Institute of Hydrology

ODA

REGIONAL FLOOD ESTIMATION METHODS FOR DEVELOPING COUNTRIES

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Report to the Overseas Development Administration, prepared as part of the project "Extension to the World Flood Study"

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List of symbols, abbreviations and acronyms

a	constant in a rating equation
AAR	catchment average annual rainfall (mm)
APBAR	mean annual maximum catchment 1-day rainfall (mm)
AREA	catchment area (km^2)
b	exponent in a rating equation
BRS	Bureau of Research and Standards (Philippines)
DWA	Department of Water Affairs (Namibia)
f.s.e.e.	factorial standard error of the estimate (from a regression equation)
F_i	probability of non-exceedance of the value in a series which has rank = i
GEV	general extreme value (distribution)
h	river stage (m)
h_o	river stage which corresponds to zero flow
i	rank of an item in a series of ranked data
k	the curvature parameter of the GEV distribution
log	logarithm to the base 10
ln	logarithm to the base e
LAKE	the proportion of the catchment area which is upstream of lakes or reservoirs (if the total surface area of lakes is less than 1% of the catchment controlled, LAKE = 0)
M	number of flood peaks exceeding threshold in a peaks-over-threshold series
MAF	mean annual flood, the mean of a series of annual maximum flood peaks (m^3/s)
MAF_1	mean annual flood for data up to 1980 (m^3/s)
MAF_2	mean annual flood for data after 1980 (m^3/s)
MWRD	Ministry of Water Resources and Development (Zimbabwe)
N	number of values in a series
N	number of complete years of flow data
NIA	National Irrigation Administration (Philippines)
NPC	National Power Corporation (Philippines)
p	probability
P	probability that a flood is equalled or exceeded in a defined period
PADDY	percentage of catchment under wet rice cultivation
PAGASA	Philippine Atmospheric, Geophysical and Astronomical Services Administration
PWM	probability weighted moments (method of fitting a flood frequency distribution)
q	standardised flood peak (Q/MAF)
q_T	standardised flood peak having return period T
Q	river flow (m^3/s)
Q	instantaneous flood peak (m^3/s)
Q_d	maximum daily flow for a particular year (m^3/s)
Q_i	flood peak in a peaks-over-threshold series (m^3/s)
Q_{med}	median of a series of annual maximum flood peaks (m^3/s)
Q_p	instantaneous flood peak for a particular year (m^3/s)
Q_t	threshold flow used to define a peaks-over-threshold series (m^3/s)

Q_T	flood peak having return period T (m^3/s)
r^2	coefficient of determination of a regression equation
SLOPE	the slope from the catchment outlet to the highest point above the end of the longest stream in the catchment (m/km)
STMFRQ	the number of stream junctions (as shown on a 1:50,000 scale map) divided by the catchment area (junctions/km^2)
S1085	the slope of the longest stream in the catchment between the 10% and 85% points (m/km)
T	return period of a flood event (years)
u	the intercept parameter of the GEV distribution
y	reduced variate used in flood frequency analysis
α	the scale parameter of the GEV distribution
β	mean exceedance of a peaks-over-threshold series (m^3/s)
λ	average number of exceedances per year in a peaks-over-threshold series

Summary

This report presents flood estimation methods for a number of developing countries (the countries and regions covered are indicated in Figure 3). The approach used is regional frequency analysis which combines data from many flow gauging stations within a region treated as reasonably homogeneous in its flood response.

Regional flood estimation methods allow estimation of flood peaks for return periods of up to about 500 or 1000 years at sites throughout the regions studied. They are suitable for use in a wide variety of smaller projects and for preliminary analysis of major projects. The methods can be used to produce flood estimates at several sites very rapidly, and they have the particular advantage that estimates can be easily made at sites which have no observed river flow data. As this is the case in most locations, this constitutes the major advantage of the approach. Where local flow data are available at the site of interest, these can be incorporated into the procedure.

As part of the study, new flood estimation methods have been developed for four countries: the Philippines, Sri Lanka, Namibia and Zimbabwe. In addition to this, methods which have been developed previously are summarised. In some cases the previous studies only provided one part of the solution, and these have been completed and updated. Thus the report provides, in a uniform format, a compilation of flood estimation methods for a total of 17 regions or countries.

A brief "Manual of regional flood estimation procedures" is included to help readers apply the methods presented here to particular flood estimation problems in the areas covered. And, to facilitate the development of further regional flood estimation methods for regions not covered by the report, a software package has been developed as part of the study. The software, called FLOODS, which provides a user-friendly means to store the data and develop regional flood frequency curves, is explained in a separate operation manual.

1. Introduction

1.1 Introduction to flood estimation

1.1.1 Flood statistics, return period and probability

For any flood estimation problem it is necessary to specify the return period, or probability, of the flood being considered. The return period used will vary according to the nature of the project and the consequences of the design flood being exceeded. In practice it is often useful to construct a curve relating the size of the flood to its probability of occurrence. Such a curve, called a flood frequency curve, enables flood magnitudes corresponding to various design criteria to be estimated and the implementation costs and implications of failure of such criteria to be appraised. Figure 1 shows such a curve. The probability scale gives an exceedance probability (*ie*. the probability of a flood level being exceeded in any one year); the scale beneath this shows return period (the average interval between years which contain floods exceeding this level). Return period, T, is the reciprocal of the exceedance probability and can give a more tangible appreciation of the severity of the flood.

If a very long flow record exists for a point on a river it is possible to construct a flood frequency curve from an examination of the record. Figure 2(a) illustrates one approach to this; the record is divided into hydrological years (to ensure independence of the flood peaks) and the largest flood in each year is noted. By ranking the floods and assuming a particular form for their distribution each can be assigned an exceedance probability and so a flood frequency curve can be constructed. It is interesting to note some of the properties of this annual maximum flood series. It might be expected that the mean of the annual maxima would be exceeded by approximately half the floods, and so have an exceedance probability of 0.5 and a return period of two years. However, since it is possible to have floods very much bigger than the mean but there is a limit to how much smaller they can be, the distribution of floods is skewed, and the mean annual flood has an exceedance probability of less than 0.5 and a return period of more than 2 years. Rather than looking at the exceedance probability, it is often more useful to work in terms of the non-exceedance probability, or the probability of a flood not being exceeded in any one year. This leads to an easy estimation of the risk of failure during the projected life of a scheme (see Section 4.4.1).

When considering only the largest flood in each year, the return period is not the average interval between floods of a given magnitude, but the average interval between years containing floods of that size or greater. In Figure 2(a) it can be seen that the largest flood in some years is exceeded by the second or third largest flood in others; an alternative approach to flood frequency analysis that avoids this problem considers all the floods over a certain limiting size, not just the biggest in each year. Such a flood sequence is called a partial duration, or peaks-over-threshold, series. In Figure 2(b) all years containing floods over a certain size have been marked and in Figure 2(c) all floods over that same size are indicated. Immediately it can be seen that the average interval between floods is less than the average interval between years with floods. The return period of the mean annual flood

A flood frequency curve

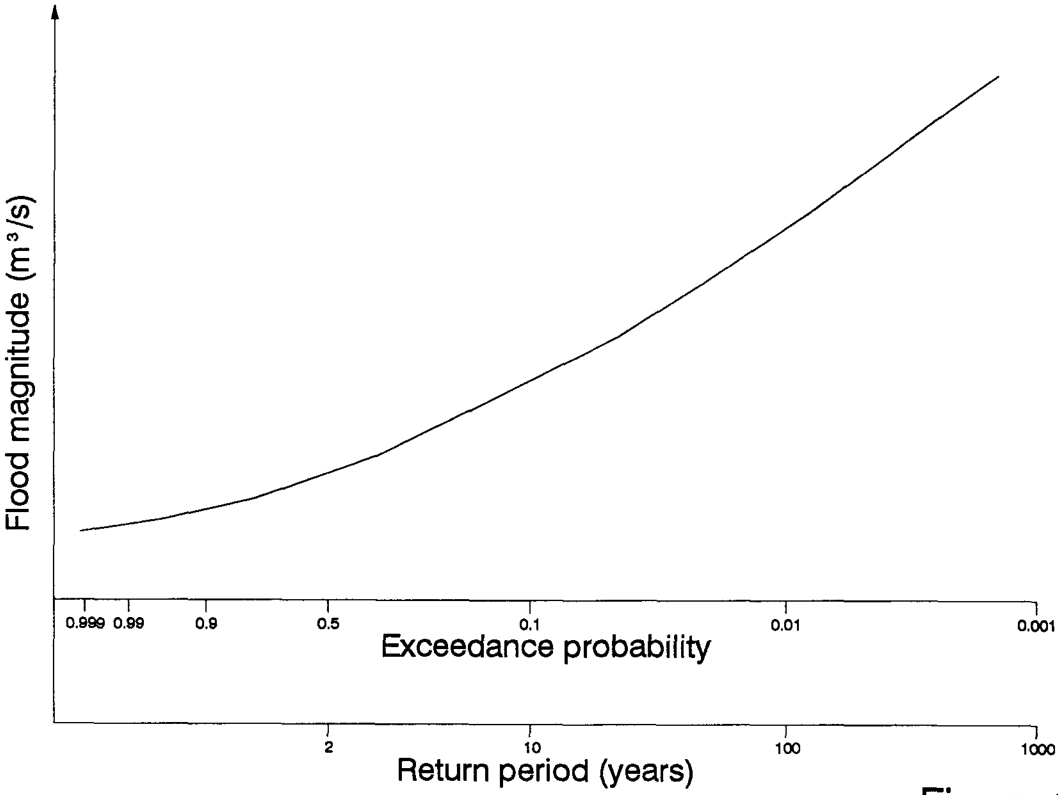


Figure 1

Identification of floods and their associated return periods

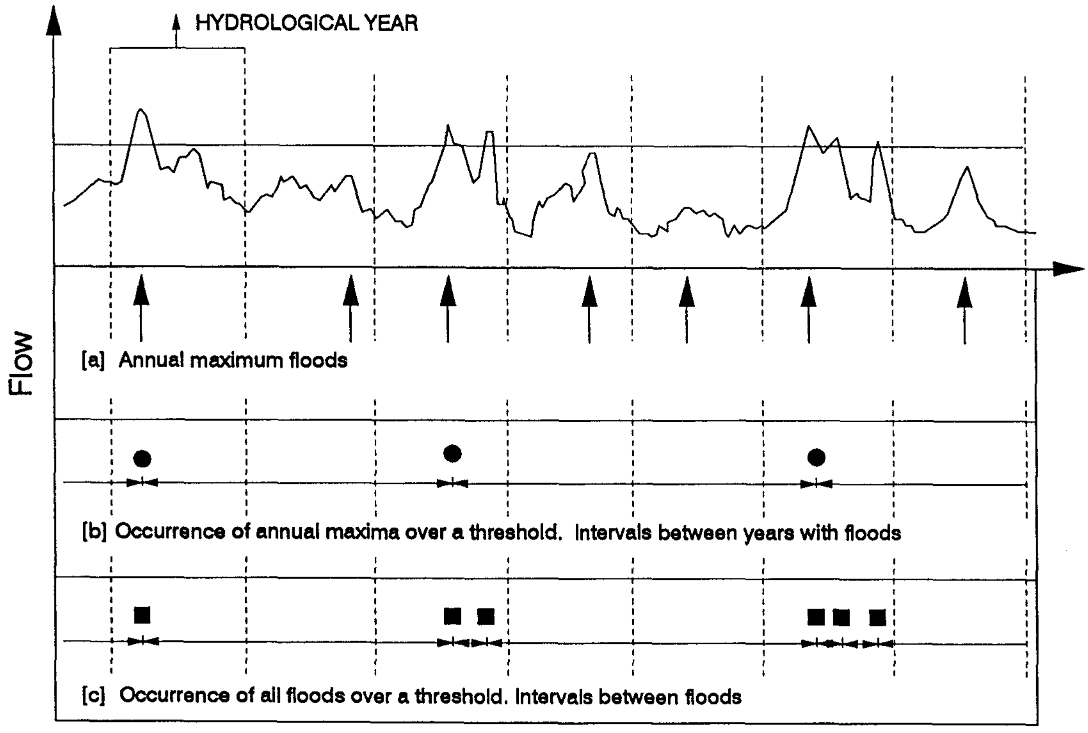


Figure 2

estimated from the annual maximum series is typically about half a year greater than from the partial duration series, but this difference decreases as return period increases, becoming insignificant for return periods of more than about 10 years. Although the partial duration series approach is the more fundamental one, the negligible difference at large return periods and the easy application of the annual maximum method makes it the more popular choice for flood frequency studies.

1.1.2 Flood estimation methods

When a long flow record is available, estimation of the flood of a specified return period is a straightforward task as outlined above. However, it is usually the case that no data or only a limited period of data is available, and it is not possible to construct a flood frequency curve or it is difficult to extend it to the required return period. There are three broad classes of method that can be used in such circumstances: empirical methods, rainfall-runoff methods and statistical methods.

The empirical methods are usually simple formulae relating flood magnitudes to physiographic properties of the drainage area. They are often based on a straightforward conceptualisation of the rainfall-runoff process and calibrated on a specific data set. The growth of flood magnitudes with return period is achieved through the use of rainfall frequency relationships which are generally more widely available than flood frequency curves. Because of their generality and in the absence of anything better they have been adopted and used very widely, but unfortunately they do not take account of local conditions and are often not really suitable for the situations in which they are used. Examples include the Rational method (see standard textbooks such as Wilson, 1990), and the Creager and Francou-Rodier equations (Creager *et al.*, 1947; Francou and Rodier, 1967).

Rainfall-runoff methods also require rainfall frequency relationships, often over a variety of durations. The rainfall input is routed through a rainfall-runoff model to give the design flood. The methods have the advantage that they provide the complete design hydrograph rather than just the flood peak. However, good quality flow and short period rainfall data are needed to calibrate the model for a gauged site, and extension of the approach to provide a method which can be used to estimate floods at ungauged sites represents a large-scale undertaking for each region being studied.

Statistical methods are based on the regional generalisation of statistical properties of flood distributions. Typically the methods involve the estimation of an index flood and the scaling of this by a factor dependent on return period to give the design flood or T-year flood, where T is the required return period. This method has been adopted for use in the studies presented in this report as it makes the best use of the available data, provides for easy incorporation of local data in application and, above all, provides the best approach to allow rapid estimation at ungauged sites.

The index flood chosen was the mean annual flood (the mean of the annual maximum flood series) as this can easily be estimated at a large number of sites from existing records available in most countries. In applying the methods, the mean annual flood can be estimated from the observed data at sites where long records are available. Where only short records are available the partial duration or peaks-over-threshold series can be used. Where the records are extremely short or, as is very often the case, there are no observed data at all, the mean annual flood can be estimated from the equations relating it to catchment characteristics, which have been developed as part of the studies.

As described above, where a very long record is available at the site of interest, the flood frequency curve can be constructed from the record itself. However, when a flood estimate is required for a return period considerably longer than the record length or when there are no observed data at the site, the regional flood frequency curves presented in the report can be used to estimate the flood peak for the required return period.

1.2 Aims and contents of this report

This report presents flood estimation methods for a number of developing countries (the countries and regions covered are indicated in Figure 3). The approach used is regional frequency analysis which combines data from many flow gauging stations within a region treated as reasonably homogeneous in its flood response. This approach provides a method which allows rapid estimation of instantaneous flood peaks for a range of return periods at sites throughout the regions studied. The method consists of two parts: an equation to estimate an index flood for the site, and a regional flood frequency curve which relates the flood peak corresponding to the required return period to this index flood. The index flood used is the mean annual flood, or MAF, which, at a gauged site, is the mean of the series of the maximum flood peaks occurring in each year of record. In the first part of the method, the MAF prediction equation is used to estimate the MAF at the site of interest, based on the catchment area and, in some cases, a number of other physical or climatic characteristics of the catchment. This approach allows the MAF to be estimated at ungauged sites, or at those with very short or unreliable records. Where the site of interest has a reliable flow record, it is preferable to use this to estimate the MAF; and observed data can also be used to improve the MAF estimate when the gauged site is near to, but not actually at, the site of interest. Having estimated the MAF, it is straightforward to apply the appropriate regional flood frequency curve to obtain the flood peak corresponding to a return period suitable to the problem under investigation.

This approach to flood estimation has a number of limitations. Being based on a general method covering large regions, the estimates can only be treated as preliminary. For major projects, particularly large dams where failure could have catastrophic consequences, the estimates should always be supplemented by detailed studies of the particular catchments using a variety of other approaches. The methods are also not suitable for use on heavily urbanised catchments. Again, depending on the amount of data used in developing the method for a particular region, the regional approach is limited in the rarity of the event which it can reasonably be used to predict. For most of the regions studied, a maximum return period in the range of about 500 to 1000 years would be reasonable. While this is much more than can be achieved from the analysis of the observed record at a single site, it is insufficient for estimates at very long return periods (of say 10,000 years) and for probable maximum flood estimates needed for the design of major dams. The method is also limited in that it provides estimates of the flood peak only, and the complete flood hydrograph is not determined. While these limitations mean that the regional approach must

Countries and regions studied

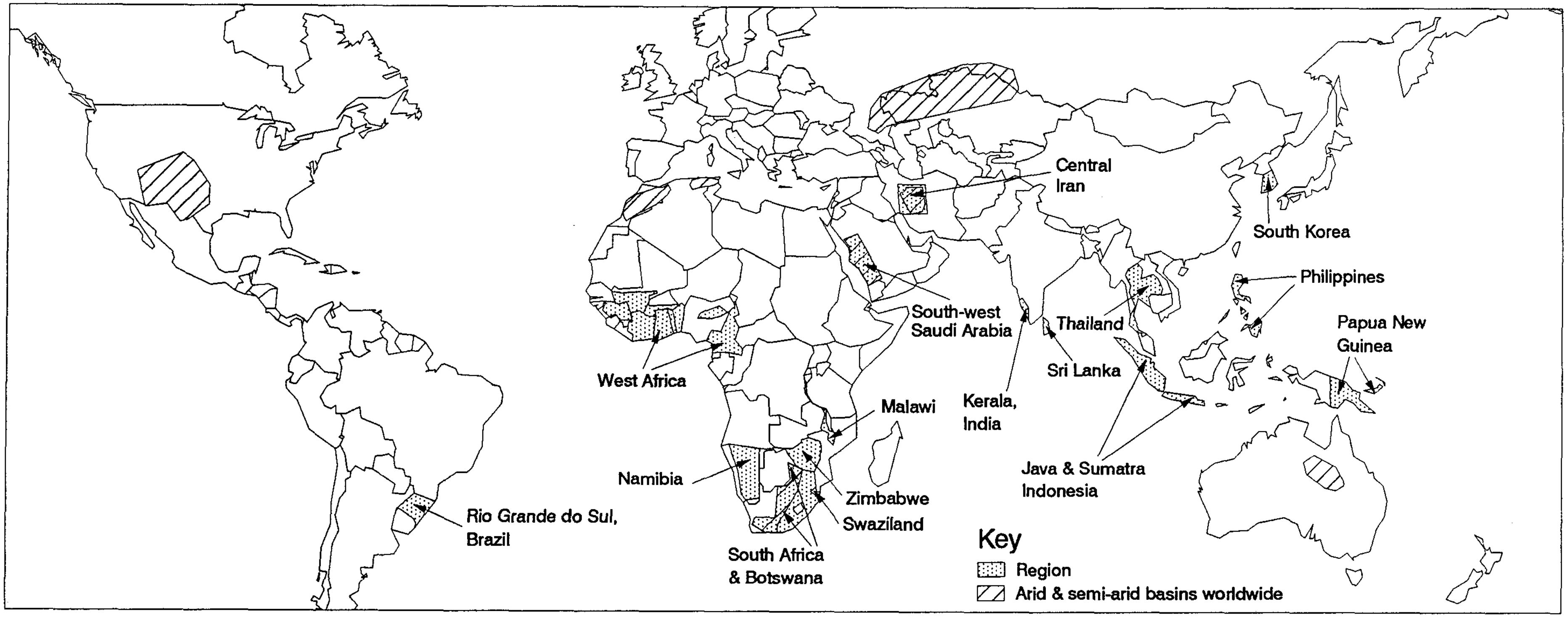


Figure 3

be supplemented by more detailed studies for the detailed design of large projects, it has the great advantage that rapid preliminary flood assessments can be carried out at a large number of sites. In particular, it has the advantage that estimates can be easily made at sites which have no observed river flow data; and, as this is, of course, the case in most locations, this constitutes the major advantage of the approach. In addition, even where data are available at the site of interest, the use of the regional flood frequency curve, by incorporating data from a large number of stations, increases the reliability of the estimates at long return periods.

This report presents the results of many years' work in flood estimation studies. In particular, it is a follow up to the work presented in the World Flood Study report (Meigh and Farquharson, 1985; also summarised by Farquharson *et al.*, 1987). That report was itself an extension and adaption of the methods used in the UK Flood Studies Report (NERC, 1975), and it incorporated experience gained in applying the regional approach in a wide range of countries. The World Flood Study report presented regional flood frequency curves for many countries, but it was incomplete in that it did not provide any MAF prediction equations. Thus, by itself, it was not sufficient to make flood estimates in the regions studied, and additional work was always required. The present study makes good this omission, and also extends the work to other countries in the developing world. Coverage of developing countries has been considerably increased, but the results from Australia, Japan and countries in North America and Europe, which were included in the World Flood Study, have been omitted. Adequate flood design methods are generally already available in these areas, and the main focus of the present study was on developing countries. In addition some results from developing countries where the coverage of data was insufficient to provide an adequate flood estimation method have also been omitted. Overall, the total number of flow gauging stations used has increased from 1121 in the World Flood Study to about 1700 now. The study draws on a variety of other projects which have been carried out in recent years as well as presenting work which has been specially carried out as part of the study. It also includes results which have already been published elsewhere (for example, Farquharson *et al.*, 1992 and 1993); this has been done so that as many results as possible can be presented in one place in a uniform format.

The remainder of the report is as follows: Chapter 2 describes the general methodology used in developing the flood estimation methods for each country or region, and Chapter 3 provides a summary of the results, and a comparison between the different countries. More detailed discussion of how the method was derived for each country is provided in Appendices A to E, and limitations of, or shortcomings in, the methods presented are also discussed there.

In Chapter 4, a brief "Manual of regional flood estimation procedures" is provided to help readers apply the methods presented here to particular flood estimation problems in the areas covered. For other regions not covered by the study, it would be possible to develop additional methods using the approaches discussed in this report. This would require the assembly of considerable amounts of data and a range of quite complex analyses. To assist in such investigations, a software package has been developed as part of the study. The software, called FLOODS, which provides a user-friendly means to store the data and develop regional flood frequency curves, is explained in a separate operation manual.

2. General methodology

2.1 Compilation of flood peak and catchment characteristics data

Two types of data are required for the development of the flood estimation method for a particular region: flood peak data and catchment characteristics data. The flood peak data consist of the series of instantaneous maximum discharges in each year of record at a number of flow gauging stations (the records used do not necessarily have to be complete; missing years are simply omitted from the analysis). These data were gathered from a wide variety of sources: some were obtained from yearbooks or other publications of the relevant gauging authorities; some were obtained as part of a variety of projects investigating flooding problems; some were collected specially for this project either from yearbooks or from the gauging authority's files; and a few were supplied by the authorities in computer format. Because, in some countries, river flow information is regarded as, in some degree, a security issue, we were not able to obtain data from some regions that it would have been interesting to study, and the coverage is less complete than it might have been for this reason.

There were a number of potential problems with the flood peak data, and efforts were taken to eliminate these as far as possible. One of the problems is data quality. It is extremely difficult to obtain measurements of large flood flows, and most gauging stations are poorly calibrated at the upper end of the flow scale for this reason. Inevitably flood data are not of very high accuracy, but it is important that the stations used should have a moderate level of data quality. In particular, the extrapolation of the rating curve from the measured flows to the flood flows should not be too large. Where data have been taken from published sources it has had to be assumed that they have only been published when their quality is adequate. In other cases, advice has been taken from the gauging authority on which stations are acceptable. Some of the studies reported here have included detailed programs of data checks and field inspection to ensure good data quality, but this was not practicable in most cases, and a lower level of assurance has had to be accepted. In addition to this, some anomalous stations have been identified and removed from the analysis as part of carrying out the MAF regressions (see Section 2.3) or because they were found to have extremely anomalous station flood frequency curves. Generally, it is believed that the great majority of data used achieves a moderate but still adequate level of accuracy.

Another problem can occur in extracting the annual maximum values when data are missing for part of the year. Some authorities list peak values for years in which there are missing data, and for these cases it was necessary to carry out checks to ensure that only true peaks are extracted; *ie.*, that the peak did not occur in the missing period. Generally, when missing data occur, the year was rejected. The exception is in strongly seasonal climates where, if there are missing data only in the dry season when a large flood is extremely unlikely, the peak flood value can still be accepted. Yet another problem relates to the true assessment of instantaneous peak flows. Where stage is monitored with an autographic recorder this is not a problem, but in some cases stage is read by observers a specified number of times per day. This is not a problem on large catchments where flows change relatively slowly, but on small catchments it leads to under-estimation of the instantaneous peak. In these cases a correction to the observed values is needed to obtain estimates of the true peaks, although only crude corrections are usually possible. An example of such a correction is the work done for the Philippines (see Appendix A).

The minimum catchment characteristics data needed are the station locations and catchment areas. These were obtained from the same sources as the flood peak data. In nearly every case, average annual rainfall estimates have also been obtained for each catchment, either from the same data sources, as a special study, or from a variety of published isohyetal maps. Other catchment characteristics have been obtained for the cases where it was possible to do a more detailed study, but not all of these turned out to be useful. Those which have been used in the final equations for at least one region were:

APBAR	the mean annual maximum catchment 1-day rainfall;
LAKE	the proportion of the catchment area which is upstream of lakes or reservoirs;
PADDY	percentage of catchment under wet rice cultivation;
SLOPE	the slope from the catchment outlet to the highest point above the end of the longest stream in the catchment;
STMFRQ	the number of stream junctions per unit area; and
S1085	the slope of the longest stream in the catchment between the 10% and 85% points.

While it is worth investigating these characteristics in a detailed study, it is also notable that their inclusion often provides only a very minor improvement in the results (as can be seen from some of the examples in the next chapter). As the derivation of a satisfactory range of characteristics is extremely time-consuming, it was not practicable to obtain them in most cases. However, because of their relatively small effect, the omission is not of major importance, and most of the methods developed still provide adequate flood estimation tools.

2.2 Selection of regions

Having obtained the flood peak and catchment characteristics data, they are combined in regional groups. The groups used should be hydrologically homogeneous; that is, within a reasonable margin, the hydrological and, particularly, the flood response should be the same. There are no hard and fast rules about how this should be done. A number of studies have been carried out to investigate statistical tests for regional homogeneity. For instance Wiltshire (1986a) has produced a straightforward test, and he has successfully derived homogeneous clusters of basins in Britain where the clusters are defined by catchment characteristics rather than geographically (Wiltshire, 1986b). However the test is more powerful when the region contains sites with long records, and in an examination of the approach for stations in Indonesia, Hall (1992) could not find any homogeneous regions. The same problem with this test was also revealed by tests carried out in the earlier World Flood Study work where we were unable to define any useful regions which were homogeneous according to the test (Meigh and Farquharson, 1985). Another approach to testing homogeneity, using L-moments, has been proposed by Hosking and Wallis (1991). Rao and Hamed (1994) used this approach to examine a small part of the Cauvery basin in India, but they found the basin to be hydrologically heterogeneous. This result again indicates the difficulty of applying statistical tests to determine regional homogeneity in practical situations.

Our feeling is that the difficulty of finding homogeneous regions using statistical tests is largely a result of the inherent variability of the flooding process and of the available data: short records and the inevitable low accuracy of flood data mean than the stations can appear heterogeneous even when it is, in fact, reasonable to treat the region as homogeneous. It must be remembered that the aim of developing the flood estimation methods is to produce practical solutions which provide flood estimation tools at ungauged sites. It is not easy to do this other than by regional methods, and therefore it is necessary to turn to a more empirical approach to determine the regions to be used. This approach depends on experience and judgement of the hydrologist carrying out the investigation. In our studies, the determination of the homogeneity, or otherwise, of the region was carried out by first examining the physical and climatic characteristics of the area, and second, by comparison of the flood frequency curves for the individual sites. The approach is described by Meigh *et al.* (1993). Briefly, the topography, average annual rainfall and climate type were examined to check the range of hydrological behaviour expected over the region. Where other information, such as maps of geology, soils, land use or vegetation, were available these provided additional clues. After this initial examination, the individual station curves were compared to find groups of broadly similar behaviour, allowing for natural variability and outliers in the data. Judgement must be used to decide how much variation from the general pattern is permissible. As discussed further in Section 2.4, a geographical area was often treated as a homogeneous region, but several flood frequency curves were produced for it, defined according to the catchment characteristics. Most commonly bands of catchment area were defined, and the ability to do this is another factor which must be considered when selecting the regions to be used.

2.3 Derivation of mean annual flood estimation method

The approach to deriving the mean annual flood estimation method, or MAF prediction equation, was to carry out a multiple regression analysis of MAF on the catchment characteristics. Because of the wide range of the variables (for instance, within a region, catchment area can range from less than 1 km^2 to more than 100,000 km^2) this is only practicable in the log domain.

The mean annual flood is first calculated for each observed flow record as the mean of the series of annual peak flows at the site. In a few cases where records are very short, MAFs have also been estimated using the peaks-over-threshold method (see Chapter 4 for a discussion of this). In the UK flood study (NERC, 1975) a test was carried out to check for outliers in the series. Outliers were defined as the maximum flood being greater than three times the median of the series, Q_{med}; and when this occurred, the estimate of MAF was taken as 1.07 Q_{med} rather than the simple mean of the data, as this reduces bias in the estimation of MAF. This type of approach has not been used here because a different multiplier would be required for each region as the variability of floods is very much greater in some regions than others, and in arid regions where variability is extremely high, the definition of outliers would hardly be practicable.

The regression analyses were first carried out using catchment area as the only independent variable, then the others were introduced one at a time. The statistical significance of the exponents were tested (at the 5% significance level) to determine the validity of each new variable, and the overall quality of the fit of the regression was examined. The two measures of fit were the coefficient of determination, r^2, which expresses the proportion of the variance of the MAF which is explained by the regression, and the factorial standard error of the estimate, f.s.e.e.. This expresses the likely deviation of the estimates from the 'true' values; for example, an f.s.e.e. of 1.5 indicates that the 'true' MAF is likely (68% probability) to fall within +50% to -33% of the estimate given by the equation. Thus, the aim of the analysis was to maximise r^2 and to minimise f.s.e.e.. Plots of MAF versus catchment area were also used to give a visual indication of the quality of the regression, although they could not be used when additional variables were included. Plots served to identify possible anomalous stations; those that fell very far from the general trend of the data were investigated to see if there were erroneous data or other anomalies which indicated that the stations should not be included in the analysis.

Another important point in developing the MAF prediction equations was to make sure that the exponents of the catchment characteristics were hydrologically realistic. This can best be explained by example. For instance, it might have been found that when average annual rainfall (AAR) was included, the regression was improved, but that the exponent was negative. This would mean that wetter catchments have smaller floods, but this goes against experience and physical sense, and is likely to indicate that the improved regression is spurious, or that the AAR values are poorly estimated, or that AAR is linked to some other variable which has not been explicitly included. In any case, AAR should not be used for MAF prediction in this example as the equation including it does not make good physical sense.

Further investigation of the MAF prediction equation was carried out in some cases, especially when the approach outlined above gave rather poor or unrealistic results, by dividing the stations into a number of groups and searching for relationships between MAF and the other variables within the groups. Normally, dividing into groups according to catchment area or average annual rainfall would not be used as the variation in MAF explained by these factors will already have been taken into account by their inclusion as independent variables in the regression. However, division into groups on a geographical basis was sometimes found to be useful, giving improved relationships or providing prediction equations which are more in line with knowledge about the response of the catchments in different areas, especially where these differences are not adequately represented by catchment characteristics.

2.4 Derivation of regional flood frequency curves

The frequency distribution used was the general extreme value (GEV) distribution, fitted by the method of probability weighted moments (PWM) (Hosking *et al.*, 1985). While there are a range of different frequency distributions that have been used by different workers, our experience is that the GEV is generally applicable over a wide range of catchments and climates. Shortcomings in the data that are available mean that it is generally not worthwhile to investigate a range of distributions for practical flood problems. Hosking *et al.* have shown that fitting with the PWM method produces estimates which are less variable and less biased than conventional moment or maximum likelihood estimators. Our own experience with real-world data supports this, with the PWM approach appearing to be more robust and less likely to give extreme predictions (Meigh and Farquharson, 1985).

The GEV distribution was fitted to the data for individual sites, and the stations were then grouped into regions. To make the data from individual stations comparable, they were standardised by dividing the annual flood peak values at each station by the MAF for that station. The GEV was then fitted to the pooled data for the region to derive the regional flood frequency curve. In fitting the GEV by PWM, the standardised annual flood peaks, $q_i = Q_i/MAF$, are ranked in ascending order and assigned a probability of non-exceedance, F_i, given by

$$F_i \quad = \quad (i - 0.35) / N \qquad [1]$$

where i is the rank, and N is the number of annual values. Note that, while equation [1] is found to give the least bias in fitting by PWM, this is not the formula used for plotting the data. For plotting the Gringorten formula

$$F_i \quad = \quad (i - 0.44) / (N + 0.12) \qquad [2]$$

is appropriate. Returning to equation [1], the reduced variate, y_i, is calculated as

$$y_i \quad = \quad -\ln (-\ln F_i) \qquad [3]$$

The pooled data within a region are fitted by the GEV distribution which has the form

$$F(q) \quad = \quad \exp \{ - [1 - k(q-u)/\alpha]^{1/k} \} \qquad [4]$$

when $k \neq 0$, or if $k = 0$, this reduces to

$$F(q) \quad = \quad \exp \{ - \exp [- (q-u)/\alpha] \} \qquad [5]$$

where q is the standardised flood peak, and u, α and k are the parameters of the distribution. These three parameters may be interpreted as

u = the intercept of the fitted curve,
α = a scale parameter, and
k = the curvature.

Introducing the reduced variate, y, q is calculated as

$$q \quad = \quad u + \alpha (1-e^{-ky}) / k \qquad \text{for } k \neq 0, \text{ or} \qquad [6]$$

$$q \quad = \quad u + \alpha y \qquad \text{for } k = 0. \qquad [7]$$

The foregoing assumes that the stations which have been pooled can reasonably be treated as a homogeneous region. Comparison of the individual curves is carried out to check that this is so, although the amount of variation between curves that is accepted is a rather subjective decision (as discussed in Section 2.2 above). It was often found that there was wide variation between individual curves, but that this could be largely explained by the catchment characteristics. The most common case was that stations could be grouped into bands defined by their catchment areas. Within a fairly narrow band of catchment area there tended to be acceptable variation between the individual stations, and the regional curves for small catchments tended to be steeper than those for large ones. This makes hydrological sense as there is a smaller probability of an extreme rainfall occurring uniformly over a large area, so that large catchments tend to have a less extreme response than small ones. Other catchment characteristics or geographical sub-regions were also sometimes found to give satisfactory groupings of stations. This procedure was continued by trial-and-error to find groups in which the variation between stations was not excessive so that the stations within each group could all be reasonably represented by a single regional curve. At the same time, the groups chosen must make good physical sense. The division into smaller groups is, of course, limited by the need to retain an adequate amount of data in each group. The final result was to produce either a single curve for the region, or a set of curves which are defined by one or more of the catchment characteristics or by geographical sub-regions.

3. Summary of results

3.1 Results

The detailed methods and results of the study are provided in Appendices A to E. In the current project, detailed studies were carried out for the Philippines, Sri Lanka, Namibia and Zimbabwe, and these are discussed in the first four appendices. For 13 other countries or regions less detailed studies have been done or the results have been extracted from other reports or have been previously published elsewhere, and a brief discussion of these is given in Appendix E.

The key results from all the regions studied are summarised here. The results consist of two parts which together make up the flood estimation method for each region: the first part is the mean annual flood (MAF) prediction equation, given in Table 1; and the second is the regional flood frequency curve, given in Table 2.

The MAF prediction equations are the recommended ones in each case. For some regions there is more than one equation; for instance, five equations for five geographical sub-regions are given for West Africa. In some cases, besides the final recommended equation, an additional simpler equation has been included. This has been done when the recommended equation provides only a small improvement compared to the simpler equation, and it would still be adequate to use the simpler equation to make a quick estimate. For each equation, the number of catchments used, the coefficient of determination (r^2) and the factorial standard error of the estimate (f.s.e.e.) have been listed so that the reader can judge the quality of fit to the data and the likely uncertainty of estimates using the equation. The interpretation of the f.s.e.e. is given in Section 2.3. Some of the f.s.e.e. values may seem surprisingly large; however they are mostly typical of the results expected in regional flood studies. As a comparison, the f.s.e.e. of the prediction equation for the United Kingdom, based on data from 532 basins, was 1.49 (NERC, 1975). For further details of the limitations of the method for any particular region, readers should refer to the relevant Appendix.

The regional flood frequency curves in Table 2 are also the recommended ones. For some regions there is only one curve, while for others there are a number of different curves, and the appropriate one to be used for a particular situation depends on the catchment area or on the average annual rainfall of the catchment being studied (or in the case of Thailand on more complex criteria also involving the elevation of the gauging station). For each curve the three parameters of the GEV distribution are given, and, for quick reference, the standardised flood peaks, q_{20}, q_{100} and q_{500}, corresponding to 20, 100 and 500 year return periods respectively, are also included. The number of stations and the total number of years of data are given for each curve so that the reader may judge up to what return period it can reasonably be used. No estimates of the likely errors in the flood frequency curves are given, as these are not easy to quantify. For the UK, it was suggested that the standard errors are of the order of 15% at a return period of 10 years, 30% at T = 100 years and 50% at T = 1000 years (NERC, 1975). However, these results are not necessarily applicable elsewhere.

TABLE 1 *Summary of recommended MAF prediction equations*

Country or grouping	Prediction equation	r^2	f.s.e.e.
Rio Grande do Sul, Brazil			
(59)	$MAF = 8.75 \times 10^{-5}\ AREA^{0.987}\ S1085^{0.419}\ AAR^{1.017}$	0.913	1.49
West Africa			
>8°W (35)	$MAF = 7.86 \times 10^{-9}\ AREA^{0.933}\ AAR^{2.260}$	0.910	1.38
8°W to 2°W (86)	$MAF = 4.22 \times 10^{-12}\ AREA^{0.807}\ AAR^{3.378}$	0.905	1.60
2°W to 4°E (41)	$MAF = 7.34 \times 10^{-7}\ AREA^{0.747}\ AAR^{1.887}$	0.856	1.58
9°E to 16°10'E and >8°N (16)	$MAF = 3.87 \times 10^{-6}\ AREA^{0.335}\ AAR^{2.308}$	0.819	1.54
9°E to 16°10'E and <8°N (46)	$MAF = 2.80 \times 10^{-10}\ AREA^{0.929}\ AAR^{2.652}$	0.943	1.44
Malawi			
(28)	$MAF = 2.89\ AREA^{0.553}\ STMFRQ^{0.360}$	0.381	2.39
Namibia			
(40)	$MAF = 2.63\ AREA^{0.460}$	0.651	1.92
Zimbabwe			
(234)	$MAF = 1.46\ AREA^{0.665}$	0.836	1.87
South Africa & Botswana			
(109)	$MAF = 6.97\ AREA^{0.450}$	0.542	2.19
	$MAF = 0.0964\ AREA^{0.515}\ AAR^{0.587}$	0.593	2.10
Swaziland			
(38)	$MAF = 2.93\ AREA^{0.570}$	0.657	1.76
South-west Saudi Arabia			
(28)	$MAF = 0.0625\ AREA^{0.578}\ AAR^{0.727}$	0.452	2.41
Central Iran			
(24)	$MAF = 4.09 \times 10^{-4}\ AREA^{0.618}\ AAR^{1.362}$	0.694	2.21

.... *continued*

TABLE 1 *Summary of recommended MAF prediction equations (continued)*

Country or grouping	Prediction equation	r^2	f.s.e.e.
Kerala, India (75)	$MAF = 5.14\ AREA^{0.722}$	0.613	2.04
Sri Lanka (69)	$MAF = 0.0285\ AREA^{0.670}\ AAR^{0.688}$	0.790	1.49
South Korea			
Area < 1000 (9)	$MAF = 1.71x10^{-4}\ AREA^{0.680}\ AAR^{1.545}$	0.767	1.59
Area > 1000 (24)	$MAF = 2.50x10^{-3}\ AREA^{0.646}\ AAR^{1.288}\ (1+PADDY)^{-0.186}$	0.830	1.36
Thailand			
Main part (106)	$MAF = 2.56\ AREA^{0.625}$	0.729	1.91
S. Peninsula (16)	$MAF = 1.23\ AREA^{0.841}$	0.818	2.05
Java & Sumatra, Indonesia (110)	$MAF = 8.20x10^{-6}\ AREA^{0.852}\ APBAR^{2.640}$	0.881	1.61
	$MAF = 8.00x10^{-6}\ AREA^{v}\ APBAR^{2.445}\ SLOPE^{0.117}\ (1+LAKE)^{-0.85}$ where $v = 1.02 - 0.0275 \log(AREA)$	0.889	1.59
Philippines			
Regions 1-2 (49)	$MAF = 15.3\ AREA^{0.623}$	0.675	1.92
Regions 3-8 (222)	$MAF = 11.7\ AREA^{0.616}$	0.638	2.10
Regions 9-12 (62)	$MAF = 11.5\ AREA^{0.502}$	0.459	2.61
Papua New Guinea (29)	$MAF = 6.08\ AREA^{0.676}$	0.918	1.58
Arid and semi-arid basins worldwide (162)	$MAF = 1.87\ AREA^{0.578}$	0.55	2.88
	$MAF = 0.172\ AREA^{0.573}\ AAR^{0.416}$	0.57	2.85

(n) (value in brackets) = number of catchments studied

TABLE 2 *Summary of recommended regional flood frequency curves*

Country or grouping	No. stations	No. years	GEV parameters u	α	k	Predicted floods q_{20}	q_{100}	q_{500}
Rio Grande do Sul, Brazil								
	57	1209	0.830	0.348	0.0959	1.73	2.12	2.46
West Africa								
AAR 600-1250	53	1034	0.806	0.424	0.1360	1.84	2.26	2.59
AAR 1250-1500	51	795	0.813	0.390	0.1095	1.80	2.22	2.57
AAR 1500-1750	70	1286	0.881	0.234	0.0756	1.50	1.79	2.04
AAR > 1750	27	487	0.908	0.219	0.1826	1.41	1.59	1.72
Area < 1000	26	304	0.804	0.314	-0.0437	1.80	2.41	3.05
Malawi	28	509	0.655	0.422	-0.1968	2.36	3.81	5.80
Namibia								
AAR < 175	9	100	0.336	0.448	-0.4834	3.30	7.97	18.09
AAR > 175	37	510	0.448	0.513	-0.3391	3.08	6.14	11.39
Zimbabwe								
Area < 100	53	954	0.486	0.516	-0.3018	2.97	5.63	9.93
Area 100-2500	139	2575	0.527	0.541	-0.2332	2.85	4.99	8.09
Area > 2500	42	737	0.562	0.534	-0.1996	2.73	4.59	7.13
South Africa & Botswana								
AAR < 1250	101	3808	0.470	0.430	-0.4039	2.94	6.23	12.50
AAR > 1250	8	233	0.733	0.343	-0.1710	2.06	3.13	4.53
Swaziland	38	756	0.485	0.410	-0.4128	2.87	6.12	12.39
South-west Saudi Arabia								
	30	378	0.427	0.459	-0.4094	3.09	6.67	13.57
Central Iran								
Area < 7500	16	198	0.559	0.376	-0.3806	2.63	5.27	10.10
Area > 7500	9	145	0.636	0.419	-0.2307	2.42	4.07	6.43
Kerala, India	76	1171	0.747	0.370	-0.0991	2.02	2.90	3.92

.... *continued*

TABLE 2 *Summary of recommended regional flood frequency curves (continued)*

Country or grouping	No. stations	No. years	GEV parameters u	α	k	Predicted floods q_{20}	q_{100}	q_{500}
Sri Lanka								
AAR < 2000	17	360	0.525	0.404	-0.3818	2.76	5.59	10.81
AAR 2000-3200	29	699	0.703	0.330	-0.2486	2.15	3.54	5.59
AAR > 3200	23	595	0.773	0.311	-0.1358	1.91	2.76	3.81
South Korea	24	542	0.775	0.373	-0.0256	1.93	2.60	3.29
Thailand*								
Group 1	18	290	0.828	0.310	0.0233	1.72	2.18	2.62
Group 2	13	284	0.919	0.243	0.3128	1.39	1.51	1.58
Group 3	54	942	0.691	0.388	-0.1835	2.22	3.50	5.19
Group 4	24	496	0.780	0.330	-0.0829	1.89	2.63	3.47
S. Peninsula	16	284	0.708	0.352	-0.2050	2.15	3.40	5.13
Java & Sumatra, Indonesia								
Area < 600	47	541	0.812	0.290	-0.0671	1.77	2.37	3.05
Area > 600	48	468	0.866	0.239	0.0175	1.56	1.92	2.27
Philippines								
Area < 25	47	887	0.558	0.450	-0.2941	2.69	4.95	8.54
Area 25-50	37	646	0.603	0.466	-0.2206	2.56	4.32	6.81
Area 50-250	127	2208	0.641	0.457	-0.1752	2.42	3.88	5.79
Area 250-2500	104	1762	0.696	0.422	-0.1276	2.22	3.34	4.70
Area > 2500	18	243	0.768	0.356	-0.0715	1.94	2.70	3.55
Papua New Guinea	50	450	0.818	0.280	-0.0682	1.74	2.33	2.98
Arid and semi-arid basins worldwide								
All stations	162	3637	0.476	0.428	-0.4003	2.92	6.15	12.28

* In Thailand, groups 1-4 are in the main part of the country, while the southern peninsula is treated separately. The groups are defined as follows:

Group 1: Elevation < 100, Area < 15000
Group 2: Elevation < 100, Area > 15000
Group 3: Elevation > 100, Area < 5000
Group 4: Elevation > 100, Area > 5000

3.2 Using the flood estimation methods

The flood estimation methods presented in this report can be used to make estimates of floods for return periods of up to about 500 or 1000 years, or sometimes more, in the regions studied. However, there are a number of limitations to the results that can be obtained. Before attempting to make a flood estimate, readers should refer to Section 1.2 for a discussion of the general limitations of the regional approach and what kind of problems it can reasonably be used to solve. Readers should also refer to the appropriate Appendix for more detail on the data used in developing the method for the particular region to see if there are other limitations which should be observed. An example of the most common limitation would be if the method was developed with catchments in the range 100 to 10,000 km^2 in area. In this case, it would clearly be unwise to apply it to catchments of only 10 km^2 without some additional supporting evidence that this can reasonably be done. The ranges of the catchment characteristics used are summarised in Tables 3 and 4 in Chapter 4.

For further advice on how to apply the flood estimation methods in a variety of situations, readers should refer to Chapter 4 which explains the procedure step-by-step. This includes discussion on how to make use of the local or nearby data that may be available to improve the estimates.

