87.9	88.6	89.1	1000
CV	0.080	0.077	0.073	0.069	0.066	0.064	0.059	0.055	0.052	0.050	0.046	0.042	0.040	0.038	0.036	
SKEW	0.060	0.057	0.054	0.051	0.049	0.047	0.044	0.041	0.039	0.037	0.034	0.031	0.029	0.028	0.026	

AREA PERIMETER DEFINED BY D-MAC TRACE SEVERN-TRENT WA 1911 TO 1970

PERCENTAGE OF AVERAGE RAINFALL CORRESPONDING TO GIVEN RETURN PERIODS

RAINFALL SUMMED OVER A NUMBER OF MONTHS STARTING IN A GIVEN MONTH

NUMBER OF MONTHS

QUANTILE	1	2	3	4	5	6	7	8	9	10	11	12	14	16	18	20	RETURN PERIOD
0.99900	286.4	225.6	200.5	186.1	176.4	169.4	164.0	159.7	156.2	153.2	150.6	148.4	144.7	141.8	139.4	137.3	1000
0.99800	270.0	215.3	192.5	179.3	170.5	164.1	159.2	155.2	151.9	149.2	146.3	144.8	141.4	138.7	136.5	134.6	500
0.99500	247.6	201.0	181.3	169.9	162.2	156.6	152.3	148.8	146.0	143.6	141.5	139.8	136.8	134.4	132.4	130.7	200
0.99000	229.9	189.5	172.4	162.3	155.5	150.6	146.8	143.7	141.2	139.1	137.2	135.6	133.0	130.8	129.1	127.6	100
0.98000	211.4	177.4	162.8	154.2	148.4	144.1	140.8	138.2	136.0	134.2	132.6	131.2	128.9	127.0	125.5	124.2	50
0.95000	185.2	160.0	149.0	142.4	138.0	134.7	132.1	130.1	128.4	127.0	125.7	124.6	122.8	121.4	120.2	119.2	20
0.90000	163.4	145.2	137.1	132.3	129.0	126.5	124.6	123.0	121.8	120.7	119.8	118.9	117.6	116.5	115.6	114.8	10
0.80000	138.7	128.2	123.3	120.4	118.4	116.9	115.7	114.7	113.9	113.3	112.7	112.2	111.3	110.6	110.0	109.5	5
0.50000	96.1	97.9	98.6	98.9	99.1	99.3	99.4	99.5	99.5	99.6	99.6	99.6	99.7	99.7	99.7	99.8	2
0.20000	59.0	70.6	75.8	79.0	81.1	82.7	83.9	84.9	85.8	86.5	87.1	87.6	88.5	89.2	89.8	90.3	5
0.10000	41.6	57.4	64.7	69.1	72.2	74.4	76.2	77.7	78.9	79.9	80.8	81.5	82.8	83.9	84.8	85.5	10
0.05000	28.4	47.0	55.8	61.2	65.0	67.8	70.0	71.8	73.3	74.6	75.7	76.6	78.3	79.6	80.7	81.6	20
0.02000	16.4	35.8	46.2	52.7	57.1	60.5	63.2	65.3	67.1	68.7	70.0	71.2	73.2	74.8	76.1	77.3	50
0.01000	10.7	28.8	40.0	47.1	52.1	55.8	58.7	61.1	63.1	64.8	66.3	67.6	69.9	71.6	73.1	74.4	100
0.00500	6.9	23.0	34.5	42.1	47.4	51.5	54.7	57.4	59.5	61.4	63.0	64.4	66.8	68.8	70.4	71.8	200
0.00200	3.9	17.0	28.1	36.3	42.0	46.4	50.0	52.9	55.2	57.3	59.0	60.6	63.2	65.4	67.2	68.8	500
0.00100	2.5	13.5	24.0	32.2	38.3	43.0	46.7	49.7	52.2	54.4	56.3	57.9	60.8	63.1	65.0	66.6	1000
CV	0.481	0.345	0.284	0.247	0.222	0.204	0.189	0.177	0.168	0.159	0.152	0.146	0.136	0.127	0.120	0.114	
SKEW	0.506	0.363	0.299	0.260	0.234	0.214	0.199	0.187	0.176	0.168	0.160	0.154	0.143	0.134	0.126	0.120	

QUANTILE	22	24	27	30	33	36	42	48	54	60	72	84	96	108	120	RETURN PERIOD
0.99900	135.6	134.0	132.1	130.4	129.0	127.8	125.7	124.1	122.7	121.5	119.7	118.2	117.1	116.1	115.3	1000
0.99800	133.0	131.6	129.7	128.2	126.9	125.8	123.9	122.3	121.1	120.0	118.3	116.9	115.9	115.0	114.2	500
0.99500	129.3	128.1	126.5	125.1	123.9	122.9	121.2	119.9	118.8	117.8	116.3	115.1	114.2	113.4	112.7	200
0.99000	126.3	125.2	123.8	122.6	121.5	120.6	119.1	117.9	116.9	116.1	114.7	113.6	112.8	112.0	111.4	100
0.98000	123.1	122.1	120.9	119.8	118.9	118.1	116.8	115.7	114.9	114.1	112.9	112.0	111.2	110.6	110.1	50
0.95000	118.3	117.5	116.6	115.7	115.0	114.4	113.3	112.5	111.8	111.2	110.3	109.5	108.9	108.4	108.0	20
0.90000	114.1	113.5	112.8	112.2	111.6	111.1	110.3	109.7	109.2	108.7	108.0	107.4	106.9	106.5	106.2	10
0.80000	109.1	108.7	108.3	107.9	107.5	107.2	106.7	106.3	105.9	105.7	105.2	104.8	104.5	104.3	104.1	5
0.50000	99.8	99.8	99.8	99.8	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9	99.9	100.0	100.0	2
0.20000	90.8	91.1	91.6	92.0	92.4	92.7	93.2	93.7	94.0	94.3	94.8	95.2	95.5	95.7	95.9	5
0.10000	86.2	86.7	87.4	88.0	88.6	89.0	89.8	90.4	91.0	91.4	92.1	92.7	93.1	93.5	93.8	10
0.05000	82.4	83.1	84.0	84.8	85.5	86.0	87.0	87.8	88.5	89.0	89.9	90.7	91.2	91.7	92.1	20
0.02000	78.3	79.1	80.2	81.2	82.0	82.7	83.9	84.9	85.7	86.4	87.5	88.4	89.1	89.7	90.2	50
0.01000	75.5	76.5	77.7	78.8	79.7	80.5	81.9	83.0	83.9	84.7	85.9	86.9	87.7	88.4	88.9	100
0.00500	73.0	74.1	75.5	76.6	77.6	78.5	80.0	81.2	82.2	83.1	84.5	85.5	86.4	87.1	87.8	200
0.00200	70.1	71.3	72.8	74.0	75.1	76.1	77.8	79.1	80.2	81.2	82.7	83.9	84.9	85.7	86.4	500
0.00100	68.0	69.2	70.9	72.2	73.4	74.5	76.2	77.6	78.8	79.8	81.5	82.8	83.8	84.7	85.4	1000
CV	0.109	0.105	0.099	0.094	0.090	0.086	0.080	0.075	0.071	0.067	0.062	0.057	0.054	0.051	0.048	
SKEW	0.115	0.110	0.104	0.099	0.095	0.091	0.084	0.079	0.075	0.071	0.065	0.060	0.057	0.054	0.051	