3.3 Discussion

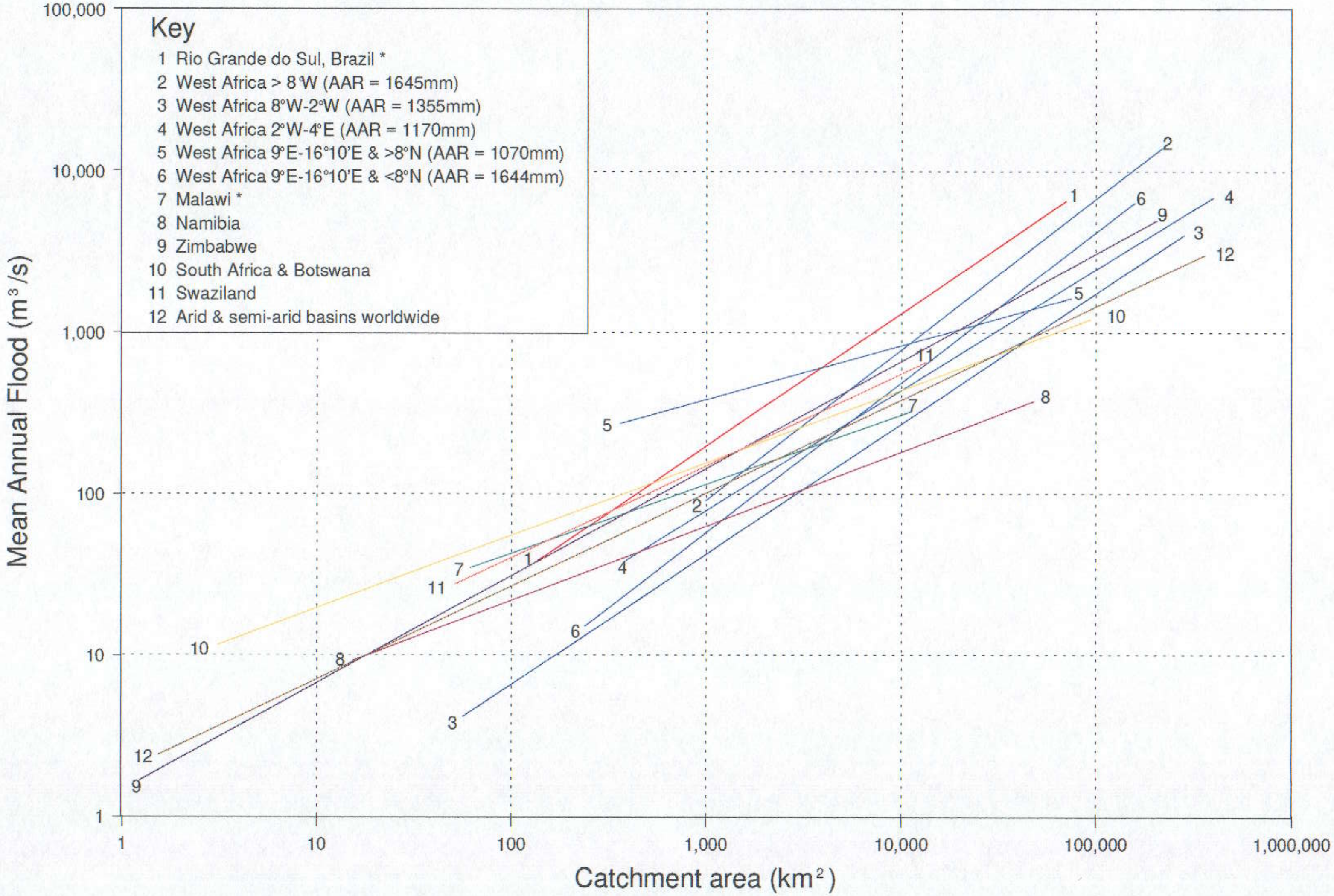
While it is not intended to discuss the results in great depth, a brief comparison of the different countries and regions may be worthwhile. To facilitate this, the MAF prediction equations are compared in Figures 4 and 5, and the regional flood frequency curves are compared in Figures 6 and 7.

The MAF equations are each plotted as a line on a logarithmic graph of mean annual flood against catchment area. This is suitable as catchment area is always the key independent variable, but many of the recommended equations include other variables. To enable them to be plotted, in some cases, the simplified equations given in Table 1 using area only have been plotted. In a few cases, the simplified equations plotted are not given in Table 1 as it is not recommended that they should be used. Where an equation which includes a second variable has been plotted, the second variable has been fixed at the median value for the range of catchments used in the derivation. The values used are noted in the figures. Because of the large number of equations to be compared, they have had to be shown on two separate figures, but the equation for arid and semi-arid basins worldwide is shown on both to provide a point of reference between the two.

In a similar way, the regional flood frequency curves listed in Table 2 are plotted in Figures 6 and 7, and the curve for arid and semi-arid basins worldwide is again shown on both to facilitate comparison.

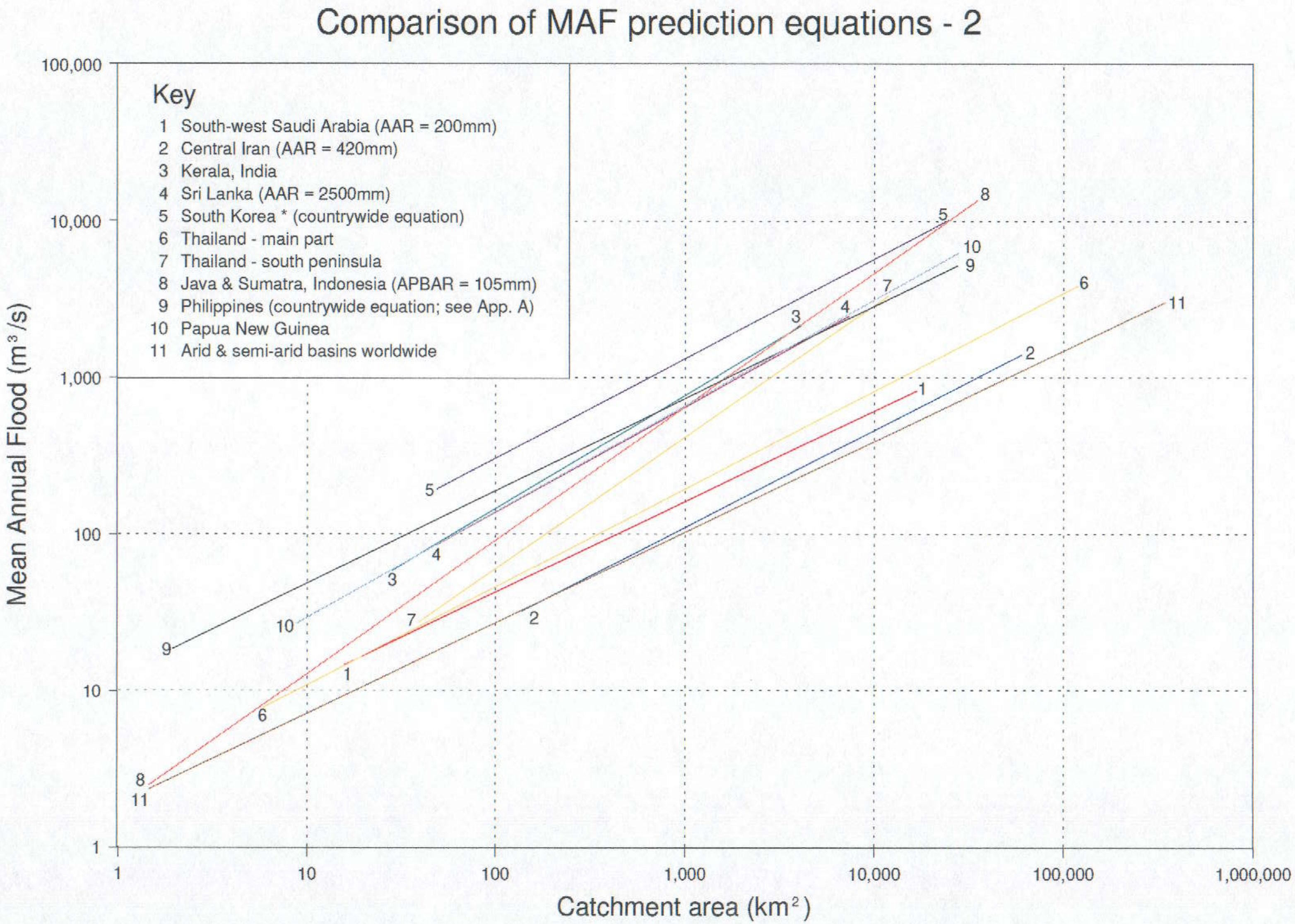
The comparison of the MAF equations is confused by the variation in slope between the different equations, but a considerable number of them do seem to have similar slopes, and about half are close to an exponent of AREA of 0.6; this seems to be a central value, typical

Comparison of MAF prediction equations - 1



* Simplified equation using AREA only plotted, but equation not given in Table 1

Figure 4



* Simplified equation using AREA only plotted, but equation not given in Table 1

Figure 5

Comparison of regional flood frequency curves - 1

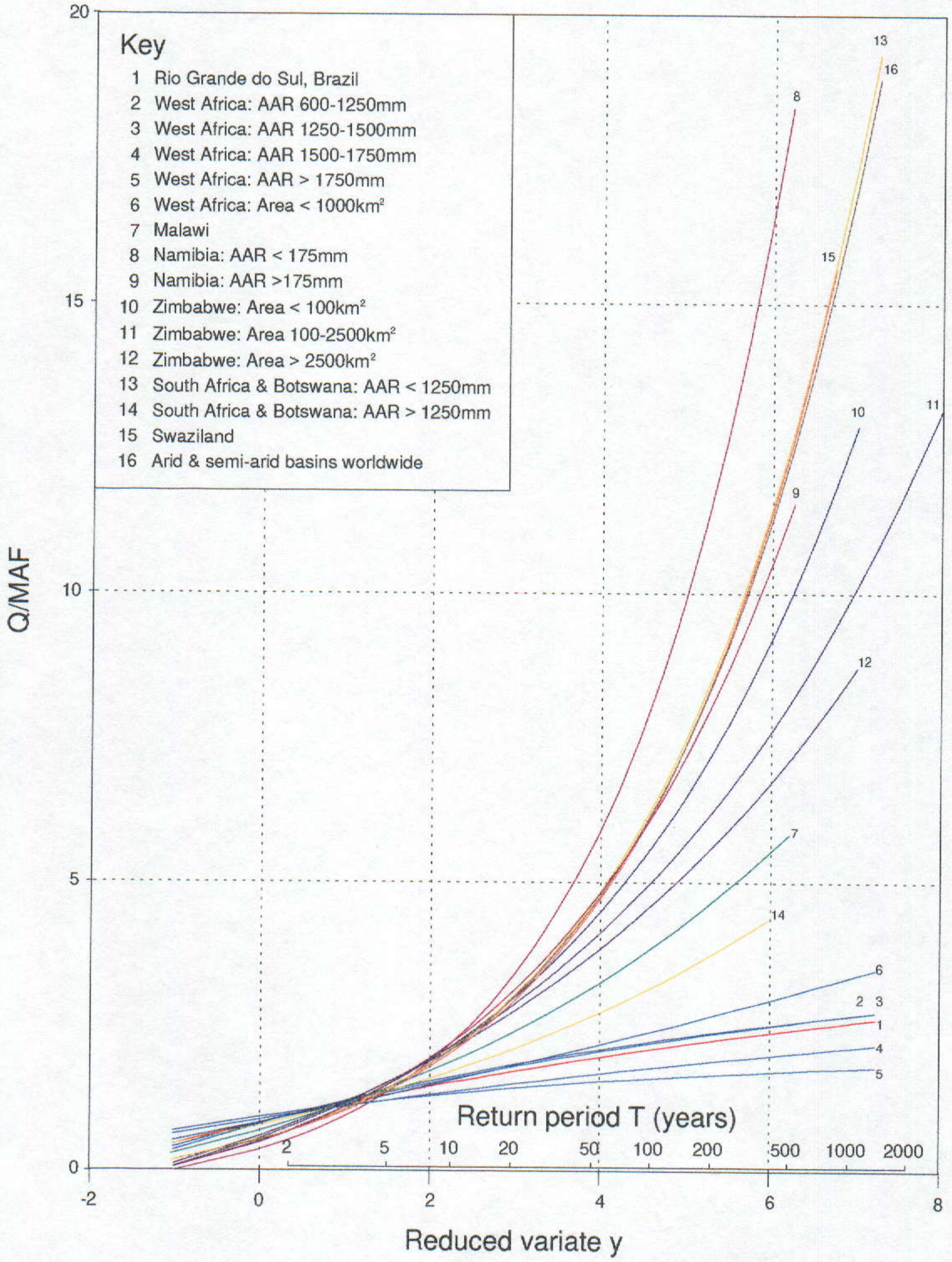


Figure 6

Comparison of regional flood frequency curves - 2

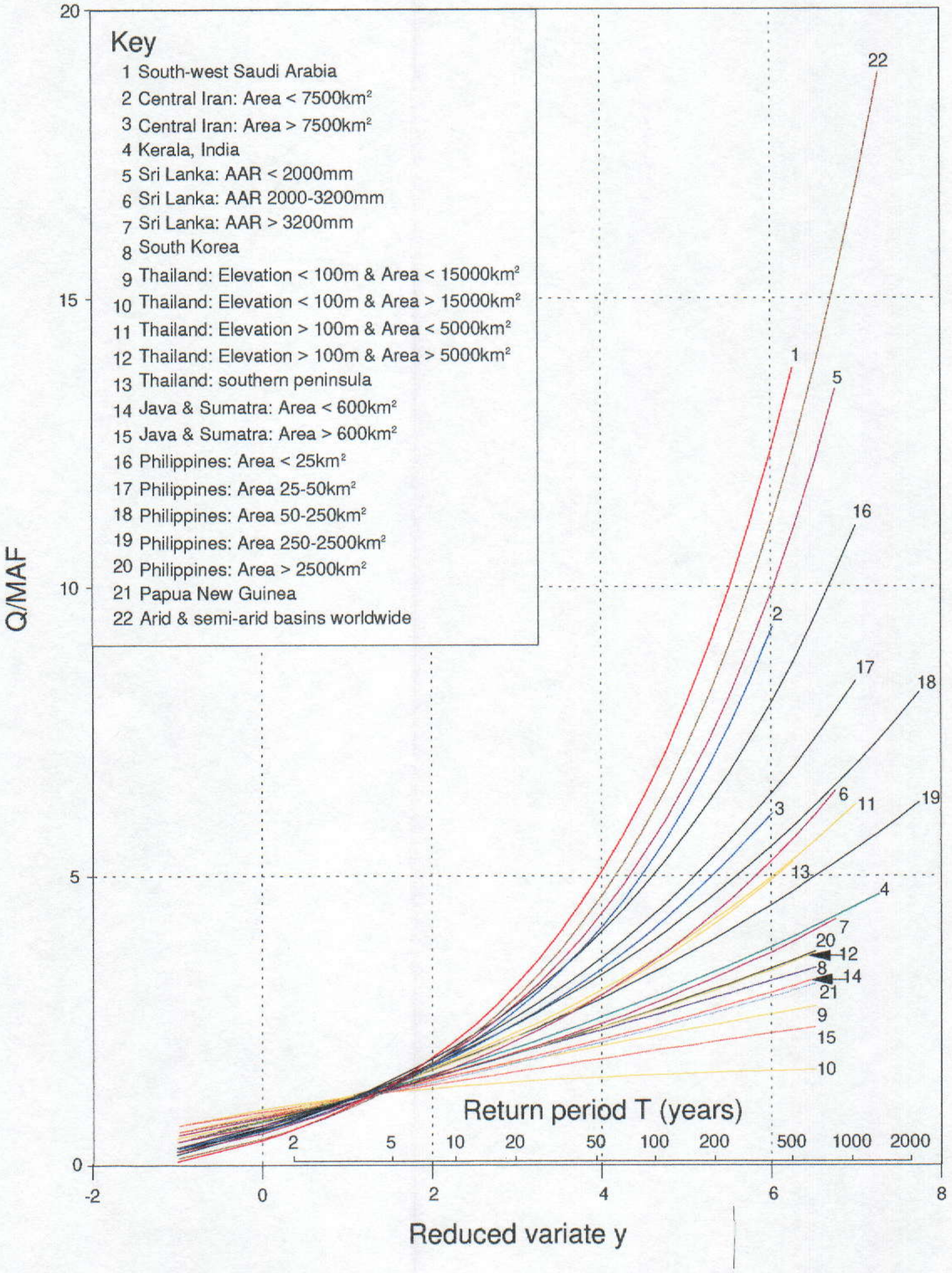


Figure 7

of many regions throughout the world. In contrast to these, there is a group with distinctly steeper slopes, notably most of the West African regions, Java & Sumatra, and the southern Peninsula of Thailand. Another group, concentrated in Southern Africa (Namibia, South Africa & Botswana, Malawi) and one of the West African regions (9°E - 16°10'E & >8°N) are particularly flat. Of the anomalous regions, this West African one and Peninsular Thailand have only 16 stations, considerably fewer than most, and they may diverge from the general trend simply because they lack representative data. These two equations should perhaps be treated with caution. The other West African regions may differ because they have few small catchments (only 26 of the 224 are less than 1000 km^2, and only 12 are less than 500 km^2), and the inclusion of more small catchments might have had a considerable effect on the slopes of these. Although no other general reason for the divergent equations is apparent, it is notable that the considerably steeper ones tend to be from more humid regions while the much flatter ones come from drier regions.

Besides the slope, the other aspect of the MAF equations which should be considered is their intercept: very broadly, the different regions have similar slopes, but the equations are shifted more or less upwards or downwards on the MAF axis. This shift seems to be broadly related to climate, and it is in the expected direction: that is, arid areas generally have the lowest MAF for any given catchment area, and the MAF increases for more humid climates. One of lowest equations is that for arid and semi-arid basins worldwide; Namibia with some of the most arid catchments is distinctly lower. Other mostly arid and semi-arid regions lie a little above, for instance Saudi Arabia, Iran and South Africa & Botswana. The more humid regions tend to lie above these, with the humid parts of south and east Asia (that is: Sri Lanka, Kerala, Korea, Java & Sumatra, Philippines and Papua New Guinea) generally at the top. Areas with strongly monsoonal climates such as Korea and the Philippines seem to produce high specific MAFs. While it is not suggested that there is a direct correlation between the MAF equation and climate type, it is clear that the data do show a tendency for higher MAFs in more humid climates.

Turning to the comparison of the regional flood frequency curves (Figures 6 and 7), this is again somewhat confusing because there are several curves for some of the regions. However, generally the reverse tendency to that shown by the MAF prediction equations can be seen. Thus, the driest areas tend to have the lowest MAFs but the steepest flood frequency curves, reflecting the extreme year-to-year variability found in these areas, and conversely, humid areas tend to have higher MAFs, but flatter frequency curves. On top of this pattern is laid the tendency for smaller catchments within any one region to have steeper curves: this can be seen where there were sufficient data to split the regions. However, as it is expected that this would be a general result, it would probably have been found in every case if enough data from a sufficiently wide range of catchment sizes had been available. For regional curves that have not been split according to area, the comparison is also probably affected by the range of catchment sizes available for analysis, so that the position of any one curve is the result of this factor as well as of the inherent flood response of the region.

Despite these difficulties of interpretation, it can be clearly seen that the driest areas have the steepest curves of all. The most arid region studied is Namibia with AAR $<$ 175 mm; this is the steepest curve of all and the only one which is significantly steeper than the curve for arid and semi-arid basins worldwide. Other arid areas such as Saudi Arabia are very similar to the worldwide curve, while the curves for South Africa & Botswana and for Swaziland are also similar, although these regions also include some more humid catchments. At the other end of the scale large humid catchments have the flattest curves. The flattest of all are for West Africa (which is dominated by large catchments) and the large catchments in Thailand (here the effect is increased by the river overflowing into a network of channels). Other humid areas and those affected by a monsoon also tend to be fairly flat. One seemingly anomalous region (although supported by good data) is the drier part of Sri Lanka. This region has AAR $<$ 2000 mm and thus is, in fact, relatively humid, but the curve is as steep as some from much more arid areas. In contrast to this, the wetter part of Sri Lanka (AAR $>$ 3200 mm) has a fairly flat curve, much like other humid regions, and it is satisfyingly similar to the curve for Kerala which is nearby and climatically similar.

4. Manual of regional flood estimation procedures

4.1 Introduction

The aim of this chapter is to explain how the flood estimation methods presented in this report can be applied in practice. It does not cover all aspects of regional flood frequency analysis, but only those procedures which are necessary to apply the approach developed in this study. The regional approach is suitable for a wide variety of flood problems, but it should not be the sole method used for major structures which represent an appreciable safety risk; in these situations, a more detailed study of the particular site should be carried out in addition. The reader should refer to Chapter 1 for a discussion of the general limitations of the regional approach and what kind of problems it can reasonably be used to solve.

While we have tried to set out the best procedures for making flood estimates using the regional approach, it is not possible to cover every eventuality that might arise. The methods should never be applied mechanically, and results should always be examined critically. The hydrologist must exercise his or her judgement and experience to ensure that realistic results are attained. When working on these type of problems, there is no substitute for experience of making estimates over a range of different catchments or for familiarity with the hydrological response of the area being studied.

The basic flood estimation procedure consists of two stages: first the estimation of the mean annual flood (covered in Section 4.3); and second, the estimation of the flood peak corresponding to the required return period (Section 4.4). Preliminary work required to obtain the data necessary for application of the methods is discussed in Section 4.2.

4.2 Preliminary work and measuring the catchment characteristics

Before carrying out the flood estimation procedure, some initial work is needed. This includes assessing the availability of flow data which could be used to help in making the estimate and measuring the catchment characteristics that will be needed.

4.2.1 Flow data

Flow gauging stations at or very close to the site of interest will be the most useful, but any gauges reasonably close in the same basin or in adjoining basins of a similar character may also be helpful. Unless the records are very short or broken, the annual flood peak series for these gauges should be obtained. Annual peaks are the maximum instantaneous flows in each year. The year should be defined as a suitable hydrological year rather than the calendar year: the hydrological year used should start and end in the season which typically has low flows and when large floods are unlikely to occur. By doing this, the possibility that two dependent floods occurring a few days apart will be assigned to separate years is reduced. In abstracting the annual peak floods, there are a number of other points which should be checked:

- Carry out a check on data quality to see if the data are reasonably accurate at high flows. The siting of the gauging station should be examined to check that it is not bypassed or frequently overtopped by floods so that the peaks are not observed. If it is situated in a wide flood plain, flood flows may spread out over the flood plain and be very poorly measured. If possible, the river cross-section should be obtained in order to ascertain the degree of overbank flow at maximum flood stages. You should also examine the rating curve to see how reliable it is for estimating floods. In particular, examine the amount of extrapolation from the stage at which discharges have been measured in the field to the stages attained during flood flows. Some extrapolation is nearly always necessary, but check that it is not based on only a few very low gaugings and that the method used for extrapolation is adequate. If it is decided that the gauging station is not adequate to observe high flows, then the data will have to be rejected.

- Determine the type of gauging station; in particular, whether there was an autographic recorder, or whether only a manually-read staff gauge was used at the time the data were recorded. If there was only a staff gauge, then the number of readings per day should be considered in relation to the typical rate of change of flood flows at the site, to see whether there were sufficient readings to observe the flood peaks with some degree of reliability. Generally, for large catchments there should be no problem, but for smaller catchments where the gauge is read only two or three times per day, the peaks might easily be missed. Unfortunately the size of catchment for which this could become a problem cannot be easily specified, and it is likely to vary from region to region. If it is suspected that this might be a problem, then some other similar catchments in the region which do have autographic recorders should be examined to assess the rate of change of flow which is likely to apply, and thus, whether peaks are likely to have been adequately observed. If the result is that it seems that peaks have not been adequately observed, then it is not easy to estimate what the real peak flows would have been. This has been attempted in some areas; for instance, a crude adjustment was developed for catchments in the Philippines (see Appendix A), but otherwise the station will have to be rejected.

- When abstracting the peaks, it is necessary to check for missing data in each year of record. If there are missing values you need to decide whether the observed peak was a real peak, or whether the real peak might have occurred during the missing period. Generally if there are missing data, the year will have to be rejected. However, if the gap is very short and clearly in a recession period, or if the region being studied has a distinct dry season and the missing data occur only in the dry season, it is normally reasonable to accept the peak as valid. In addition to this, it is desirable to include particularly large floods which occur in years with missing data even if you cannot be sure they are the true maxima for the year. As a guide to doing this, first extract all the peaks for the complete years and for years in which the missing data occur only in the low flow season. Calculate the mean of these peaks, and then check to see if there are other uncertain years which have peaks greater than this mean; if there are, these peaks should be included in the series, despite the missing data.

4.2.2 Catchment characteristics

The two catchment characteristics most often required are the catchment area (AREA) and average annual rainfall (AAR). AREA is always needed, but the other characteristics required will depend on the particular region.

Catchment area

The catchment area at a particular point on a river is the area of land, defined by the topographic divide, from which water would flow to that point. It is important to obtain the precise location of the site of interest so that the catchment boundary can be drawn correctly. A relatively small error in the location can lead to a large errors in the catchment area, especially if the location is close to a major tributary; and it is surprising how often erroneous catchment areas are used because of poor precision in defining site locations. Ideally, the map scale used should be the same as that used to measure the catchment areas for the gauging stations used to develop the method. However, in practice, this does not really matter, and any scale at which the catchment can be adequately defined can be used. In most cases 1:50,000 maps are used. If the catchment is large enough to cover several sheets at this scale, then smaller scale maps can be used provided topography is adequately shown. For very small catchments 1:25,000 or even 1:10,000 scale maps may be more appropriate. Measuring the area from the map can be done using a planimeter, a cartographic software package such as AUTOCAD, or if these are not available, counting squares on graph paper is adequate.

Average annual rainfall

Average annual rainfall refers to the rainfall over the catchment of interest. It can be calculated by overlaying the catchment boundary on an isohyetal map of the region and measuring the areas between each pair of isohyets. Assign each measured area a rainfall value equal to the mean of the two isohyets which define it, and the AAR is then the weighted average of the assigned rainfall values, using the measured areas as weights. The availability of isohyetal maps of annual rainfall varies widely from country to country. Ideally, the same source of information should be used as was originally used in developing the method for the particular region. However, this may not always be practicable, and generally, it should be adequate to obtain any reliable maps at a scale suitable to the catchment being studied. Preferably, the maps should show isohyets for a standard 30-year period and have been derived only from reliable long-term gauges.

Other catchment characteristics

There is a range of other catchment characteristics that are needed for certain regions, and their precise definition varies from study to study. The reader should refer to the original reports to determine how to measure these characteristics.

4.3 Estimating the mean annual flood

The mean annual flood is the mean of the series of annual flood peaks at the site of interest. How this should be estimated depends on the amount of flow data which is available.

4.3.1 With no flow data

If there are no flow data at or near the site of interest, the MAF is estimated from the appropriate MAF prediction equation using the catchment area and other catchment characteristics. The equations are listed in Table 1. Before doing this, it is necessary to check that the catchment characteristics of the basin under study are within, or close to, the ranges of the characteristics used to develop the equation. The ranges are given for each region in the Appendices, and the maximum and minimum values are also listed in Table 3. The most

TABLE 3 *Ranges of catchment characteristics used in developing MAF prediction equations*

Country or grouping	AREA (km^2) Min	AREA (km^2) Max	AAR (mm) Min	AAR (mm) Max	Other Min	Other Max
Rio Grande do Sul, Brazil	132	68,300	1280	1850	0.19	9.15 (S1085)
West Africa (>8°W)	990	218,000	750	2630		
West Africa (8°W-2°W)	56	282,000	837	2160		
West Africa (2°W-4°E)	378	394,000	738	1630		
W Africa (9°E-16°E & >8°N)	355	73,700	810	1550		
W Africa (9°E-16°E & <8°N)	235	158,000	1440	3600		
Malawi	64	10,600	710	1480	0.076	3.68 (STMFRQ)
Namibia	17	63,300	130	485		
Zimbabwe	0.21	196,000	520	2000		
South Africa & Botswana	3	92,300	196	2740		
Swaziland	58	12,600	809	1480		
South-west Saudi Arabia	59	16,900	50	500		
Central Iran	213	60,800	200	750		
Kerala, India	29	4,240	-	-		
Sri Lanka	65	7,340	1390	4950		
South Korea (Area < 1000)	34	937	1220	1500		
South Korea (Area > 1000)	1,120	25,000	945	1460	1	20 (PADDY)
Thailand (Main part)	6	121,000	1100	3400		
Thailand (S. Peninsula)	39	11,900	1900	3300		
Java & Sumatra, Indonesia	0.4	36,400	1850	4950	62	162 (APBAR)
					0.97	200 (SLOPE)
					0	0.79 (LAKE)
Java & Sumatra, Indonesia	10	30,000	-	-	65	160 (APBAR)
(recommended limits - see Appendix E11)					1	150 (SLOPE)
					0	0.25 (LAKE)
Philippines (Regions 1-2)	28	28,000	-	-		
Philippines (Regions 3-8)	1	6,490	-	-		
Philippines (Regions 9-12)	2	17,700	-	-		
Papua New Guinea	9	28,500	2000	4500		
Arid & semi-arid worldwide	1	357,000	50	600		

usual limitation is likely to be in catchment area; for example, if the method for a particular region was developed with catchments in the range 100 to 10,000 km^2, it would clearly be unwise to apply it to catchments of only 10 km^2. In practice some extension of the range would be possible, but it must be left to the judgement of the user to decide how far outside the range of data the estimates are still acceptable. To some extent, this may also depend on the nature of the flood estimation problem and the availability of alternative estimation techniques for the region.

In particular cases where the catchment being studied is close to the borders of two regions, the MAF prediction equations for both might be suitable, but they will give different MAF estimates. When this happens it is suggested that MAF is estimated from both equations, and a mean of the two estimates used, unless there seem to be good reasons to bias the result towards one or other of the regions.

To assess the likely error in the MAF estimated using the prediction equation, the factorial standard error of the estimate (f.s.e.e), given in Table 1, can be used. The f.s.e.e. is analogous to the standard deviation; this means that there is a 68% probability that the 'true' MAF for the site lies within the range MAFxf.s.e.e. to MAF/f.s.e.e..

4.3.2 Using a long flow record at the site

If there is a long flow record at the site of interest, and the data have been validated as described in Section 4.2.1, this is the best estimate of the MAF. The annual peaks are abstracted and the mean calculated. Normally, if there are at least 10 years of data, the MAF will be well defined, and this estimate should be preferred to the estimate from catchment characteristics. It does not matter if there are years missing from the record, provided that there are 10 annual peaks in all.

4.3.3 Using a short flow record at the site

If there are fewer than 10 years of data at the site, and the data have been validated as in Section 4.2.1, they can still be used to estimate the MAF. With 5 to 9 years of data, calculate the simple mean of the annual maximum flood series as before. If there are only 2, 3 or 4 years, use the peaks-over-threshold method, as follows:

Using complete years of data only (a minimum of two, or preferably three, complete years is required), choose a flow threshold value, Q_t, such that, on average, between two and five peaks per year exceed the threshold. The choice of year used here can be such as to maximise the amount of data available, rather than keeping strictly to the hydrological year. From the N complete years of data, all flood peaks exceeding the threshold are abstracted; these M flood peaks, Q_i (i = 1, 2, ... M), form the peaks-over-threshold series. Perform a check to ensure that the peaks are independent. A simple, but somewhat arbitrary, test for this is as follows: if the time separating two consecutive peaks is greater than three times the rise time of the first peak, and the trough in flow between the two peaks is less than two thirds of the first peak, then the peaks can be treated as independent. If the test indicates that the peaks are not independent, include only the first in the series.

Calculate the mean exceedance, β, of the M flood peaks over the threshold, Q_t, as

$$\beta = (1/M) \sum_{i=1}^{M} (Q_i - Q_t)$$

and the average number of exceedances per year,

$$\lambda = M/N$$

The mean annual flood is then estimated from

$$MAF = Q_t + \beta\,(0.5772 + \ln \lambda)$$

This method is based on work in the UK (NERC, 1975), but the approach should be generally applicable.

When the MAF estimate has been made from the observed data using either of the above methods, it should be compared to the estimate from the prediction equation. A final MAF value is then selected as a compromise between the two estimates, weighting your decision more towards the observed data the longer the observed record and the greater your confidence in the reliability of the observed values.

4.3.4 Using data from nearby stations

Unless there are 10 or more years of good quality flow data at the site, data from nearby stations should be used wherever possible. There are two different situations to be considered:

- the nearby station is in the same basin and the catchment area does not differ by more a factor of more than about 2 from that at the site of interest; or

- the nearby station is in a different basin. In this case the areas should also be within a factor of about 2, the catchment characteristics should be broadly similar, and the general topography and climate of the two basins should be similar. You should also check for other factors, such as the presence of lakes, which might cause differences in flood response between the two catchments.

Assuming a gauged catchment can be found which is judged to be sufficiently similar, calculate the MAF for the nearby station from flow data using one of the methods discussed above, and also calculate the MAF using the MAF prediction equation. Then an improved estimate for the MAF at the site of interest, MAF_A, is:

$$MAF_A = MAF'_A . MAF_B \,/\, MAF'_B$$

where MAF'_A is the MAF estimate using the prediction equation at the site of interest, MAF_B is the value at the nearby station from flow data, and MAF'_B is the value at the nearby station using the prediction equation.

4.3.5 Combining different approaches

If more than two estimates of MAF are available, using different approaches, then they should all be considered in deciding on the final MAF estimate for the site of interest. Generally, it is best to consider as many different approaches as possible. The exceptions are: when there are more than 10 years of good quality data at the site, only the estimate from these data need be considered; and when there are no gauged data at the site or in any comparable nearby catchments, when the MAF prediction equation is the only possible approach. For example, the different estimates of MAF might be from:

- a gauge upstream of the site with catchment area about 0.7 of the site area and MAF estimated from 2 years' data by peaks-over-threshold; and

- a comparable adjoining catchment with an area 1.6 times the area at the site and MAF estimated directly from 5 years of data.

Alternatively, a short record at the site of interest might be supplemented by MAF estimates deduced from one or more adjoining catchments.

To combine the estimates, the appropriate technique is used to estimate MAF from the available flow data for each catchment, and these are each transferred to the site of interest using the equation given in the preceding section. These different estimates of MAF at the site are compared, and a final estimate chosen; the final estimate could be a weighed average of the different estimates, putting more weight on the longer records and the catchments which are judged to be more similar to the site of interest.

As an alternative, rather than transfer the estimates to the site of interest using the equation in Section 4.3.4, a graphical approach can be used to compare the estimates. This is only suitable when the MAF prediction equation depends on AREA alone. An example is illustrated in Figure 8 where the MAFs from three different estimates are plotted on a graph of MAF against catchment area and compared to the MAF prediction equation. The regional regression line is then shifted to pass close to the observed data points, without altering its slope; the final position is again decided by which estimates are judged to be most reliable. The final estimate for the site can then be read from the shifted regression line.

4.4 Estimating the flood peak for a given return period

4.4.1 Flood peaks and return periods

In estimating flood peaks at a particular site, we want to find the peak flood which corresponds to a particular return period. The return period is expressed in years, and is the time which, on average, elapses between two years containing peak flows which equal or exceed a particular value. The return period, T, is related to the annual probability of non-exceedance, p, by

$$p = (T-1) / T$$

Combining MAF estimates from nearby gauging stations

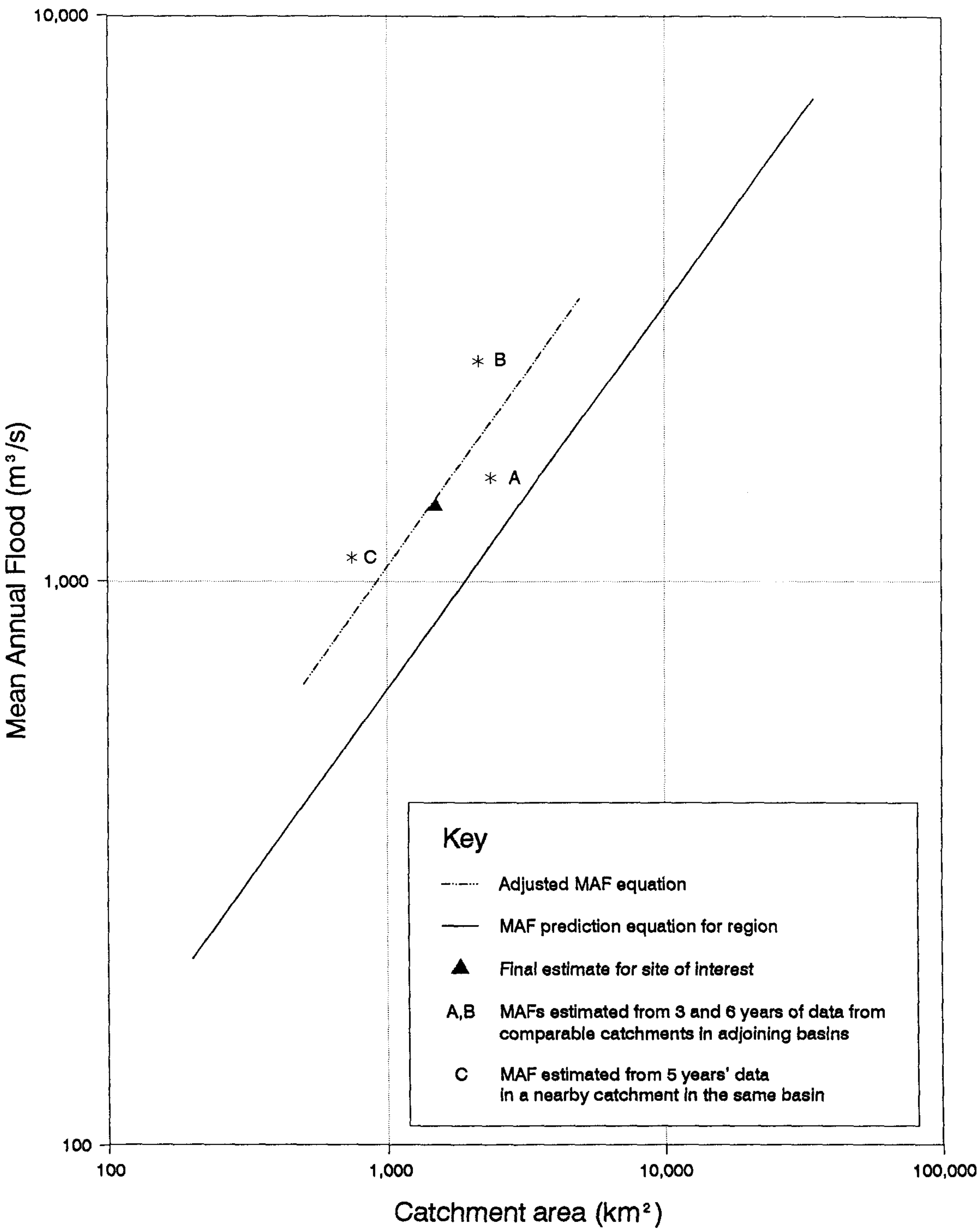


Figure 8

Thus a 100-year return period flood has a probability of non-exceedance of 0.99, and hence the probability of this flood peak being exceeded in any one year is 0.01. However, it should be noted that this does not mean that the 20-year flood, for instance, has a probability of 1 of occurring in any period of 20 years. Rather, the probability, P, that the flood of return period T is equalled or exceeded in a period of n years is

$$P = 1 - p^n$$

Thus a 20-year flood has a probability of 0.05 of being equalled or exceeded in any one year, 0.226 in a 5 year period, and 0.64 in 20 years. Conversely, if the 20-year flood is exceeded more than once in a period of 20 years, this does not necessarily mean that the flood estimate was wrong. The above approach can be used to find the probability that the design flood will be exceeded during the expected life of the scheme being studied.

For each flood estimate a suitable design return period has to be chosen, depending on the type of project to which the flood estimate relates, and on the risks associated with the flood being exceeded. Many countries have national standards for these design return periods which should be followed. Where there are no national standards, a suitable design return period needs to be selected; but, unfortunately, this topic is beyond the scope of the present report.

4.4.2 Using the regional curve

In most cases, the appropriate regional flood frequency curve should be used to estimate the flood peak for the required return period. For the regions studied, the regional curves and the standardised flood peaks, q_T, for return periods of 20, 100 and 500 years are given in Table 2. For these return periods, it is simply a matter of multiplying the standardised flood peak by the MAF for the catchment to obtain the final flood peak estimate, Q_T, in m^3/s. For other return periods, the three parameters (u, α and k) of the flood frequency curve can be used to calculate the flood peak. The method is as follows:

Find the non-exceedance probability, p, corresponding to the required return period, T, from

$$p = (T-1)/T$$

and then calculate the reduced variate, y, as

$$y = -\ln(-\ln p)$$

The standardised flood peak, q_T, is then given by

$$q_T = u + \alpha (1-e^{-ky}) / k \qquad \text{for } k \neq 0, \text{ or}$$

$$q_T = u + \alpha y \qquad \text{for } k = 0.$$

and the final peak flood estimate, Q_T, in m^3/s is

$$Q_T = q_T.MAF$$

In some cases a catchment might fall close to the limits of two different curves. For instance, consider the case of a catchment in the Philippines with a catchment area close to 25 km². The results given in Table 2 show that there are different curves for the Philippines for catchments of less than 25 km² and for catchments of 25-50 km². Clearly, flood peaks do not suddenly change at a catchment size of 25 km², so an appropriate solution would be to estimate q_T with both curves and average the results to get the final estimate.

TABLE 4 *Ranges of catchment characteristics used in developing regional flood frequency curves**

Country or grouping	AREA (km²)		AAR (mm)	
	Min	Max	Min	Max
West Africa (AAR 600-1250)	182	394,000	738	1250
West Africa (AAR 1250-1500)	110	282,000	1260	1490
West Africa (AAR 1500-1750)	56	158,000	1510	1750
West Africa (AAR > 1750)	800	42,300	1760	3600
West Africa (Area < 1000)	56	990	810	2160
Namibia (AAR < 175)	1,480	63,300	130	171
Namibia (AAR > 175)	17	46,400	177	485
Zimbabwe (Area < 100)	0.21	99	530	2000
Zimbabwe (Area 100-2500)	101	2,470	540	1400
Zimbabwe (Area > 2500)	2,530	196,000	520	910
S Africa & Botswana (AAR < 1250)	3	92,300	196	1190
S Africa & Botswana (AAR > 1250)	20	713	1320	2740
South-west Saudi Arabia	16	16,900	50	500
Central Iran (Area < 7500)	141	5,650	90	750
Central Iran (Area > 7500)	7,820	60,800	200	600
Sri Lanka (AAR < 2000)	91	3,070	1390	1940
Sri Lanka (AAR 2000-3200)	119	7,340	2010	3170
Sri Lanka (AAR > 3200)	65	2,600	3280	4950
South Korea	582	25,000	981	1500
Thailand (Group 1)	366	13,600	1150	3400
Thailand (Group 2)	19,400	121,000	1200	1350
Thailand (Group 3)	6	4,610	1100	1800
Thailand (Group 4)	6,060	107,000	1100	1600
Java & Sumatra (Area < 600)	0.4	588	1950	4950
Java & Sumatra (Area > 600)	622	12,400	1850	4050
Philippines (Area < 25)	1	25	-	-
Philippines (Area 25-50)	26	49	-	-
Philippines (Area 50-250)	51	247	-	-
Philippines (Area 250-2500)	253	2440	-	-
Philippines (Area > 2500)	2,580	28,000	-	-

* Where ranges are the same as for MAF equations they are given in Table 3 only.

Using the regional curves, the maximum return period for which floods can reasonably be estimated is limited by the total number of years used in developing the curves (as listed in Table 2). It would be reasonable to use return periods up to about the same length as this total number of years, or to a maximum of about twice this. In most of the regions studied, the reasonable limit is about 500 to 1000 years. As mentioned above, users should always pay attention to the range of catchments used in developing the curves (listed in Table 4), and not try to apply them outside this range. For example, a curve should not be used for small catchments when no small catchments were available in developing the curve.

4.4.3 Using local data to improve the estimate

Generally, it is recommended that the regional curve should be used even when there is a flood record available at the site of interest. However, if there is a particularly long and reliable record at the site or very close to it, it is worth comparing the flood frequency curve for the local data to the regional curve. This is done as follows: Standardise the local flood peaks by dividing each by the MAF for the series, and rank them in ascending order; that is, assign rank $i = 1$ to the smallest value and $i = N$ to the largest, where N is the number of values. The probability of non-exceedance, p, is then calculated as:

$$p = (i - 0.44) / (N + 0.12)$$

and reduced variate, y, is:

$$y = -\ln(-\ln p)$$

The flood peaks can then be shown on the same graph as the appropriate regional flood frequency curve by plotting each of the standardised peaks against y. An example of this is given in Figure 9. It can be seen that, in this case, there is very good agreement between the regional curve and the local data, so there is no problem. However, in some cases, there may be a considerable divergence between the two. If there is a long local record and you are confident in the reliability and accuracy of the data, then for return periods within the length of the local data, the local curve would normally be preferred. For longer return periods, a compromise value lying between the estimates produced by the two different curves would be a reasonable solution. However, in most cases the regional curve should be used unless there are strong reasons to do otherwise.

Comparison of local data and regional flood frequency curve

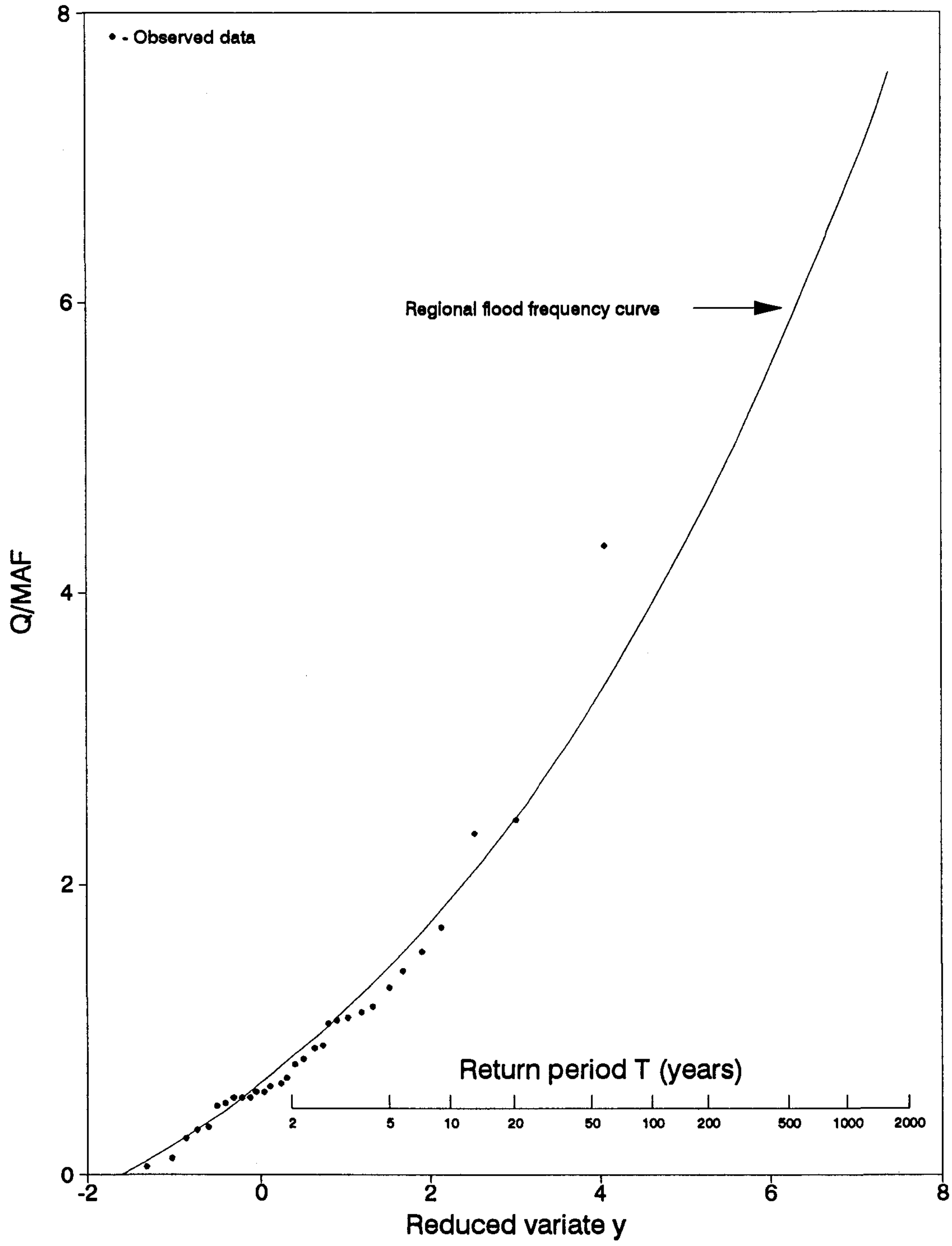


Figure 9

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Appendix A Development of flood estimation method for the Philippines

The general approach used in the development of the flood estimation methods for all the countries or regions is discussed in Chapter 2 of the main report.

The development of the method for the Philippines involved two aspects of the work which were not included in the studies for other countries. The first was related to the fact that most river basins are small and flows change rapidly, but most gauging stations only have staff gauges. This means that flood peaks are not properly observed, and to overcome this, an approximate method of estimating what the peaks would have been has been developed. Secondly, there has been considerable concern in the Philippines that flood peaks are increasing due to land-use change, particularly deforestation, and therefore, evidence for changes in flood peaks over time was examined.

A1 Data

A1.1 Flood peak data

Three separate agencies are involved in the collection of river flow data in the Philippines: the Bureau of Research and Standards (BRS), the National Power Corporation (NPC), and the National Irrigation Administration (NIA). Until recently there was no overall listing of the stations. However, a complete register of gauging stations was assembled in a recent study (HR Wallingford *et al.*, 1994) and this gives details of a total of 1170 stations which have been operated at some time. Despite this very large number of stations, the number which in practice actually have flow data is much smaller. This is for a variety of reasons: some stations have never been calibrated so that only water level records exist and no flows are available (often because the site is unstable or is affected by tides so that a usable rating could not be obtained); other stations have records which are extremely short or broken so that the data are of little use; while at others no details, such as station location or catchment area, are available, so again the data cannot be used.

In deriving the flood peak estimation method, we have concentrated on the data collected by BRS. This was because BRS has been responsible for the greatest number of stations and their data are the only ones which have been published, and so are relatively easily accessible. This yielded more than enough data to carry out a satisfactory analysis. Two publications which list summary data for BRS stations up to 1980 were the main source of data (National Water Resources Council, 1980; Bureau of Research and Standards, 1991). Because there is also interest in more recent data to examine whether flood peaks have changed over time, data for 1981 to 1993 were extracted directly from the (mostly) hand-written files at the BRS office.

The summary data volumes and the hand-written sheets list the peak flow value for each year, and also give an indication of data quality as either "Good", "Fair" or "Poor" for each gauging station. It is not clear how the indicators of quality were assigned, and it was assumed that "Good" and "Fair" stations could be accepted, while "Poor" stations were rejected. As there are rather few long records which extend into the 1980s, "Poor" stations were sometimes accepted in these cases to enable changes in flood peaks to be examined. The other criteria of acceptance of a station was that each should have at least 5 annual peak flow values, as this was judged to be the minimum that could be used in the analysis. Using these criteria, data were extracted for a total of 348 stations (of which 15 were later rejected - see the next Section). These stations are listed in Section A7, which also gives the number of years of data, the station locations and the catchment characteristics. Most of the available data covers the period 1950 to 1970; there are fewer stations from 1971 to 1980, and even fewer after 1980. Only 58 of the stations having data in the earlier period also had data after 1980 and in many cases there are only two or three annual values after 1980. There are also 25 newly-established stations having typically 5 or 6 years of data after 1980. The longest period of record after 1980 at any station was 9 years.

The locations of the gauging stations are plotted in Figure A1.

A1.2 Problems with the flood peak data

While compiling the flood peak data a number of problems and difficulties were noted. These were as follows:

Even for gauging stations which are generally classed as "Good" or "Fair", it is clear that most of the rating curves are considerably less well defined at high flows and thus that flood flows are less accurately observed. This is a common problem in flood studies and it cannot easily be avoided. It was also noted that the peak stage values were sometimes not read very precisely; for instance, it was apparent in come cases that readings were only to the nearest 0.1 m. This may well be explained by unstable flows, but again, it will inevitably lead to loss of accuracy.

The summary data volumes list peak flows for each year and also give tables of monthly flows for the same years. In many cases, some of the monthly values in a particular year are missing, but flood peaks are still given. This means that there is some uncertainty in determining flood peak values. Two possibilities present themselves: The compilers of the data books may have checked each year to see whether the flood peak given is a true peak; that is, they may have checked through the values for the whole year and examined circumstantial evidence to determine that the maximum flow observed really was the largest that occurred in the year and did not occur during the period of missing observations. Alternatively, they may have simply published the highest observed value, without checking whether or not it is a true peak. From discussions with BRS staff, it was found that it is not now known exactly how this task was carried out. Ideally, all the old records should be re-examined year-by-year to check the validity of the flood peak data, but this would be a major piece of work which would be far beyond the scope of the present study. However, it proved possible to draw some reasonable conclusions on which data to accept by examining the patterns of data and of missing periods as given in the data volumes. It was concluded that in the earlier data, up to 1970, most of the flood peaks are true peaks, but that in the second volume for 1971-80, many of the peak flows given do not represent true peaks. In extracting the data, each station was examined and a decision taken whether or not to accept each annual peak value. For example, where there were some missing monthly values in a

Philippines - location of river flow gauging stations (northern part)

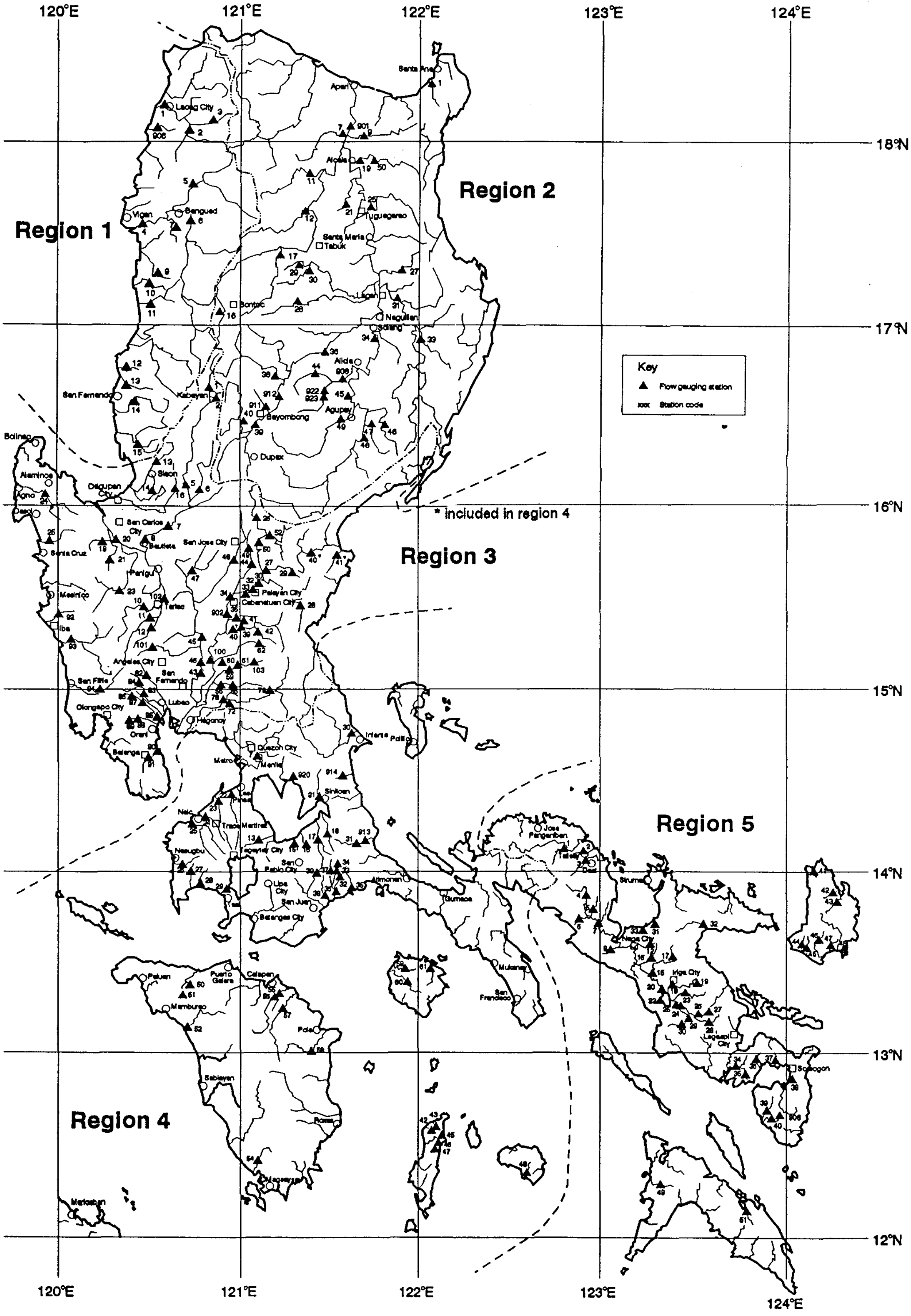

Figure A1

Philippines - location of river flow gauging stations (southern part)

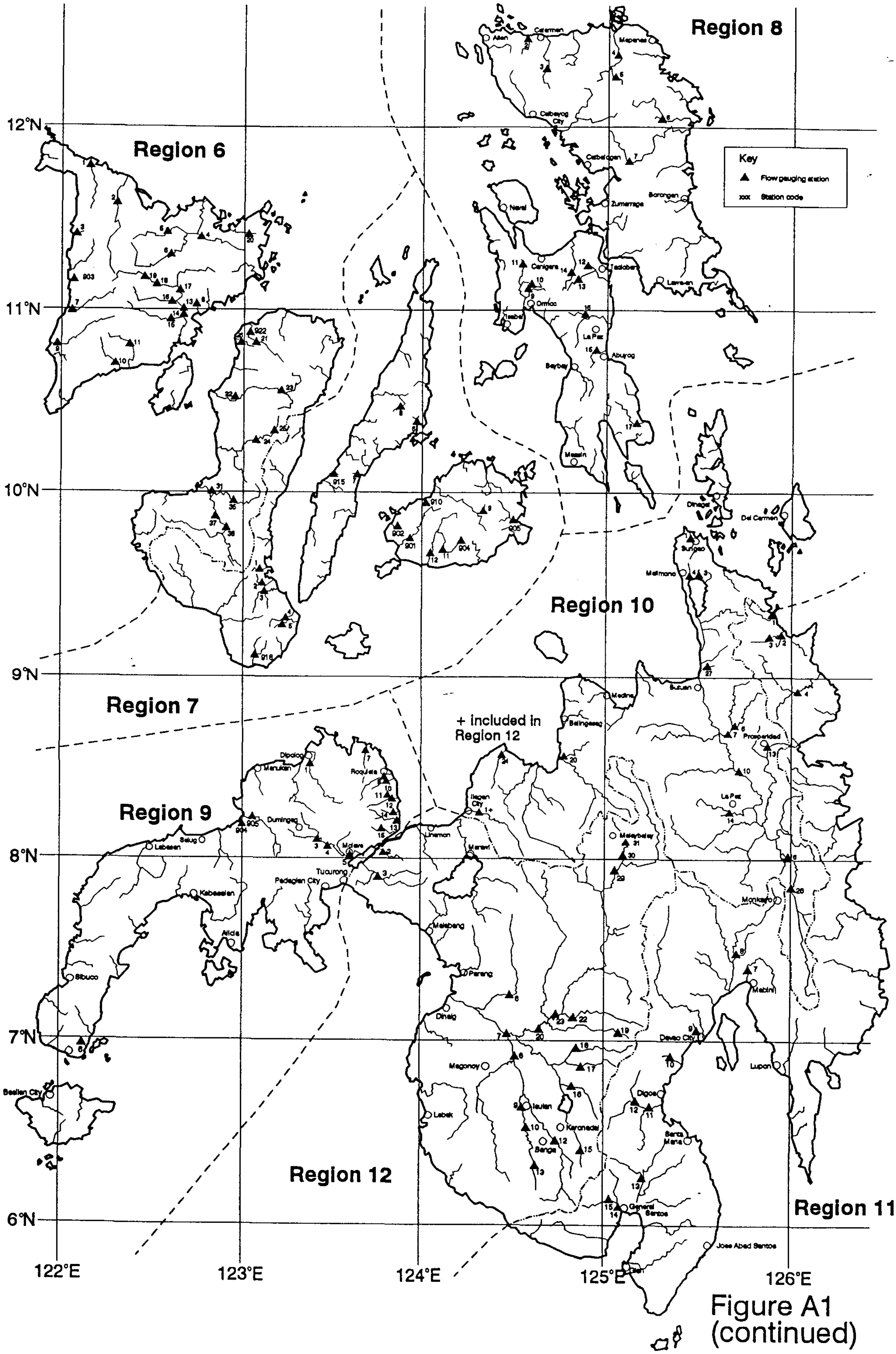

Figure A1 (continued)

particular year, the flood peak would still have been accepted if the missing months were only in the dry season (for a station with a distinctly seasonal climate) when a large flood would be very unlikely to occur. Also, when the dates of the peaks corresponded to missing months and the flood values were still reasonable, it was generally assumed that there were still sufficient observations in the month to define the flood peak adequately. Based on this type of approach, data were either accepted or rejected. A similar exercise was carried out for the data after 1980, working from the hand-written data sheets. The result of this exercise was the compilation of annual flood peak series which, although they must contain some errors, were believed to be reasonably representative.

Another problem which was noticed is that a few stations had very atypical flood peaks. These consisted of the same flood peak or closely similar values which tended to occur repeatedly. The problem is illustrated by the flood frequency curve shown in Figure A2, where several of the highest flood peaks are the same. This situation could come about because the gauging station is bypassed in flood flows, or because high flows spread out over a wide flood plain. The result would be that the flood peaks would have been considerably under-estimated. A similar result could occur in situations where the gauge tends to be washed out in extreme flood events. Surveys to determine the flood peaks are rarely carried out after such events, and this means that the largest peaks are missing from the record, causing the flood frequency curve to be biassed downwards. To try to overcome these problems, an examination of the flood frequency curve for each of the stations was carried out. This revealed a total of 15 stations with very atypical curves, and these stations were rejected from the study.

Because most of the gauging stations are staff gauges, read two or three times a day, and there are relatively few stations with autographic recorders, the true flood peaks are often not observed. A correction to the data to deal with this problem was derived, and this is discussed in Section A1.3 below.

In conclusion, the problems noted with the flood peak data mean that they are of fairly low quality, but the deficiencies cannot easily be rectified. Some recommendations for further studies to compile an improved database of flood peaks are given in Section A7. For the time being, it is believed that the work in the present study is sufficient to derive a preliminary flood estimation method.

A1.3 Estimation of instantaneous peaks at non-autographic gauging stations

Many of the gauged catchments are fairly small; most are less than 1000 km^2 and many are only around 10 km^2 or less. On small catchments such as these, floods rise and fall very rapidly, and to observe the flood peaks reliably an autographic record of water level is required. For the data up to 1970, 109 of the 333 stations finally selected are noted as having an autographic recorder. But for the data from 1971-80 and also for the more recent data, no autographic recorders were in use. It appears that the autographic recorders that had been installed fell out of use some time before the end of 1970 and they were not replaced. Although instructions are issued to the gauge readers, asking them to take additional readings during flood events so that the peaks are more reliably observed, there is evidence that this is done very infrequently. Thus, for most stations we have to rely on the two or three daily staff gauge readings, and these inevitably record lower peak values than the true peaks.

Illustration of an atypical flood frequency curve with repeated peak values (station PH308008, Mas-in at Mas-in, Ormoc, Leyte)

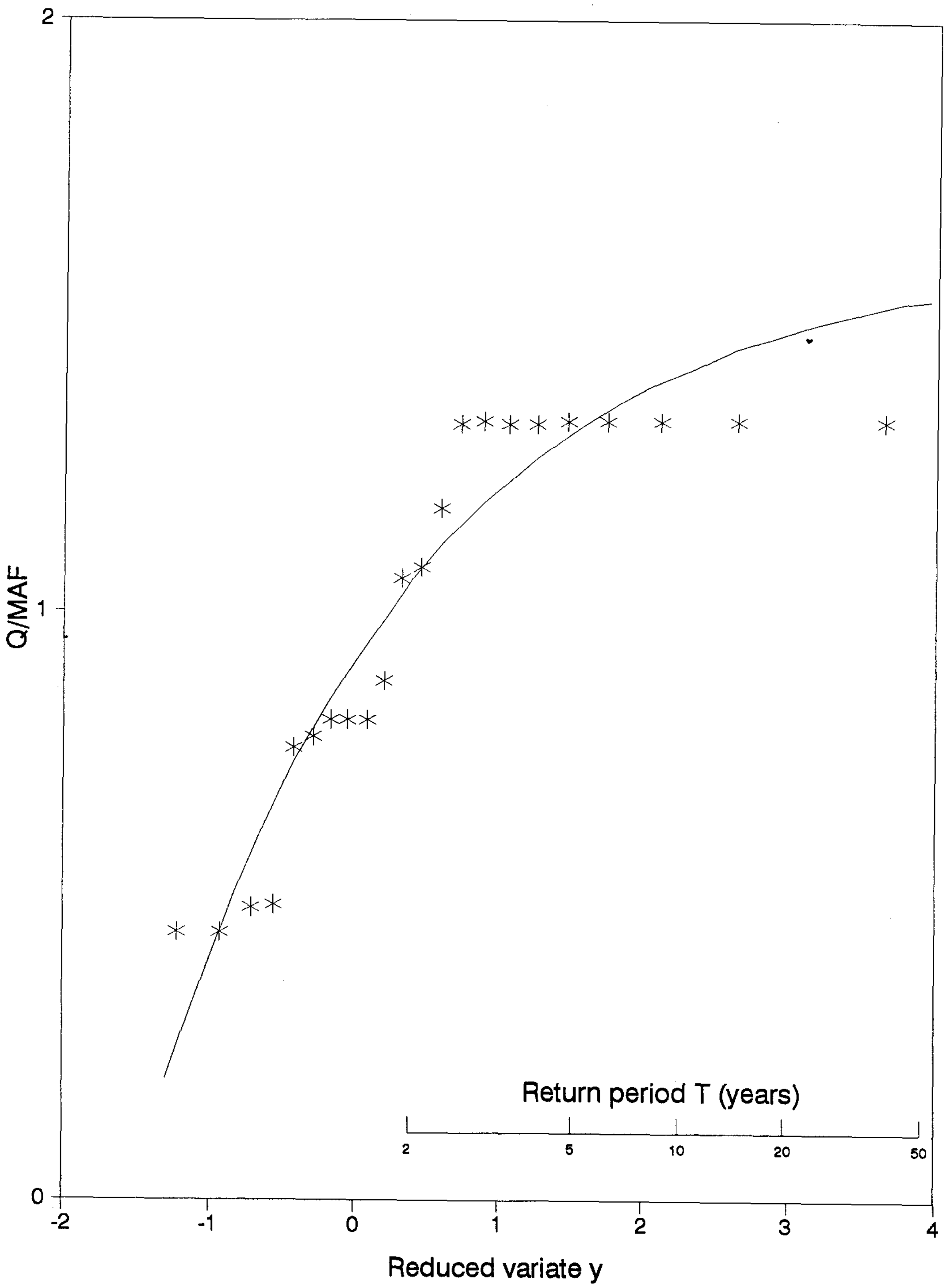

Figure A2

To investigate this problem, flood peaks were examined in relation to the maximum daily flows. Besides the flood peak values, Q_p, the maximum daily flows, Q_d, were extracted for each year, and the average of the ratio Q_p/Q_d found for each station. This was done for three different conditions: autographic stations (up to 1970), staff gauge stations up to 1970, and all stations after 1970. These ratios are plotted against catchment area in Figure A3. Although there is a great deal of scatter it can be seen that Q_p/Q_d tends to increase as catchment size decreases, and that the ratio is higher for autographic stations, indicating that these observe the peaks more effectively. Regressions of Q_p/Q_d against catchment area (AREA) gave the following results:

Autographic:	$Q_p/Q_d = 4.04 - 0.901 \log(AREA)$		$r^2 = 0.445$
Staff, up to 1970:	$Q_p/Q_d = 2.50 - 0.398 \log(AREA)$		$r^2 = 0.193$
Staff, after 1970:	$Q_p/Q_d = 2.62 - 0.413 \log(AREA)$		$r^2 = 0.024$

The two fitted lines for staff gauges are very similar, while the line for autographic gauges is distinctly steeper. These lines meet at AREA $\approx$ 1000 km^2, and for larger catchments, no significant differences between autographic and staff gauges are observed. Because it is clear that not all the sites which are noted as having autographic gauges did in fact have them up to the end of 1970, the same relationships were also examined on the assumption that the autographic recorders only operated up to the end of 1966. This produced very similar results, indicating that the assumption that 1970 was the end of autographic operation at all sites did not produce any significant errors.

For practical application, these results were simplified to:

Autographic:	$Q_p/Q_d = 4.2 - \log(AREA)$
Staff gauge:	$Q_p/Q_d = 2.5 - 0.434 \log(AREA)$

for catchments less than 1000 km^2 in area. These relationships are also plotted on Figure A3. These results can be used to estimate how much greater are the average true flood peaks (as observed with an autographic recorder) than the average flood peak taken from a staff gauge record for any particular size of catchment. For catchments less than 1000 km^2, the average staff gauge peaks should be increased by the factor:

$$[\ 4.2 - \log(AREA)\ ]\ /\ [\ 2.5 - 0.434 \log(AREA)\ ]$$

to yield the average of the true flood peaks. This factor is 1 for catchments of 1000 km^2, increasing as catchment sizes decreases, to a value of 1.68 for a catchment of 1 km^2.

To apply these results in the following analysis, it was assumed that this same ratio could also be applied to the individual flood peak values. Clearly, it is not the case that each of true flood peaks at a particular station was a uniform factor larger than the corresponding staff gauge peaks, and the actual factor would vary from year to year. However, on average, the adjustment will be the correct, and the method provides reasonable estimates which make it possible to use the staff gauge data without seriously under-estimating the peak flows that actually occurred. Some under-estimation will, in fact, remain since not all the autographic gauges operated up to 1970, and therefore some of the ratios of Q_p to Q_d for autographic gauges probably should be higher. However, this under-estimation is expected to be small,

Ratio of flood peak to maximum daily flow for autographic and staff gauge stations

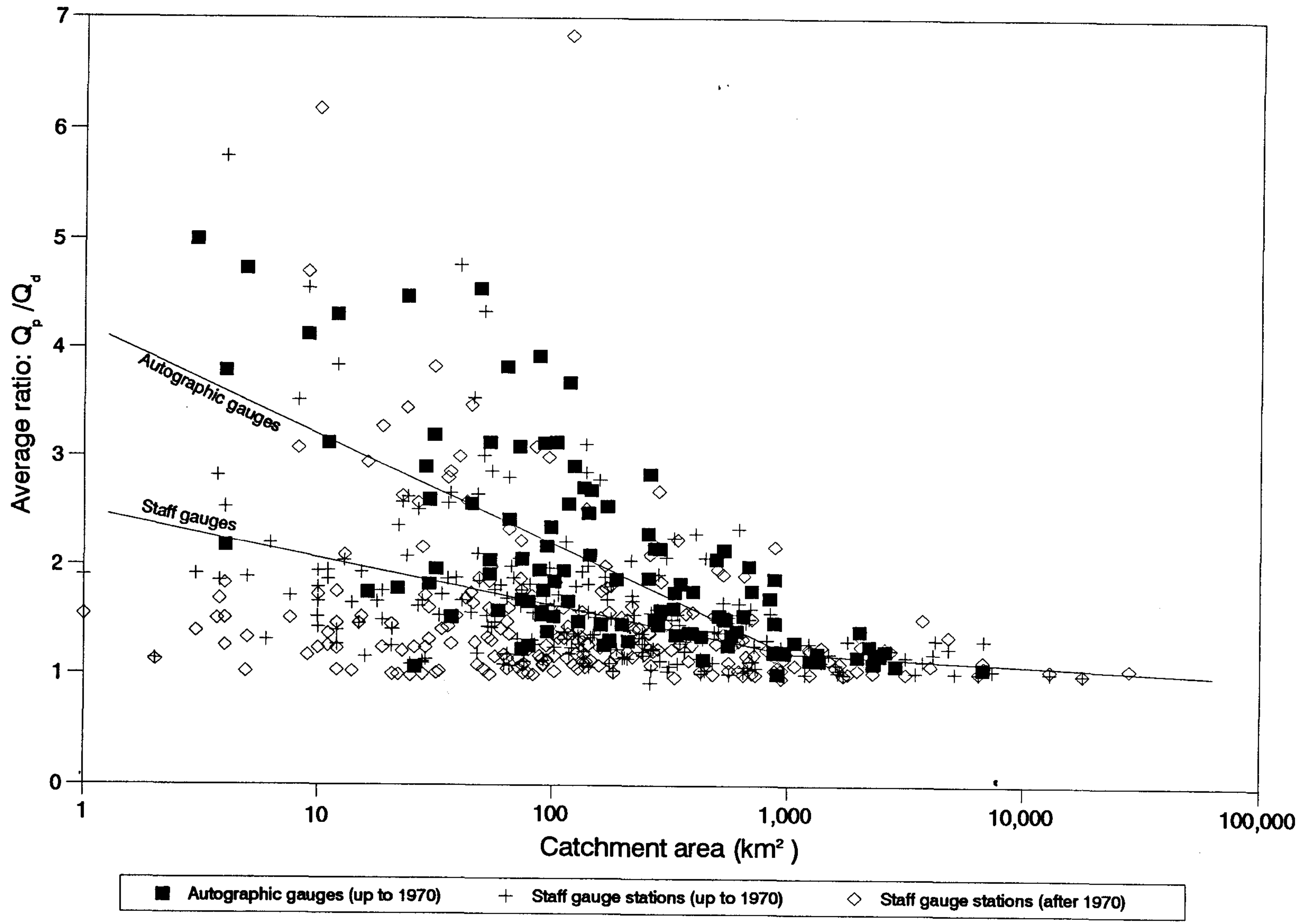

Figure A3

and it is not possible to quantify it further.

A1.4 Catchment characteristics data

The primary catchment characteristic data required are catchment areas for each gauging station used. These values were taken from the summary data volumes or from BRS files. For some of the stations, areas have been re-assessed by HR Wallingford *et al.* (1994), and these corrected values were used where available. In that study it was found that the actual values were sometimes significantly different to the published value. This was usually a result of errors in the listed station locations, and therefore it is not possible to establish correct area for all the stations without first visiting each site to determine its precise location.

The other catchment characteristics which were considered were average annual rainfall, rainfall intensity and climate type. However, because of the high variability of rainfall from place-to-place in the Philippines and the poor coverage of raingauges in mountainous regions, it probably would not be possible to obtain reliable estimates of average annual rainfall for the catchments. This was illustrated in the study by HR Wallingford *et al.* (1994) where the relationship between runoff depth and average annual rainfall was examined. A very poor relationship was obtained, with runoff exceeding rainfall in some cases, and this result was thought to come about both because of uncertainty in the catchment areas and because of the poor estimation of rainfall. Consequently, it was judged that it would probably not be worthwhile to attempt to estimate average annual rainfall values for each catchment for use in this study. A measure of rainfall intensity such as the 24-hour 5-year return period rainfall might also have been useful. Autographic raingauges are needed for this, and an investigation of the data from the available gauges showed that they would be insufficient to estimate this characteristic. As a final characteristic, climate type was investigated, and the modified Coronas climate type, which gives a broad indication of rainfall seasonality, was estimated for each catchment. The values were taken from the map of "Rainfall and tropical cyclone climatological normals of the Philippines, 1961-1990", prepared by PAGASA (no date). Each catchment was assigned to one of four climate types, defined as follows:

1. Two pronounced seasons: dry from November to April, wet during the rest of the year.
2. No dry season, with a very pronounced maximum rainfall from November to January.
3. Seasons not very pronounced: relatively dry from November to April, and wet during the rest of the year.
4. Rainfall more or less evenly distributed throughout the year.

In summary, only catchment area and climate type were found to be practicable and likely to be useful in the study. These data are listed for each catchment in Section A7.

A2 Estimation of mean annual flood

The value of the mean annual flood (MAF) was calculated as the average of the series of annual peak flows for each site (after adjusting the peaks as discussed in Section A1.3). The values are listed in Section A7. The logarithmic regression of MAF on catchment area using all the stations gave the following result:

$$MAF = 12.35\ AREA^{0.589} \qquad r^2 = 0.598$$

The data and the fitted line are plotted in Figure A4. This regression shows that AREA alone can explain about 60% of the variation in MAF when all the stations throughout the Philippines are considered.

The other factors which can be considered in looking for a relationship to predict MAF are climate type and geographical location. Because the climate type is a somewhat arbitrary value, rather than carry out a multiple regression of MAF on AREA and climate type, the primary regression of MAF on AREA alone was repeated separately for the stations in each climate type. The results are summarised in Table A1. It can be seen that most of the climate types have MAF regressions similar to the regression for all stations. The most dissimilar one is climate type 4 which has a somewhat flatter regression line, but this may be partially explained by the lack of large catchments in this climate type.

TABLE A1 *Results of MAF regressions for the Philippines*

	No. of stations	Constant	Exponent	r^2	f.s.e.e
All stations	333	12.35	0.589	0.598	2.29
Grouped by climate type					
Climate type 1	101	14.31	0.611	0.590	2.10
Climate type 2	57	12.76	0.609	0.598	2.17
Climate type 3	117	11.48	0.588	0.666	2.26
Climate type 4	58	13.28	0.495	0.363	2.43
Grouped by water resources region					
Region 1	15	19.77	0.660	0.785	1.73
Region 2	34	8.30	0.688	0.740	1.81
Region 3	66	11.64	0.628	0.660	1.95
Region 4	47	8.45	0.721	0.612	2.40
Region 5	45	24.83	0.435	0.415	2.06
Region 6	31	12.68	0.582	0.585	1.98
Region 7	18	5.60	0.671	0.485	2.19
Region 8	15	6.07	0.762	0.790	1.56
Region 9	15	113.5	(0.079)	0.009	2.33
Region 10	13	5.37	0.720	0.792	2.43
Region 11	13	12.33	(0.434)	0.184	3.42
Region 12	21	8.89	0.504	0.626	2.05

(Figures in brackets are not significant at the 5% level)

Mean annual flood against catchment area for the Philippines

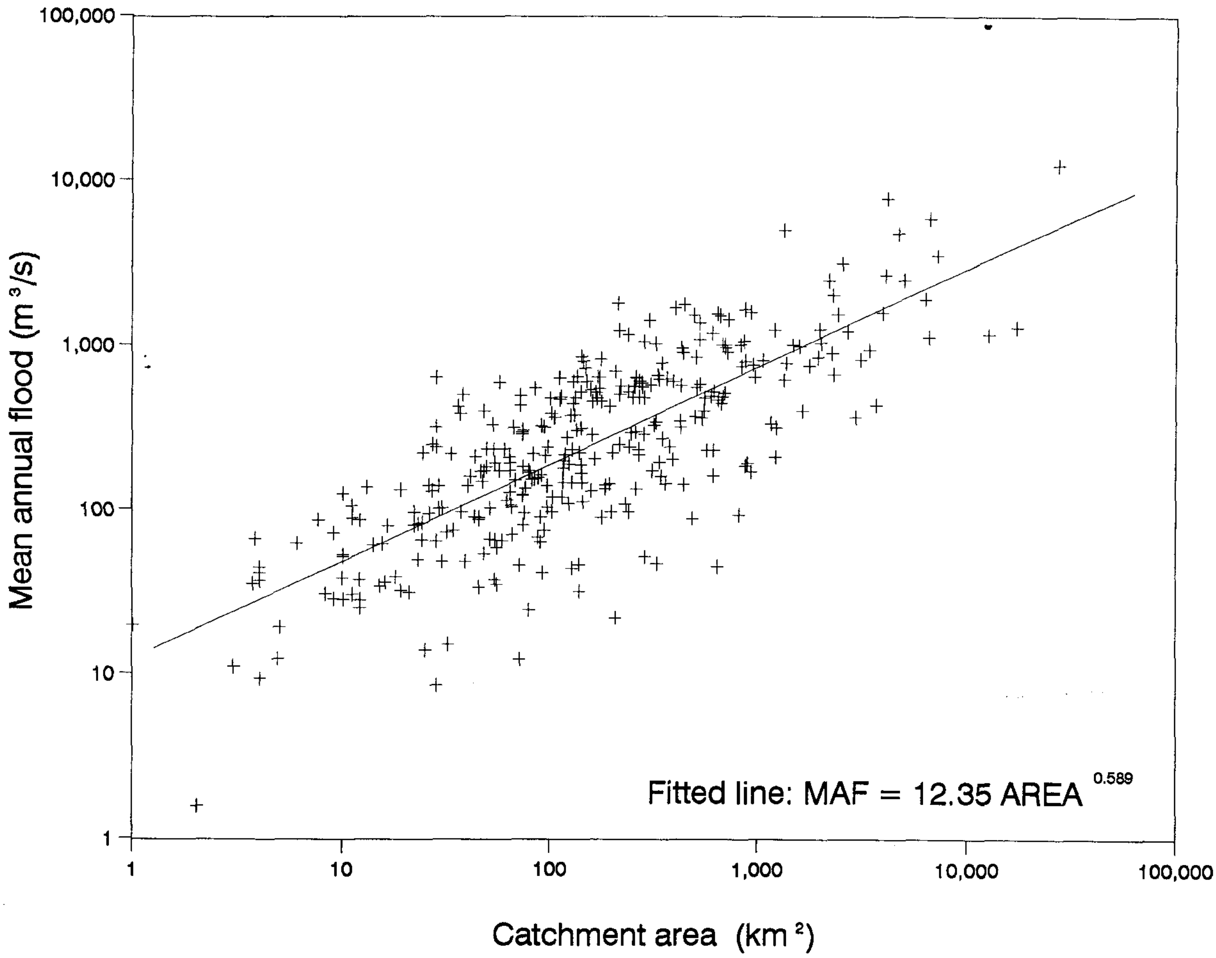

Figure A4

TABLE A2 *MAF regressions for three geographical groupings*

	No. of stations	Constant	Exponent	r^2	f.s.e.e
Regions 1-2	49	15.33	0.623	0.675	1.92
Regions 3-8	222	11.66	0.616	0.638	2.10
Regions 9-12	62	11.50	0.502	0.459	2.61

To examine the effect of geographical location on the regressions they were repeated separately for each of the 12 water resources regions into which the country has been divided (the regions used were those defined in National Water Resources Council (1980), and are shown on Figure A1). These results are also given in Table A1. Many of the regions are similar to the regression for all stations, but the differences are greater in the south of the country, and in this area the regressions are less well defined. This could be due to greater inherent variability in this area, to poorer quality data or to the fact that there are fewer stations in the southern regions. For two of the regions (9 and 11) the exponents of the regressions were not significantly different from zero, and the coefficients of determination are very low. In both these cases there is a relatively small range in catchment area, meaning it is difficult to determine adequate regression lines. Overall, there does not appear to be a very systematic pattern in the regressions for the different regions, and it is thought that much of the difference between regions can be attributed to differences in the availability of data and the range of catchment sizes that are observed. However, it is clear that there is a difference in flood behaviour in different parts of the country, with a general tendency for large MAFs towards the north.

To investigate this further, regressions were tried for various groups of regions. The most logical groupings appeared to be to divide country into three areas: water resources regions 1 & 2 in the north of Luzon; regions 3 to 8 in central and southern Luzon and the Visayas; and regions 9 to 12 in Mindanao. The results of the regressions for these three areas are given in Table A2 and are plotted in Figure A5. While the differences between the groupings are not statistically significant, the plot shows that there is a clear tendency for increasing MAF towards the north, especially for larger catchments. This result also corresponds well with the behaviour of tropical cyclones over the Philippines. From the map produced by PAGASA (no date) it can be seen that the incidence of cyclones crossing the country is greatest from July to December and that the tracks of these almost invariably cross the northern part of the country; conversely in the rest of the year when cyclone tracks are more southerly the frequency of storms is about an order of magnitude less. Based on this, the three separate regression equations given in Table A2 are considered to provide the best MAF prediction method. The coefficients of determination for the two northern regions are reasonable, with 68% and 64% of the variation explained by the regression. The factorial standard errors of the estimates are 1.92 and 2.10, meaning that the 'true' MAFs are likely to fall within about +100% and -50% of the estimates given by the equations. These

Mean annual flood against catchment area for geographical groupings of stations

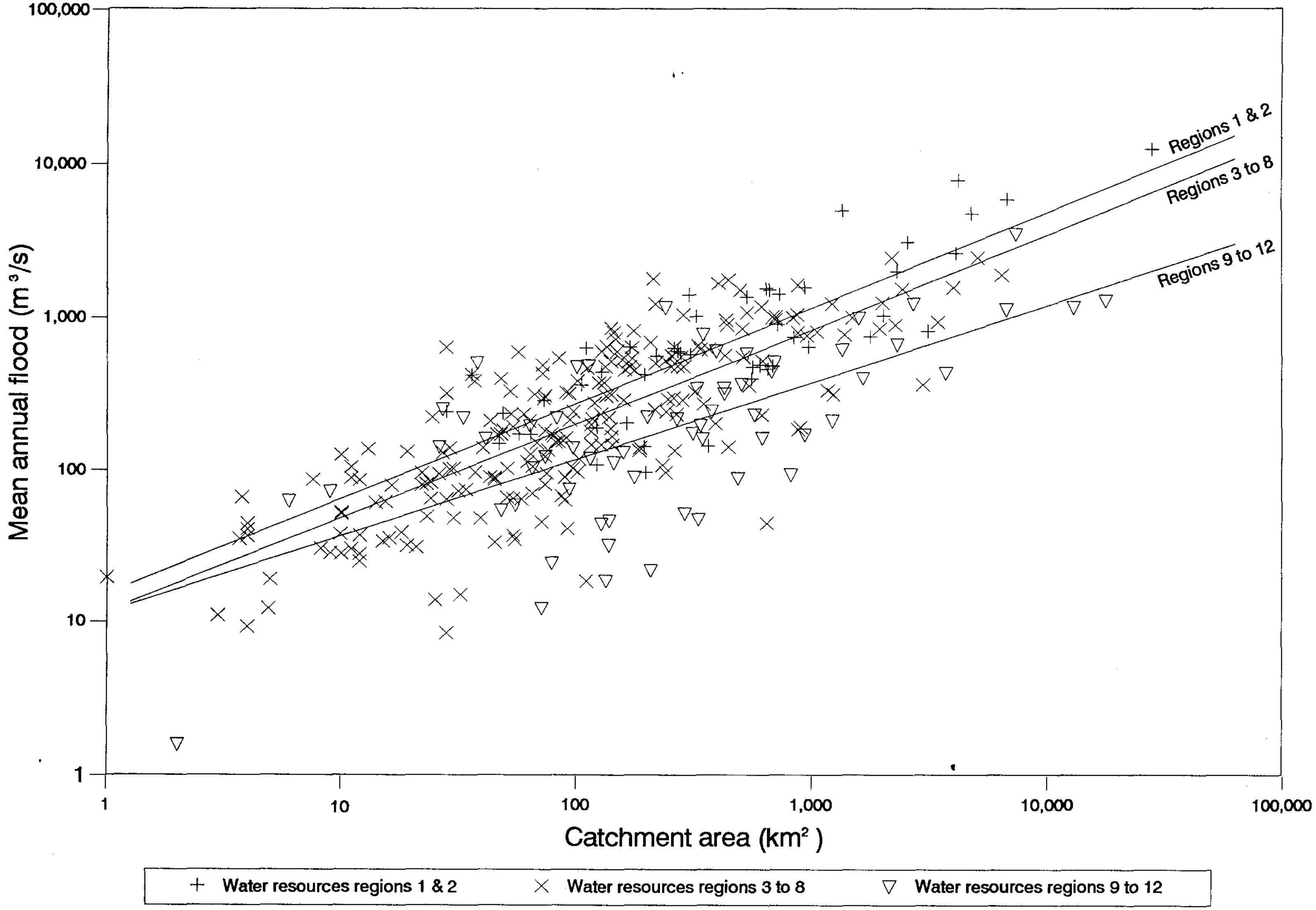

Figure A5

prediction equations are not dissimilar to those obtained for a range of other countries and regions. However, the equation for the southern area (regions 9-12) is much weaker, with r^2 of only 46% and f.s.e.e. increased to 2.61. This is a rather poor estimation equation, but as it reflects the observable differences in MAFs between the south and north of the country, it is felt that it is best to retain it.

A3 Regional flood frequency curves

Regional flood frequency curves were derived by fitting the GEV distribution to the pooled annual flood peak data for various groups of stations. As for the MAF regressions, the suitability of dividing the stations into groups according to their climate type, according to geographical location, and according to catchment area was investigated.

The results for the four climate types are given in Table A3. The curves for climate types 1, 3 and 4 are very similar while that for type 2 is considerably steeper, showing generally larger floods in this climate. However, this result was thought to be more due to the distinctly smaller catchments with this climate (median catchment area for climate type 2 is 45 km^2, compared to 176, 169 and 128 km^2 for the other three climates), than due to any effects of the climate itself on flood behaviour. When the curves for each of the 12 water resources regions were examined, there was found to be considerable variation between the regions, but no logical pattern of variation between the different regions was found, and it was thought that the main factors causing differences were the different sizes of catchments and random effects. The three geographical groupings used for the MAF prediction equations show increasingly steep curves moving from north to south (Table A3), but again, this is partly due to again different sizes of catchments in the groupings, and there was wide variability within each of the three regions.

TABLE A3 *Regional flood frequency curves for the Philippines grouped by climate type and by geographical region*

	No. stations	No. years	GEV parameters			Predicted floods		
			u	α	k	q_{20}	q_{100}	q_{500}
Climate type 1	101	1867	0.663	0.457	-0.1411	2.35	3.62	5.21
Climate type 2	57	1024	0.600	0.424	-0.2735	2.54	4.51	7.53
Climate type 3	117	1907	0.653	0.441	-0.1773	2.38	3.79	5.65
Climate type 4	58	948	0.648	0.434	-0.1930	2.39	3.86	5.86
Regions 1-2	49	773	0.679	0.459	-0.1112	2.29	3.43	4.79
Regions 3-8	222	4057	0.641	0.447	-0.1879	2.42	3.91	5.91
Regions 9-12	62	916	0.638	0.405	-0.2451	2.41	4.09	6.57

Regional flood frequency curves for the Philippines

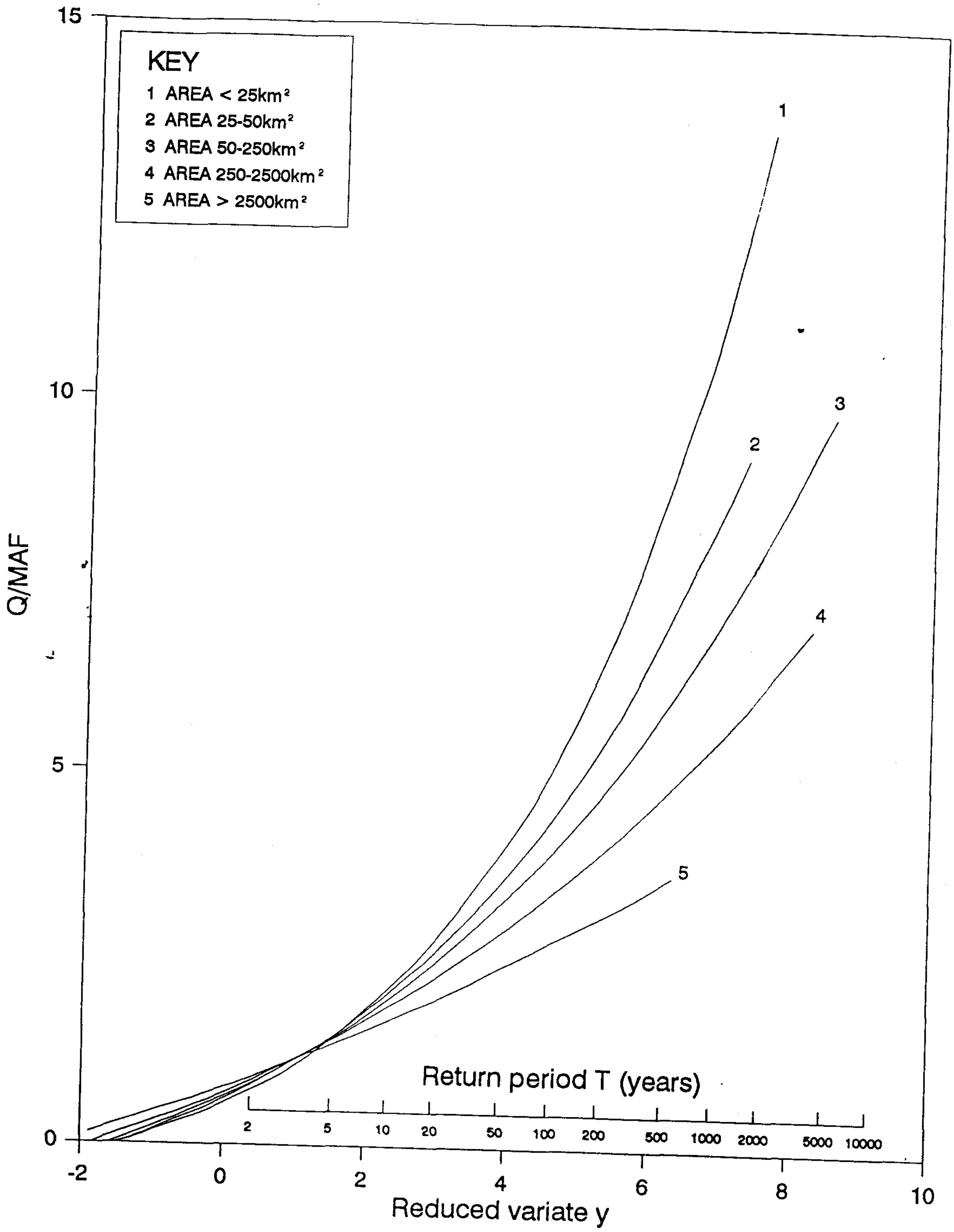

Figure A6

Another approach of grouping catchments from the whole country, according to catchment area, was found to be the most effective determinant of the flood frequency curve. A number of different groupings were tried, and the results for the most effective groupings are given in Table A4. The regional flood frequency curves are also plotted in Figure A6. These results show that catchment area is a powerful factor in determining the flood frequency curve, with the smallest catchments (less than 25 km^2) having particularly steep curves and the largest catchments rather flat curves. Within each grouping there was found to be considerable variation between individual station curves, but less so than for the groupings in Table A3, and the regions grouped by catchment area were judged to be reasonably homogeneous. The variation between stations was not beyond what might reasonably be expected, especially considering the short length of many of the records and the problems with data quality as discussed in Section A1.2. Further investigation of the effect of the climate type and of location of the catchments with these are groupings showed again that these factors cannot easily be used to improve the results.

It was concluded that the regional flood frequency curves grouped according to catchment area provide reasonable estimates which can be used over most of the Philippines.

TABLE A4 *Regional flood frequency curves for the Philippines grouped by catchment area*

AREA range	No. stations	No. years	GEV parameters u	α	k	Predicted floods q_{20}	q_{100}	q_{500}
< 25 km^2	47	887	0.558	0.450	-0.2941	2.69	4.95	8.54
25 to 50 km^2	37	646	0.603	0.466	-0.2206	2.56	4.32	6.81
50 to 250 km^2	127	2208	0.641	0.457	-0.1752	2.42	3.88	5.79
250 to 2500 km^2	104	1762	0.696	0.422	-0.1276	2.22	3.34	4.70
> 2500 km^2	18	243	0.768	0.356	-0.0715	1.94	2.70	3.55

A4 Evidence for changes in flood peaks over time

As mentioned at the beginning of this Appendix, it is of particular interest to examine the evidence for changes in flood behaviour over time. To do this stations having at least 15 years of data, and at least 4 values after 1980 were selected. 43 stations satisfying these criteria were found. The annual flood peaks for these stations, as available in the period 1945 to 1993, are plotted in Figure A7. The values are plotted as standardised deviation from the mean so that they all appear on a common scale.

Two methods of looking for changes over time were used. The first was to search for trends in the series. This was done by carrying out linear regressions of the annual peaks against

Variation in flood peaks over time

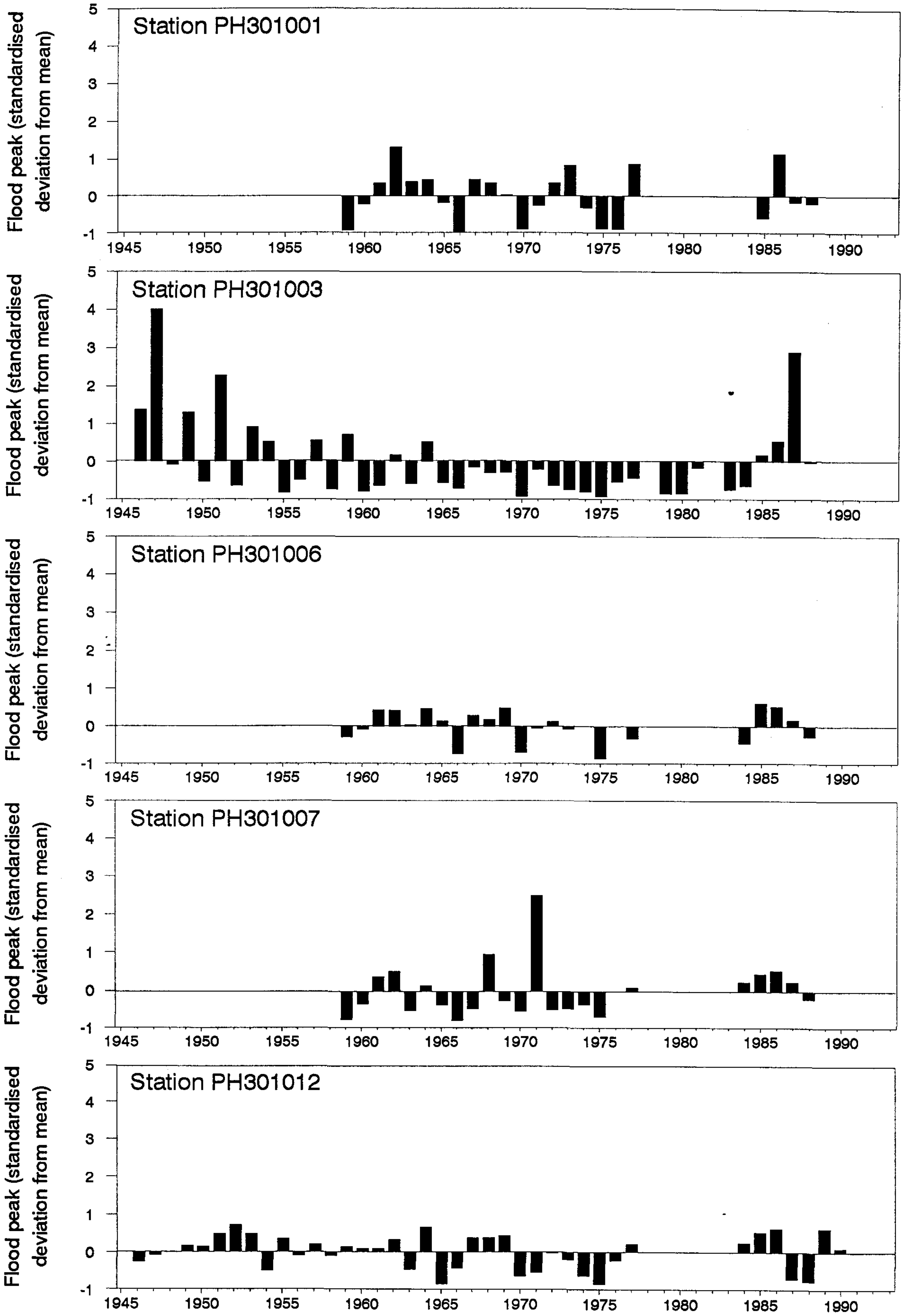

Figure A7 (continued...)

Variation in flood peaks over time

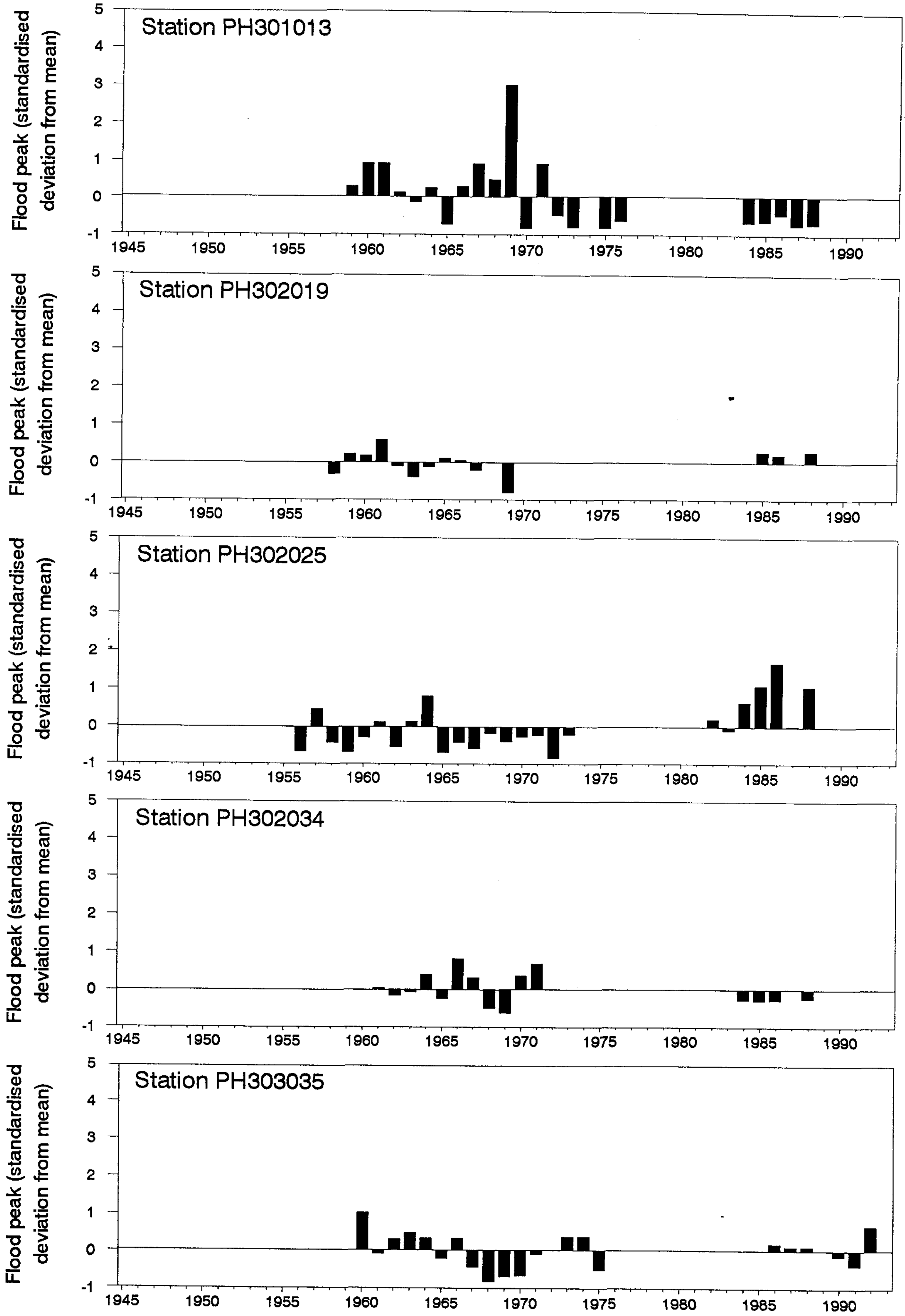

Figure A7 (continued...)

Variation in flood peaks over time

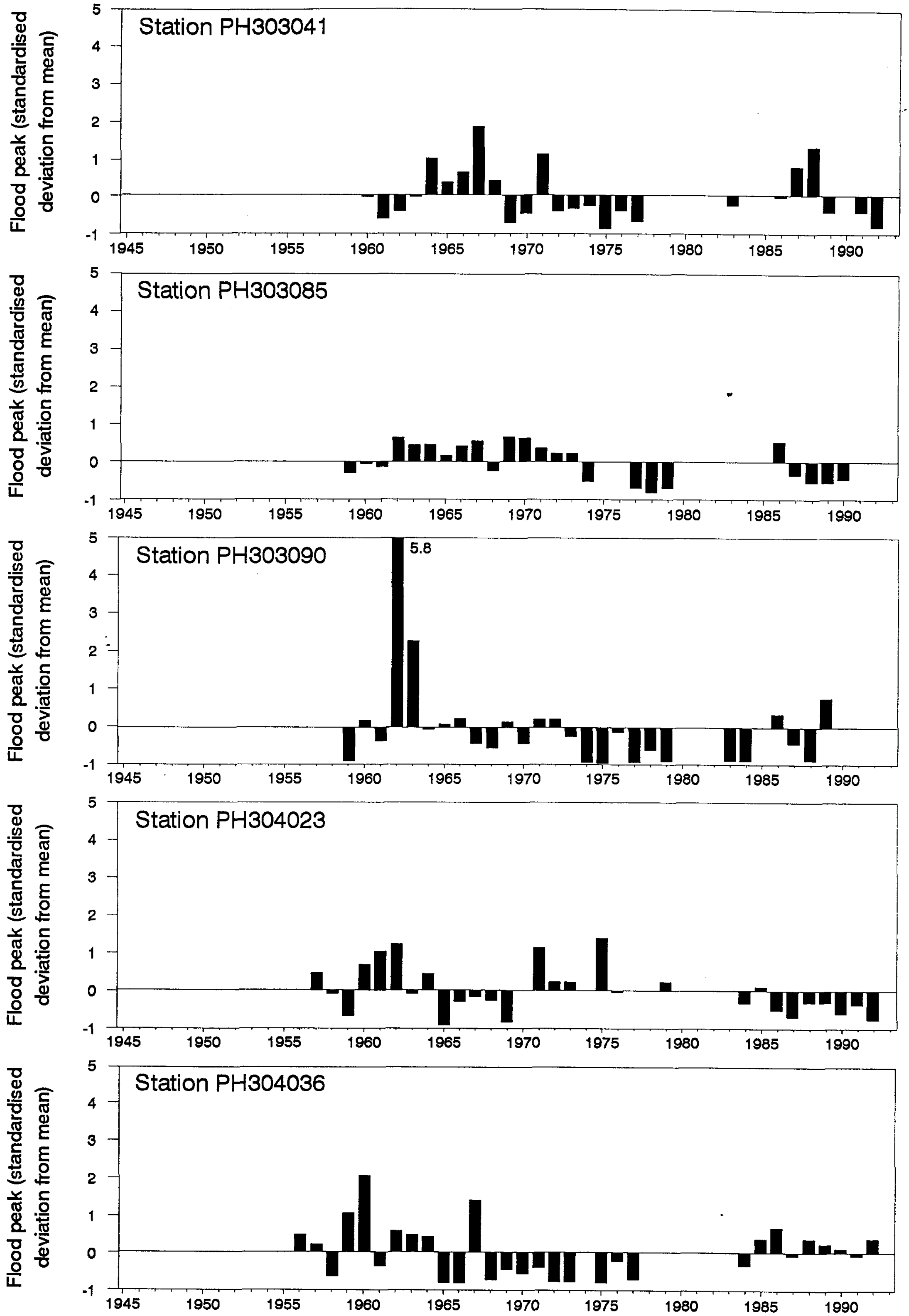

Figure A7 (continued...)

Variation in flood peaks over time

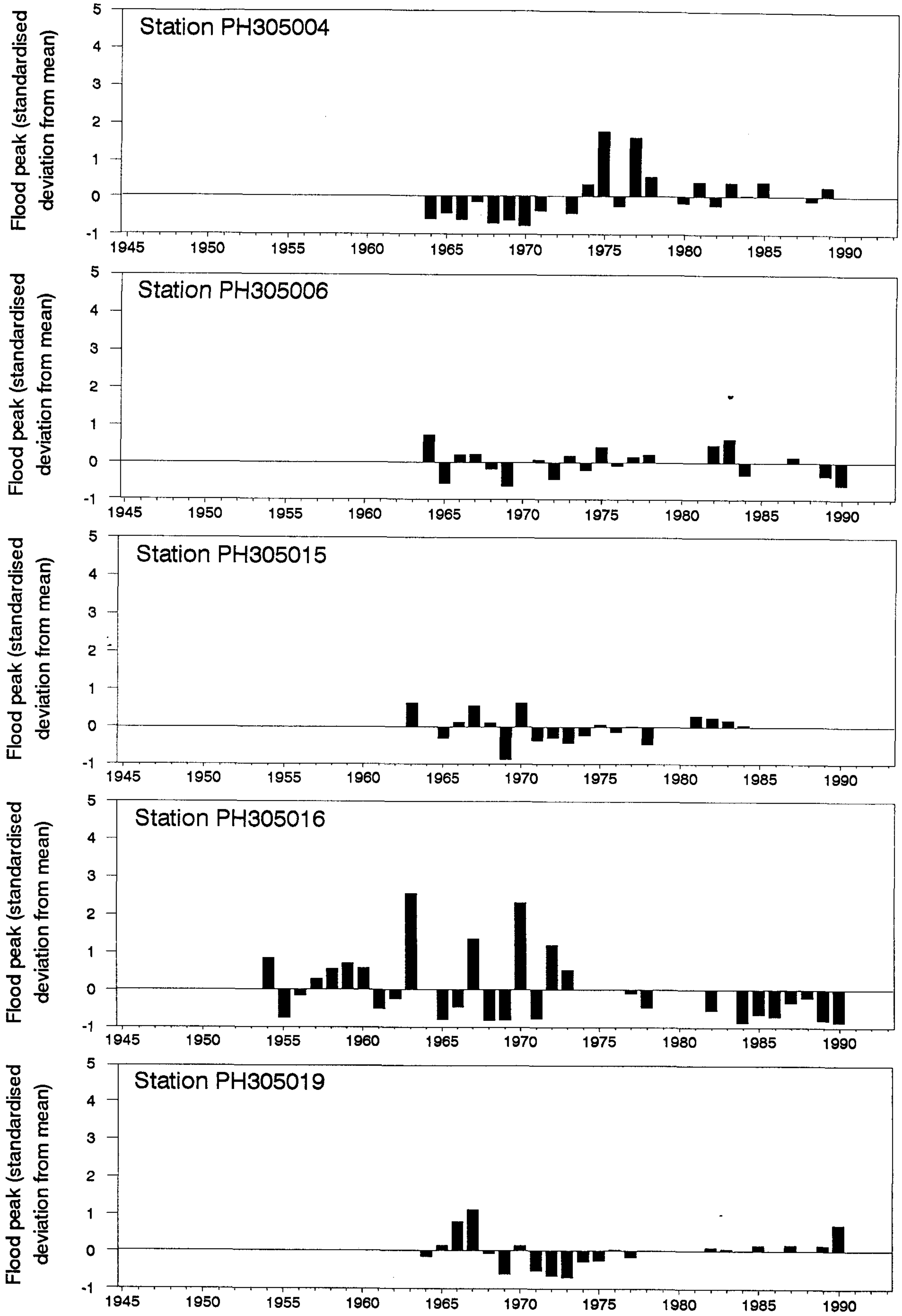

Figure A7 (continued...)

Variation in flood peaks over time

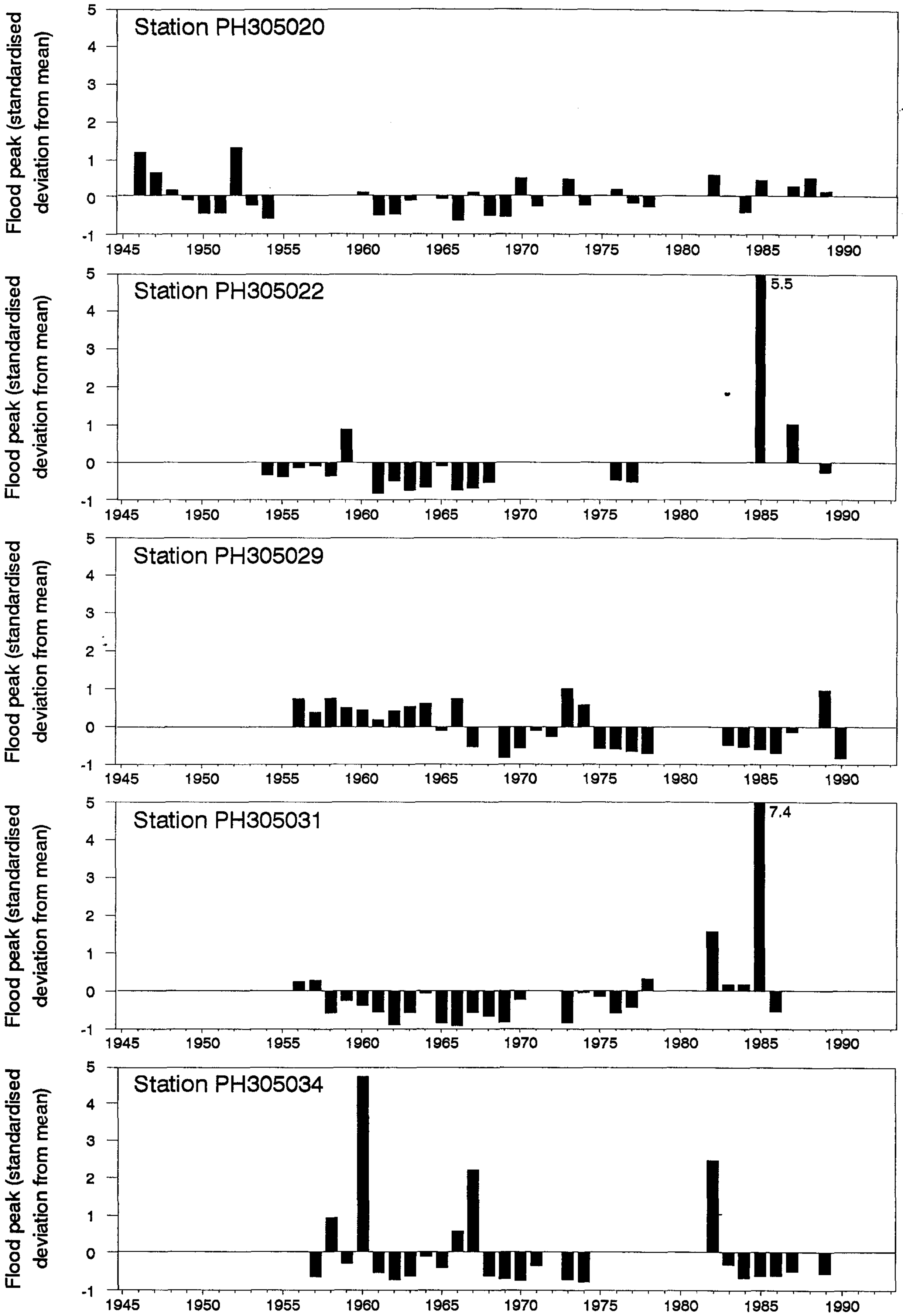

Figure A7 (continued...)

Variation in flood peaks over time

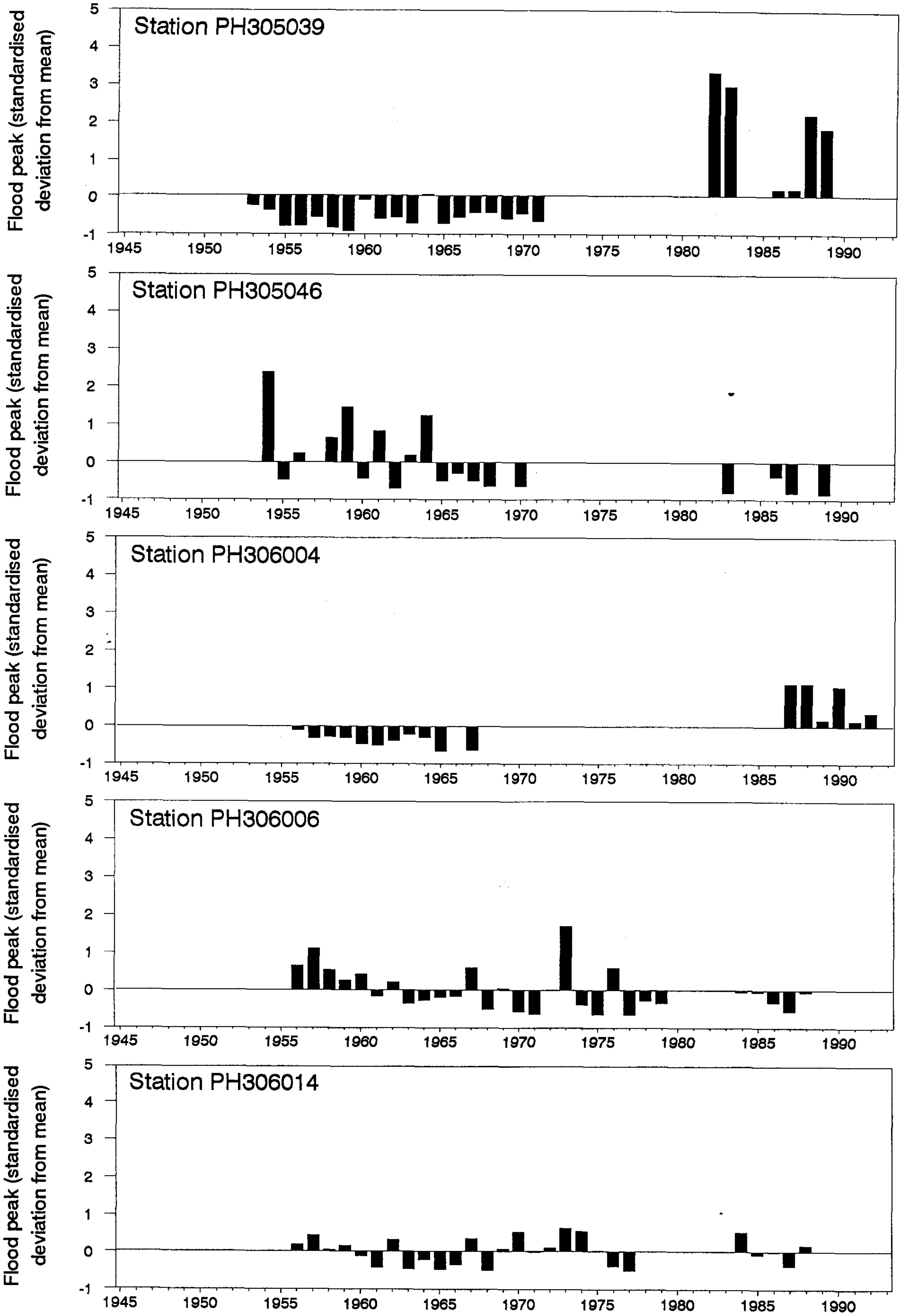

Figure A7 (continued...)

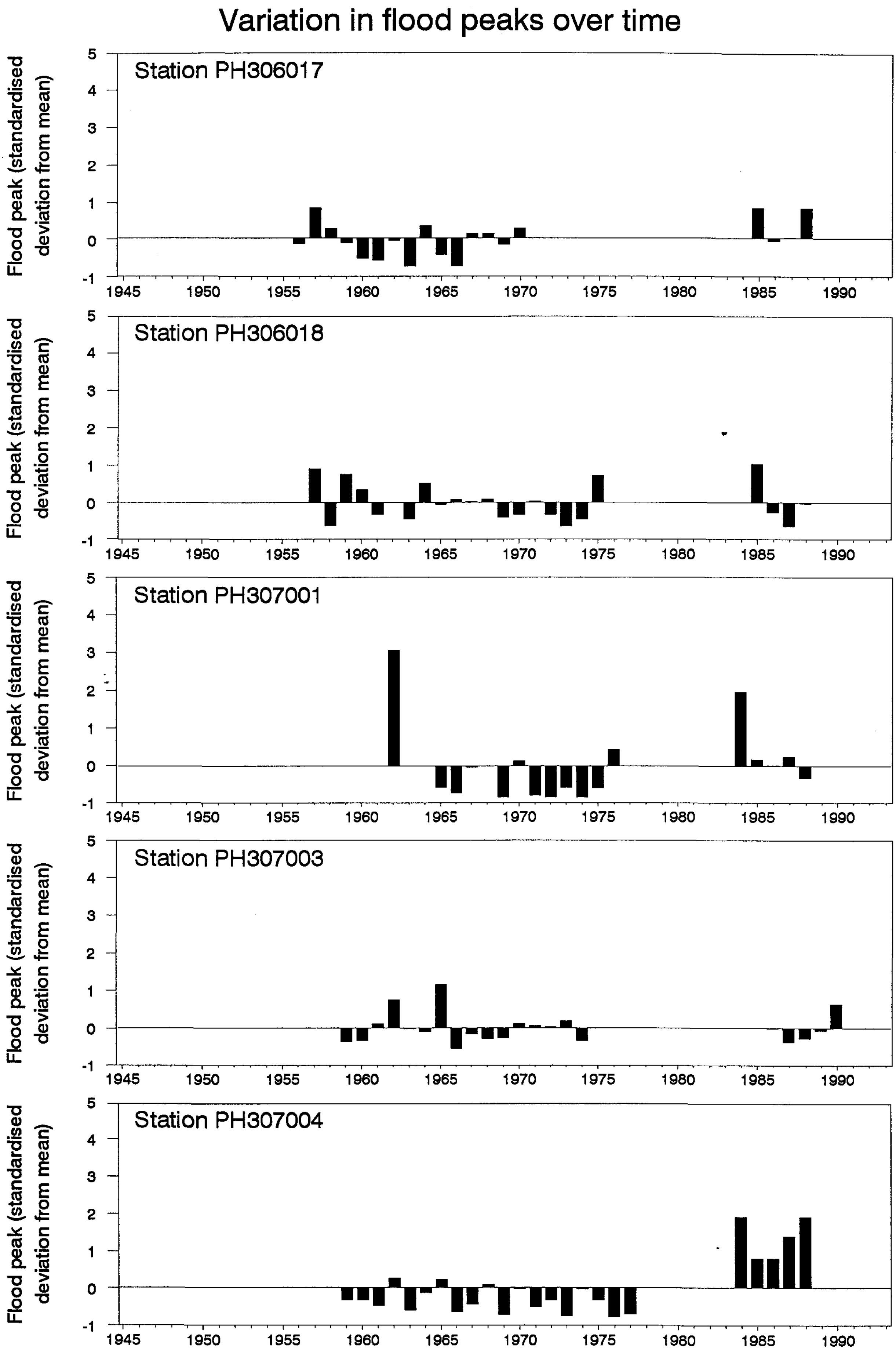

Figure A7 (continued...)

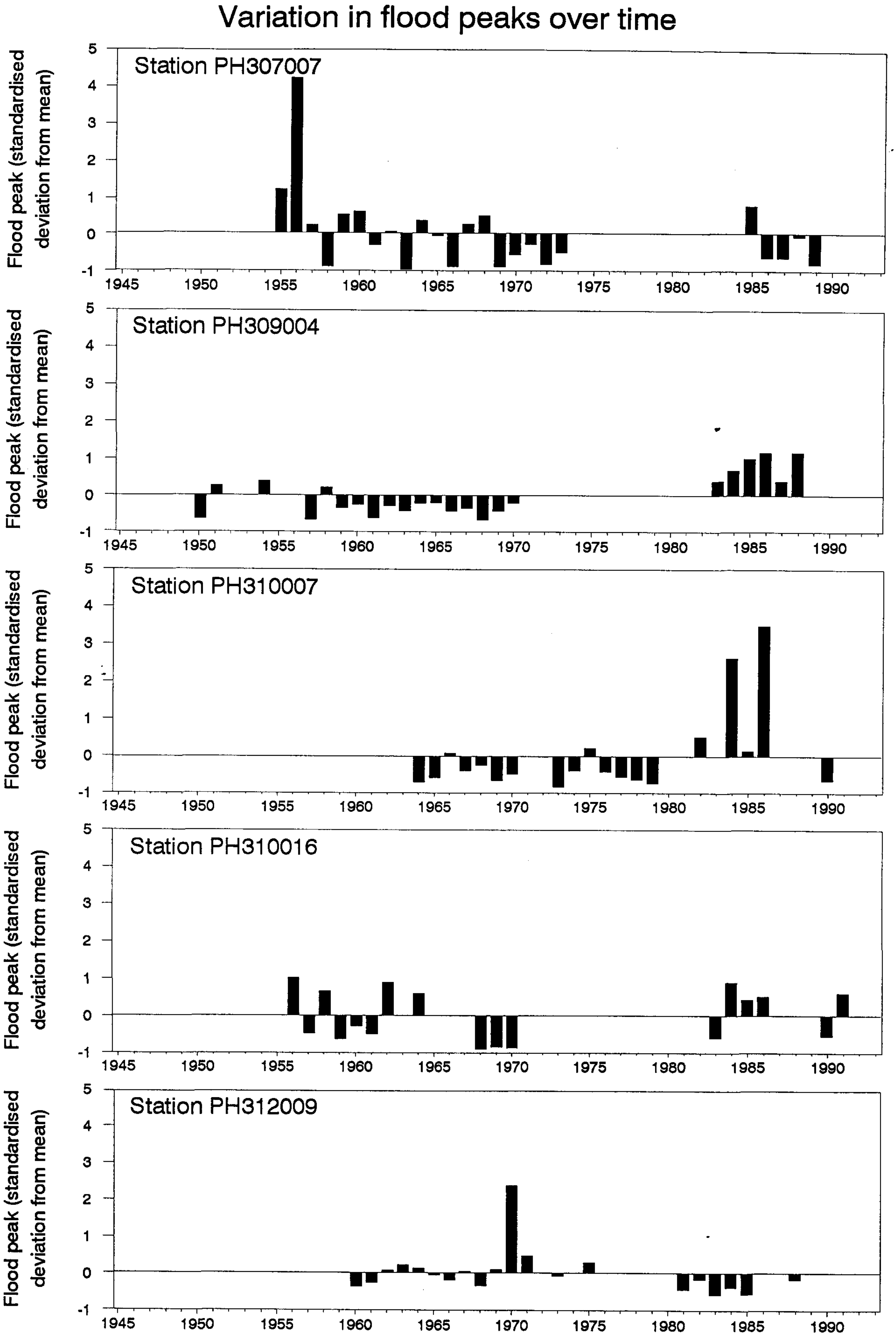

Figure A7 (continued...)

Variation in flood peaks over time

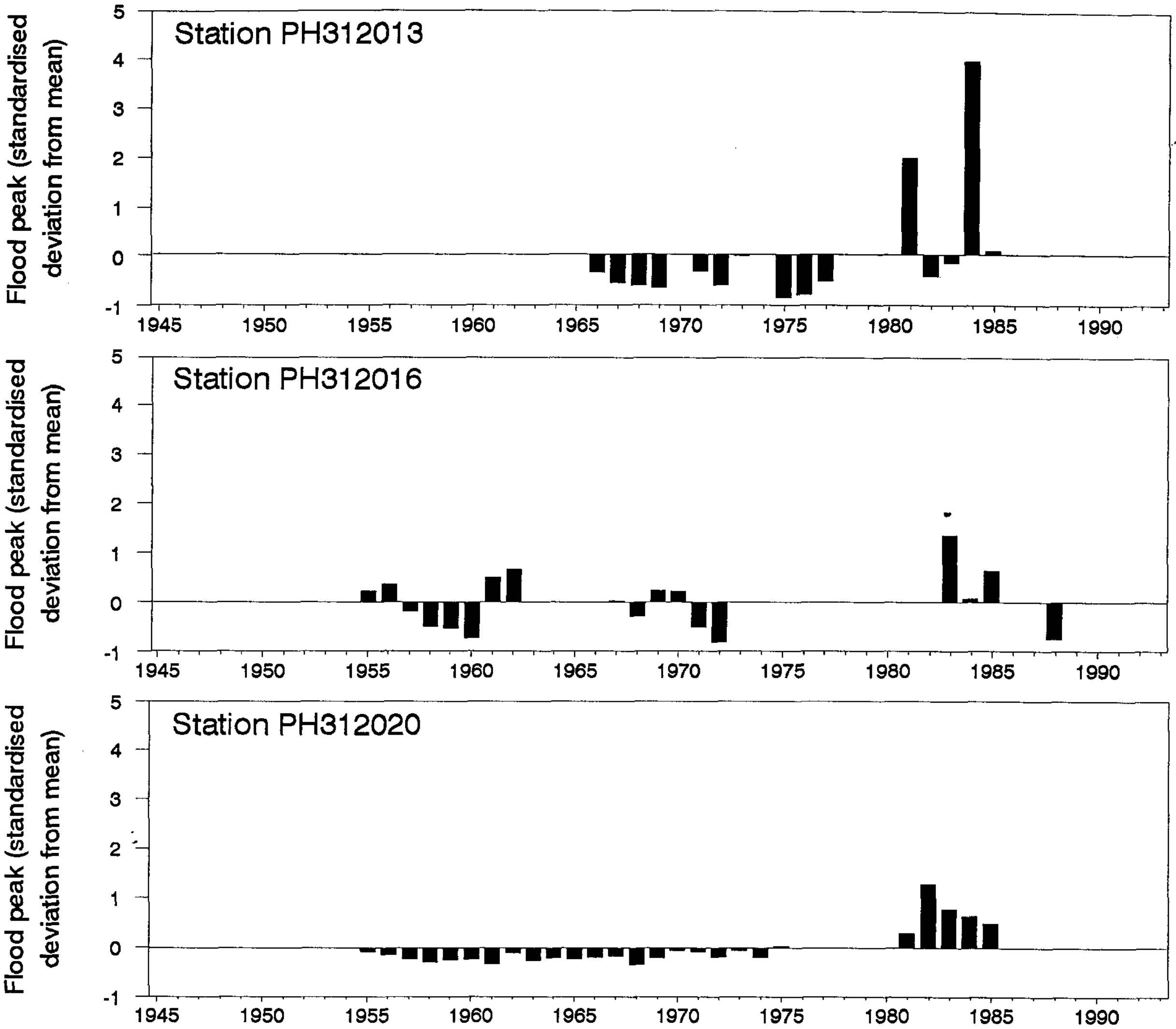

Figure A7

the year, and testing whether the slope of the fitted line was significantly different from zero. The second method was to compare the values for the period after 1980 to those for the earlier period. The year 1980 was chosen to split the data because the break in the records most often occurs around this time; also, it is recent changes that are of most interest and this is the latest date which would still leave a reasonable amount of data in the more recent period; even so, in many cases there are only four years of data after 1980 and the statistics in this period can only be estimated with poor accuracy. The Mann-Whitney rank-sum test was used to test the significance of the change between the two periods. This is a non-parametric test which looks at the change in the medians. It is preferred to the more usual t-test which examines the changes in the mean, because the t-test assumes the data are normally distributed, while the flood peaks actually have a much more skewed distribution.

Table A5 presents the results of these tests, with the stations having a downward trend given first, followed by those with an upward trend. In each case the stations are listed in order of increasing trend. The next to last column of the table gives the ratio MAF_2/MAF_1 where MAF_1 is the mean annual flood for data up to 1980 and MAF_2 refers to data after 1980. The last column gives the results of the significance test for the medians of these two periods.

The results of the tests are rather mixed. Looking at the trend test, 24 stations have a downward trend compared to 19 which are upward. However, if only the trends that are significant at the 5% level are considered, 7 are downwards and 11 upwards. Thus, overall, there appears to be more of a tendency for flood peaks to increase rather than decrease. Examining the period after 1980 against the earlier period shows a more decisive tendency towards increasing flood peaks. Of the 43 stations, 29 have the ratio MAF_2/MAF_1 greater than 1, while for 14 stations it is less than 1. The test for significant changes in the median shows that 11 sites have an increase in median significant at the 5% level, while 4 have a significant decrease. This is far more than would be expected by chance.

These results seem to indicate a definite tendency for there to be an increase in flood peaks after 1980. However, there are several points which complicate this conclusion. First, it is worrying that some stations show such a strong opposite tendency. If there had been a general change in flood behaviour, for instance due to deforestation which has proceeded over most of the country, one would expect nearly all sites to show the same trend. Instead we find that most sites show no significant change, a proportion show significant increases and a smaller proportion significant decreases. In the light of the difficulties of compiling the flood peak series and the high levels of uncertainty in the data (see Section A1.2), there is the suspicion that these apparent changes over time are the result of the inadequate quality of the data. In particular, changes in hydrometric practices and in the rating curves used could easily cause the changes that have been observed, and this would also explain the unsystematic nature of the changes. Some of the plots in Figure A7 tend to support these suspicions; for instance the plots for stations PH305039 or PH306004 look very strange and lead one to suspect errors in the data. A further uncertainty is where new records have been started which may not always be at the same site as the previous data. And finally, the correction which has been introduced to allow the estimation of instantaneous peaks at staff gauge sites may be introducing errors where there is a change from autographic recorder to staff gauge and the date of the change is not precisely known. Because of these difficulties, it must be concluded that the case for an increase in flood peaks in recent years is not proven. Further studies, in particular the detailed and careful re-examination of the data at

TABLE A5 *Examination of changes in annual flood peak data over time*

Station code	Total no. values	No. values 1981->	Coeff. regress. line	Student's t-value of coeff.	Trend signif. at 5% ?	Ratio MAF_2: MAF_1	Medians different (5%) ?
Trend downwards							
305020	34	7	-0.01	-0.01	No	1.27	No
304036	30	9	-0.05	-0.46	No	1.28	No
303035	21	6	-0.31	-0.17	No	1.12	No
305006	20	6	-0.36	-0.43	No	0.98	No
307003	21	5	-0.42	-0.09	No	0.98	No
305015	19	4	-1.44	-0.18	No	1.27	No
301012	40	8	-1.55	-0.69	No	1.11	No
305034	24	7	-1.61	-0.96	No	0.83	No
304023	28	9	-2.18	-2.12	Yes	0.49	Yes
307007	24	5	-2.46	-1.90	No	0.65	No
303041	25	7	-2.68	-0.63	No	1.01	No
303090	27	6	-2.91	-1.71	No	0.63	No
306018	23	4	-3.33	-0.61	No	1.04	No
312009	21	6	-3.47	-1.05	No	0.52	Yes
305046	19	4	-4.02	-2.86	Yes	0.24	Yes
305016	29	8	-4.18	-2.09	Yes	0.30	Yes
305029	29	7	-4.45	-3.17	Yes	0.62	No
301006	22	5	-6.00	-0.19	No	1.15	No
301003	41	7	-7.19	-1.89	No	1.37	No
301001	23	4	-7.23	-0.09	No	1.06	No
303085	24	5	-15.3	-2.64	Yes	0.68	No
306006	28	5	-17.4	-2.06	Yes	0.76	No
301013	22	5	-21.2	-2.50	Yes	0.28	No
302034	15	4	-83.3	-1.22	No	0.67	No
Trend upwards							
307001	17	5	0.20	0.10	No	1.72	No
305019	20	6	0.27	0.63	No	1.36	Yes
306014	27	5	0.56	0.07	No	1.05	No
312016	18	4	2.01	0.62	No	1.48	No
307004	24	5	2.10	4.27	Yes	3.71	Yes
312013	15	5	2.50	2.22	Yes	4.57	Yes
310016	17	6	4.70	0.33	No	1.40	No
305031	26	5	5.49	2.19	Yes	4.71	Yes
309004	23	6	6.60	4.44	Yes	2.53	Yes
306004	17	6	7.56	4.97	Yes	2.63	Yes
301007	23	5	9.26	0.87	No	1.36	No
305022	21	4	9.39	2.00	No	4.10	Yes
302019	15	4	10.5	0.82	No	1.28	No

TABLE A5 *(continued)*

Station code	Total no. values	No. values 1981->	Coeff. regress. line	Student's t-value of coeff.	Trend signif. at 5% ?	Ratio MAF_2: MAF_1	Medians different (5%) ?
306017	19	4	18.2	1.65	No	1.56	No
305004	23	8	22.5	2.09	Yes	1.23	No
305039	25	6	31.9	5.13	Yes	6.26	Yes
312020	26	5	37.0	5.74	Yes	2.05	Yes
310007	20	5	41.7	2.30	Yes	3.77	Yes
302025	25	7	54.6	3.43	Yes	2.25	Yes

individual sites to ensure only properly validated records are tested, and the examination of the circumstances in the catchments which may be responsible for the changes, should be carried out to conclude this issue definitively.

The results presented here must be treated as very preliminary. However, as they *do* show a tendency for increase in flood peaks, it would be prudent to take them into account in some degree. To do this, it is suggested that approximately the median of the ratios of the mean annual flood between the two periods should be used. This median ratio is 1.23. In deriving the MAF regression, the more recent data were also included, but these will not have had much effect as they are dominated by the far greater quantity of older data. Thus, in round terms an increase of 20% should be applied to mean annual flood estimates derived using the regression equations given in Section A2. There are far too few recent data to allow the flood frequency curves to be adjusted to take account of the possible changes, and these should not be altered. Overall, these results, must be treated as preliminary, and need to be confirmed by a more detailed study.

A5 Comparison to existing methods

The only existing flood estimation method for the Philippines which has national coverage is that developed by the National Irrigation Administration (NIA, 1986). The method is a regional analysis somewhat similar to that used here. The log-Pearson type III frequency distribution is used and a regression analysis relates MAF to catchment area. The results are presented as graphs for each region, from which the flood peak for a variety of return periods can be read off directly, given the catchment area. Generally, the NIA method is a satisfactory approach, but it has a number of shortcomings. There is no mention of data quality in the report, and it is felt that it is inappropriate to carry out such an analysis without at least a preliminary assessment of the adequacy of the data being used. The method does not try to overcome the problem of the poor observation of flood peaks at staff gauge stations, and this could lead to significant under-estimation of floods in small catchments. The water resources regions are used to define the regions for the method without any consideration of the best way to pool the data, and the effect of catchment area on the flood frequency curve is not considered. Finally, the flood is estimated directly from the catchment area, whereas a two-stage approach which first estimates the MAF and then goes on to find the flood for a particular return period is preferable, as this allows the estimates to be improved by the incorporation of local data into the assessment of MAF.

The results of the NIA method and the new method developed in this study are compared in Figure A8 which shows the predicted floods for MAF, 20-year and 100-year return periods for catchment areas of 10, 100 and 1000 km^2. It can be seen that the results from this study are broadly similar to the NIA method for medium-sized catchments of 100 km^2, but give generally higher flood estimates for small catchments of 10 km^2. For large catchments of 1000 km^2, the results are again similar except in a few regions where the NIA estimates are much higher. The reasons for these discrepancies are likely to be that, for small catchments, the NIA method did not incorporate the adjustment to account for the under-estimation of flood peaks at staff gauge stations, thereby producing estimates which are too low. For the large catchments, particularly in regions 1 and 4, it is believed that the NIA estimates are too high, and this has been brought about by unjustified extrapolation of the regression relationship between MAF and catchment area to large catchments, when there were very few large catchments in those regions.

As discussed above, it was found that simply using the water resources regions to define the regions for flood frequency analysis is not the best approach, and it was also found that catchment area is the most significant factor in distinguishing the flood frequency curves. For these reasons, it is considered that the new flood estimation method derived in this study should be preferred.

A6 Conclusions and recommendations for further studies

The conclusion of the study is that the regression equations listed in Table A2, that is:

$MAF = 15.3\ AREA^{0.623}$ for water resources regions 1 & 2,
$MAF = 11.7\ AREA^{0.616}$ for water resources regions 3 - 8, and
$MAF = 11.5\ AREA^{0.502}$ for water resources regions 9 - 12

should be used to estimate mean annual flood at ungauged sites, but the resulting MAFs should be increased by 20% to account for the possible tendency for flood peaks to have increased in recent years. Where a reasonable length of good quality data is available at or close to the site of interest, these should be preferred for the estimation of MAF. The regional flood frequency curves grouped according to catchment area (presented in Table A4 and Figure A6) should then be used to estimate the flood peak for the required return period. Although it is rather preliminary, this method provides an adequate means of making flood peak estimates at ungauged sites over most of the Philippines. The MAF regression equation is less reliable for Mindanao (regions 9-12), and there are no data from Palawan and some outlying islands, so the method should only be used with caution in these areas. The regional

Comparison of flood estimation methods for the Philippines

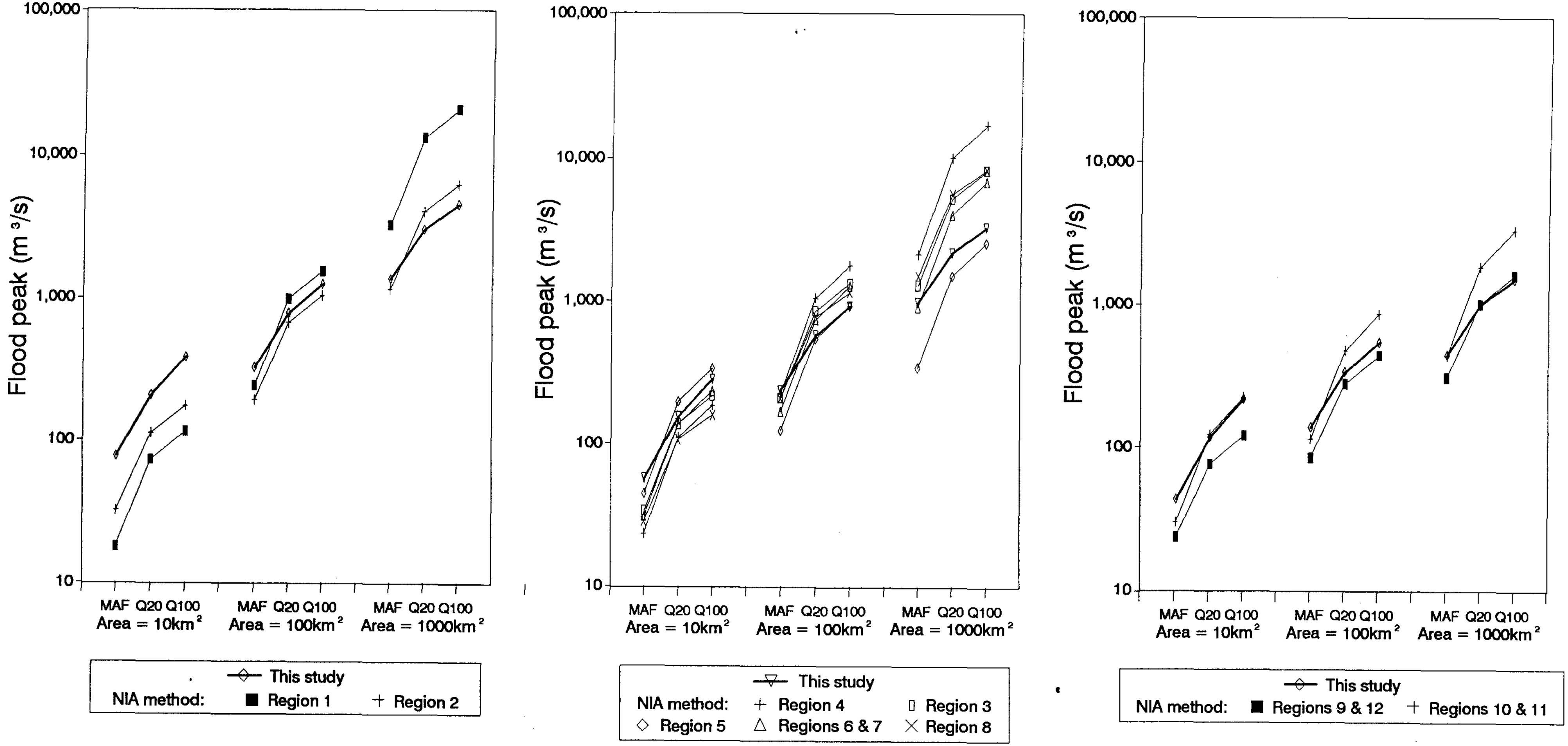

Figure A8

curves are also useful to make estimates for long return periods even at sites which do have a reasonable observed flow record.

Because of the relatively poor quality of the available data and the fact that flood peaks at the staff gauge stations are not observed properly, the results presented here are inevitably somewhat preliminary. A major study would be needed to improve the situation and produce improved flood estimates. In brief, the elements of such a study would include:

- Careful validation of all data, including checking rating curves for each site, checking that peaks are not missed because of overtopping or diversion around the gauge or because of periods of missing data.

- Refinement of the method used to estimate instantaneous peaks at staff gauge sites, including checking of the precise periods when autographic recorders were in operation. In cases where it is not possible to adequately estimate the instantaneous peaks at a particular site, the station should be eliminated from the study.

- Checking the precise location of each flow gauge in the field, and using these checked locations to re-evaluate all the catchment areas.

- Based on the checked locations, estimate mean annual rainfall (if data are sufficient) and a range of other physical and climatic characteristics of the catchments.

With this validated database it would be possible to derive a more reliable flood estimation method, based on the best available data. As for the possible changes in flood behaviour over time, only with carefully validated long-term records and continued good quality observations at these sites, will it be possible to determine the extent of the changes that may be occurring.

A7 List of river flow gauging stations and catchment characteristics

The table on the following pages lists the river flow gauging stations used in the study. For each station, the station code, name, number of years of annual flood peaks, location, mean annual flood (MAF), catchment area (AREA), and modified Coronas climate type are given. These were derived as explained in Section A1 above. Where data are from staff gauges, the MAF values have been adjusted to take into account the under-estimation of flood peaks by these gauges (Section A1.3).

The station codes used consist of 8 characters; the first two are PH, and the remainder are the 6 digit number assigned by HR Wallingford *et al.* (1994). The first digit indicates the agency responsible for the data; always 3, for BRS, in this study. The second and third digits are the water resources region number, and the remaining digits are an identifier for the station within that region.

Station code	Name	No. years	Latitude (°N)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	Climate type
Region 1							
PH301001	Laoag at Poblacion, Laoag, Ilocos Norte	23	18:12:12	120:35:18	4902	1355	1
PH301002	Bonga at Bangay, Dingras, Ilocos Norte	32	18:05:00	120:42:00	1336	534	1
PH301003	Gasgas at Manalpac, Solsona, Ilocos Norte	41	18:04:47	120:50:06	285	73	1
PH301004	Abra at Banaoang, Bantay, Ilocos Sur	19	17:33:20	120:28:30	4703	4813	1
PH301005	Tineg at Pangot, Lagayan, Abra	20	17:45:10	120:44:20	1487	664	1
PH301006	Abra at Bumagcat, Tayum, Abra	22	17:36:57	120:43:35	3058	2575	1
PH301007	Sinalang at Lingsad, Penarubia, Abra	23	17:32:20	120:39:20	626	111	1
PH301009	Sta. Maria at No.2 Sabangan-Pingan, Burgos, Ilocos S.	16	17:16:27	120:31:14	107	123	1
PH301010	Bucong at Salvador, Candon, Ilocos Sur	26	17:13:50	120:28:50	233	49	1
PH301011	Buaya at Palali Sur, Sta. Lucia, Ilocos Sur	31	17:06:42	120:30:18	559	221	1
PH301012	Maragayap at Sta. Rita, Bacnotan, La Union	40	16:45:20	120:22:22	417	36	1
PH301013	Baroro at Cabaruan, San Juan, La Union	22	16:40:50	120:22:50	436	129	1
PH301014	Naguilian at Mamatling, Naguilian, La Union	36	16:33:35	120:23:44	1387	304	1
PH301015	Aringay at Masalep, Tubao, La Union	30	16:21:26	120:21:17	586	279	1
PH301906	Quiaoit at Batac, Ilocos Norte	5	18:03:26	120:33:42	239	28	1
Region 2							
PH302001	Baua at Baua, Gonzaga, Cagayan	20	18:21:15	122:05:30	361	106	4
PH302007	Sinundungan at Simay, Lasam, Cagayan	12	18:03:31	121:35:07	626	263	3
PH302009	Dummon at Calaoagan Dacquel, Gattaran, Cagayan	7	18:02:35	121:43:00	568	308	3
PH302011	Matalag at Escolta, Rizal, Cagayan	13	17:49:40	121:25:28	456	655	3
PH302012	Saltan at Pinukpuk, Pinukpuk, Kalinga, Apayao	5	17:37:00	121:24:00	740	846	3
PH302016	Sabangan at Supang, Sabangan, Mt. Province	6	17:00:28	120:54:21	171	57	1
PH302017	Tanudan at Baba-Alan, Tabuk, Kalinga, Apayao	6	17:23:10	121:15:42	142	365	3
PH302019	Paret at Baybayog, Alcala, Cagayan	15	17:54:22	121:41:00	1550	937	3
PH302021	Pangul at Pangul, Solana, Cagayan	15	17:39:45	121:37:30	1009	326	3
PH302025	Pinacanauan at Larion, Alto, Tuguegarao, Cagayan	25	17:37:44	121:46:12	1524	646	3
PH302027	Pinacanauan de Tumauini at Antagan, Tumauini, Isabela	7	17:17:04	121:55:48	637	170	4
PH302028	Casile at Casile, Mallig, Isabela	20	17:12:45	121:35:42	142	195	3
PH302029	Mallig at Munoz, Malingay, Roxas, Isabela	24	17:10:54	121:35:42	472	563	3
PH302030	Siffu at Munoz, Roxas, Isabela	20	17:16:42	121:25:00	478	686	3
PH302031	Pinacanauan de Iligan at Minangas, San Mariano, Isab.	10	17:05:00	121:55:00	809	3145	4
PH302033	Disabungan at Dipalin, Binatog, San Mariano, Isabela	5	16:56:46	122:03:35	96	198	4
PH302034	Cagayan at Palattao, Naguilian, Isabela	15	17:00:30	121:49:55	5758	6837	3
PH302036	Magat at Oscariz, San Antonio	25	16:51:00	121:31:35	2590	4150	3
PH302038	Ibulao at Hapid, Lamut, Ifugao	7	16:42:41	121:14:40	485	606	3
PH302039	Magat at Bato, Bayombong, Nueva Viscaya	15	16:25:55	121:07:04	744	1784	1
PH302040	Matuno at Bante, Bambang, Nueva Viscaya	15	16:27:15	121:03:30	394	558	1

Station code	Name	No. years	Latitude (°N)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	Climate type
PH302044	Diadi at Cabulay, Santiago, Isabela	15	16:43:42	121:28:58	189	123	3
PH302045	Cagayan at Pangal, Echague, Isabela	12	16:36:12	121:41:00	7688	4244	3
PH302046	Dibuluan at Minuri, Jones, Isabela	7	16:26:40	121:46:31	598	272	4
PH302047	Dabubu at Dabubu Pequino, San Agustin, Isabela	7	16:26:40	121:46:31	201	165	4
PH302048	Cagayan at Dippadin, Madella, Nueva Viscaya	6	16:23:08	121:44:26	1974	2323	3
PH302049	Addalam at Guinalyin, Aglipay, Nueva Viscaya	11	16:29:02	121:39:00	897	721	3
PH302050	Paret at Asassi, Baggao, Cagayan	7	17:54:35	121:47:20	1399	730	3
PH302901	Cagayan at Bangag, Lal-lo, Cagayan	6	18:06:42	121:40:08	12195	28048	3
PH302908	Ganano at Ipil, Echague, Isabela	6	16:41:56	121:38:06	634	977	3
PH302911	Lanog at Careb, Bagabag, Nueva Viscaya	5	16:34:28	121:11:58	171	64	3
PH302912	Magat at Baretbet, Bagabag, Nueva Viscaya	5	16:35:02	121:15:06	1012	2030	1
PH302922	Dumatata at Gamis, Saguday, Quirino	5	16:39:54	121:31:42	148	47	3
PH302923	Ganano at Aurora East, Diffum, Quirino	8	16:34:36	121:30:09	420	196	3
Region 3							
PH303001	Agno at Adaoay, Kabayan, Benguet	11	16:35:00	120:49:00	476	287	1
PH303002	Bokod at Bokod, Benguet, Benguet	22	16:35:15	120:50:00	96	102	1
PH303005	Agno at San Roque, San Manuel, Pangasinan	32	16:08:07	120:41:45	1216	1225	1
PH303006	Ambayoan at Santa Maria, San Nicolas, Pangasinan	20	16:07:10	120:46:50	550	281	1
PH303007	Agno at Carmen, Rosales, Pangasinan	29	15:53:30	120:35:30	2405	2209	1
PH303008	Agno at Poblacion, Bayambang, Pangasinan	19	15:49:07	120:27:22	886	2284	1
PH303010	Bulsa at Villa Aglipay, Tarlac, Tarlac	11	15:28:06	120:26:56	1644	405	1
PH303011	O'Donnel at Palublub, Capas, Tarlac	7	15:23:47	120:30:05	95	240	1
PH303012	Bangat at Sta. Lucia, Capas, Tarlac	10	15:23:15	120:29:14	321	91	1
PH303013	Bued at Dungon, Tuba, Benguet	28	16:14:50	120:30:50	513	141	1
PH303014	Tagamusing at San Felipe, Binalonan, Pangasinan	20	16:02:50	120:30:40	232	53	1
PH303016	Toboy at Kalipkip, San Manuel, Pangasinan	10	16:07:36	120:40:00	80	74	1
PH303019	Bayaoas at Maples, Aguilar, Pangsinan	16	15:49:24	120:15:00	127	64	1
PH303020	Agno at Dorongan, Urbiztondo, Pangasinan	10	15:52:00	120:19:32	2418	5134	1
PH303021	Pila at Pacalat, Mangatarem, Pangasinan	14	15:45:52	120:16:53	369	126	1
PH303023	Camiling at Nambalan, Mayantok, Tarlac	7	15:32:42	120:19:48	843	142	1
PH303024	Balincaguing at Nibaliw, Mabini, Pangasinan	12	16:04:10	119:56:20	794	145	1
PH303025	Nayom at Guisguis, Santa Cruz, Zambales	24	15:48:31	119:58:48	477	134	1
PH303026	Carranglan at Balwarte, Carranglan, Nueva Ecija	15	15:58:00	121:03:14	554	258	1
PH303027	Santor at San Vicente, Laur, Nueva Ecija	14	15:36:08	121:09:57	355	544	3
PH303028	Santor at Cuyapa, Gabaldon, Nueva Ecija	14	15:28:30	121:18:48	186	141	3
PH303029	Digmala at Labi, Bongabon, Nueva Ecija	12	15:38:52	121:15:50	64	59	3
PH303030	Coronel at Bankerohan, Bongabon, Nueva Ecija	19	15:35:35	121:07:35	992	709	1
PH303032	Pampanga at Malate, Bongabon, Nueva Ecija	17	15:30:57	121:02:40	1234	2015	1

Station code	Name	No. years	Latitude (°N)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	Climate type
PH303033	Cabu at Cabu, Cabanatuan City, Nueva Ecija	14	15:31:45	121:03:30	146	143	1
PH303034	Pampanga at Valfuente, Cabanatuan City, Nueva Ecija	7	15:31:00	120:57:20	1506	2441	1
PH303035	Tabuating at Soledad, Santa Rosa, Nueva Ecija	21	15:24:04	120:59:44	173	79	1
PH303039	Penaranda at San Josef (RRBR), Penaranda, Nueva Ecija	14	15:21:10	121:00:25	548	512	1
PH303040	Penaranda at San Josef (HW), Penaranda, Nueva Ecija	11	15:19:10	120:56:52	834	511	1
PH303041	Chico at Ilog Na Munti, General Tinio, Nueva Ecija	25	15:21:50	121:03:54	283	160	1
PH303042	Sumacbao at Pias, General Tinio, Nueva Ecija	11	15:20:28	121:06:25	1033	287	1
PH303043	Pampanga at San Agustin, Arayat, Pampanga	27	15:10:06	120:46:48	1858	6487	1
PH303044	Talavera at Caboboloonan, Talavera, Nueva Ecija	12	15:41:26	120:58:10	563	431	1
PH303045	Rio Chico at Sto. Rosario, Zaragoza, Nueva Ecija	10	15:27:00	120:45:00	331	1177	1
PH303046	Rio Chico at Banga, Arayat, Pampanga	7	15:13:11	120:46:54	359	2982	1
PH303047	Benituan at Pasong Intsik, Guimba, Nueva Ecija	19	15:40:08	120:44:40	683	208	1
PH303048	Baliwag at Catalanacan, Munoz, Nueva Ecija	22	15:43:22	120:53:00	286	284	1
PH303049	Talavera at Lomboy, San Jose, Nueva Ecija	15	15:51:30	121:00:45	479	271	1
PH303050	Pampanga at Pialuan, Pantabangan, Nueva Ecija	12	15:49:39	121:06:51	985	838	1
PH303052	Pantabangan at Poblacion, Pantabangan, Nueva Ecija	12	15:51:31	121:08:04	474	253	3
PH303055	Maasim at Bahay Pare, Candaba, Pampanga	15	15:01:58	120:53:00	538	174	1
PH303056	Maasim at Diliman, San Rafael, Bulacan	24	15:02:15	120:57:25	597	150	1
PH303060	San Miguel, San Vicente, San Miguel, Bulacan	23	15:08:48	120:58:20	557	256	1
PH303061	Balaong-Madlum at Santa Ines, San Miguel, Bulacan	21	15:09:15	121:00:18	499	218	1
PH303062	Bulo at Malibay, San Miguel, Bulacan	7	15:13:45	121:04:12	208	63	1
PH303072	Santa Maria at Bagbagin, Santa Maria, Bulacan	5	14:48:50	120:57:38	139	187	1
PH303078	Angat at Longos, Pulilan, Bulacan	21	14:53:30	120:51:50	753	959	1
PH303079	Bayabas at Pulong Sampaloc, Angat, Bulacan	7	14:57:20	121:03:45	180	74	3
PH303082	Pasig-Potrero at Hda. Dolores, Porac, Pampanga	5	15:06:37	120:31:58	8.4	28	1
PH303083	Porac at Valdez, Floridablanca, Pampanga	12	14:58:55	120:32:06	214	118	1
PH303084	Porac at Del Carmen, Floridablanca, Pampanga	24	14:59:34	120:32:05	273	121	1
PH303085	Gumain at (Floodway) Santa Cruz, Lubao, Pampanga	24	14:55:00	120:34:08	617	370	1
PH303086	Gumain at Pabanlag, Floridablanca, Pampanga	33	14:59:12	120:28:18	231	128	1
PH303087	Caulaman at Pabanlag, Floridablanca, Pampanga	16	14:57:30	120:28:30	489	72	1
PH303088	Colo at San Benito, Dinalupihan, Bataan	24	14:50:50	120:24:48	133	76	1
PH303089	Bulate at Bulate, Dinalupihan, Bataan	21	14:50:54	120:22:50	35	16	1
PH303090	Pilar at Nagwaling, Pilar, Bataan	27	14:39:40	120:32:54	61	14	1
PH303091	Miray at Lahing Buhi, Balanga, Bataan	25	14:38:00	120:31:25	11	3.0	1
PH303092	Bagsit at Dampay, Palauig, Zambales	11	15:25:52	120:01:00	150	68	1
PH303093	Bucao at San Juan, Botolan, Zambales	15	15:16:40	120:05:10	1162	615	1
PH303094	Santo Tomas at Dalanawan, San Marcelino, Zambales	21	14:59:54	120:15:44	449	177	1
PH303100	Pampanga at San Vicente, Cabiao, Nueva Ecija	10	15:13:18	120:48:31	916	3467	1

Station code	Name	No. years	Latitude (°N)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	Climate type
PH303101	Parua at San Nicolas, Bamban, Tarlac	10	15:15:38	120:33:26	152	84	1
PH303102	Tarlac at Tibag, Tarlac, Tarlac	22	15:29:55	120:34:00	1031	872	1
PH303103	Madlum at Sibul Spring, San Miguel, Bulacan	14	15:10:04	121:03:30	382	102	1
PH303902	Pampanga at Poblacion, Sta. Rosa, Nueva Ecija	5	15:25:38	120:56:05	1546	4028	1
Region 4							
PH304007	Marikina at Santo Nino, Marikina, Rizal	18	14:38:15	121:05:30	1495	499	1
PH304013	Arangilan at Calamias, Cabuyao, Laguna	20	14:14:10	121:07:30	67	87	1
PH304015	Mabacan at Mabacan, Calauan, Laguna	23	14:09:52	121:17:29	170	46	1
PH304016	Paputok at Mabacan, Calauan, Laguna	23	14:08:12	121:21:03	28	9.0	3
PH304017	Santa Cruz at Calumpang, Lilio, Laguna	30	14:11:55	121:24:30	118	103	3
PH304018	Balanac at Bukal, Magdalena, Laguna	23	14:12:24	121:26:33	178	116	3
PH304021	Mayor at Bagumbayan, Siniloan, Laguna	28	14:28:00	121:27:40	86	45	3
PH304022	Ilang-Ilang at Alapan 2nd, Imus, Cavite	25	14:24:30	120:54:20	232	60	1
PH304023	Panaysayan at Palubluban, General Trias, Cavite	28	14:20:22	120:52:48	101	30	1
PH304024	Balsahan at Palangue, Naic, Cavite	22	14:16:59	120:48:30	95	22	1
PH304025	Maragondon at Mabacao, Maragondon, Cavite	31	14:16:20	120:44:20	1752	215	1
PH304026	Palico at Bilaran, Nasugbu, Batangas	22	14:03:20	120:41:45	528	158	1
PH304027	Molino at Guinhawa, Tuy, Batangas	21	14:01:14	120:43:16	102	51	1
PH304028	Dacanlao at Sampaga, Balayan, Batangas	17	13:56:04	120:47:47	138	40	1
PH304029	Pansiipit at Poblacion, San Nicolas, Batangas	21	13:56:20	120:56:54	44	644	1
PH304030	Agus at Banugao, Infanta, Quezon	24	14:45:15	121:36:45	1599	879	4
PH304031	Maapon at Poblacion, Sampaloc, Quezon	17	14:10:00	121:38:20	156	88	3
PH304032	Ibia at Ayaas, Tayabas, Quezon	21	14:01:42	121:36:51	72	32	3
PH304033	Dumaca-a at Alsam, Tayabas, Quezon	31	14:02:20	121:37:30	191	54	3
PH304034	Dumaca-a at Lakawan, Tayabas, Quezon	24	14:03:24	121:37:20	303	74	3
PH304035	Morong at Morong, Sariaya, Quezon	20	13:55:58	121:33:18	37	12	3
PH304036	Sariaya at Tumbaga, Sariaya, Quezon	30	13:57:05	121:31:26	9.2	4.0	3
PH304037	Hibanga at Mamala, Sariaya, Quezon	20	14:02:10	121:30:45	12	4.9	3
PH304038	Lagunas at Lagalag, Tiaong, Quezon	22	13:57:15	121:21:00	37	54	3
PH304039	Bulakin at Bulakin, Tiaong, Quezon	14	14:02:30	121:21:15	28	10	3
PH304040	Cabatangan at Diamman, Ma. Aurora, Quezon	15	15:44:09	121:24:28	240	242	3
PH304041	Disalit at San Luis, Baler, Quezon	20	15:43:30	121:31:40	14	25	4
PH304042	Balogo at Balogo Grande, San Agustin, Romblon	16	12:35:53	122:01:54	44	4.0	3
PH304043	Banadero at Malamig, Calatrava, San Agustin, Romblon	17	12:36:00	122:04:30	30	8.2	3
PH304045	Binonga-an at Binonga-an, San Agustin, Romblon	16	12:32:47	122:06:12	19	1.0	3
PH304046	Hinugusan at San Agustin, Romblon	20	12:30:17	122:05:35	19	5.0	3
PH304047	Luzong at Luzong, San Agustin, Romblon	20	12:31:02	122:05:16	36	4.0	3
PH304048	Cantingas at Taclobo, San Fernando, Romblon	15	12:19:45	122:34:47	171	48	3

Station code	Name	No. years	Latitude (°N)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	Climate type
PH304050	Tuay at Tuay, Abra de Ilog, Occidental Mindoro	10	13:24:27	120:42:09	82	24	1
PH304051	Mamburao at Cabaco, Abra de Ilog, Occidental Mindoro	10	13:19:35	120:39:30	165	142	1
PH304052	Pagbahan at Talabaan, Mamburao, Occidental Mindoro	8	13:08:25	120:41:55	635	263	1
PH304054	Caguray at Otoyan, San Jose, Occidental Mindoro	12	12:20:18	121:11:03	642	136	1
PH304055	Bucayao at Bucayao, Calapan, Oriental Mindoro	17	13:18:03	121:11:00	615	339	3
PH304056	Pangalaan at Pangalaan, Naujan, Oriental Mindoro	16	13:15:33	121:11:24	632	28	3
PH304057	Mag-asawan Tubig at Bacoron, Naujan, Oriental Mindoro	17	13:14:15	121:14:15	950	435	3
PH304058	Pola at Inclanay, Pinamalayan, Oriental Mindoro	17	13:00:30	121:23:38	717	148	3
PH304059	Mangamnan at Butinsapa, Mogpog, Marinduque	10	13:28:00	121:55:00	220	24	3
PH304060	Boac at Tampus, Boac, Marinduque	10	13:26:30	121:55:00	1203	218	3
PH304061	Malabon at Malabon, Santa Cruz, Marinduque	10	13:25:45	122:03:50	393	48	3
PH304913	Maapon at Sampaloc, Quezon	5	14:10:06	121:38:27	94	75	3
PH304914	Tignoan at Tignoan, Real, Quezon	6	14:34:08	121:36:52	540	85	4
PH304920	Pililia at San Lorenzo, Pililia, Rizal	6	14:29:47	121:18:27	94	26	3
Region 5							
PH305001	Matogdon at Matogdon, Labo, Camarines Norte	23	14:08:53	122:50:18	129	27	2
PH305002	Talisay at Cahabaan, Talisay, Camarines Norte	15	14:08:25	122:55:42	79	22	2
PH305003	Daet at Aliwahao, Daet, Camarines Norte	17	14:05:43	122:54:18	166	80	2
PH305004	Pulantuna at Napolidan, Lupi, Camarines Sur	23	13:53:52	122:58:14	633	174	2
PH305005	Yabo at Yabo, Sipocot, Camarines Sur	14	13:48:03	122:55:47	151	82	2
PH305006	Culacling at Del Rosario, Lupi, Camarines Sur	20	13:46:38	122:47:25	70	65	4
PH305007	Sipocot at Sabang, Sipocot, Camarines Sur	18	13:48:44	122:59:40	1732	447	2
PH305008	Aslong at San Isidro, Libmanan, Camarines Sur	21	13:40:04	123:00:41	85	12	3
PH305012	Yabo at San Isidro, Naga City, Camarines Sur	15	13:37:25	123:14:45	40	4.0	2
PH305015	Pawili at San Roque, Bula, Camarines Sur	19	13:28:15	123:16:40	518	240	2
PH305016	Anayan at San Roque, Pili, Camarines Sur	29	13:34:24	123:17:30	137	13	2
PH305017	Pawili at San Vicente, Ocampo, Camarines Sur	21	13:32:56	123:21:24	463	112	2
PH305018	Barit at Santo Nino, Iriga, Camarines Sur	26	13:24:09	123:24:42	310	142	2
PH305019	Lallo at Antipolo, Buhi, Camarines Sur	20	13:22:45	123:32:13	31	21	2
PH305020	Bicol at Santo Domingo, Nabua, Camarines Sur	34	13:24:19	123:19:26	190	905	4
PH305022	Agus at Agus, Polangui, Albay	21	13:20:08	123:23:35	184	879	4
PH305023	San Agustin at San Agustin, Libon, Albay	23	13:19:32	123:29:55	133	262	2
PH305024	Irraya at Obaliw-Rinas, Oas, Albay	20	13:15:26	123:29:58	247	217	4
PH305025	Quinali at Busac, Oas, Albay	25	13:16:16	123:28:05	107	233	4
PH305026	Nasisi at Nasisi, Ligao, Albay	30	13:15:30	123:35:30	48	39	2
PH305027	San Francisco at Bobongsoran, Ligao, Albay	22	13:14:00	123:31:34	96	37	2
PH305028	Ugsong at Benanuan, Ligao, Albay	16	13:14:05	123:35:40	30	11	2
PH305029	Cabilogan at Bobongsoran, Ligao, Albay	29	13:14:08	123:31:12	146	117	4

Station code	Name	No. years	Latitude (ºN)	Longitude (ºE)	MAF (m^3/s)	AREA (km^2)	Climate type
PH305030	Talisay at Aliang, Ligao, Albay	15	13:11:27	123:27:12	89	90	3
PH305031	Hinagianan at Manguiring, Calabanga, Camarines Sur	26	13:42:56	123:16:45	79	16	2
PH305032	Lagonoy at Cagaycay, Goa, Camarines Sur	20	13:44:38	123:31:52	88	45	2
PH305033	Tigman at Cabanbanan, Calabanga, Camarines Sur	22	13:40:53	123:11:07	74	34	2
PH305034	Cumadcad at Cumadcad, Castilla, Sorsogon	24	12:58:00	123:46:45	61	15	2
PH305035	Malbog at Cumadcad, Castilla, Sorsogon	14	12:58:25	123:47:40	38	10	4
PH305036	Pili at San Isidro, Castilla, Sorsogon	16	12:58:50	123:51:00	38	18	2
PH305037	Cawayan at Basud, Sorsogon, Sorsogon	24	12:59:50	123:57:00	34	15	2
PH305038	Namuat at Santa Cruz, Casiguran, Sorsogon	22	12:53:45	124:02:30	52	10	2
PH305039	San Francisco at San Francisco, Bulan, Sorsogon	25	12:44:15	123:55:50	419	36	4
PH305040	San Ramon at San Ramon, Bulan, Sorsogon	17	12:40:00	123:55:45	327	53	4
PH305041	Mambang at Bugtong, pandan, Catanduanes	24	14:01:30	124:09:30	104	11	2
PH305042	Payo at Poblacion, Panganiban, Catanduanes	21	13:53:09	124:15:57	138	29	2
PH305043	Oco at Oco, Viga, Catanduanes	20	13:51:00	124:16:30	587	57	2
PH305044	Alibuag at Alibuag, Calolbon, Catanduanes	21	13:36:18	124:05:10	88	11	2
PH305045	Patorok at Timbaan, Calolbon, Catanduanes	17	13:36:20	124:06:25	125	10	2
PH305046	Cawayan at Hicming, Virac, Catanduanes	19	13:36:59	124:11:51	85	7.6	2
PH305047	Sebanjan at San Vicente, Virac, Catanduanes	24	13:35:50	124:14:20	66	3.8	2
PH305048	Libjo at Libjo, Bato, Catanduanes	22	13:37:20	124:18:50	35	3.7	2
PH305049	Batongan at Cabitan, Mandaon, Masbate	11	12:19:16	123:20:00	429	72	3
PH305051	Pinangapugan at Pinangapugan, Uson, Masbate	20	12:11:10	123:47:47	317	28	3
PH305908	Pawic at San Isidro, Bulan, Sorsogon	8	12:39:42	123:57:15	89	43	4
Region 6							
PH306001	Tangalan at Panayakan, Tangalan, Aklan	21	11:45:35	122:13:30	379	37	3
PH306002	Aklan at Rosario, Malinao, Aklan	28	11:35:23	122:18:14	953	705	3
PH306003	Bacong at Valderama, Culasi, Antique	22	11:24:45	122:05:30	64	54	3
PH306004	Maayon at Palaguian, Maayon, Capiz	17	11:23:24	122:46:39	231	269	3
PH306005	Mambusao at Tumalalud, Mambusao, Capiz	20	11:25:55	122:34:03	324	320	3
PH306006	Panay at Santa Rita, Cuartero, Capiz	28	11:17:13	122:35:31	787	880	3
PH306007	Paliuan at Tagudtod, Bugasong, Antique	24	11:04:42	122:02:21	813	176	1
PH306008	Barotac at Rizal, Barotac Viejo, Iloilo	14	10:56:00	122:45:00	63	90	3
PH306009	Sibalom at Pangpang, Sibalom, Antique	25	10:48:30	121:51:25	517	619	1
PH306010	Sibalom at Omambong, Leon, Iloilo	30	10:44:24	122:24:10	197	117	1
PH306011	Inabasan at Colini, Alimodian, Iloilo	17	10:50:23	122:26:55	102	97	1
PH306013	Jalaur at San Matias, Dingle, Iloilo	24	10:59:30	122:39:30	796	1065	3
PH306014	Jalaur at Calyan, Pototan, Iloilo	27	10:55:50	120:40:10	986	1499	3
PH306015	Suague at Mina, Pototan, Iloilo	35	10:56:00	122:34:47	133	186	1
PH306016	Ulian at Pader, Duenas, Iloilo	17	11:03:58	122:35:12	290	247	3

Station code	Name	No. years	Latitude (°N)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	Climate type
PH306017	Jalaur at Poblacion, Passi, Iloilo	19	11:06:15	122:37:40	1064	534	3
PH306018	Jalaur at Simsiman, Calinog, Iloilo	23	11:07:15	122:31:45	471	169	3
PH306019	Jalaur at Alibunan, Calinog, Iloilo	10	11:09:43	122:27:24	313	67	3
PH306020	Sibajao at Santa Ana, Battad, Iloilo	20	11:25:46	123:05:45	28	12	3
PH306021	Malogo at Hacienda Cabungahan, Silay City, Negros Oc.	21	10:49:03	123:04:52	595	129	3
PH306022	Bago at Ma-ao, Bago, Negros Occidental	23	10:44:30	123:02:00	993	683	3
PH306023	Bago at Pandanon, Murcia, Negros Occidental	8	10:33:20	123:08:22	141	445	3
PH306024	Binalbagan at Cadre, Magallon, Negros Occidental	22	10:15:36	123:05:05	270	350	3
PH306025	Piguian at Cabacangan, La Castellana, Negros Occid.	13	10:21:15	123:08:15	25	12	3
PH306026	Imbamg at Dos Hermanas, Talisay, Negros Occidental	31	10:44:20	123:02:47	100	29	3
PH306031	Ilog at Camugao, Kabankalan, Negros Occidental	15	09:59:15	122:48:30	835	1959	3
PH306035	Hilabangan at Tagbac, Kabankalan, Negros Occidental	20	09:56:58	122:56:12	200	392	3
PH306037	Ilog at Dahile, Kabankalan, Negros Occidental	22	09:53:20	122:50:40	769	1390	3
PH306038	Ilog at Inapoy, Kabankalan, Negros Occidental	15	09:49:42	122:52:20	313	1245	3
PH306903	Cairawan at Dalipe, Laua-an, Antique	5	11:07:08	122:02:20	293	73	3
PH306922	Malogo at Pasil, E.B. Magalona, Negros Occidental	5	10:53:44	123:02:14	451	161	3
Region 7							
PH307001	Bais at Consolacion, Bais, Negros Oriental	17	09:35:46	123:04:42	65	51	3
PH307002	Nagsala at Novallas, Tanjay, Negros Oriental	14	09:30:15	123:06:15	49	23	3
PH307003	Tanjay at Pinanlayan, Pamplona, Negros Oriental	21	09:27:48	123:06:20	509	167	3
PH307004	Okoy at Palinpinon, Valencia, Negros Oriental	24	09:18:36	123:13:45	35	55	3
PH307005	Maite at Palinpinon, Valencia, Negros Oriental	12	09:16:03	123:12:05	11	3.0	3
PH307006	Pitogo at Pitogo, Consolacion, Cebu	22	10:22:42	123:57:38	15	32	3
PH307007	Carcar at Guadalupe, Carcar, Cebu	24	10:07:52	123:36:05	64	24	3
PH307008	Balamban at Lusaran, Cebu City, Cebu	14	10:29:07	123:52:57	180	49	3
PH307009	Pamacsalan at Pamacsalan, Sierra Bulones, Bohol	21	09:50:58	124:21:09	45	71	4
PH307011	Bilar at Owac, Bilar, Bohol	18	09:41:30	124:06:42	41	92	4
PH307012	Loboc at Tigao, Loboc, Bohol	22	09:39:57	124:02:04	228	618	4
PH307901	Abatan at San Isidro, Balilihan, Bohol	6	09:48:38	123:58:11	220	139	4
PH307902	Antequera at Sto. Rosario, Antequera, Bohol	5	09:45:35	123:54:00	210	43	4
PH307904	Cantimoc at Villarcayo, Carmen, Bohol	5	09:50:12	124:10:45	122	74	4
PH307905	Gabayan at Canawan, Candihay, Bohol	6	09:50:34	124:26:30	64	28	4
PH307910	Nahawan at Nahawan, Clarin, Bohol	5	09:58:30	124:03:10	81	23	4
PH307915	Sta. Ana at Barili, Cebu	8	10:06:40	123:30:58	33	45	3
PH307918	Siaton at Poblacion, Siaton, Negros Oriental	6	09:03:38	123:10:32	371	132	1
Region 8							
PH308002	Bobon at Casulgan, Bobon, Samar	18	12:29:25	124:32:37	161	91	2
PH308003	Catarman at Polangui, Catarman, Samar	17	12:21:30	124:39:22	888	439	2

Station code	Name	No. years	Latitude (°N)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	Climate type
PH308004	Hirawahan at Hirawahan, Catubig, Samar	19	12:25:12	125:01:54	131	19	2
PH308005	Catubig at San Isidro, Las Navas, Samar	18	12:17:19	125:02:22	294	261	2
PH308006	Jicontrol at Cabuwanan, Hinolaso, Dolores, Samar	15	12:01:35	125:19:22	212	95	2
PH308007	Tenane at Tenane, Wright, Samar	19	11:48:25	125:08:00	651	334	4
PH308009	Baleon at Valencia, Ormoc City, Leyte	16	11:06:41	124:34:20	32	19	4
PH308010	Bao at Masarayao, Kamanga, Leyte	25	11:08:12	124:35:52	105	65	4
PH308011	Calingcaguin at Calingcaguin, Barugo, Leyte	28	11:14:45	124:31:30	145	128	4
PH308012	Mainit at Binongto-an, Alang-alang, Leyte	29	11:13:21	124:49:30	240	98	4
PH308013	Lingayon at Lingayon, Alang-alang, Leyte	29	11:11:10	124:51:45	51	10	4
PH308014	Dapdap, Buenavista, Alang-alang, Leyte	27	11:13:00	124:51:00	48	30	4
PH308015	Bito at Inayopan, Abuyog, Leyte	11	10:46:10	124:57:22	317	94	4
PH308016	Daguitan at Poblacion, Burauen, Leyte	20	10:58:00	124:53:40	303	135	4
PH308017	Das-ay at Catublian, Hinunangan, Leyte	20	10:22:24	125:09:47	112	62	2
Region 9							
PH309002	Disacan at Siparok, Manukan, Zamboanga del Norte	9	08:28:49	123:02:48	477	113	4
PH309003	Dipolo at San Jose, Molave, Zamboanga del Norte	14	08:06:52	123:23:53	173	313	4
PH309004	Salug-dacu at Mahayag, Zamboanga del Sur	23	08:09:58	123:27:02	193	340	4
PH309005	Labangan at Bucong, Labangan, Zamboanga Del Sur	12	07:54:45	123:26:04	314	430	4
PH309006	Mercedes at Pasobalong, Zamboango City	7	06:59:00	122:07:46	497	38	3
PH309007	Langaran at Tipolo, Plaridel, Misamis Occidental	10	08:35:26	123:40:54	217	83	2
PH309008	Layawan at Lambacugan, Oroquita, Misamis Occ	23	08:28:00	123:47:00	118	115	2
PH309010	Pinis at Oroquieta, Misamis Occidental	17	08:27:00	123:48:00	248	27	2
PH309011	Aloran at Mitazan, Aloran, Misamis Occ	9	08:20:00	123:48:19	140	26	2
PH309012	Jimenez at Corrales, Jimenez, Misamis Occidental	12	08:19:46	123:49:46	138	97	2
PH309013	Clarin at Canicapan, Clarin, Misamis Occidental	16	08:12:52	123:50:03	46	139	2
PH309014	Paca at Masabod, Clarin, Misamis Occidental	15	08:13:14	123:50:00	31	138	2
PH309015	Lagu at Calabayan, Ozamis City, Misamis Occ	16	08:10:29	123:43:31	58	55	2
PH309904	Ingin at Maras, Sindangan, Zamboanga del Norte	7	08:11:35	122:58:38	215	270	4
PH309905	Sindagan at Dicoyong, Sindagan, Zamboanga del Norte	5	08:13:02	123:02:51	363	505	4
Region 10							
PH310001	Surigao at Quezon, Surigao, Surigao	20	09:44:26	125:29:17	469	101	2
PH310003	Sonkoy at Marga, Tubod, Surigao del Norte	14	09:32:25	125:34:18	1.6	2.0	2
PH310004	Mayag at Matinao, Mainit, Surigao	16	09:32:45	125:29:35	159	41	2
PH310006	Andanan at Bayugan, Agusan Del Sur	9	08:44:00	125:43:00	221	201	2
PH310007	Wawa at Wawa, Esperanza, Agusan	20	08:47:50	125:42:23	598	396	2
PH310010	Agusan at San Isidro, Talacogon, Agusan	7	08:32:04	125:46:31	3407	7390	2
PH310013	Gibong at Bah-Bah, Prosperidad, Agusan	10	08:36:40	125:54:46	343	427	2
PH310014	Kayawan at Langasian, La Paz, Agusan Del Sur	7	08:14:56	125:42:59	769	348	4

Station code	Name	No. years	Latitude (°N)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	Climate type
PH310016	Agusan at Santa Josefa, Bunawan, Agusan	17	07:59:25	126:02:00	972	1597	4
PH310020	Tagoloan at Santa Cruz, Tagoloan, Misamis Oriental	11	08:32:02	124:47:45	394	1656	3
PH310024	Alubijid at Munay, Alubijid, Misamis Oriental	26	08:34:15	124:27:48	74	94	3
PH310026	Agusan at Kalaw Br., Monkayo, Davao Del Norte	13	07:50:00	126:03:00	609	1355	4
PH310027	Sanghan at Sanghan, Cabadbaran, Agusan	6	09:05:27	125:34:30	61	6.0	2
Region 11							
PH311001	Bacuag at Paotao, Bacuag, Surigao del Norte	14	09:37:00	125:37:00	193	64	2
PH311002	Boya-an at Lisob, Madrid, Surigao del Sur	11	09:14:12	126:00:00	217	33	2
PH311003	Carac-an at Parang, Cantillan, Surigao	12	09:14:25	125:56:10	1139	240	2
PH311004	Tago at Libas, Tago, Surigao del Sur	7	09:00:50	126:04:00	438	676	2
PH311007	Hijo at Tipaz, Tagum, Davao	19	07:27:00	125:49:40	161	617	4
PH311008	Tagum at Pagsabangan, Tagum, Davao	20	07:28:00	125:45:00	655	2326	4
PH311009	Matina at Matina, Pangi, Davao City	16	07:07:16	125:32:21	53	48	4
PH311010	Sibulan at Sibulan, Santa Cruz, Davao del Sur	20	06:58:05	125:22:40	44	128	4
PH311011	Padada at Lapulabao, Hagonoy, Davao del Sur	28	06:40:00	125:17:00	92	821	4
PH311012	Mal at Dongangpilong, Matanao, Davao	21	06:41:30	125:14:42	89	177	4
PH311013	Buayan at Kiblat, Malandag, General Santos City, Cot.	8	06:20:36	125:13:13	22	208	4
PH311014	Clinan at Upper Clinan, Polomolok, Southern Cotabato	18	06:08:15	125:11:19	12	71	4
PH311015	Siluay at Lagao, General Santos City, Cotabato	20	06:11:06	125:05:40	102	65	4
Region 12							
PH312001	Mandulog at Taparac, Iligan City, Lanao del Norte	13	08:15:32	124:16:16	228	576	3
PH312002	Maigo at Balagatasa, Kolambugan, Lanao del Norte	11	08:09:07	123:57:00	120	74	4
PH312003	Maranding at Rebe, Lala, Lanao del Norte	19	07:54:10	123:47:53	158	345	4
PH312006	Libungan at Abaya, Libungan, Cotabato	23	07:14:50	124:31:30	574	534	3
PH312007	Mindanao at Poblacion, Datu Piang, Cotabato	9	07:01:59	124:29:57	1260	17744	3
PH312008	Dansalan at Sapakan, Sultan Sa Barongis, Maguindanao	10	06:54:53	124:32:27	426	3749	3
PH312009	Allah at Impao, Isulan, Sultan Kudarat	21	06:40:30	124:34:00	208	1231	3
PH312010	Allah at Kolambog, Isulan, Cotabato	17	06:31:30	124:36:05	167	936	3
PH312012	Banga at Poblacion, Banga, Cotabato	14	06:26:45	124:45:43	47	331	3
PH312013	Lonon at Lam-alo, Surala, South Cotabato	15	06:14:31	124:43:52	24	79	4
PH312015	Marbel at Marbel, Koronadal, Cotabato	28	06:24:26	124:54:28	51	290	3
PH312016	Alip at Datu Paglas, Maguindanao	18	06:44:17	124:50:59	239	380	3
PH312017	Malasila at Bagontapay, M'Lang, Cotabato	21	06:50:45	124:54:10	110	145	3
PH312018	M'Lang at Ogpay, M'Lang, Cotabato	22	06:56:18	124:55:31	129	159	3
PH312019	Saguing at Perez, Kidapawan, Cotabato	15	07:01:30	125:09:08	72	9.0	4
PH312020	Pulangui at Inug-ug, Pikit, North Cotabato	26	07:03:09	124:42:27	1135	12999	3
PH312022	Kabakan at Mateo, Matalam, Cotabato	11	07:06:32	124:52:39	507	698	3
PH312023	Pulangui at Lumayong, Carmen, Cotabato	13	07:09:00	124:48:30	1103	6752	3

Station code	Name	No. years	Latitude (°N)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	Climate type
PH312029	Pulangui at Poblacion, Valencia, Bukidnon	10	07:54:20	125:05:35	1196	2730	3
PH312030	Manupali at Colonia, Valencia, Bukidnon	9	07:58:15	125:08:10	87	487	3
PH312031	Suwaga at Linabo, Malaybalay, Bukidnon	6	08:03:27	125:10:16	339	327	3

Appendix B Development of flood estimation method for Sri Lanka

The general approach used in the development of the flood estimation methods for all the countries or regions is discussed in Chapter 2 of the main report.

B1 Data

B1.1 Flood peak data

River flows have been recorded for some period at about 150 sites in Sri Lanka. Based on the list of stations given in Dharmasena (1987), these were investigated and data from the 72 stations that had annual flood peak records of 10 or more years were compiled for the analysis. Because of the dense network of stations and the relatively long records, it was not necessary to make use of stations with short records of less than 10 years. The annual flood peaks were abstracted from the station files held in the Hydrology Division of the Irrigation Department. The files list the daily flows for each hydrological year (October - September) on a single sheet, and the instantaneous maximum flow for the year is also noted with its date of occurrence. The stations used are listed in Section B5, which also gives the number of years of data, the station locations and the catchment characteristics. The location of each gauging station is plotted in Figure B1.

Some brief checks on data quality were carried out to ensure that the data used were adequate, but detailed checks were not possible within the time available. For some stations summaries of the numbers of discharge measurements and their range and the dates of validity of the various rating curves were included in the files, and these were examined. It was evident that a considerable extrapolation of most rating curves has been necessary to obtain flood flows. The extrapolation has been based on the standard rating curve equation of the form: $Q = a\ (h-h_o)^b$; and this should be valid, at least for simple cross-sections without discontinuities. Checks on the highest flood in each year are carried out by the Hydrology Division; these consist of a comparison of the flood volume deduced from the hydrograph with the corresponding volume of storm rainfall estimated by Thiessen polygons from the available raingauges. Both these procedures should help to ensure that the extrapolated ratings are reasonable. A number of stations were discussed with the Hydrology Division, and records were discounted where major changes have occurred upstream, making them invalid for the analysis. This was particularly the case on the Mahaweli Ganga. Flows for a number of stations in the Mahaweli basin were revised by Nedeco (Nedeco/Irrigation Department, 1981) and these have been used in preference - the stations are marked "Nedeco" in Section B5. These records are based on calendar years rather than the hydrological years used in the Irrigation Department files, so they cannot be compared directly. Nedeco also criticise the data at Talawakanda (station SRI087) and those in the south-east of the country, but as these did not appear particularly anomalous in comparison with the other stations, they have been accepted for this study.

Sri Lanka - location of river flow gauging stations

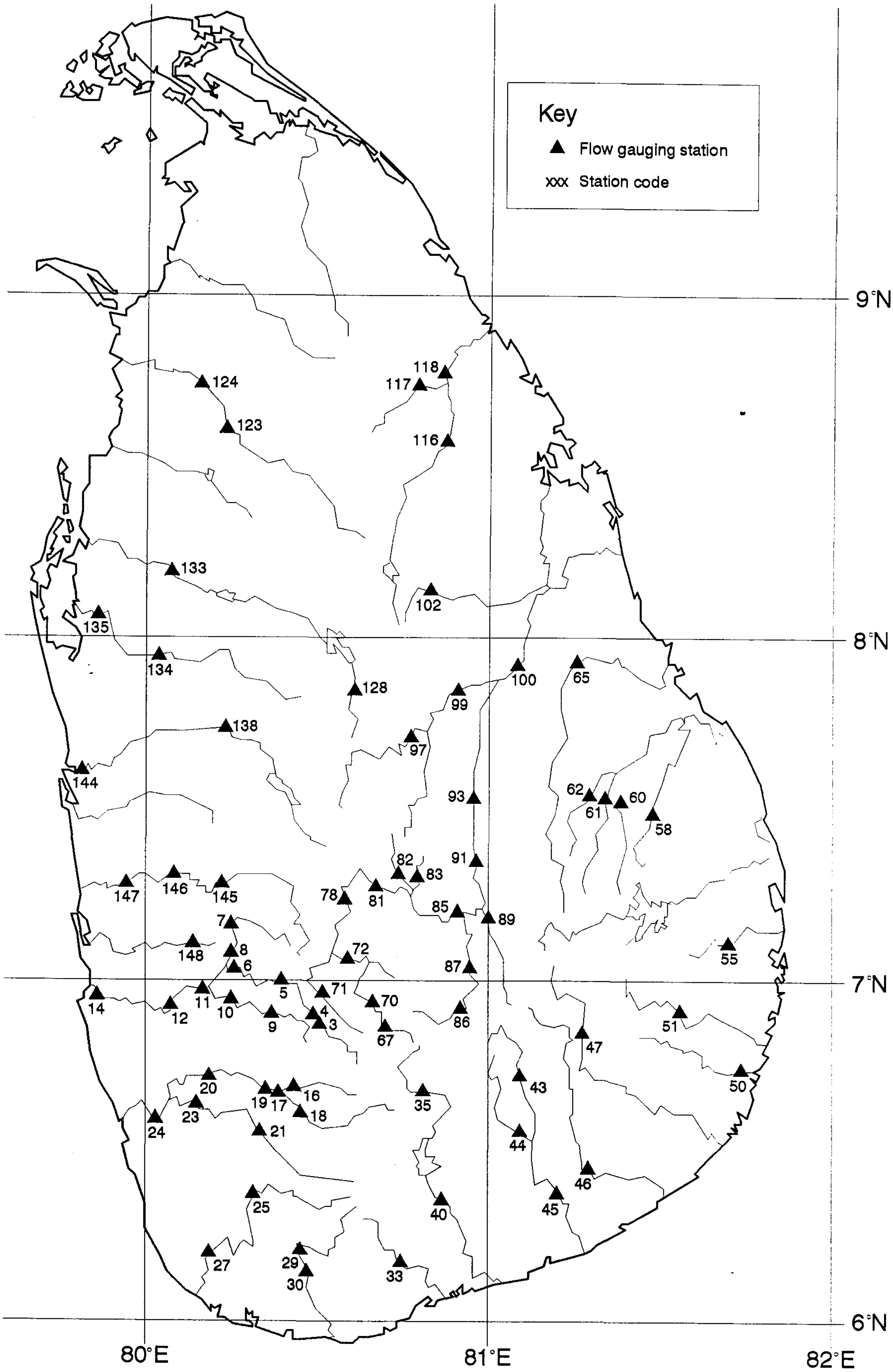

Figure B1

B1.2 Catchment characteristics data

Besides latitude and longitude for each station, the catchment characteristics data available were limited to catchment area and average annual rainfall. The latitudes and longitudes for many of the stations were taken from a report by the Irrigation Department (1974). For others stations, positions given on a local grid system were abstracted from the files and translated to latitude and longitude using topographic maps.

Catchment areas and average annual rainfall values were abstracted from the same report or from the Hydrological Annual for 1986/87. In the Annual, the rainfall data given correspond to the period of flow record, rather than some standard period. For a small number of stations not listed in either source, the catchment rainfall was estimated from isohyetal maps for the period 1931-60. The rainfall estimates derived from different sources are not entirely homogeneous, but they should be adequate for this study.

B2 Estimation of the mean annual flood

The value of the mean annual flood (MAF) was calculated as the average of the series of annual peak flows for each site; the values are listed in Section B5. A logarithmic regression of MAF on catchment area (AREA) using all the stations gave the following result:

$$MAF = 8.68\ AREA^{0.615} \qquad r^2 = 0.605$$

The data and this fitted regression line are plotted in Figure B2. A preliminary examination of the data shows that the rainfall is also a very important factor in determining the MAF, and when this is included, the regression becomes:

$$MAF = 0.0120\ AREA^{0.640}\ AAR^{0.821} \qquad r^2 = 0.708$$

Both the coefficients are significant and there is a considerable improvement in r^2, so the inclusion of rainfall is justified. An examination of Figure B2 shows that three stations (SRI128, SRI135 and SRI148) stand out as being very far from the regression line, and, in the regression on AREA and AAR, these three stations also stand out as having the largest residuals. A further examination of MAF was carried out by plotting the ratios of MAF to catchment area according to geographical position. This revealed a number of apparently anomalous values: that is, stations where the ratio was very much higher or lower than the surrounding ones. In general, it was thought that it was not justified to exclude these stations because MAF values would be expected to show high variability depending on whether or not a particularly large flood has been observed. However, the three stations mentioned above were again shown to be the most anomalous and were excluded from the analysis. In the case of SRI135, comparison with the upstream station SRI134 suggested that overbank flow was likely to have been occurring during high floods, meaning that the peaks have not been properly observed. For the other two stations, no nearby stations are available for comparison, and a detailed study of the sites and the rating curves would be needed to reveal the cause of the anomalies.

Mean annual flood against catchment area for Sri Lanka

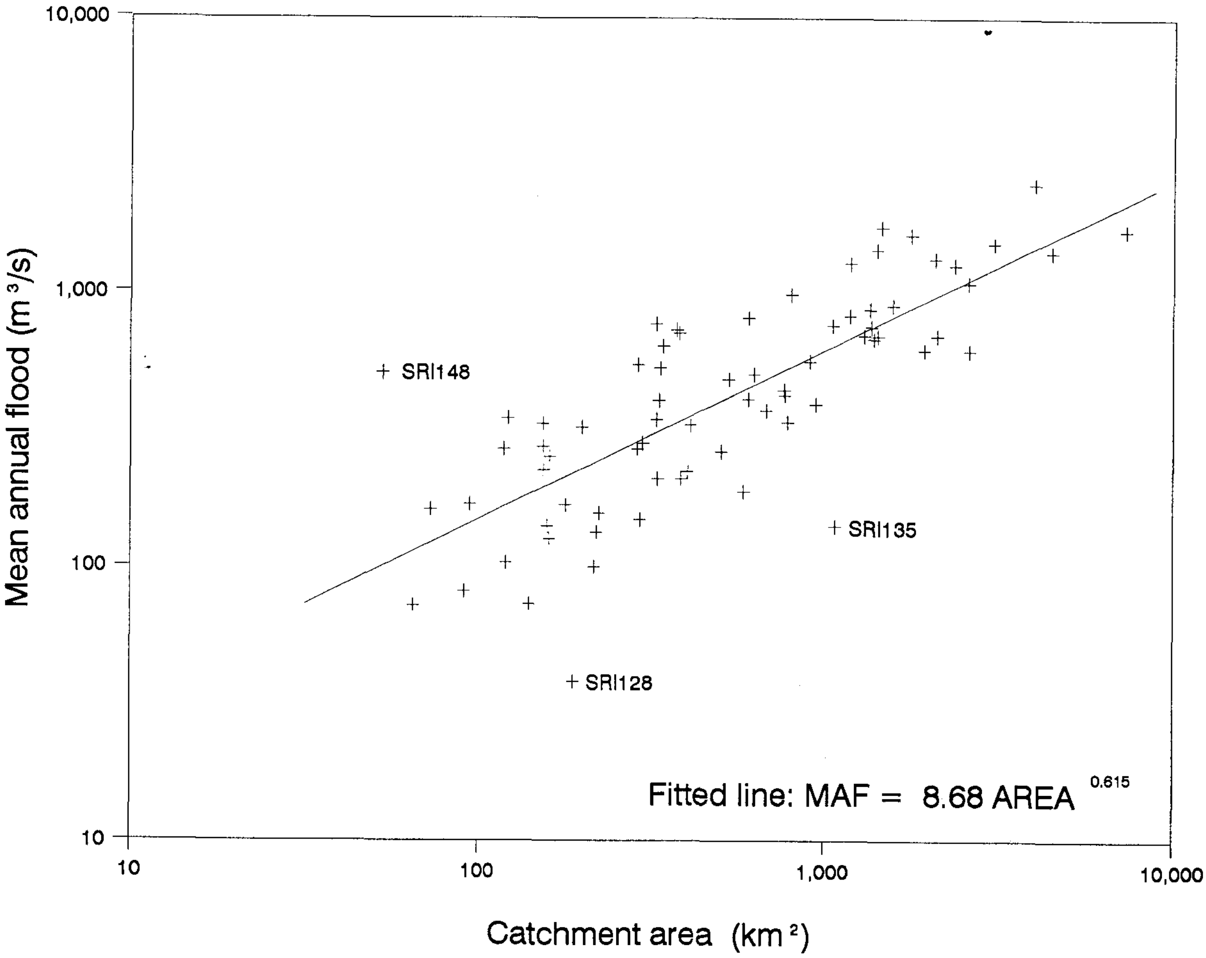

Figure B2

When these three stations are excluded, the regressions become:

$$\text{MAF} = 7.08\ \text{AREA}^{0.652} \qquad r^2 = 0.714$$

and, when AAR is included:

$$\text{MAF} = 0.0285\ \text{AREA}^{0.670}\ \text{AAR}^{0.688} \qquad r^2 = 0.790$$

There is a considerable improvement due to the exclusion of the anomalous stations, and the inclusion of rainfall is again justified by the improvement in r^2 and by the significance of the coefficients. This last equation is recommended as the MAF estimation equation for Sri Lanka. The fit of the data is good, having relatively low scatter, and the equation would be expected to give reasonably good estimates of MAF at ungauged sites. The factorial standard error of the estimate is 1.49, meaning that the 'true' MAF is likely to fall within the range +49% to -33% of the estimate given by the equation.

B3 Regional flood frequency curves

Regional flood frequency curves were derived by fitting the GEV distribution to the pooled annual flood peak data for various groups of stations. The three anomalous stations discussed in the preceding station were again excluded. As Sri Lanka is a fairly small country, it is reasonable to treat it as a single region. However, there is considerable climatic variation, with annual rainfall varying from about 1300 mm in some parts of the north to around 5000 mm in some locations in the south-west. The wetter locations also tend to have two rainy seasons a year, as opposed to a single rainy season in the rest of the country. This variation means that climate is likely to be a significant factor in determining the regional curves.

The other factor which was investigated was catchment area. In contrast to the results for nearly all other regions studied, catchment area was not found to be an effective determinant of the flood frequency curve, with no very consistent behaviour shown by the smaller or the larger catchments. This appears to be because the flood behaviour is dominated by climatic effects. A division of the catchments into three groups based on AAR values was found to give a very effective separation of the curves. The best groupings found and the curves for each are given in Table B1, and the regional curves are also plotted in Figure B3. These results show that AAR is a powerful factor in determining the flood frequency curve, with the drier catchments having very much steeper curves than the wettest. Within each grouping there was found to be considerable variation between individual station curves, but the regions were judged to be reasonably homogeneous, with variation between stations not beyond what might reasonably be expected.

This approach gives fairly similar results to dividing the country into three separate geographical areas. The wettest catchments (AAR > 3200 mm) being mostly in the south-west, the driest (AAR < 2000 mm) mostly in the north and east, with the remainder generally lying in the intermediate area. However, the approach using regions defined by AAR was preferred as being more logical.

Regional flood frequency curves for Sri Lanka

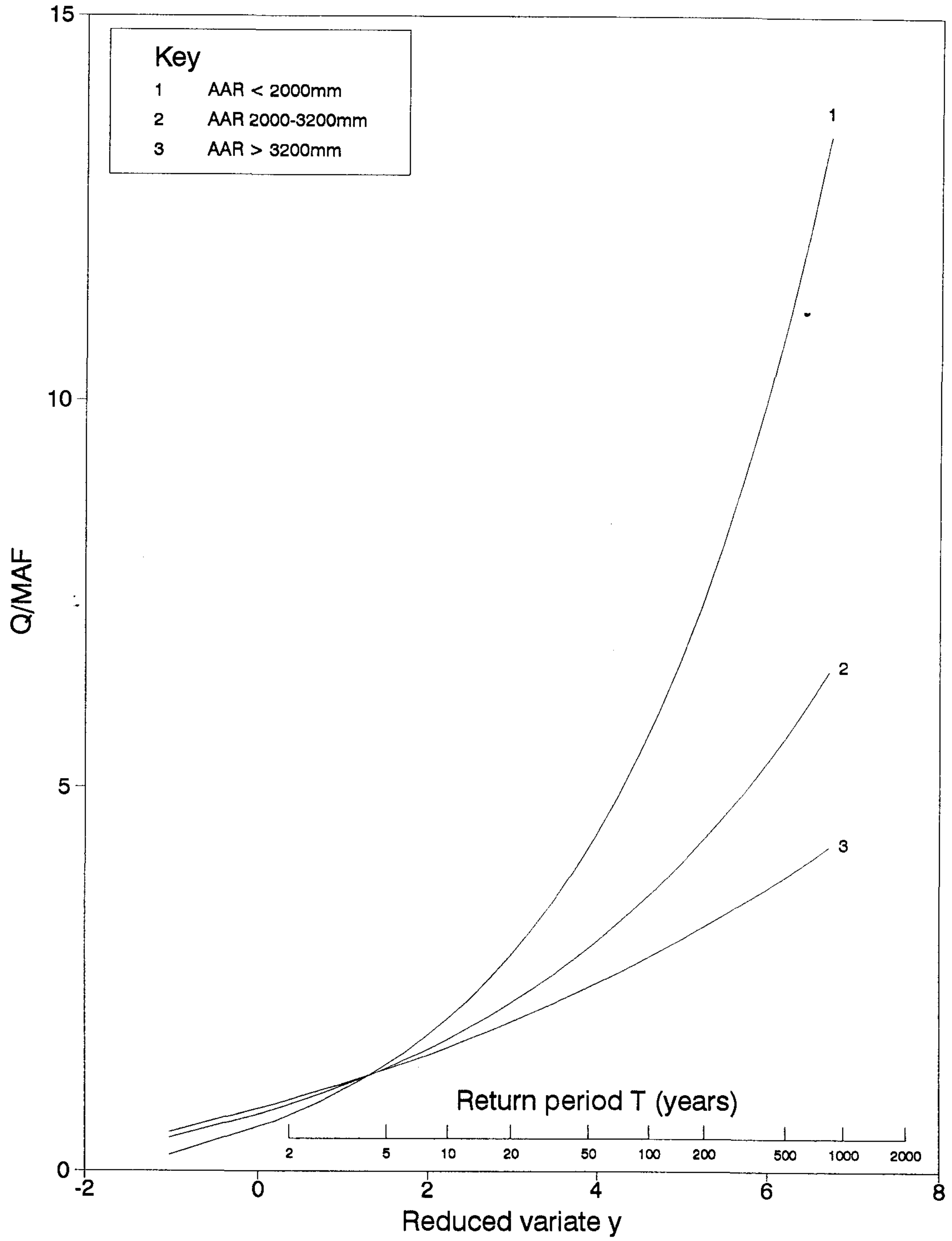

Figure B3

TABLE B1 *Regional flood frequency curves for Sri Lanka*

Grouping	No. stations	No. years	GEV parameters u	α	k	Predicted floods q_{20}	q_{100}	q_{500}
All stations	69	1654	0.688	0.339	-0.2616	2.21	3.71	5.97
AAR < 2000	17	360	0.525	0.404	-0.3818	2.76	5.59	10.81
AAR 2000-3200	29	699	0.703	0.330	-0.2486	2.15	3.54	5.59
AAR > 3200	23	595	0.773	0.311	-0.1358	1.91	2.76	3.81

B4 Conclusions

In conclusion, the result of the study is that the regression equation:

$$MAF = 0.0285\ AREA^{0.670}\ AAR^{0.688}$$

should be used to estimate mean annual flood at ungauged sites. Where a reasonable length of good quality flow data is available at or close to the site of interest, the local record should be preferred for the estimation of MAF. The regional flood frequency curves grouped according to average annual rainfall (table B1) should then be used to estimate the flood peak for the required return period. This method provides a reasonably good means of making flood estimates at ungauged sites in Sri Lanka. Because of the greater density of gauging stations in the centre and south-west of the country, the results are inevitably biassed towards this region. There is poorer coverage elsewhere, and particularly in extreme northern part, where no data are available, the method should be used with caution.

The method presented here is somewhat preliminary; derivation of an improved method would only be possible after a major study, involving detailed quality control of all the flow data and derivation of a wider range of catchment characteristics for each gauged catchment.

B5 List of river flow gauging stations and catchment characteristics

The table on the following pages lists the river flow gauging stations used in the study. For each station, the station code, name, number of years of annual flood peaks, location, mean annual flood (MAF), catchment area (AREA), and average annual rainfall (AAR) are given. These were derived as explained in Section B1.2 above. The station codes used consist of 6 characters; the first three are SRI, and the remainder is the three digit number assigned to the station by Dharmasena (1987).

Station code	Name	No. years	Latitude (°N)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	AAR (mm)
SRI003	Maskeli Oya at Mausakele	19	06:52:30	80:31:30	347	122	2820
SRI004	Maskeli Oya at Laxapana	12	06:53:10	80:31:05	274	154	3170
SRI005	Kelani Ganga at Kitulgala	40	06:59:30	80:24:45	706	383	3670
SRI006	Kelani Ganga at Matiyadola	33	07:01:34	80:16:26	802	606	3930
SRI007	Gurugoda Oya at Holombuwa	18	07:11:35	80:15:45	224	155	3330
SRI008	Gurugoda Oya at Imbulanala	26	07:03:47	80:15:40	343	329	3420
SRI009	Sitawaka Ganga at Deraniyagala	28	06:55:15	80:20:40	332	154	4950
SRI010	Sitawaka Ganga at Algoda	16	06:56:55	80:15:40	634	344	4620
SRI011	Kelani Ganga at Glencourse	39	06:58:30	80:10:51	1708	1463	4060
SRI012	Kelani Ganga at Hanwella	14	06:54:36	80:05:00	1603	1782	3840
SRI014	Kelani Ganga at Nagalagam Street	33	06:57:30	79:52:30	1314	2085	3940
SRI016	Kalu Ganga at Malwala	24	06:41:15	80:25:24	759	329	4420
SRI017	Kalu Ganga at Ratnapura	12	06:40:36	80:24:18	407	604	3420
SRI018	Wey Ganga at Dela	31	06:37:20	80:27:10	133	220	2720
SRI019	Kalu Ganga at Nambapana	22	06:41:11	80:23:05	499	629	3740
SRI020	Kalu Ganga at Ellagawa	32	06:43:52	80:13:00	674	1393	4010
SRI021	Kukule Ganga at Kukulegama	9	06:33:48	80:19:48	403	334	3280
SRI023	Kuda Ganga at Millakanda	27	06:37:25	80:10:25	438	769	4230
SRI024	Kalu Ganga at Putupaula	41	06:36:40	80:03:55	1073	2598	3970
SRI025	Gin Ganga at Tawalama	13	06:20:30	80:19:48	726	377	3910
SRI027	Gin Ganga at Agaliya	53	06:11:15	80:11:45	369	681	3850
SRI029	Nilwala Ganga at Pitabeddhara	14	06:12:42	80:29:00	208	333	3400
SRI030	Nilwala Ganga at Bopagoda	44	06:09:20	80:29:05	328	411	3360
SRI033	Urubokka Oya at Julampitiya	11	06:11:10	80:44:40	73	141	2510
SRI035	Walawe Ganga at Samanalawewa	18	06:40:30	80:48:05	527	337	2860
SRI040	Walawe Ganga at Embilipitiya	22	06:20:40	80:53:55	892	1580	2190
SRI043	Kirindi Oya at Wellawewa	29	06:43:55	81:06:25	140	159	2300
SRI044	Kuda Oya at Kuda Oya	21	06:31:30	81:07:24	543	291	1780
SRI045	Kirindi Oya at Lunuganwehera	25	06:21:40	81:13:10	560	913	1830
SRI046	Menik Ganga at Kataragama	37	06:25:25	81:19:45	335	787	1710
SRI047	Kumbukkan Oya at Nakkala	14	06:53:18	81:17:48	99	216	1390
SRI050	Wila Oya at Wedagama	9	06:45:42	81:44:36	221	404	1730
SRI051	Heda Oya at Siyambalanduwa	28	06:54:20	81:32:40	148	295	2080
SRI055	Pannal Oya at Thottama	13	07:06:30	81:41:25	168	95	1880
SRI058	Magalavadavan Aru at Periya Aru	32	07:30:05	81:29:20	268	119	2060
SRI060	Rambukkan Oya at Nilobe	30	07:30:40	81:22:40	126	161	2150
SRI061	Maha Oya at Maha Oya	11	07:31:54	81:26:36	282	300	2150
SRI062	Galodai Aru at Weragoda	35	07:33:35	81:19:50	156	224	2140

Station code	Name	No. years	Latitude (°N)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	AAR (mm)
SRI065	Maduru Oya at Welikanda	29	07:56:10	81:15:15	754	1062	2100
SRI067	Agra Oya at Holbrook	16	06:52:52	80:41:40	103	121	2390
SRI070	Kotmale Oya at Talawakele	23	06:56:25	80:39:45	269	290	2390
SRI071	Mahaweli Ganga at Watawala	18	06:56:50	80:32:10	72	65	3950
SRI072	Kotmale Oya at Morape (Nedeco)	31	07:03:40	80:37:20	481	531	2760
SRI078	Mahaweli Ganga at Peradeniya	37	07:15:42	80:35:30	1264	1189	2970
SRI081	Mahaweli Ganga at Gurudeniya	33	07:16:30	80:40:30	1412	1417	2810
SRI082	Hulu Ganga at Teldeniya	23	07:17:48	80:45:54	252	161	3560
SRI083	Galmal Oya at Moragahamula	16	07:16:57	80:48:26	161	73	3670
SRI085	Mahaweli Ganga at Randenigala (Nedeco)	24	07:12:10	80:56:10	1251	2370	2760
SRI086	Uma Oya at Welimada	17	06:54:15	80:54:30	167	179	2010
SRI087	Uma Oya at Talawakanda	19	07:00:30	80:58:25	262	505	1890
SRI089	Badulu Oya at Kandeketiya	15	07:10:30	81:00:24	209	387	2100
SRI091	Mahaweli Ganga at Weragantota (Nedeco)	35	07:19:02	80:59:10	2447	4040	2500
SRI093	Mahaweli Ganga at Hembarawa	10	07:31:35	80:58:20	1385	4530	2580
SRI097	Amban Ganga at Elahera (Nedeco)	33	07:40:45	80:45:25	421	772	2520
SRI099	Amban Ganga at Anagamedilla (Nedeco)	13	07:51:12	80:55:00	691	1435	2350
SRI100	Mahaweli Ganga at Manampitiya (Nedeco)	28	07:54:40	81:05:10	1666	7343	2500
SRI102	Gal Oya at Gal Oya	12	08:09:12	80:50:20	321	199	1590
SRI116	Yan Oya at Horowupotana	34	08:34:36	80:52:42	390	948	1520
SRI117	Yan Oya at Wahalkada	18	08:43:36	80:51:05	81	91	1620
SRI118	Yan Oya at Pangurugaswena	33	08:44:55	80:52:45	689	1311	1710
SRI123	Aruvi Oya at Kappachchi	35	08:35:45	80:16:30	690	2121	1450
SRI124	Malwathu Oya at Tekkam	11	08:44:30	80:11:00	1492	3072	1430
SRI128	Kala Oya at Dambulla	12	07:51:00	80:37:00	38	189	1780
SRI133	Kala Oya at Kala Oya	26	08:12:00	80:05:48	614	1948	1520
SRI134	Mi Oya at Mahauswewa	16	07:57:50	80:04:08	187	588	1450
SRI135	Mi Oya at Tabbowa	17	08:02:50	79:55:05	140	1077	1380
SRI138	Deduru Oya at Ridibandi Ela	18	07:43:42	80:15:48	746	1370	1940
SRI144	Deduru Oya at Chilaw	19	07:40:00	79:48:58	612	2611	1790
SRI145	Maha Oya at Alawwa	20	07:17:30	80:14:26	973	803	2450
SRI146	Maha Oya at Giriulla	26	07:19:30	80:06:55	815	1191	2480
SRI147	Maha Oya at Badalgama	31	07:18:10	79:58:50	860	1360	2380
SRI148	Attanagola Oya at Karasnagala	17	07:06:30	80:10:30	508	53	3170

Appendix C Development of flood estimation method for Namibia

The general approach used in the development of the flood estimation methods for all the countries or regions is discussed in Chapter 2 of the main report.

C1 Data

C1.1 Flood peak data

The flood peak data were supplied by the Hydrology Division of the Department of Water Affairs. The stations include all the reasonably long flood records in the country, and the data have been checked by DWA (although they were not able to confirm that the data were correct). DWA answered a number of queries about the data, and one station which is only suitable for low flows, and a number of years with spurious zero peaks at some of the other stations were eliminated. Data were assembled for a total of 51 stations having 5 or more years of record, although the great majority of stations had at least 10 years of flood peaks.

The stations are listed in Section C6, which also gives the number of years of data, the station locations and the catchment characteristics. Not all the stations were used in the final analysis, for a number of reasons, and this is discussed further in Sections C2 and C3. The location of each gauging station is plotted in Figure C1.

C1.2 Catchment characteristics data

Most of the catchment characteristics data were supplied by the Department of Water Affairs. These include station location, catchment area, catchment slope and average annual rainfall. For a few of the catchments, average annual rainfall values were not available, and the missing values have been estimated in this study. For the catchments solely within Namibia the values were taken from the "Updated Isohyetal Rainfall Map of Namibia" (Department of Water Affairs, 1992), and for the large catchments which extend outside Namibia they were estimated from the appropriate map in the "Atlas of World Water Balance" (UNESCO, 1977). Clearly these will not be quite consistent with the AAR values for the catchments solely within Namibia; however, this does not matter as these large catchments were not used in the final development of the method. Catchment slope values, provided by DWA, were available for most of the stations, and information on dams affecting the floods was also supplied by DWA.

C2 Estimation of the mean annual flood

The value of the mean annual flood (MAF) was calculated as the average of the series of annual peak flows for each site; the values are listed in Section C6. A logarithmic regression of MAF on catchment area (AREA) using all the stations gave the following result:

Namibia - location of river flow gauging stations

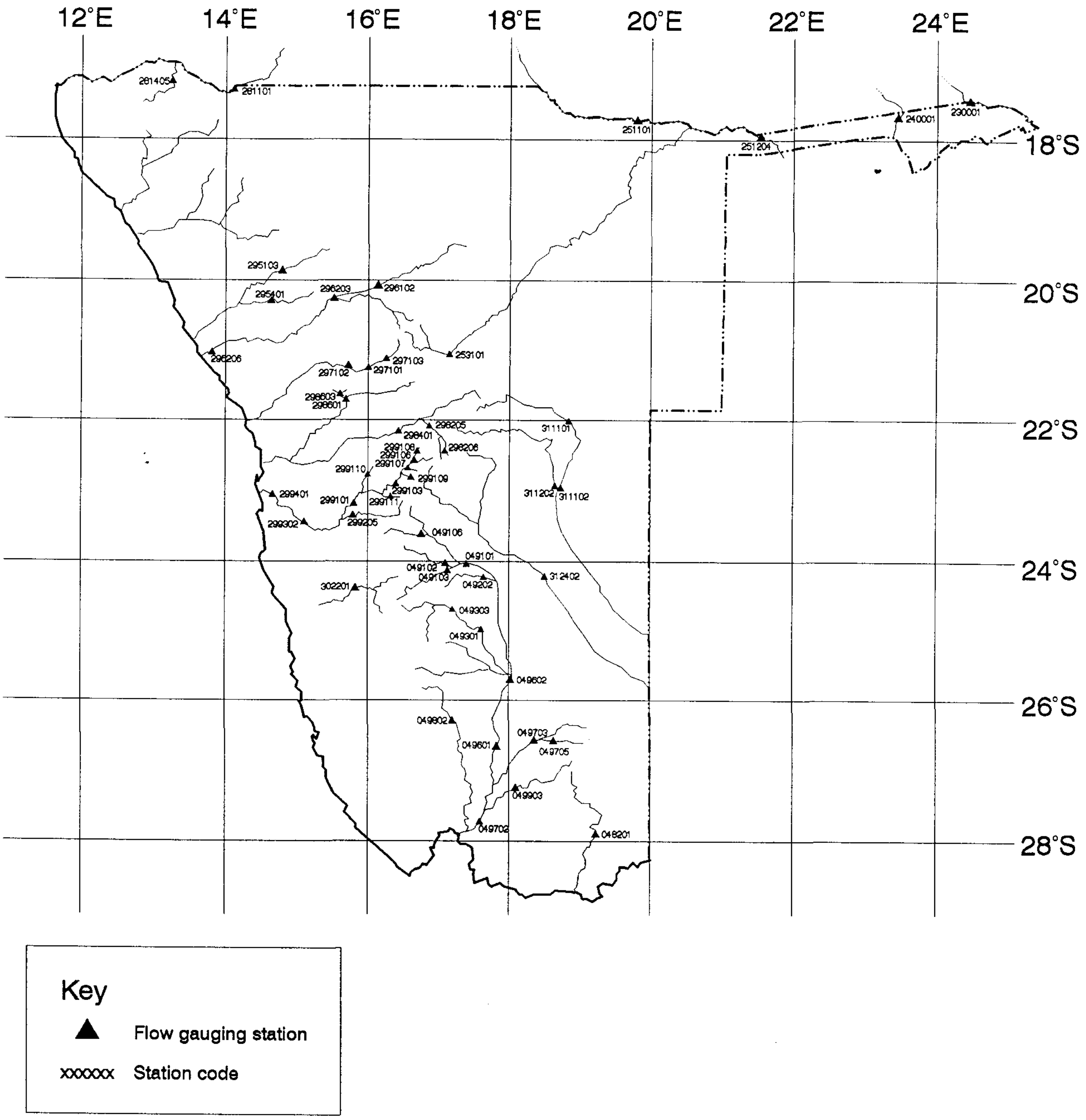

Figure C1

$$\text{MAF} = 4.00\ \text{AREA}^{0.368} \qquad r^2 = 0.344$$

The data and this fitted regression line are plotted in Figure C2. It is apparent that the data do not fall into a consistent pattern, and there appear to be a number of distinct reasons for this. Six of the stations (NM296206, 299302, 299401, 311102, 311202, 312402; distinguished in the figure) have low MAF, well below the regression line. Some of these, for instance, NM296206, 299302 and 299401 are far downstream on rivers which flow towards the Atlantic coast. This area is true sand desert with annual rainfall of less than 50 mm, and it is apparent that the floods not only disperse but also tend to disappear into the sand as they move downstream. This is illustrated in Figure C3 which shows the annual peaks at four stations along the Kuiseb river; it can be seen that the annual maximum is always smaller at the two furthest downstream stations than at the upstream ones. This is the reverse of the usual result that MAF increases as catchment size increases, and is very likely to be the effect of the rivers flowing into desert regions as discussed above. Only three of the stations clearly fall into this category, and these were eliminated from the analysis. For stations NM311102 and 311202 which are on rivers flowing east, a similar effect may also be occurring, but these stations are affected by upstream dams and they were also omitted. Station NM312402 also has a very low MAF and was omitted; as there are no upstream stations for comparison it is not known whether this station is affected by loss of flow in desert areas, or whether, because of the very high variability of floods from year to year in arid regions, the very low value has occurred by chance.

The five stations on four large rivers flowing from Angola and Zambia into the country (the Zambezi, Kwando, Okavango and Kunene; stations NM230001, 240001, 251101, 251204 and 281101) would not be expected to be homogeneous with the remainder of the stations. The source of flow is geographically separate and the catchments are much more humid with average annual rainfalls between 800 and 1000 mm, while for the other catchments AAR does not exceed about 485 mm and the median is 240 mm. Although in Figure C2 some of these large catchments fall close to the regression line, they cannot be homogeneous with the remainder of the Namibian catchments, and they were eliminated from the analysis.

Several other stations besides those mentioned above are affected by dams. Station NM298401 has two dams upstream: Von Bach dam from 1970/71 and the larger Swakoppoort from 1977/78. Examination of the sequence of flood peaks showed that the later dam which is also much closer to the gauging stations has greatly reduced the floods, while the earlier dam appears to have had little effect. Based on this, data at station NM298401 were omitted from 1977/78 onwards. The other large dams are in the Fish basin: Naute dam on the Loewen river is upstream of station NM049902 (since 1970/71) and Hardap dam on the Fish is upstream of this station as well as NM049601 and 049602 (since 1962/63). Because the flow records start after the dams were constructed it is not easy to see if there have been significant effects on the floods. However, the dams do not control more than about half the catchments, and the MAFs of the affected catchments lie very close to or above the regression line, in contrast to the other gauges in the Fish basin for which the MAFs have a slight tendency to be below the regression line. Because of this it was assumed that the effect to these particular dams was small and the catchments were not removed from the analysis.

After eliminating some of the stations as discussed above, the regression based on the

Mean annual flood against catchment area for Namibia (all stations)

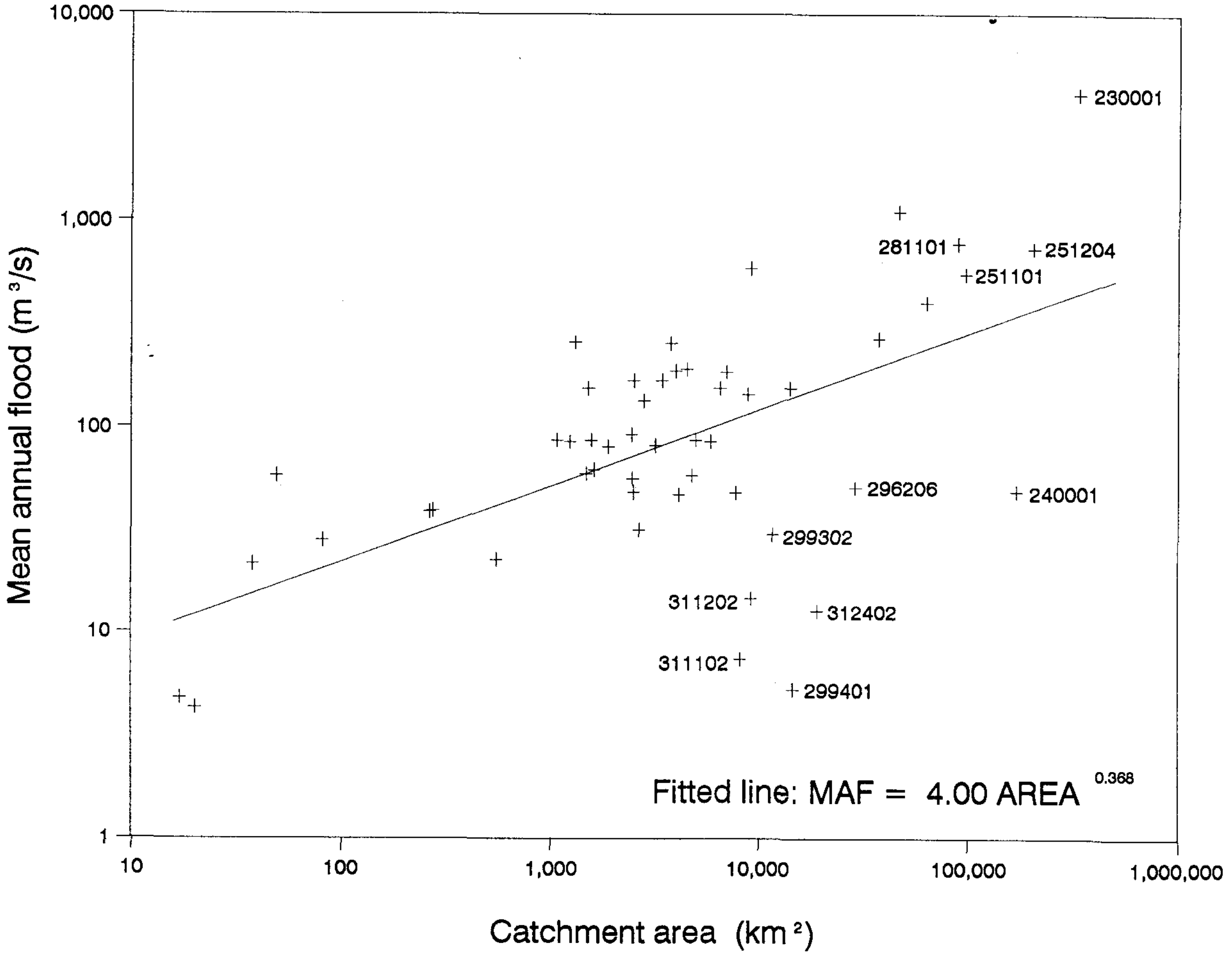

Figure C2

Annual flood peaks along the Kuiseb river

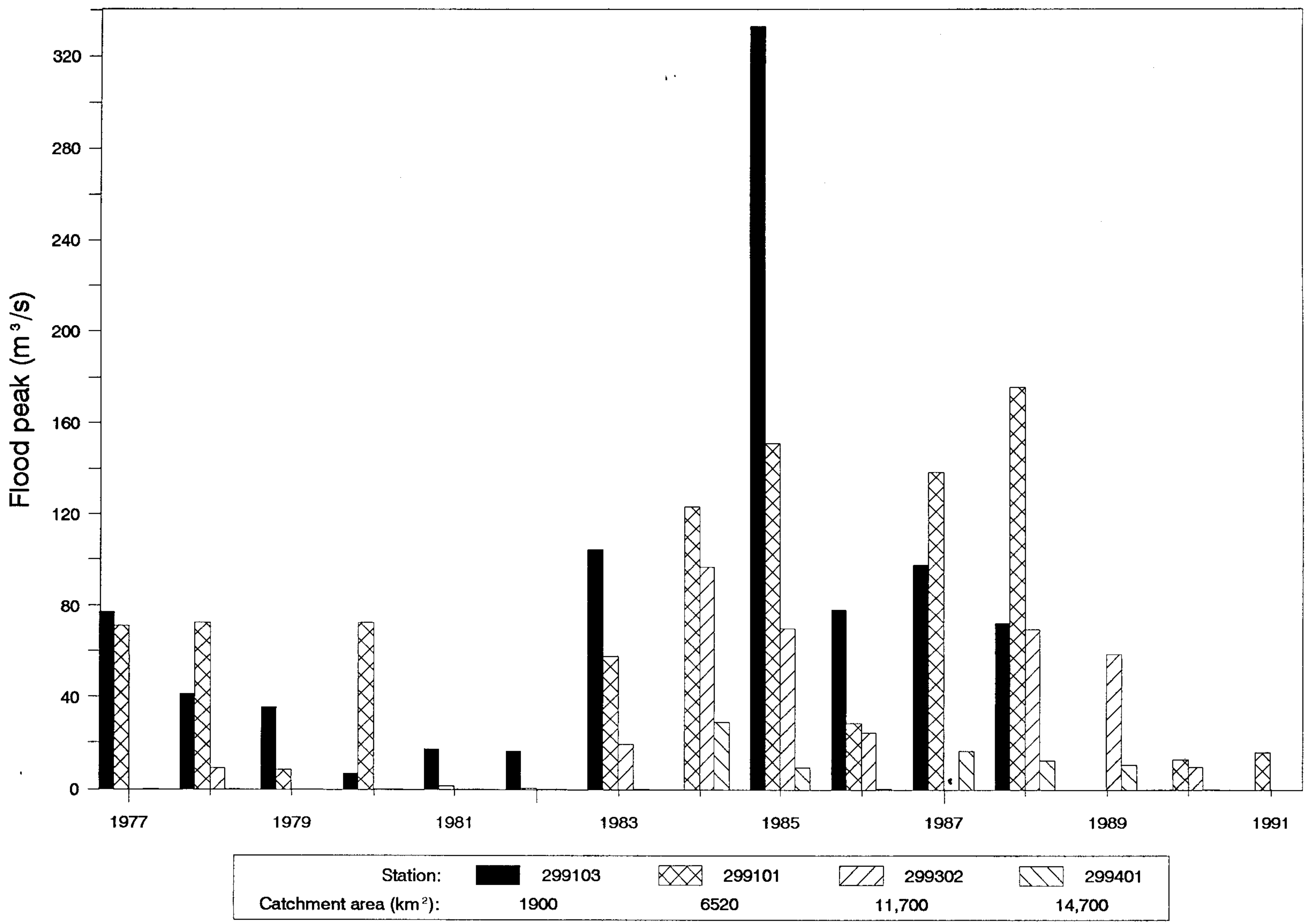

Figure C3

remaining 40 stations becomes:

$$MAF = 2.63\ AREA^{0.460} \qquad r^2 = 0.651$$

This is plotted in Figure C4. The fit of the data is much improved, giving an adequate MAF estimation equation. The factorial standard error of the estimate is 1.92, meaning that the 'true' MAF is likely to fall with the range +92% to -48% of the estimate given by the equation. The influence of the other catchment characteristics, AAR and catchment slope, was also examined. Neither of these gave any worthwhile improvement in the fit, and in both cases the coefficients were not significant at the 95% level, so these factors were not included in the estimation equation.

As discussed above, a number of stations in Namibia have been omitted from this analysis. This means that the MAF regression equation is limited in its applicability; it cannot be used for the most arid areas where rivers flow through sand desert, and it does not apply to large rivers originating outside the country.

C3 Regional flood frequency curves

Regional flood frequency curves were derived by fitting the GEV distribution to the pooled annual flood peak data for various groups of stations. The five stations on large rivers originating outside the country were not included as these are not at all typical of flood response in Namibia. The six stations which had very low MAFs and were excluded from the analysis for the MAF equation were included here because examination of their individual curves showed that they do not differ from the typical curves found in Namibia. Over the whole country, station flood frequency curves were found to be generally similar, allowing for the effect of short records and high year-to-year variability which is particularly pronounced in arid regions; and it seems reasonable to treat the whole country as a homogeneous region.

The variation in regional flood frequency curves for stations grouped according to catchment area and according to average annual rainfall was examined. Neither factor was found to produce strongly differentiated groupings. AREA was not found to be a significant factor, with the larger catchments producing slightly steeper curves than the small catchments, possibly because they are more likely to suffer from loss of flow in desert areas which would tend to increase variability. Generally, AAR groupings also did not produce distinctly different regional curves, except that it was found that the driest catchments did tend to produce somewhat steeper curves. An effective grouping was found by dividing the catchments at an AAR of 175 mm, and the two curves produced by this were taken as the most suitable regional flood frequency curves for the country. The parameters of the curves are given in Table C1 and they are plotted in Figure C5.

Mean annual flood against catchment area for Namibia
(omitting anomalous stations)

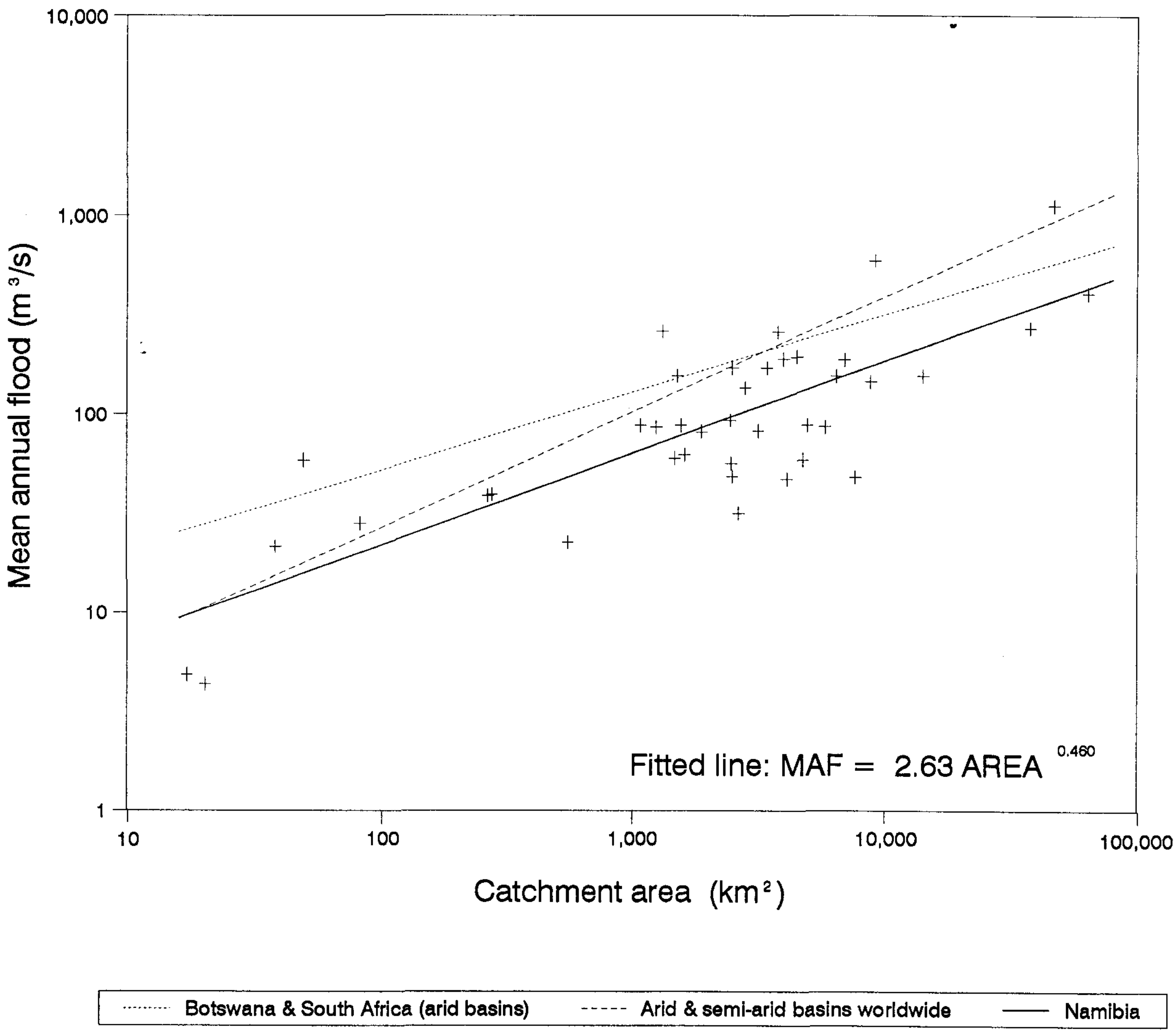

Figure C4

Regional flood frequency curves for Namibia

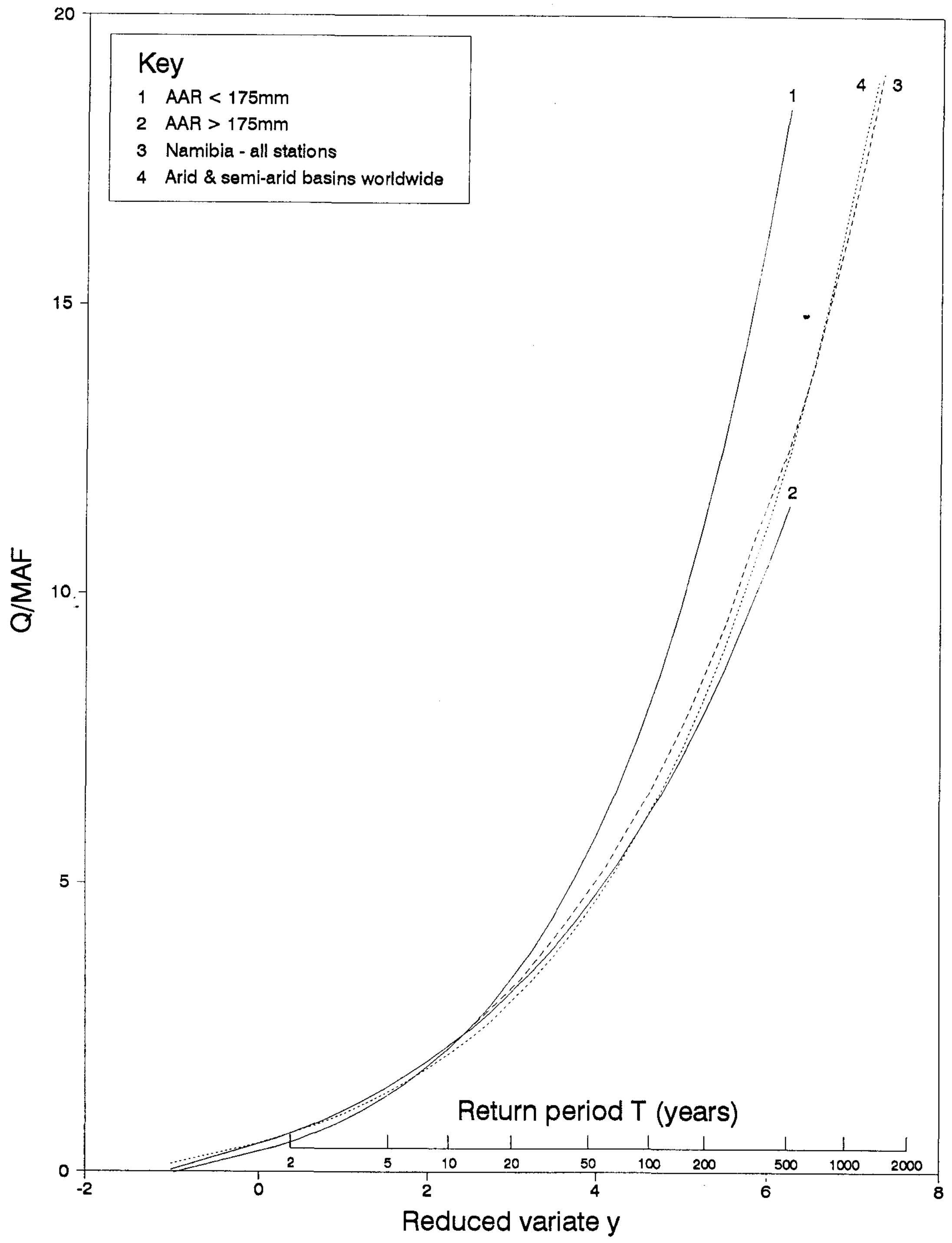

Figure C5

TABLE C1 *Regional flood frequency curves for Namibia*

Grouping	No. stations	No. years	GEV parameters u	α	k	Predicted floods q_{20}	q_{100}	q_{500}
All stations*	46	610	0.429	0.502	-0.3667	3.13	6.45	12.42
AAR < 175	9	100	0.336	0.448	-0.4834	3.30	7.97	18.09
AAR > 175	37	510	0.448	0.513	-0.3391	3.08	6.14	11.39

* Stations on the large rivers originating outside Namibia are excluded.

C4 Comparison to results for other arid regions

The study by Farquharson *et al.* (1992) has shown that arid and semi-arid regions worldwide have remarkably similar flood behaviour (see Section E13 in Appendix E). Namibia was not included in the study, and it is worthwhile to compare the present results to see how similar they are to areas with similar climates in other parts of the world.

Farquharson *et al.* used data from 162 stations in arid or semi-arid regions around the world. The catchments were selected as having annual rainfall of less than 600 mm, although cold arid regions were excluded. Data were available from south-west USA, north-west Africa, Botswana and South Africa, Arabia and the Middle East, and Australia. Combining all stations, the MAF equation was:

$$MAF = 1.87\ AREA^{0.578}$$

while for the nearest area to Namibia which had data, the dry areas of Botswana and South Africa, the equation was

$$MAF = 8.75\ AREA^{0.388}$$

Both these are compared to the Namibian equation in Figure C4. The regression for Namibia differs less from the all arid basins line than some of the regions which were included in that analysis, and the Namibian stations lie well within the range of variation found in the worldwide study. It can been seen from Figure C4 that while the Namibian line does not differ greatly from the worldwide or the Botswana and South Africa lines, it lies slightly below both. It is likely that this is at least partly a result of the Namibian catchments being generally more arid than those in the other regions: the median AAR is 240 mm, while for the catchments in Botswana and South Africa it was 470 mm, and worldwide it was 405 mm.

The flood frequency curves are compared in Figure C5, and it can be seen that the results for Namibia are remarkably close to the curves for other regions. The curve for all the Namibian stations is practically identical to the worldwide arid and semi-arid curve, while the curve for Botswana and South Africa (not shown in the figure) is slightly steeper than these. Farquharson *et al.* found that, except for a few special cases, all the arid and semi-arid regions studied had very similar flood frequency curves, and Namibia fits closely into this pattern. When the Namibian data are split according to the AAR value, the curve for the wetter catchments still lies close to the worldwide and other curves, while, as might be expected, the curve for the extremely arid catchments (AAR < 175 mm) is somewhat steeper than is found elsewhere.

C5 Conclusions

In conclusion, the result of the study is that the regression equation:

$$MAF = 2.63 \, AREA^{0.460}$$

should be used to estimate mean annual flood at ungauged sites. Where a reasonable length of good quality flow data is available at or close to the site of interest, the local record should be preferred for the estimation of MAF. The regional flood frequency curves grouped according to average annual rainfall (Table C1) should then be used to estimate the flood peak for the required return period. This method provides a reasonably good means of making flood estimates at ungauged sites in Namibia; however, coverage of stations is sparse in this large country and records are fairly short, so the results should be used with caution. On the other hand, it has been shown that these results agree well with studies for areas with similar climates worldwide and in adjoining countries, and this helps to substantiate the method.

As discussed above, the method is limited in its applicability and cannot be applied over the whole country. In particular, the MAF equation should not be used in the most arid areas where rivers flow through sand desert, and neither the MAF regression nor the flood frequency curves can be applied to the large rivers originating outside the country. There were insufficient data in this study to examine the problem of flood estimation in the most arid areas where flows tend to decline downstream, and it is probable that indices of vegetation or soil type would need to be included to derive a method which can also predict floods in these regions.

C6 List of river flow gauging stations and catchment characteristics

The table on the following pages lists the river flow gauging stations used in the study. For each station, the station code, name, number of years of annual flood peaks, location, mean annual flood (MAF), catchment area (AREA), slope, and average annual rainfall (AAR) are given. These were derived as explained in Section C1.2 above. The station codes used consist of 8 characters; the first two are NM, and the remainder is the six digit number based on one of the two numbering systems used by the Namibian Department of Water Affairs.

Station code	Name	No. years	Latitude (°S)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	Slope	AAR* (mm)
NM048201	Ham at Tsamab	18	28:09	19:15	92.1	2470	.00403	140
NM049101	Fish at Gras	17	24:11	17:21	584.2	9170	.00270	211
NM049102	Kam at Draaihoek	11	24:12	17:02	167.6	3450	.00325	229
NM049103	Fish at Dirichas	12	24:16	17:05	133.3	2830	.00262	180
NM049106	Kam at Klein Aub	11	23:49	16:37	86.3	1080	.00417	241
NM049202	Packriem at Karris	11	24:21	17:35	153.7	1520	.00218	205
NM049301	Hutup at Rietkuil	13	25:07	17:31	85.1	5850	.00206	179
NM049303	Hutup at Breckhorn	10	24:50	17:10	58.3	4780	.00174	177
NM049601	Fish at Seeheim	21	26:49	17:48	1105.8	46400	.00124	181
NM049602	Fish at Tses	7	25:54	17:59	265.9	37600	.00161	189
NM049703	Loewen at Altdorn	12	26:48	18:14	184.1	7000	.00391	153
NM049705	Loewen at Geduld	12	26:46	18:29	81.1	3200	.00481	160
NM049802	Konkiep at Bethanien	10	26:27	17:08	47.0	4140	.00407	171
NM049902	Fish at Ai-ais	10	27:55	17:29	397.2	63300	.00148	167
NM049903	Gab at Holoog	9	27:27	17:59	48.2	2510	.00402	135
NM230001	Zambezi at Katima Mulilo	39	17:27	24:15	4128.2	334000		(1100)
NM240001	Kwando at Kongola	15	17:45	23:19	48.6	170000		(950)
NM251101	Okavango at Rundu	46	17:54	19:46	549.2	97300		(850)
NM251204	Okavango at Mukwe	41	18:02	21:26	730.7	206000		(800)
NM253101	Omatako at Ousema	27	21:13	17:06	86.6	4970	.00232	402
NM281101	Kunene at Ruacana	27	17:24	14:13	768.0	89600		(1000)
NM281405	Omuhonga at Ombuku	4	17:16	13:19	62.1	1620		(150)
NM295103	Huab at Monte Carlo	11	19:59	14:45	31.5	2670	.00481	(300)
NM295401	Aba-Huab at Rooiberg	14	20:29	14:35	86.4	1570	.00505	(198)
NM296102	Ugab at Petersburg	21	20:12	16:08	47.9	7720	.00364	(485)
NM296203	Ugab at Vingerklip	17	20:25	15:28	153.8	14200	.00317	431
NM296206	Ugab at Ugab Slab	10	21:05	13:48	50.9	28900	.00338	305
NM297101	Omaruru at Omaruru	15	21:26	15:57	167.4	2520	.00383	379
NM297102	Omaruru at Etemba	21	21:26	15:41	253.6	3810	.00383	350
NM297103	Omaruru at Omburo	17	21:18	16:12	257.0	1320	.00386	390
NM298205	Otjiseva at Duesternbrook	19	22:16	16:54	84.8	1250	.00862	359
NM298206	Arebbusch at Monravia	5	22:32	17:04	58.3	49	.01980	340
NM298401	Swakop at Westfalenhof	15	22:17	16:25	144.0	8860	.00315	389
NM298601	Khan at Ameib	17	21:50	15:38	186.5	4010	.00450	319
NM298603	Dawib at Dawib	7	21:53	15:35	22.5	554	.00763	238
NM299101	Kuiseb at Schlesien Weir	28	23:17	15:48	153.9	6520	.00568	239
NM299103	Kuiseb at Us	11	22:58	16:24	80.3	1900	.00794	(290)
NM299106	Bismarck at Stanco	12	22:44	16:36	39.3	276	.00877	(320)

Station code	Name	No. years	Latitude (°S)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	Slope	AAR* (mm)
NM299107	Simmenau at Wasservallei	13	22:48	16:32	38.7	266	.01471	(295)
NM299108	Heusis at Heusis	12	22:38	16:39	21.5	38	.01563	310
NM299109	Westende at Westende	10	22:53	16:34	4.8	17	.00243	285
NM299110	Katros at Tweespruit	10	22:56	15:56	28.2	82	.00348	243
NM299111	Huis at Kos weir	10	23:13	16:11	4.3	20	.01887	205
NM299203	Gaub at Greylingshof	10	23:29	15:46	56.0	2490	.01163	181
NM299302	Kuiseb at Gobabeb	12	23:30	14:58	30.0	11700	.00431	190
NM299401	Kuiseb at Rooibank	15	23:11	14:39	5.3	14700	.00391	159
NM302201	Tsauchab at Sesriem	10	24:31	15:46	59.3	1480		(130)
NM311101	Black Nossob at Henopsrus	17	22:09	18:50	189.5	4530	.00138	398
NM311102	Black Nossob at Mentz	11	23:07	18:42	7.4	8160	.00142	362
NM311202	White Nossob at Amasib	15	23:05	18:39	14.6	9250	.00171	362
NM312402	Auob at Stampriet	10	24:19	18:27	12.7	19200		249

*AAR values in brackets estimated in this study; other AAR values supplied by Namibian Department of Water Affairs

Appendix D Development of flood estimation method for Zimbabwe

The general approach used in the development of the flood estimation methods for all the countries or regions is discussed in Chapter 2 of the main report.

D1 Data

D1.1 Flood peak data

The source of the flood peak data was the various data volumes published by the Hydrology Branch of the Ministry of Water Resources and Development (MWRD), principally the two "Hydrological Summaries" which contain the complete records for all gauging stations up to 1970 and up to 1980 (MWRD, 1975, 1982). Besides the monthly flows, these publications list the instantaneous flood peaks for each year of record. The flood peaks were extracted for all stations having autographic recorders which had five or more years of data. As these summary data volumes only contain stations which were still operating up to the latest year that was included, data for some additional years and some additional stations were extracted from the series of hydrological yearbooks published by MWRD; the yearbooks were available for the periods 1956/57 to 1978/79.

Several stations are immediately downstream of dams or reservoirs, and these were excluded. The great majority of stations have weirs or flumes, for which theoretical ratings are used as they have mostly not been calibrated by field measurement. However, in most countries gauging stations are rarely well calibrated for flood flows, so the data would be expected to be of comparable quality to that found elsewhere. The published data are mostly nearly complete, with few years having missing data; where data are missing or have been estimated, the instantaneous peak has generally not been given, so there do not appear to be any problems with spurious peak values having been accepted.

The stations are listed in Section D6, which also gives the number of years of data, the station locations and the catchment characteristics. Not all the stations were used in the final analysis, for a number of reasons, and this is discussed further in Section D2. The location of each gauging station is plotted in Figure D1.

D1.2 Catchment characteristics data

Besides latitude and longitude for each station, the catchment characteristics were limited to catchment area and average annual rainfall. The latitudes and longitudes and the catchment areas were taken from the same sources as the flood peak data. For a few of the larger catchments, the areas given in the Hydrological Summaries were clearly in error, and these have been corrected either by reference to earlier yearbooks or by measurement from the 1:1 million scale topographic map of Zimbabwe.

Average annual rainfall was estimated for each catchment using the isohyetal map for the

Zimbabwe - location of river flow gauging stations

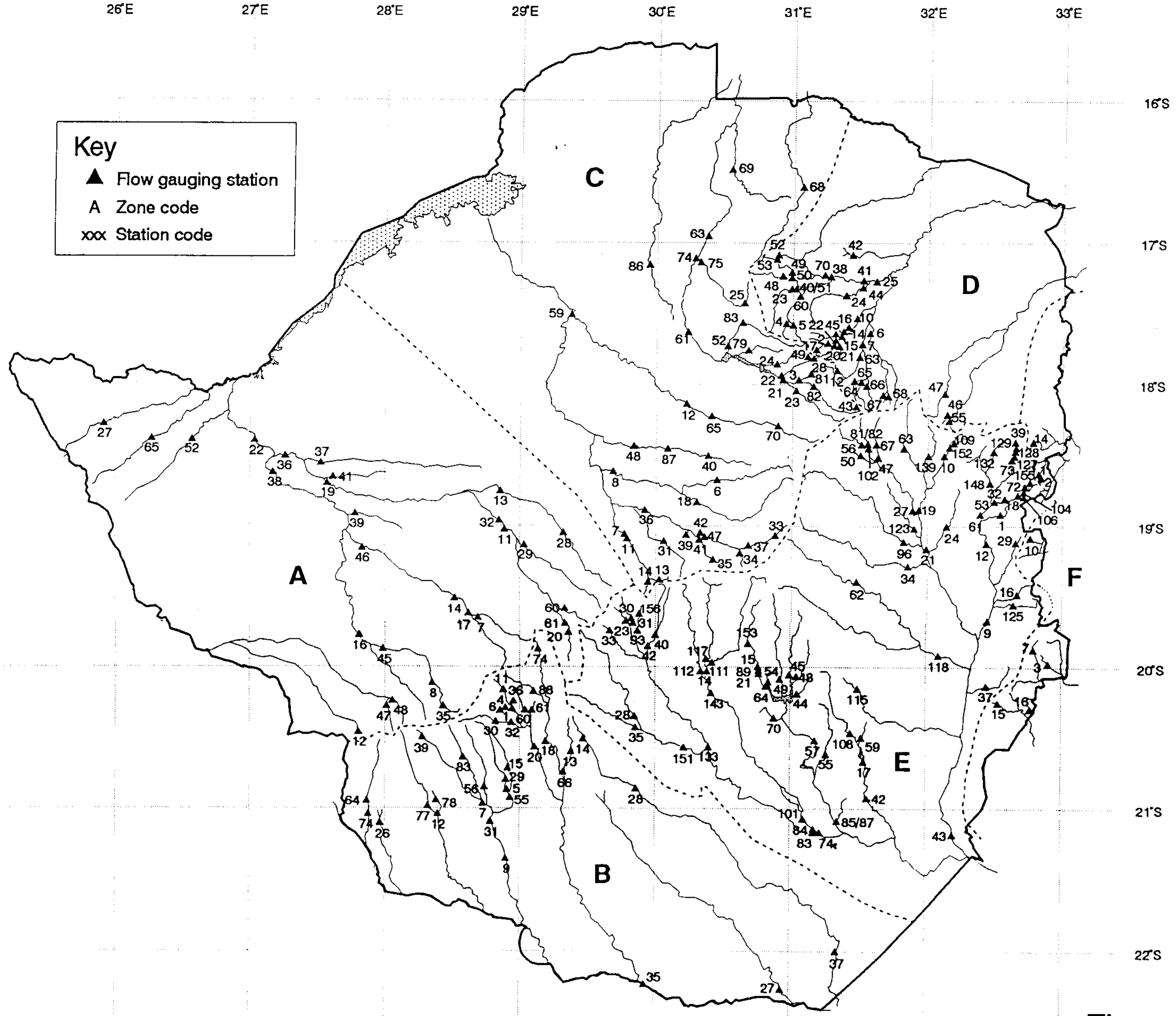

Figure D1

standard period 1941-71 prepared by the Department of Meteorological Services. For the catchments in central Zimbabwe studied by Bullock (1988), his AAR values were used (derived from the same original source). For one catchment, the Limpopo, which extends outside Zimbabwe, AAR was estimated using the appropriate map in the "Atlas of World Water Balance" (UNESCO, 1977), although this will not be quite consistent with the other catchments. Bullock also provides a number of other catchment characteristics for the 94 catchments in his study, however it was not possible to derive these for the additional catchments within the scope of this study.

D2 Estimation of the mean annual flood

The value of the mean annual flood (MAF) was calculated as the average of the series of annual peak flows for each site; the values are listed in Section D6. A logarithmic regression of MAF on catchment area (AREA) using all the stations gave the following result:

$$MAF = 1.48\ AREA^{0.656} \qquad r^2 = 0.777$$

The data and this fitted regression line are plotted in Figure D2. While the greater part of the data lies in a consistent pattern close to the regression line, a number of points are far from the line. A brief examination of the data was carried out to assess the possible reasons for these discrepancies, and the following stations were identified: B027 has a very short record and the MAF is very low; this is likely to be a result of the annual rainfall, which at 440 mm is much lower than any other catchment, (the next lowest is 520 mm). This catchment is very untypical of the general situation in Zimbabwe and was removed from the analysis. Station D022 has a short record and the data appears to be in error by comparison with nearby stations on the same river D002 and D010. The data for station E081 also look very suspicious, and both these stations were eliminated. Although they are not outliers in Figure D2, stations A052, C069, D049 had suspicious flood frequency curves where the highest observed flood was repeated at approximately the same value several times, indicating the likelihood that the station is bypassed or that floods spread out over a wide flood plain. This would mean that large floods are not properly observed, and the stations were eliminated from the analysis. Finally, stations E053 and E109 lie considerably further from the line than any other stations, and were thought likely to be in error, and were also removed.

After eliminating some of the stations as discussed above, the regression based on the remaining 234 stations becomes:

$$MAF = 1.46\ AREA^{0.665} \qquad r^2 = 0.836$$

This is plotted in Figure D3. The regression line is very similar to that originally obtained, but the fit of the data is much improved, giving an adequate MAF estimation equation. The factorial standard error of the estimate is 1.87, meaning that the 'true' MAF is likely to fall with the range +87% to -47% of the estimate given by the equation. Some apparent outliers still remain, but no reasons were found to suspect the data of being in error or otherwise anomalous, and therefore these stations were not removed from the analysis.

Mean annual flood against catchment area for Zimbabwe (all stations)

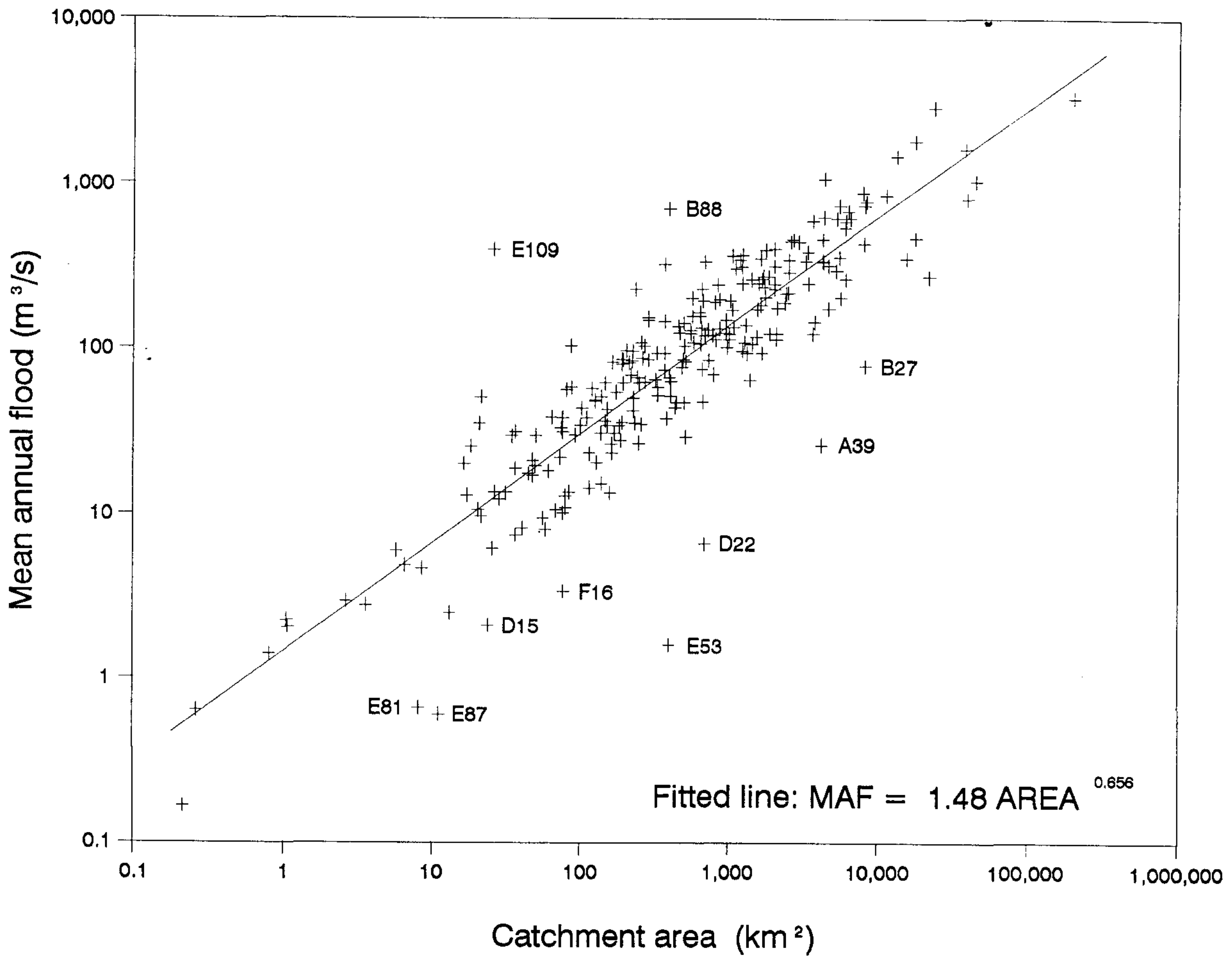

Figure D2

Mean annual flood against catchment area for Zimbabwe (omitting anomalous stations)

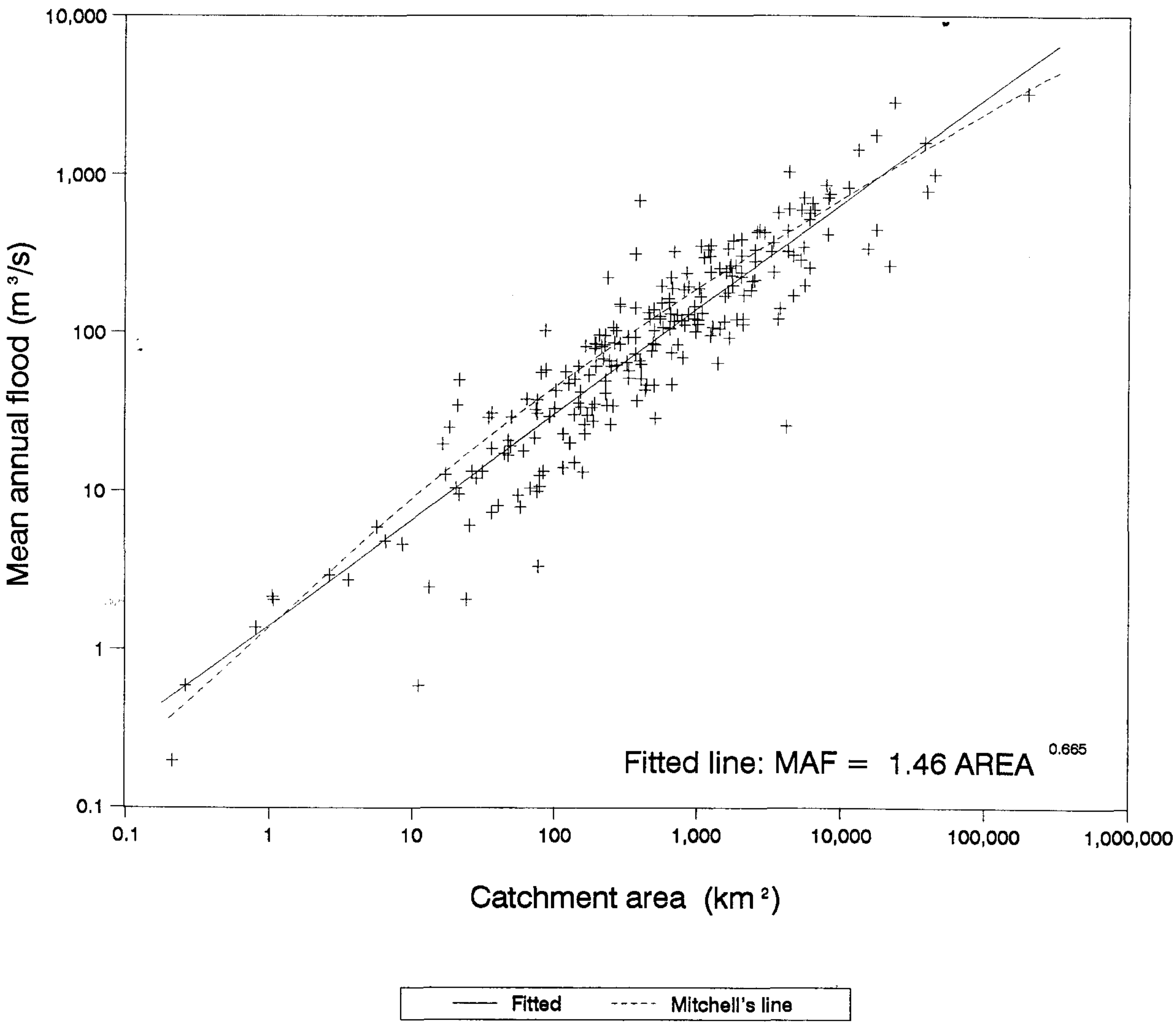

Figure D3

The influence of the other catchment characteristic which is available, AAR, was also examined. When this is included the regression becomes:

$$MAF = 28.3\ AREA^{0.643}\ AAR^{-0.425} \qquad r^2 = 0.840$$

Compared to using AREA alone, there is a marginal improvement in r^2 and the coefficient of AAR is just significant at the 95% level. However the effect of AAR is to indicate that floods would be smaller on wetter catchments which is the opposite to what would reasonably be expected. This may well come about because AAR happens to be weakly, but inversely, linked to catchment area, with the smaller highland catchment tending to be wetter than the larger catchments which include drier areas away from the central highlands. It may be concluded that average annual rainfall is not a useful indicator of flood response and should not be included in the MAF prediction equation. While the AAR values range from a minimum of 520 mm to a maximum of 2000 mm, the majority of the catchments have AAR within a relatively small range; for 80% of the catchments it is between 590 and 1000 mm, and only 10% are wetter than 1000 mm. It may be the case that AAR does have some genuine effect, but because of the small number of wetter catchments, it is difficult to detect the effect of increased rainfall, and the prediction equation may not perform so well in these areas.

There are numerous dams in Zimbabwe, and the gauges which are downstream of a large dam or reservoir and close to it were not used in the analysis as the flood flows could have been significantly affected. However, dams do affect the flows to a lesser extent at many of the stations that were used. It is thought that the scale of this effect is likely to be small, and it is still reasonable to use the data. Ideally a catchment characteristic defining the proportion of the catchment controlled by lakes or reservoirs should have been included so that their effect could be more precisely accounted, but this was beyond the scope of the project.

D3 Regional flood frequency curves

Regional flood frequency curves were derived by fitting the GEV distribution to the pooled annual flood peak data for various groups of stations. 234 stations were used, some anomalous stations being omitted as discussed in the preceding section. There was not found to be an excessive degree of variability between individual station curves, and considering the broad similarity of the climate over the country, it seemed reasonable to treat the whole country as a homogeneous region.

The variation in regional flood frequency curves for stations grouped according to catchment area and according to average annual rainfall was examined. AAR was not found to be a significant factor; although it might be expected that the curves would be steeper in the more arid areas and flatter in the more humid areas, particularly the eastern mountains, no consistent evidence was found for this effect. In contrast, when examining the effect of AREA, there was found to be some evidence of the expected effect of smaller catchments having steeper, and larger catchments flatter, curves. There is a very large range in the catchment areas, but it was found that the bulk of the catchments are similar, and only the smallest catchments (< 100 km^2) and the largest (> 2500 km^2) could be satisfactorily separated. Based on this, three regional flood frequency curves grouped by catchment area were chosen as the most suitable ones. The parameters of the curves are given in table D1 and they are plotted in figure D4.

TABLE D1 *Regional flood frequency curves for Zimbabwe*

Grouping	No. stations	No. years	GEV parameters u	α	k	Predicted floods q_{20}	q_{100}	q_{500}
All stations	234	4266	0.523	0.534	-0.2442	2.85	5.06	8.31
AREA < 100	53	954	0.486	0.516	-0.3018	2.97	5.63	9.93
AREA 100-2500	139	2575	0.527	0.541	-0.2332	2.85	4.99	8.09
AREA > 2500	42	737	0.562	0.534	-0.1996	2.73	4.59	7.13

D4 Comparison to existing methods

One of the standard methods for making flood estimates in Zimbabwe is that developed by Mitchell (1974). Based on 43 stations, the mean annual flood is estimated from catchment area using:

$$\ln(\text{MAF}+1) = 1.175 \{ \ln(\text{AREA}+1) \}^{0.775}$$

Then to obtain the flood for a particular return period, a set of multipliers (extending to the maximum probable flood) is available. Some of these multipliers for various return periods are:

T	Q_T/MAF
10	2.63
50	6.02
100	7.79
500	12.4

Mitchell's MAF prediction equation is plotted in figure D3, which shows that it is very similar to the one developed in this study. Thus the results given here usefully confirm his equation based on a much smaller data set. Mitchell's multipliers effectively provide a regional flood frequency curve for use over the whole country. This curve is considerably steeper than the present one; for instance, estimates are about 50% greater for return periods of 100 and 500 years compared to the curve for catchments between 100 and 2500 km^2, and they are more than 25% larger than the curve for catchments of less than 100 km^2. The current study did not produce any evidence that the curves should be considerably steeper, and it is suggested that Mitchell's multipliers are somewhat over-cautious.

Regional flood frequency curves for Zimbabwe

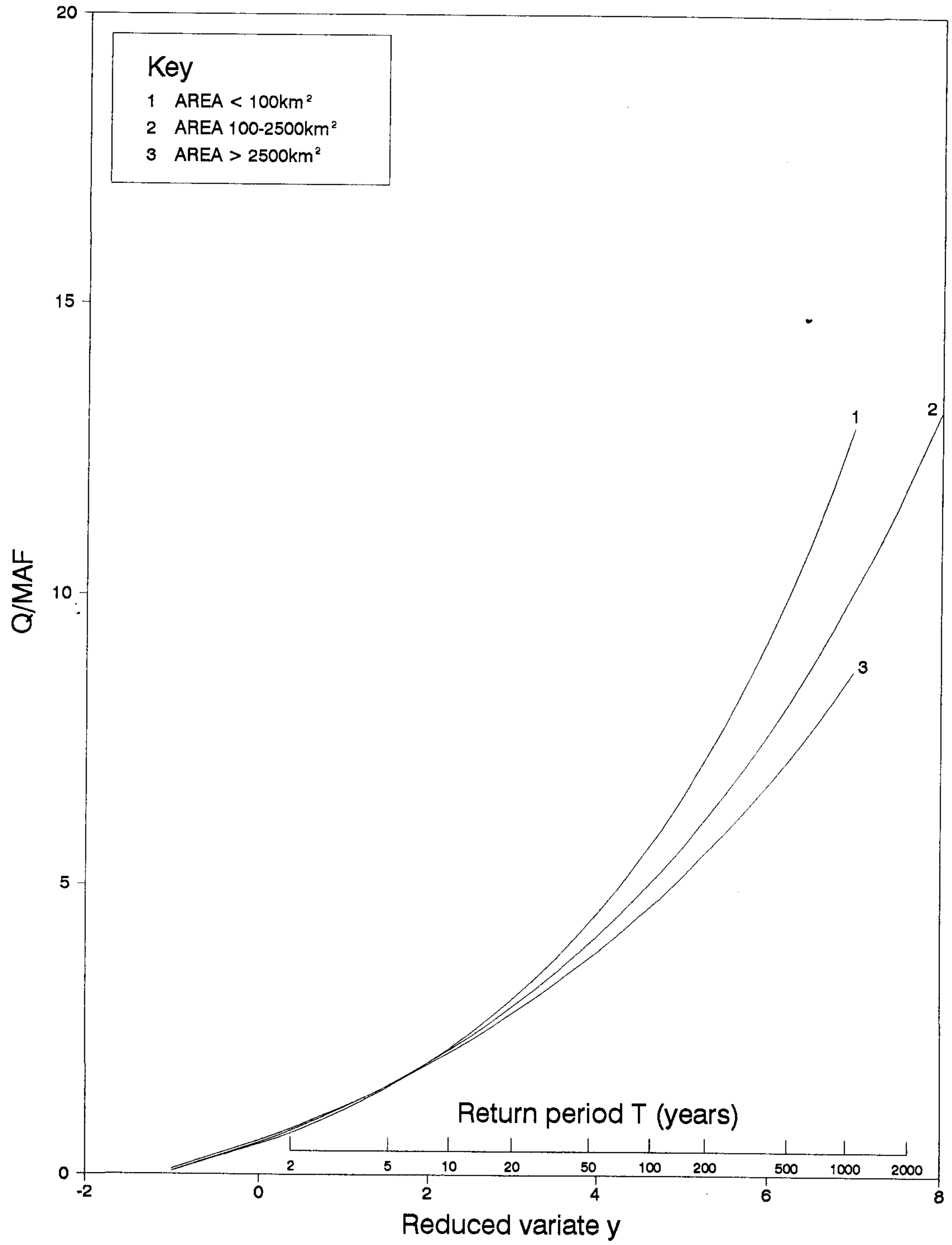

Figure D4

Bullock (1988) also presents a method covering the central part of the country. His MAF prediction equation uses several additional catchment characteristics, and should generally be preferred to the current equation in the region it covers. Bullock's regional flood frequency curve is similar to the ones presented here, although there is only a single curve and it is somewhat flatter. As the curves derived in this study differ for different catchment areas, they should generally be preferred.

D5 Conclusions

In conclusion, the result of the study is that the regression equation:

$$MAF = 1.46\ AREA^{0.665}$$

should be used to estimate mean annual flood at ungauged sites. Where a reasonable length of good quality flow data is available at or close to the site of interest, the local record should be preferred for the estimation of MAF. The regional flood frequency curves grouped according to catchment area (table D1) should then be used to estimate the flood peak for the required return period. This method provides a reasonably good means of making flood estimates at ungauged sites in Zimbabwe. Over much of the country there is a good coverage of stations, but, as illustrated in figure D1, away from the central region there a fewer stations and the method may have higher uncertainty. The method also probably has lower reliability in the wetter catchments of the eastern highlands and in semi-arid areas with less than 600 mm annual rainfall which are less well represented. For the semi-arid areas, the method based on arid and semi-arid catchments worldwide (Farquharson *et al.*, 1992; summarised in Section E13) provides a useful alternative. For the central part of the country the MAF prediction equation developed by Bullock (1988) would be expected to provide better estimates, although it requires more catchment characteristics to be measured.

D6 List of river flow gauging stations and catchment characteristics

The table on the following pages lists the river flow gauging stations used in the study. For each station, the station code, name, number of years of annual flood peaks, location, mean annual flood (MAF), catchment area (AREA), and average annual rainfall (AAR) are given. These were derived as explained in Section D1.2 above. The station codes used consist of 7 characters; the first three are ZIM, and the remainder is the zone code letter and the three digit station number assigned in MWRD publications.

Station code	Name	No. years	Latitude (°S)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	AAR (mm)
Zone A							
ZIMA007	Inkwekwesi at Braemar causeway	25	19:37	28:41	107.4	562	630
ZIMA008	Khami at Slights weir	29	20:05	28:23	46.7	492	590
ZIMA011	Shangani at Shangani causeway	17	18:56	28:52	288.7	5100	670
ZIMA012	Tegwani at Tegwani weir	28	20:23	27:48	21.8	72	580
ZIMA013	Gwelo at Gwelo river causeway	25	18:43	28:48	170.6	4560	690
ZIMA014	Bembezi at Matopo mine	14	19:29	28:33	112.7	2040	650
ZIMA016	Gwaai at Tjolotjo weir	23	19:44	27:48	141.5	3660	580
ZIMA017	Bembesi at Inkwekwesi	16	19:38	28:41	169.7	1530	610
ZIMA019	Shangani at Tjolotjo causeway	16	18:39	27.33	341.0	15000	680
ZIMA020	Shangani at lower railway weir	28	19:45	29:25	34.6	254	650
ZIMA022	Gwaai at Kamativi	25	18:22	27:03	792.7	38600	660
ZIMA027	Matetsi at Matetsi railway weir	7	18:15	25:57	383.0	1740	710
ZIMA028	Gwelo at Ambleside	17	19:03	29:21	92.3	1630	690
ZIMA029	Vungu at Riverbound	18	19:06	29:03	120.3	1840	650
ZIMA032	Shangani at Sir Godfrey Huggins bridge flume	17	18:55	28:52	256.7	5900	670
ZIMA035	Umganin at Sunnyside	20	20:11	28:30	12.8	77	600
ZIMA036	Shangani at Lower Shangani flumes	15	18:30	27:13	453.8	17200	680
ZIMA037	Kana at Japiwa Dip	19	18:34	27:33	64.0	1368	700
ZIMA038	Gwaai at Dahlia control section	11	18:36	27:10	265.4	21238	650
ZIMA039	Bubi at Lupane gauging weir	13	18:57	27:46	25.8	4082	650
ZIMA041	Tshongokwe at Kana road	18	18:40	27:34	28.9	502	650
ZIMA045	Khami at Porter	14	19:51	28:01	105.6	1410	580
ZIMA046	Bembesi at Siamkolo Pool	8	19:09	27:53	121.5	3574	620
ZIMA047	Mananda at Mananda dam u/s	11	20:15	28:03	27.6	184	590
ZIMA048	Manzamnyama at Mananda dam u/s	10	20:14	28:04	33.9	150	590
ZIMA052	Lukosi at Victoria Falls Road flume	11	18:24	26:36	92.7	1300	620
ZIMA060	Tiyabenzi at Tiyabenzi dam u/s	10	19:37	29:24	15.2	137	650
ZIMA061	Shangani at Tiyabenzi dam u/s	8	19:39	29:22	162.1	622	650
ZIMA065	Deka at Deka flume	5	18:23	26:19	121.7	2040	650
Zone B							
ZIMB001	Nċema at Ncema dam	11	20:22	29:00	130.8	640	620
ZIMB004	Fern Spruit at Plot 19	20	20:17	28:57	13.4	83	620
ZIMB005	Mchabezi at Gwanda weir	30	20:57	29:00	145.2	940	570
ZIMB006	Fern Spruit at Plot 26	32	20:18	28:54	29.3	34	630
ZIMB007	Mtsheleli at Freda weir	20	20:58	28:48	266.0	1810	590
ZIMB009	Tuli at Ntalali causeway	14	21:19	28:57	525.8	5880	560
ZIMB011	Ncema at Longden's weir	32	20:12	28:56	68.3	218	620

Station code	Name	No. years	Latitude (°S)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	AAR (mm)
ZIMB013	Kangezi at Eskdale causeway	28	20:36	29:35	121.9	456	540
ZIMB014	Nuanetsi at Inyesi weir	16	20:36	29:35	86.2	260	570
ZIMB015	Lumane at Insindi weir	31	20:46	28:59	102.5	267	575
ZIMB018	Insiza at Filabusi weir	26	20:29	29:15	225.2	1997	610
ZIMB020	Umzingwane at Glass Block g/w	25	20:36	29:11	435.1	2533	600
ZIMB026	Sansukwe at Ingwezi weir	22	21:06	28:00	35.5	189	540
ZIMB027	Bubye at Chikwarakwara weir	7	22:17	31:03	77.5	8030	440
ZIMB028	Nuanetsi at Jeka bridge	20	20:50	29:56	308.7	1990	580
ZIMB029	Mchabezi at Sheet dam u/s	21	20:44	28:55	73.4	363	575
ZIMB030	Umzingwane at Umzingwane dam u/s	20	20:22	28:54	133.8	448	620
ZIMB031	Tuli at Tuli Gorge	19	21:05	28:50	446.7	4140	580
ZIMB032	Nicholson Spruit at Ncema	17	20:21	28:29	50.5	21	590
ZIMB035	Limpopo at Beitbridge Pump Station	19	22:13	29:59	3274.7	195742	570
ZIMB036	Bumani at Ncema dam u/s	19	20:19	29:00	34.8	20	590
ZIMB037	Nuanetsi at Malipati Bridge	10	22:02	31:27	1437.0	13000	520
ZIMB039	Mpopoma at Mpopoma dam u/s	21	20:32	28:21	29.7	90	600
ZIMB055	Mchabesi at Gwanda	13	20:58	28:59	112.3	987	570
ZIMB056	Tuli at Tuli-Makwe dam u/s	12	20:54	28:47	223.7	645	575
ZIMB060	Inyankuni at Inyankuni dam u/s	13	20:18	29:06	84.5	194	595
ZIMB061	Inyali at Inyankuni dam u/s	13	20:18	29:08	29.5	49	600
ZIMB064	Ingwezi at Ingwezi dam u/s	15	20:58	27:54	127.9	712	580
ZIMB066	Kangezi at Silalabuhwa dam u/s	13	20:43	29:22	117.8	673	540
ZIMB074	Jama at Rixon dam u/s	15	19:59	29:10	37.6	75	660
ZIMB075	Insiza at Rixon dam u/s	15	19:57	29:12	51.3	401	660
ZIMB077	Shashani at Antelope dam u/s	11	20:58	28:21	126.6	539	575
ZIMB078	Zgalangamate at Antelope dam u/s	13	20:59	28:27	19.4	49	530
ZIMB083	Mtsheleli at Maizana	9	20:47	28:42	142.3	363	600
ZIMB088	Nyazani at Mayfair dam u/s	7	20:11	29:11	687.1	389	620
Zone C							
ZIMC003	Hunyani at Prince Edward dam d/s	25	17:59	31:04	187.5	793	710
ZIMC006	Ngesi at Ngesi dam u/s	34	18:40	30:31	168.7	1036	750
ZIMC007	Que Que at Cactus Poort dam d/s	20	19:03	29:47	107.2	1250	720
ZIMC008	Umniati at Power Station	28	18:39	29:47	578.8	5890	740
ZIMC011	Que Que at Cactus Poort dam u/s	30	19:04	29:49	95.6	1217	720
ZIMC012	Umfuli at Twyford	28	18:07	30:13	599.4	5180	670
ZIMC013	Kwekwe at Whitewaters dam u/s	23	19:22	30:01	42.6	150	775
ZIMC014	Kanuka at Whitewaters dam u/s	30	19:24	30:03	33.6	99	750
ZIMC018	Umniati at Dyke	22	18:49	30:19	446.8	2631	750

Station code	Name	No. years	Latitude (°S)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	AAR (mm)
ZIMC021	Hunyani at Poort dam u/s	19	17:58	30:54	116.3	1510	750
ZIMC022	Makabusi at Hunyani dam u/s	28	17:57	30:52	35.1	231	825
ZIMC023	Nyatsime at Edinburgh	28	18:04	31:04	83.2	500	800
ZIMC024	Marimba at Hunyani dam u/s	29	17:55	30:52	79.6	189	825
ZIMC025	Maquadzi at Ayres Poort	29	17:26	30:37	151.0	282	900
ZIMC028	Makabusi at Cleveland dam d/s	21	17:51	31:09	10.6	20	900
ZIMC031	Bembezaan at Rockvale	20	19:04	29:59	66.0	391	750
ZIMC033	Sebakwe at Enkeldoorn	25	19:06	30:53	61.2	194	750
ZIMC034	Little Sebakwe at Orton's Drift	21	19:09	30:36	56.6	119	700
ZIMC035	Umvuma at Nyamafufa	21	19:14	30:25	84.3	285	700
ZIMC036	Sebakwe at Dutchman's Pool dam	25	18:52	29:49	326.5	4170	720
ZIMC037	Sebakwe at Roger's Pool	18	19:09	30:41	111.8	800	750
ZIMC039	Weriwedzi at Sebakwe dam u/s	25	19:03	30:17	12.9	17	720
ZIMC040	Umsweswe at Carbis ranch	19	18:30	30:24	76.4	474	750
ZIMC041	Umvuma at Sabakwe dam u/s	26	19:04	30:21	195.1	855	700
ZIMC042	Chimache at Sebakwe dam u/s	26	19:02	30:20	18.7	36	730
ZIMC043	Hunyani trib. at Grasslands Res. Stn.	27	18:10	31:29	2.8	3.5	900
ZIMC047	Sabakwe at Sebakwe dam u/s	25	19:04	30:21	242.5	1554	750
ZIMC048	Umsweswe at Lion Farm	16	18:27	29:52	184.7	2310	660
ZIMC049	Chiripagura at Forest Nursery	23	17:49	31:05	3.0	2.6	850
ZIMC052	Gwebi at Longwood	16	17:46	30:33	119.1	759	850
ZIMC059	Sanyati at Copper Queen	14	17:30	29:24	1603.4	37500	740
ZIMC061	Hunyani at Sinoia	15	17:21	30:13	349.2	5340	830
ZIMC063	Hunyani at Mangula mine	16	16:57	30:21	421.4	7900	840
ZIMC065	Umfuli at Upper Seigneury	12	18:15	30:32	330.2	4140	750
ZIMC068	Umsengedsi at Aurelia	11	16:37	31:05	100.9	951	890
ZIMC069	Dande at Chitanha	7	16:31	30:33	135.8	1280	850
ZIMC070	Umfuli at Beatrice	11	18:15	30:46	358.1	1215	750
ZIMC074	Hunyani u/s Maquadzi confluence	9	17:05	30:18	661.9	6110	830
ZIMC075	Maquadsi u/s Hunyani confluence	11	17:06	30:19	198.5	1730	875
ZIMC079	Umzururu at Darwendale dam u/s	9	17:47	30:40	83.5	221	810
ZIMC081	Hunyani at Henry Hallam dam u/s	7	18:00	31:09	140.1	488	900
ZIMC082	Ruwa at Henry Hallam dam u/s	8	17:57	31:09	85.0	189	900
ZIMC083	Gwebi at Darwendale dam u/s	8	17:37	30:37	315.4	362	850
ZIMC086	Angwa at Chengu farm	7	17:10	29:58	190.1	656	800
ZIMC087	Umsweswe at Claw dam u/s	6	18:27	29:59	239.3	1990	720
Zone D							
ZIMD002	Umwindsi at Kilmuir	57	17:44	31:18	66.1	241	900

Station code	Name	No. years	Latitude (°S)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	AAR (mm)
ZIMD004	Dassura at Mazoe dam u/s	53	17:34	31:00	32.8	73	890
ZIMD005	Mazoe at Mazoe dam u/s	57	17:34	31:00	49.8	225	880
ZIMD006	Shawanoya at Mtoko road bridge	30	17:38	31:36	335.0	1170	875
ZIMD007	Inyagui at Mtoko road bridge	27	17:38	31:32	341.3	1600	940
ZIMD010	Umwindsi at Lion's Head	30	17:32	31:30	238.4	829	900
ZIMD012	Ruwidzi at Goromonzi dam	24	17:52	31:22	6.0	5.7	1000
ZIMD014	Marsala at Marsala	11	17:37	31:28	13.4	26	900
ZIMD015	Domvorgwe at Bally Vaughn	10	17:40	31:22	2.1	23	900
ZIMD016	Double Spruit at Frascati	15	17:35	31:27	31.0	36	900
ZIMD017	Mantongo at Nthaba	26	17:44	31:11	7.4	36	900
ZIMD020	Umtenje at Meadows	24	17:43	31:20	55.7	80	950
ZIMD021	Mabfen at Atlanta	22	17:43	31:22	14.2	114	1000
ZIMD022	Umwindsi at Bally Vaughn	6	17:40	31:23	6.6	676	925
ZIMD023	Umrodzi at Kia Ora	25	17:20	31:00	83.9	715	900
ZIMD024	Poti at Arcadia Upper	25	17:22	31:26	132.0	1060	875
ZIMD025	Mazoe at Panmure	13	17:16	31:37	309.2	4538	790
ZIMD038	Mazoe at Bindura Sangere	13	17:18	31:18	210.0	2357	910
ZIMD040	Umrodzi at Glengrey Drift	13	17:20	31:04	256.1	1400	930
ZIMD041	Mazoe at Lion's Den	13	17:17	31:31	374.2	3300	880
ZIMD042	Umfurudzi at Eben dam u/s	16	17:10	31:30	81.8	163	900
ZIMD044	Poti at Myross	12	17:16	31:33	242.6	1215	900
ZIMD045	Munenga at Bally Vaughn	13	17:40	31:23	50.7	137	900
ZIMD046	Mwarazi at Mwarazi dam u/s	14	18:12	32:12	96.4	202	850
ZIMD047	Nyagadzi at Weya TTL	10	18:01	32:09	223.3	233	875
ZIMD048	Wengi at Mwenje dam u/s	11	17:15	30:57	62.7	399	900
ZIMD049	Sawi at Mwenje dam u/s	10	17:10	30:59	37.9	109	900
ZIMD050	Nyamasanga at Mwenje dam u/s	11	17:13	30:59	2.5	13	900
ZIMD051	Umrodzi at Kilmer Flume	8	17:20	31:02	69.4	777	930
ZIMD052	Ruia at Frogmore dam u/s	10	17:05	30:57	18.0	60	900
ZIMD053	Masawere at Frogmore dam u/s	12	17:05	30:56	6.1	25	900
ZIMD055	Dora at Mwarazi dam u/s	13	18:14	32:13	38.3	63	850
ZIMD060	Mazoe at Virginia	9	17:21	31:05	47.2	655	920
ZIMD063	Nora at Northfield	6	17:50	31:30	51.8	329	925
ZIMD064	Chinyika at Chinwiri Estates	7	17:58	31:32	54.0	173	900
ZIMD065	Nyambuya at Chinwiri Estates	7	17:59	31:32	23.2	162	900
ZIMD066	Inyagui at Chinwiri Estates	8	17:58	31:34	48.1	124	900
ZIMD067	Nyakomberi at Seaton Estates	6	18:03	31:42	13.3	157	900
ZIMD068	Nyamtorwa at Seaton Estates	7	18:02	31:42	9.5	55	900

Station code	Name	No. years	Latitude (°S)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	AAR (mm)
ZIMD070	Sambi at Sambi Foothills	8	17:15	31:17	64.4	316	850
Zone E							
ZIME001	Umtali at Premier Estate	55	18:55	32:33	61.0	249	1025
ZIME002	Umshagashi at Waterworks weir	49	20:03	30:51	121.8	541	675
ZIME009	Odzi at Hot Springs	26	19:38	32:28	601.5	6300	830
ZIME010	Lesapi at Lesapi dam u/s	34	18:33	32:07	105.5	635	850
ZIME012	Odzi at Maranke	28	19:08	32:28	328.4	3200	910
ZIME014	Shashe at Gaths Mine	25	20:00	30:26	430.8	2870	700
ZIME015	Umshagashi at Jubilee dam	22	19:58	30:50	85.0	484	675
ZIME016	Wengesi at Marapara	22	19:26	32:52	20.9	47	950
ZIME017	Chiredzi at Ruware Ranch	26	20:46	31:38	230.3	1700	730
ZIME018	Odzani at Muncipal Intake	25	18:46	32:42	26.3	161	1200
ZIME019	Macheke at Condo dam u/s	26	18:55	31:57	243.1	3315	850
ZIME021	Sabi at Condo Dam	24	19:13	32:01	827.5	11000	800
ZIME023	Nyamadziwa at Gwenoro dam u/s	28	19:41	29:51	57.9	85	750
ZIME024	Tsungwesi at Condo dam u/s	24	19:05	32:07	153.4	557	750
ZIME026	Sabi at Condo dam u/s	23	19:07	31:52	582.6	3550	800
ZIME027	Ruzawi at Condo dam u/s	21	18:55	31:56	171.7	2070	825
ZIME028	Ingezi at Belingwe Road	21	20:22	29:54	268.0	1680	650
ZIME029	Impudzi at Zimunya	24	19:08	32:40	31.1	75	1200
ZIME030	Lundi at Gwenoro dam u/s	26	19:41	29:52	107.2	254	750
ZIME031	Gwenoro at Killarney	27	19:42	29:52	20.0	16	800
ZIME032	Odzani at Odzani Irrigation Board Intake	22	18:47	32:37	41.7	225	1080
ZIME033	Gwetshetshe at Standhope dam	21	19:44	29:43	25.4	18	700
ZIME034	Mwerihari at Nyashanu	19	19:16	31:54	284.1	2470	750
ZIME035	Umchingwe at Belingwe Road	17	20:25	29:52	257.2	1630	600
ZIME037	Taganda at Buffels Drift	22	20:06	32:31	26.6	246	1040
ZIME039	Erin at Hydro Station Upper weir	22	18:23	32:40	0.2	0.21	1750
ZIME040	Little Umtebekwe at Mount Bougai	15	19:49	30:00	145.5	285	825
ZIME042	Umtebekwe at Rietfontein	20	19:53	29:57	74.1	648	875
ZIME043	Sabi at Sabi Gorge Control Section	18	21:11	32:17	1007.4	44000	740
ZIME044	Bevumi at Kyle dam u/s	24	20:10	31:08	23.0	114	950
ZIME045	Umtilikwe at Kyle dam u/s	24	20:05	31:04	129.5	847	750
ZIME047	Wenimbi at Idapu	22	18:32	31:39	37.4	375	850
ZIME048	Msali at Kyle dam u/s	24	20:06	31:05	93.0	365	725
ZIME049	Popotekwe at Kyle dam u/s	23	20:07	31:01	190.1	1010	700
ZIME050	Chinekwa at Scorror Estates	24	18:32	31:32	30.3	168	800
ZIME053	Odzani at Flitell	6	18:49	32:31	1.6	391	950

Station code	Name	No. years	Latitude (°S)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	AAR (mm)
ZIME054	Umpopinyani at Kyle dam u/s	23	20:06	30:54	81.3	212	650
ZIME055	Umshavutwe at Esquilingwe weir	10	20:43	31:16	197.6	552	850
ZIME056	Karimba at Igudu	20	18:28	31:35	62.4	269	850
ZIME057	Umtilikwe at Bangala dam u/s	16	20:38	31:11	198.9	5480	760
ZIME059	Sengezi at Wedza	20	18:46	31:31	93.2	324	825
ZIME061	Odzi at Odzi Bridge	18	18:55	32:25	213.6	2450	940
ZIME062	Nyazwidzi at Buhera	15	19:23	31:28	391.5	1990	775
ZIME063	Macheke at Mere	13	18:26	31:51	120.0	989	850
ZIME067	Wenimbi at Igava	13	18:27	31:38	2.2	1.0	840
ZIME069	Umshagashi at Kyle dam u/s	20	20:07	30:52	122.1	938	660
ZIME070	Mzero at Mzero	16	20:20	30:56	43.2	101	950
ZIME072	Nyakawunga at Odzani dam u/s	19	18:48	32:45	4.7	8.4	1600
ZIME073	Odzi at Selborne	19	18:32	32:38	33.7	181	1400
ZIME074	Lundi at Tokwe confluence d/s	19	21:08	31:16	2842.7	23000	660
ZIME081	Ruzawi tributary at Edinburgh	12	18:27	31:36	0.7	8.0	820
ZIME082	Ruzawi tributary at Edinburgh	18	18:27	31:36	2.1	1.1	820
ZIME083	Lundi at Towke confluence u/s	14	21:10	31:12	1781.3	17100	630
ZIME084	Tokwe at Lundi Confluence	18	21:08	31:16	712.5	7950	690
ZIME085	Cheche at Triangle regeneration flumes	18	21:05	31:25	30.4	135	640
ZIME087	Makari at Triangle regeneration flume	18	21:05	31:25	0.6	11	580
ZIME089	Umshagashi at Copota dam u/s	13	19:56	30:49	43.6	425	675
ZIME093	Impali at Impaluli	15	19:47	29:55	47.5	124	850
ZIME101	Tokwe at Tokwe weir	15	21:03	31:10	854.5	7700	700
ZIME102	Ruzawi at Mtemwa	17	18:28	31:35	153.9	627	875
ZIME104	Odzani at Odzani dam u/s	14	18:46	32:45	8.0	57	1550
ZIME106	Nyambwa at Drennan	14	18:45	32:43	10.9	78	1550
ZIME108	Chiredzi at Manjirenji dam u/s	17	20:29	31:32	354.4	1041	700
ZIME109	Chitora at Woodlands	7	18:25	32:11	389.9	25	825
ZIME111	Shashe at Mushwe	17	19:58	30:28	178.8	1616	700
ZIME112	Tokwe at Bhganya	17	20:01	30:24	306.3	1197	750
ZIME115	Turgwe at Roswa	14	20:10	31:36	95.6	223	575
ZIME117	Ngezi at Mushwe	16	19:55	30:27	297.4	1090	700
ZIME118	Devuli at Chisurgwe	9	19:54	32:08	755.9	8200	725
ZIME123	Mare at Condo dam u/s	12	19:00	31:55	102.7	492	750
ZIME125	Umvumvumvu at Old Cashel Road bridge	10	19:31	32:37	46.6	433	1025
ZIME127	Nyamazi at Selborne	11	18:32	32:38	10.5	67	1900
ZIME128	Nyakupinga at Minnehaha	10	18:28	32:42	17.0	47	1925
ZIME129	Odzi at Minnehaha	10	18:28	32:41	10.1	75	2000

Station code	Name	No. years	Latitude (°S)	Longitude (°E)	MAF (m^3/s)	AREA (km^2)	AAR (mm)
ZIME132	Umvumira at Lisnakea	7	18:25	32:31	9.7	21	1000
ZIME133	Lundi at Ingesi confluence	9	20:37	30:27	713.8	5390	670
ZIME139	Mezi at Tandi	7	18:32	31:59	57.8	329	800
ZIME142	Chiredzi at R/B Canal Pick-up weir	8	20:55	31:38	334.4	2460	790
ZIME143	Tokwe at Austral dam spillway	8	20:08	30:27	1045.4	4250	710
ZIME148	Nyatanda at Nyatanda/Odzi confluence	6	18:44	32:19	326.8	679	900
ZIME151	Ingesi at Sivumba	7	20:34	30:17	610.6	4230	630
ZIME152	Chimbi at Glenfarg	9	18:26	32:11	36.3	146	825
ZIME153	Umshagashe at Makaholi dam u/s	7	19:49	30:44	61.2	146	700
ZIME155	Nyambwa at Eastbourne dam u/s	5	18:43	32:45	8.2	40	1600
ZIME156	Impali at Impali dam u/s	8	19:39	29:56	17.4	44	850
Zone F							
ZIMF001	Mapopo at Stapleford	21	18:40	32:51	4.9	6.5	1200
ZIMF002	Nyatsanga at Hope Patrol	20	18:40	32:52	0.6	0.26	1175
ZIMF003	Chisengu at Upper weir	19	19:55	32:54	1.4	0.80	1500
ZIMF007	Nyahodi at Nyaruwa	21	19:51	32:48	20.3	127	1100
ZIMF010	Zonwi at Hoboken	14	19:05	32:47	13.4	31	1600
ZIMF014	Pungwe at Pungwe Causeway	6	18:24	32:47	102.7	85	2000
ZIMF015	Busi at Bangazaan	9	20:13	32:36	12.2	28	1100
ZIMF016	Chipudzana at Southdown	8	20:16	32:50	3.4	76	1250

Appendix E Results for other countries and regions

This appendix gives the background to the results presented in Chapter 3 of the main report; the actual results are presented there in Tables 1 and 2, and they are not repeated here. Also, Tables 3 and 4 in the main report list the ranges of the catchment characteristics used in developing the methods. The appendix covers the 13 countries or regions for which results have been previously published, extracted from other reports, or for which less detailed studies have been done as part of the present study. The work for the four countries where more detailed analyses have been carried out is discussed in Appendices A to D.

E1 Rio Grande do Sul, Brazil

The flood design method for the state of Rio Grande do Sul is taken from the study by Farquharson (1980), but the flood frequency curve has been updated to the PWM method. Data were assembled for all the stations which had reliable flood flows, giving a total of 59 stations in all. The catchments ranged in area from 130 to 70,000 km^2 and in annual rainfall from 1280 to 1850 mm. The available stations provide good areal coverage of the state, and topographic and hydrological conditions are relatively homogeneous throughout.

For the MAF equation a wide range of catchment characteristics was considered, but in addition to the catchment area only AAR and a measure of slope, S1085, were found to be effective. However, these did not provide major improvements compared to area alone. The resulting equation has a relatively small degree of uncertainty with an r^2 of 0.913 and f.s.e.e. of 1.49. A search for different equations based on geographical grouping or on ranges of catchment area did not produce significant improvements and a single equation was recommended for the whole state. A single flood frequency curve was also recommended. Generally the method provides a good flood estimation tool, but it should be noted that there were few catchments of less than 1000 km^2, and both the MAF equation and the flood frequency curve are less reliable for these smaller catchments.

E2 West Africa

A large part of west Africa can be treated as a unit for flood estimation purposes, and data from several countries have been combined to produce a method for the whole region. These results have been published elsewhere (Farquharson *et al.*, 1993), and the present report only summarises the main findings and the recommended approach.

Data were assembled for a total of 224 stations, covering the area from approximately 13° W to 16° E, and from 2° to 15° N; the countries included were Guinea (eastern part only), southern Mali, Burkina Faso, Côte d'Ivoire, Ghana, Togo, Benin and Cameroon, and there were also a few stations in other countries adjoining these. Within the region, some areas were poorly represented, with no data from Sierra Leone or Liberia and only a few stations in Niger and Nigeria. Catchment areas ranged from about 50 to 400,000 km^2, and annual rainfall from 740 to 3600 mm. The region studied is large and diverse; for instance, climate varies widely, with rainfall generally declining northwards from the very humid coastal zone towards the semi-arid Sahel.

A number of different groupings were examined to try to define reasonably homogeneous sub-regions for which MAF prediction equations could be defined. The groupings were by country or major basins, geographical areas defined by latitude and longitude, as well as groups defined by ranges of catchment area and of annual rainfall. The most effective groupings were by latitude and longitude, and five MAF equations were recommended for the following areas: West of 8° W; from 8° W to 2° W; from 2° W to 4° E; from 9° E to 16°10' E and north of 8° N; and from 9° E to 16°10' E and south of 8° N. Between 4° and 9° E there were too few data to define an equation. In each case AAR was strongly significant in addition to catchment area. Good regressions were produced with r^2 in the range 0.819 to 0.943 and f.s.e.e. from 1.38 to 1.60.

A variety of groupings was also tried to determine the flood frequency curves. In this case it was recommended that groupings according to average annual rainfall (but covering the whole region) should be used. Separate curves were defined for AAR from 1000-1250 mm, 1250-1500 mm, 1500-1750 mm, and greater than 1750 mm. These curves conform to the expected behaviour, with the more humid areas having flatter curves. An additional grouping with AAR from 600 to 1000 mm was also examined, but the resulting curve was flatter than that found for higher rainfall areas. As this goes against the expected behaviour, it was suggested that, instead, the curve derived for stations with AAR 1000-1250 mm should also be used for stations with AAR less than 1000 mm. Other groupings were less effective than the ones by rainfall. However, it can be observed that whereas groupings according to catchment area are broadly similar to those obtained with rainfall, the curve for area less than 1000 km^2 is considerably steeper than any of the others. Thus, although it is not recommended in the published paper, it is suggested here that this curve should be used in preference for catchments of less than 1000 km^2, whatever the rainfall.

Generally the method should provide robust flood estimates, and could be extended with caution into adjoining areas. However, it should be born in mind that performance will be less good at the limits of the data. In particular, it may not perform well for small catchments; there were only 12 stations with area less than 500 km^2. The method may also not be appropriate for drier basins, as only 3 of the catchments studied had average annual rainfall less than 800 mm.

E3 Malawi

The method for Malawi is taken from the study by Drayton *et al.* (1980), but the flood frequency curve has been updated to the PWM method. Data were assembled for all the stations which had reliable flood flows, giving a total of 28 stations in all. The catchments ranged in area from 60 to 11,000 km^2 and in annual rainfall from 710 to 1480 mm. There are not a large number of gauging stations available, and they provide only reasonably adequate areal coverage of the country. Topographic and hydrological conditions in Malawi are generally rather variable.

For the MAF equation a wide range of catchment characteristics was considered, but in addition to the catchment area only stream frequency, STMFRQ, was found to be effective. A geographical division of the country into highland and lowland areas, along the escarpment, was also examined and found not to be useful. The recommended equation has a high degree of uncertainty with an r^2 of only 0.381 and f.s.e.e. of 2.39. For the flood frequency curve, a single curve is recommended for the whole country. However, there is considerable variability in the individual station curves, and this could not be satisfactorily explained by grouping either by catchment area or by annual rainfall. The resulting flood estimation tool for Malawi has a higher degree of uncertainty than that found in most other countries studied. This is probably due to the high hydrological variability over the country and the relatively poor coverage of stations as well as to sampling variation. Although the study on which these results are based was undertaken several years ago, it is understood that not many more flood data are now available, and to try to improve the method, it would probably be necessary to examine data from adjoining regions outside the country to try to form larger and, hopefully, more homogeneous zones.

E4 South Africa & Botswana

The data for South Africa and Botswana were originally assembled as part of the World Flood Study (Meigh and Farquharson, 1985), but since then some additional stations and more up-to-date data have been supplied by the Department of Water Affairs in Botswana as part of another study (Gibb, Institute of Hydrology, 1992). The area covered is the whole of South Africa except the arid north-west of the country (the area that is both north of 31°S and west of 23°E) and the adjoining easternmost part of Botswana (the rivers that form part of the Limpopo basin). The region is quite diverse in topography and climate, with annual rainfall for the catchments ranging from 200 to 2740 mm. However, the great majority of the catchments have AAR in the range 400 to 1000 mm; only 15 are less than 400 mm, 16 greater than 1000 mm, and 3 greater than 2000 mm. Data are available from 109 stations, which cover a good range of catchment sizes from 3 to 92,300 km^2, and there are many long records.

The regression of MAF on catchment area gives an adequate equation, with r^2 of 0.542 and factorial standard error of the estimate of 2.19. The data and the regression line are plotted in Figure E1. When AAR is included r^2 improves to 0.593 and f.s.e.e to 2.10. It can be seen in the figure that some stations lie far from the line, but no good reasons for the divergence could be found. The stations in Botswana are distinguished, and it can be seen that these do not stand out from the general pattern. Stations with AAR greater than 1000 mm are also distinguished, and these do tend to have higher MAFs. A number of sub-divisions of the data were examined to see if better results could be achieved by treating these more humid catchments separately, but no significant improvements were achieved. It was felt that it was better to explain the divergence of the wetter catchments by the use of AAR in the MAF equation. As can also be seen in the figure, the MAF equation (based on AREA only) agrees reasonably well with the worldwide equation for arid and semi-arid basins (see Section E13), but gives higher MAFs for all but the largest catchments, probably reflecting the generally higher rainfall in this region.

Mean annual flood against catchment area for South Africa and Botswana

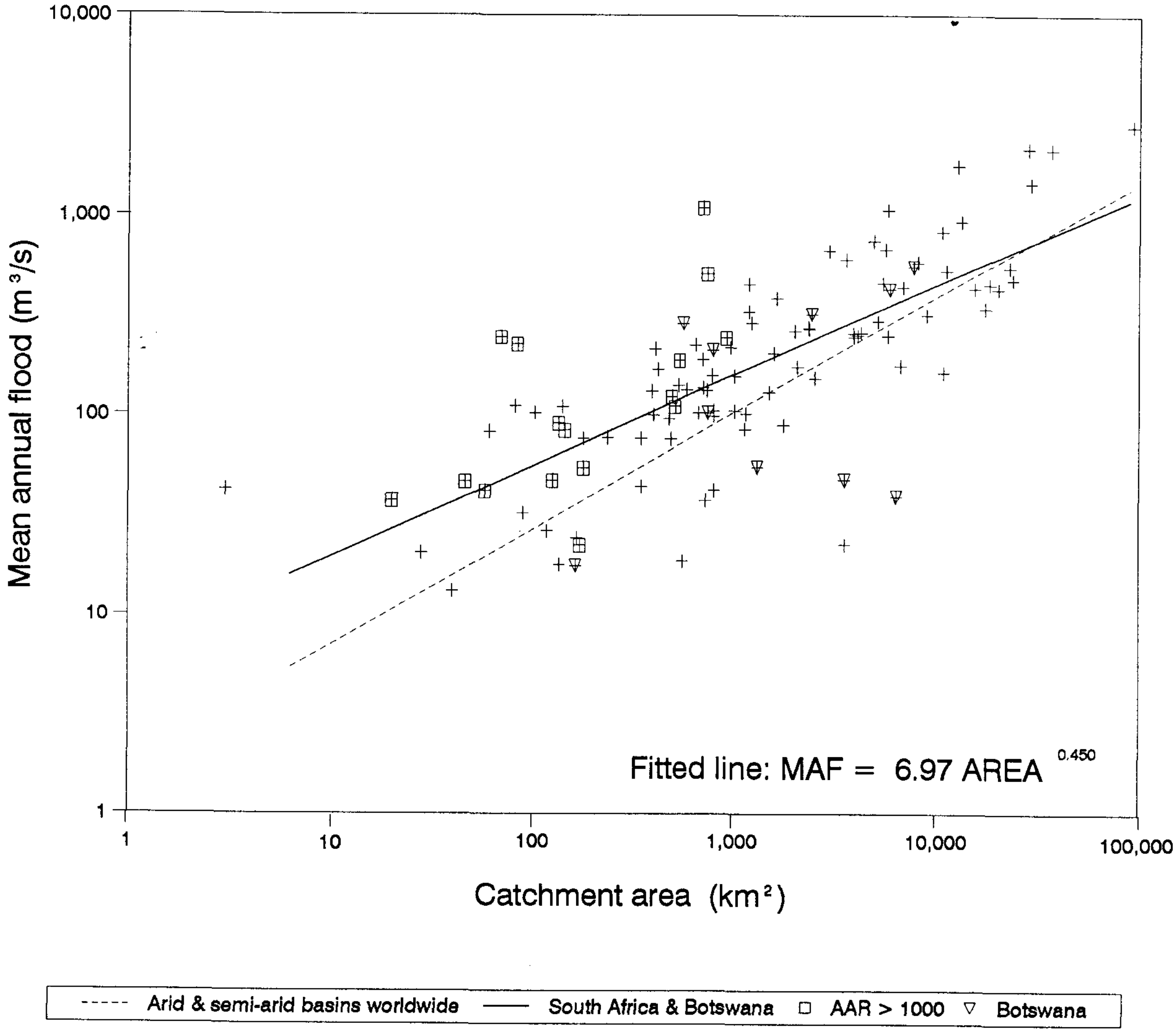

Figure E1

The more humid catchments were found to have different flood frequency curves to the majority and, separating them at an AAR of 1250 mm, two groups were formed. There are only 8 catchments in the group with AAR 1250-2750 mm, but these have a distinctly flatter curve than the remainder. The bulk of the catchments were treated as a single region and no good reason was found to sub-divide them despite the wide range of AREA and AAR. The curve is remarkably similar to that for arid and semi-arid regions worldwide even though many more humid catchments are included here, illustrating the tendency towards large floods found in this part of the world. The method presented provides a reasonable flood estimation tool, but further work, including the derivation of a wider range of catchment characteristics, is needed to improve the MAF prediction equation.

E5 Swaziland

The flood analysis for Swaziland was carried out by the Institute of Hydrology as part of a study of the Komati basin (Gibb, 1990). Data were assembled for 27 gauging stations in Swaziland; these were all those with adequate ratings and at least 5 years of flood peak data. In addition, as the adjoining area of South Africa is very similar in character and many of the rivers in Swaziland originate in South Africa, 11 South African stations were included in the analysis. The area covered is between approximately 30° and 32° East and from 25° to 27½° South. An escarpment runs from north to south through the country and continues into South Africa; all the catchments lie at least partly on the escarpment or in the highland areas to the west, and this gives them all a broadly similar character. Occasional tropical cyclones cross the country, giving extreme rainfalls on the escarpment, and this effect means that very large floods can be produced, dominating the flood response. Catchment area and average annual rainfall values were also obtained. Annual rainfall values were in the range 800 to 1220 mm (except one at 1480 mm), and catchment areas were between 58 and 12,600 km^2.

The recommended MAF equation depends on catchment area alone; the addition of AAR was not found to be effective. Although the r^2, at 0.657, is rather low, the f.s.e.e. is 1.76 which is comparable with that found in most other countries. A single flood frequency curve was developed for the whole country. Geographical grouping were not found to be effective, and although there was some tendency for the smaller catchments to have steeper curves, the difference was not thought sufficient to justify presenting separate curves. The flood frequency curve is very steep, perhaps reflecting the influence of cyclones, and it is also, not surprisingly, very similar to that for most of South Africa and Botswana (AAR $<$ 1250 mm). There is reasonably good coverage of the country and the method supplies an adequate flood estimation tool.

E6 South-west Saudi Arabia

The data for Saudi Arabia were assembled as part of a flood study of the Jeddah mountain region (Institute of Hydrology, 1985). In the present study more stations have been included to cover an area along the west coast of Arabia from about 15½° to 24½° N and extending about 300 km inland. One station from the adjoining part of Yemen has also been included.

Mean annual flood against catchment area for south-west Saudi Arabia

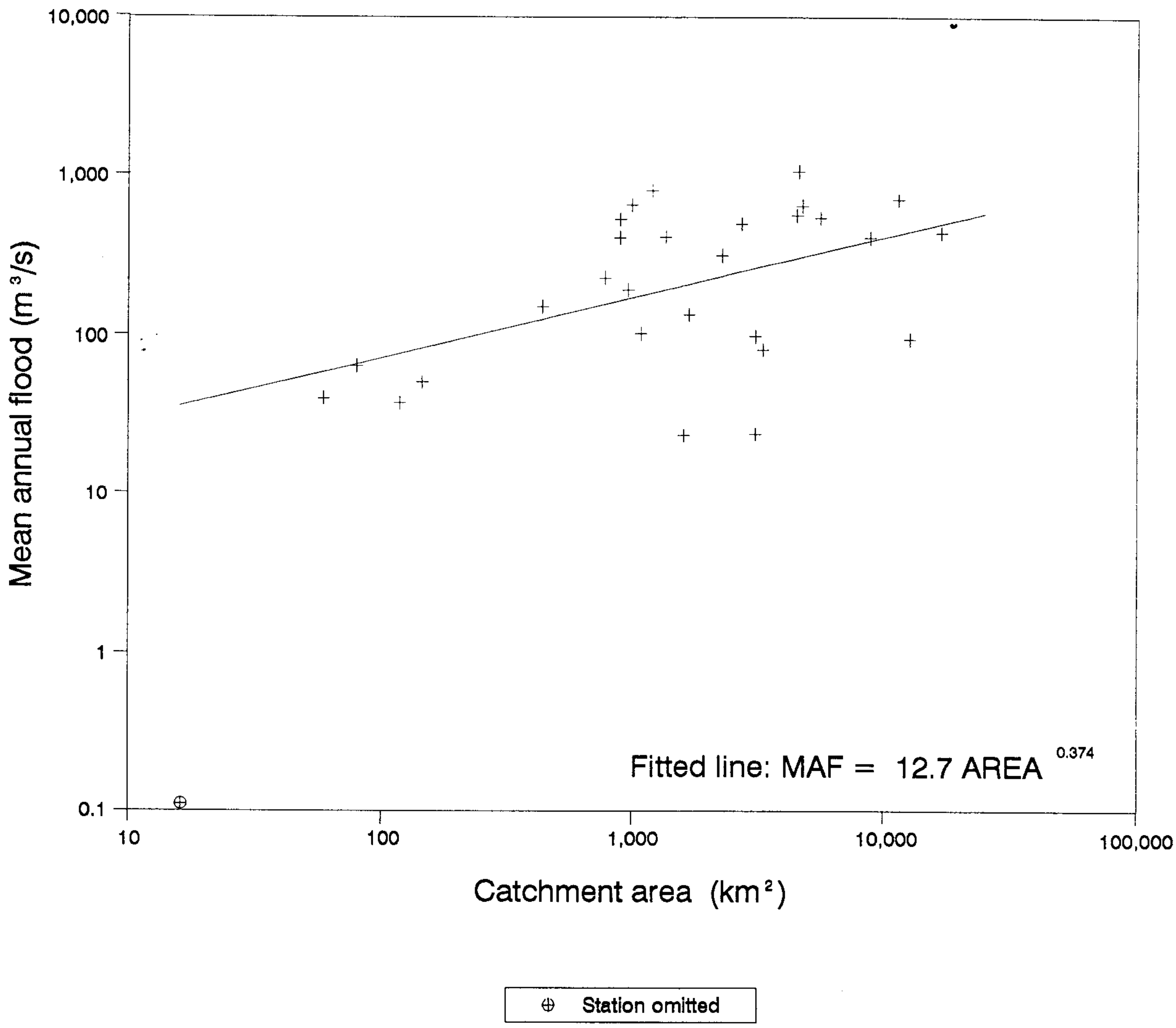

Figure E2

The region includes true desert where annual rainfall is about 50 mm as well as the more humid mountain regions, ranging up to a maximum annual rainfall of 500 mm. There are 30 stations with catchment areas from 16 to 17,000 km². In the previous study, instead of using mean annual flood the five-year return period flood, Q_5, was used as the index value as this was thought to be a better approach in a situation where the annual flood can be zero in several of the years. This is a worthwhile approach, but to keep all the regions studied on a comparable basis, the MAF has been used here in the same way as elsewhere.

Mean annual flood is plotted against catchment area in Figure E2, and this shows that one station immediately stands out as anomalous. This is a very small catchment with a short record of only 6 years. It is also very arid with an AAR of only 50 mm, and it seems likely that, in this very variable climate, the MAF is under-estimated simply because no significant flood has occurred during the period of observation. The stations was therefore omitted. The MAF regression on catchment area alone has a very low r^2 of 0.235 and factorial standard error of the estimate of 2.77. When AAR is included, the regression improves to r^2 of 0.452 and f.s.e.e. of 2.41. This is a still a rather poor regression, probably due to the short records available and the high variability experienced in arid climates.

A single regional flood frequency curve was developed for the region, as it was found that geographical groupings or division by rainfall or catchment area did not produce any appreciable differences in the curves. The single flood frequency curve seems to give reasonably good representation of the region, but the MAF prediction equation is less adequate, as noted above.

E7 Central Iran

The data for central Iran were previously presented in the World Flood Study (Meigh and Farquharson, 1985). The area covered is in the centre and west of the country between approximately 48° and 53° East and 30° and 36° North. The region is mostly mountainous, with a semi-arid climate; annual rainfall for the catchments is between 90 and 750 mm, although only one has AAR less than 200 mm. Data are available from 25 stations and catchment areas are from 140 to 61,000 km².

The initial regression of MAF on catchment area gives an r^2 of 0.593 and a high factorial standard error of the estimate of 3.32. The data are plotted in Figure E3, and one station immediately stands out as anomalous. This station is much more arid than the remainder, with AAR of only 90 mm, and it also has only 4 years of record. It seems very likely that the MAF is under-estimated from the short record, and the catchment may also not be homogeneous with the others. It was therefore omitted, and the MAF regression (plotted in Figure E3) is improved with r^2 of 0.555 and f.s.e.e. of 2.36. When AAR is included, the regression improves further to r^2 of 0.694 and f.s.e.e. of 2.21. This is the recommended equation and should provide reasonably good estimates. As can be seen in the figure, the MAF equation (based on AREA only) agrees closely with the worldwide equation for arid and semi-arid basins (see Section E13), although it includes some more catchments which are more humid than the AAR limit of 600 mm used to define the arid and semi-arid region.

Mean annual flood against catchment area for central Iran

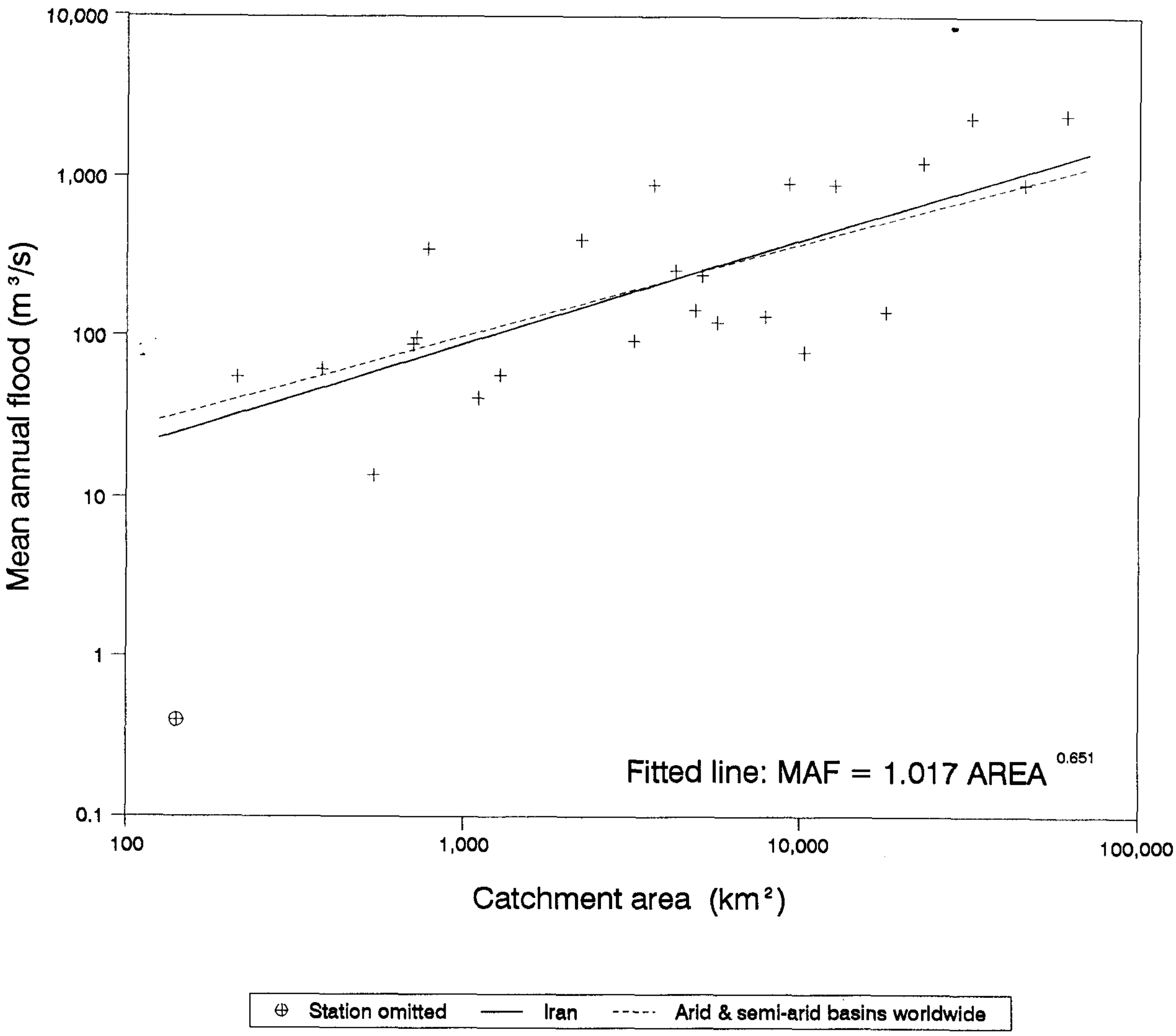

Figure E3

Two regional flood frequency curves were developed, divided at a catchment area of 7500 km^2, with the smaller catchments having steeper curves, as would be expected. These curves are significantly less steep than found for arid and semi-arid basins worldwide (despite the similarity of the MAF equations), and this may be explained by snow-melt being an important factor in flood generation in Iran. This method provides a reasonably good design tool for this part of Iran, although it would probably not apply to catchments drier than about 200 mm, or to small catchments of less than 100 or 200 km^2.

E8 Kerala, India

The data for Kerala state in India were originally assembled as part of the World Flood Study (Meigh and Farquharson, 1985). The state stretches along the west coast of the southern tip of India, and includes the mountains of the Western Ghats and the coastal plain. The climate is tropical monsoon with a pronounced rainfall peak from June to September. Data are available from 76 stations giving good areal coverage, although there is some doubt about data quality as most stations are not well calibrated. The catchments are mostly mountainous and fairly small, with drainage areas from 29 to 4200 km^2. No data on average annual rainfall are available for the catchments.

The regression of MAF on catchment area gives a reasonably good equation, with r^2 of 0.613 and factorial standard error of the estimate of 2.04. The data and the regression line are plotted in Figure E4. Some stations stand out as lying far from the line, but there was insufficient information to examine the reasons for this, and no stations were eliminated from the analysis. Kerala is relatively homogeneous and this regression equation can reasonably be applied to the whole state, although it is very likely that inclusion of AAR would improve the regression, if data were available. The MAF regression for Sri Lanka (based on catchment area only, see Appendix B) is compared to the Kerala one in the figure, and it is notable that they are very similar. Sri Lanka is nearby and has broadly similar climate and topography so it is satisfying that there is good agreement between the two equations.

A single regional flood frequency curve is provided for the state, and no subdivision of this by geographical region or catchment area was necessary. Again, in comparison with Sri Lanka, it was found that the curve was very similar to the Sri Lankan curve for AAR greater than 3200 mm. Although there are no catchment AAR values for Kerala, rainfall over the state is generally high with much of it in the range 3000 to 4000 mm. Thus, this good agreement with the wetter part of Sri Lanka seems reasonable.

E9 South Korea

The flood analysis of South Korea was carried out by the Institute of Hydrology as part of a rural infrastructure project (Binnie/Hyundai Engineering Co., 1978). Data were assembled for 33 stations, and these were all those with adequate ratings. Because some of the records were very short, the mean annual floods were estimated using the peaks-over-threshold approach for some of the sites, and this meant that only 24 stations were available for use in the regional flood frequency curve. Korea experiences the same monsoonal rainfall over

Mean annual flood against catchment area for Kerala

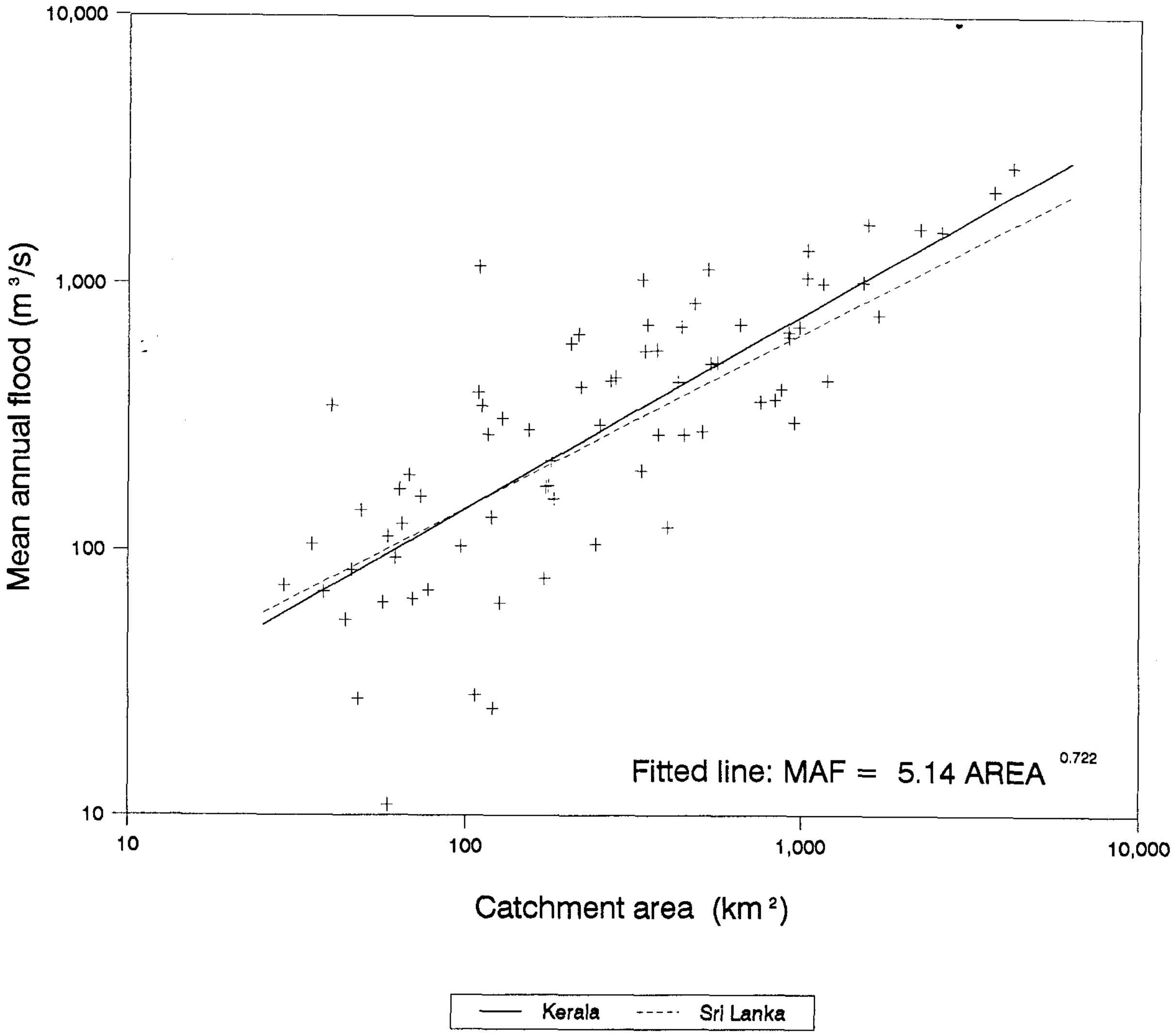

Figure E4

the whole country and topography, geology and soils are relatively uniform, with the result that flood response is also fairly uniform and the country can be treated as a homogeneous unit. Annual rainfall values were in the range about 950 to 1500 mm, and catchment areas were between 34 and 25,000 km^2.

Treating all the stations together, a MAF equation was developed for the whole country. Several different catchment characteristics were examined, and it was found that besides catchment area it was appropriate to use AAR and PADDY, the proportion of the catchment under wet rice cultivation. However, this countrywide equation was found to give rather poor estimates for small catchments (less than 1000 km^2), and so separate MAF equations were developed for these two groups. The resulting equations are reasonably good with r^2 of 0.767 and 0.830 and f.s.e.e of 1.59 and 1.36 respectively. As there are only 9 catchments with area less than 1000 km^2, this equation is inevitably less good.

A single flood frequency curve was found to be satisfactory for the whole country and it was not necessary to sub-divide the stations according to catchment characteristics. However, it should be noted than no catchments of less than 500 km^2 were available for development of the flood frequency curve, so its applicability to small catchments is doubtful. There is reasonably good coverage of data, and generally the method provides an adequate flood estimation tool, but with reservations on its suitability for small catchments.

E10 Thailand

The data for Thailand were previously presented in the World Flood Study (Meigh and Farquharson, 1985). A total of 121 stations cover the whole country, and an additional four stations in Malaysia, adjoining the southern peninsula of Thailand, are also included. The region is quite varied with a mixture of mountainous and low-lying areas, and a wide range of rainfall. Annual rainfall for the catchments studied ranges from 1100 to 3400 mm, and drainage areas are from 6 to 121,000 km^2.

Mean annual flood is plotted against catchment area in Figure E5. The stations in the southern peninsula are distinguished in the plot, and these stand out as substantially different to the remainder. As discussed below, when studying the flood frequency curves, the stations in low-lying areas were found to have a quite different response to the remainder; these groups were also examined when looking at the MAF equation, but no distinct differences could be found, perhaps because of the narrow range of catchment areas within each group. Treating the peninsula separately, the regressions on catchment area alone are reasonably good with r^2 of 0.729 and 0.818 and f.s.e.e. of 1.91 and 2.05. Introducing AAR into the regression did not bring significant improvements and the exponent of AAR was not statistically significant in either case.

In examining the flood frequency curves, the southern peninsula area (and the catchments in the adjoining part of Malaysia) are both geographically separated and climatically distinct, being considerably more humid. This area was treated separately, and a single curve was produced for it. In fact, it was found that smaller catchments tended to have flatter curves than large catchments, and as this is contrary to experience in nearly all other regions

Mean annual flood against catchment area for Thailand

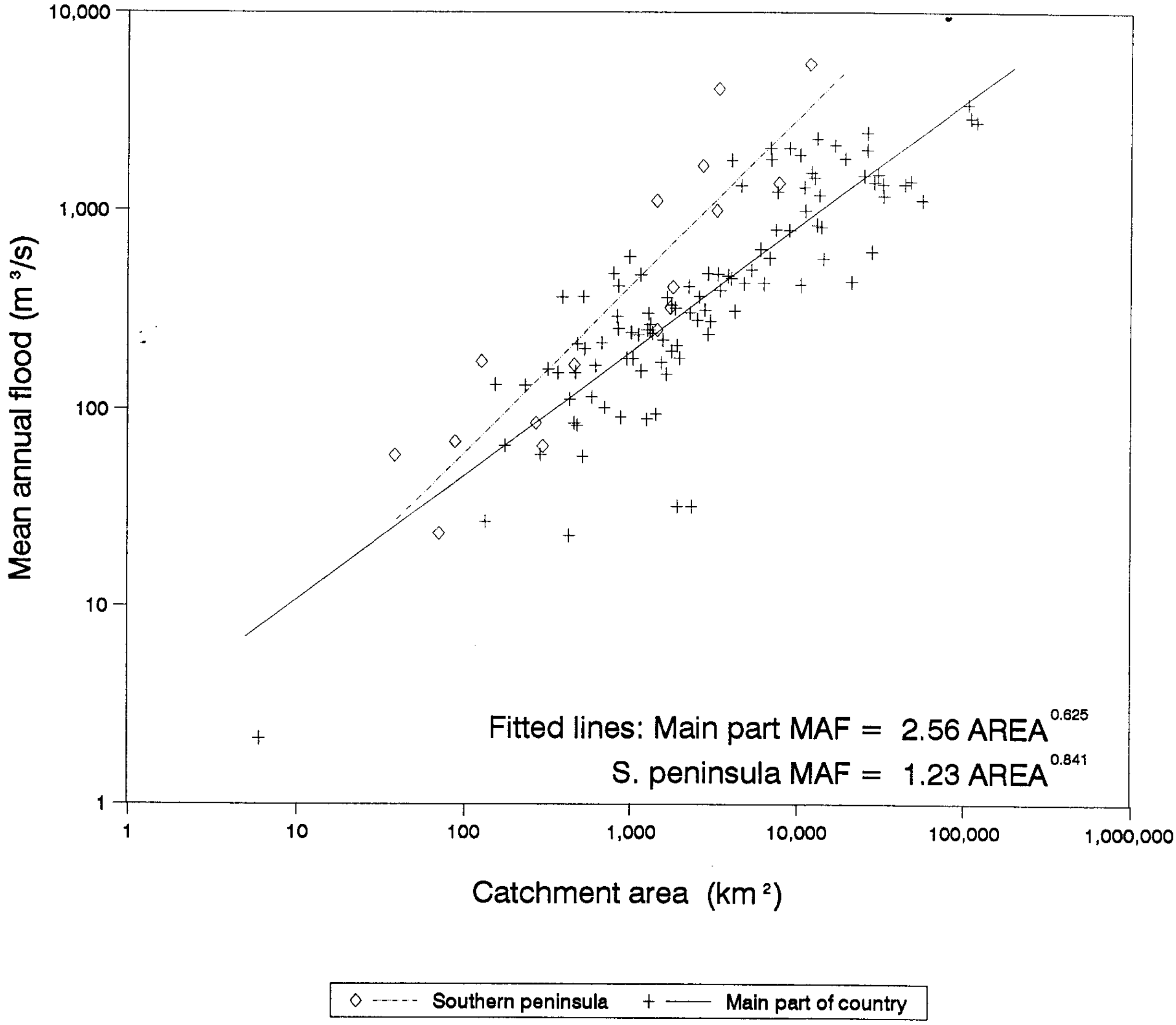

Figure E5

studied, it was thought likely to be a spurious result. Therefore, only a single curve is presented, and this should be used with considerable caution. For the main part of the country it was found the flood frequency curves fell into two distinct groups: one in low-lying areas near the coast, and the other at higher altitudes. The higher catchments have relatively steep curves while the low-lying ones typically have straight or flattening curves. This is particularly so in the very flat lower Chao Phraya basin which is made up of a network of interconnecting channels. Here floods are limited by the tendency for large discharges to flow out of the main channel into a network of subsidiary channels. For convenience, the division between these two groups was taken at an elevation (for the gauging station) of 100 m. This proved a satisfactory division, and within each of these groups the stations were further divided into large and small catchments, giving a set of four regional flood frequency curves.

With good coverage of data and a good range of catchments, the method provides a reasonably good design tool for Thailand, except that the flood frequency curve for the southern peninsula is doubtful.

E11 Java & Sumatra, Indonesia

The flood study of Java and Sumatra was carried out to develop a flood design manual for the two islands (Institute of Hydrology/DPMA, 1983). This report reproduces these results, except that the flood frequency curves have been updated to the PWM method. The original study involved a detailed examination of data quality and inspection of each gauging station to establish a set of 110 flood records which are known to be of good quality. The topography of both islands is dominated by the chain of volcanic mountains which runs along them, and both experience a tropical rain forest climate. The catchments studied had annual rainfall in the range 1850 to 5000 mm, and catchment areas were from less than 1 to 36,400 km^2.

In developing the MAF prediction equation, a wide range of catchment characteristics was examined. Besides catchment area, the final equation included three other characteristics defined as follows:

APBAR	mean annual maximum catchment 1-day rainfall (mm);
LAKE	the proportion of the catchment area which is upstream of lakes or reservoirs (if the total surface area of lakes is less than 1% of the catchment controlled, LAKE = 0).
SLOPE	the slope from the catchment outlet to the highest point above the end of the longest stream in the catchment (m/km);

The equation has a variable exponent for AREA, and this exponent is itself dependant on AREA. This was done by introducing [log(AREA)]^2 as an independent variable in the regression, in addition to AREA itself, to represent the attenuation that a large catchment can impose on a flood as it travels downstream, thereby reducing the effect of the increase in drainage area. The regression produced an exponent for LAKE which was felt to be unrealistic, and so the one presented was adopted from the UK Flood Studies Report (NERC, 1975); this was thought appropriate because the attenuation of floods by lakes is the same process anywhere in the world. A number of different regression models were considered, for instance treating Java and Sumatra separately, and dividing the data according to AREA or APBAR, but none of these produced a significant improvement, and a single equation for both islands was considered the best solution. Because of the good coverage of data and the comprehensive data validation, this MAF equation is expected to be of good quality. Because there is some uncertainty at the limits of the catchment characteristics, the design manual recommends that the validity of the equation is limited to the following ranges: AREA from 10 to 30,000 km^2; APBAR from 65 to 160 mm; SLOPE from 1 to 150 m/km; and LAKE from 0 to 0.25.

For the development of the regional flood frequency curves only 95 stations were available rather than the 100 used in the MAF equation; this was because MAFs for some of the shorter records were estimated using the peaks-over-threshold approach, and these stations could not be used in the flood frequency analysis. A number of groupings of stations was considered; groupings according to location, to average annual rainfall and to APBAR were not found to be effective, but dividing the data into two groups at the median catchment area of 600 km^2 was found to give the expected steeper curve for smaller catchments. Statistical tests confirmed this difference. The recommended approach is to use the small catchment curve for catchments of 180 km^2 or less, the large curve for catchments of 1500 km^2 or more, and to carry out a linear interpolation to estimate the curve between these two limits. As mentioned above, because of the thorough data checking, reasonable coverage of stations and examination of a wide range of catchment characteristics, the design method for Java and Sumatra is expected to provide a robust and reliable design tool.

E12 Papua New Guinea

The data for Papua New Guinea were originally assembled as part of the World Flood Study (Meigh and Farquharson, 1985). The country is mostly mountainous, with a tropical rainforest climate almost everywhere. Data are available from 50 stations, but records are mostly short, with an average record length of 9 years. Of the 50 stations only 28 have data for the catchment area and annual rainfall; areas range from 9 to 28,500 km^2 and AAR from 2000 to 4500 mm.

Based on the 28 catchments with AREA and AAR values, the MAF regression produces a good equation with r^2 of 0.918 and factorial standard error of the estimate of 1.58. The data and the regression line are plotted in Figure E6. Introducing AAR does not provide an improvement, and the exponent of AAR was not statistically significant, so the recommended equation is based on catchment area alone. A single regional flood frequency curve is provided for the country; although there was considerable diversity in the individual station curves, there were insufficient catchment characteristics data to investigate the sub-division of the regional curve in an adequate manner. Because of this the flood estimation method for Papua New Guinea must be considered as preliminary.

Mean annual flood against catchment area for Papua New Guinea

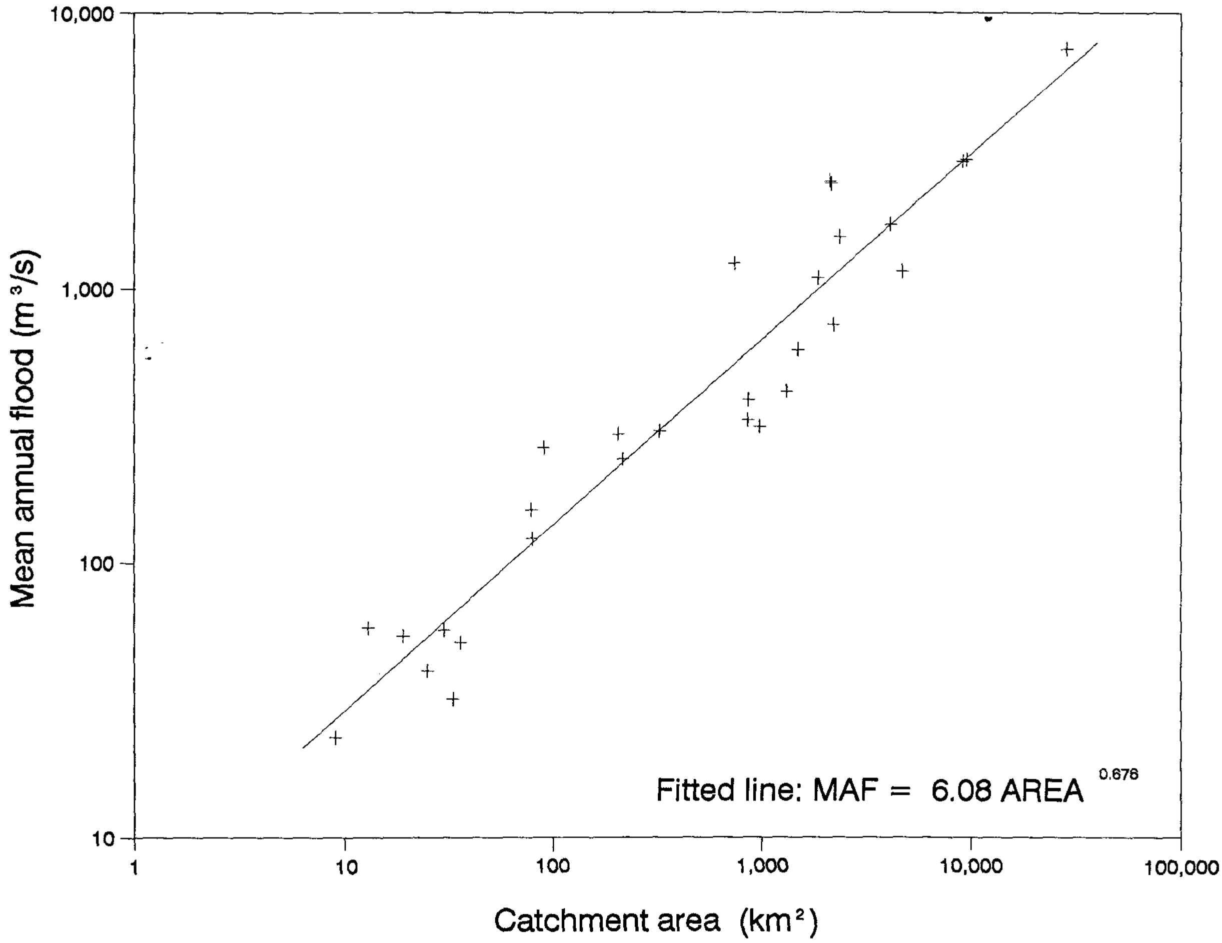

Figure E6

E13 Arid and semi-arid basins worldwide

Arid and semi-arid catchments from many locations worldwide were found to have broadly similar flood characteristics and a method has been developed to allow preliminary flood estimates for basins with this climate wherever they are located. These results have been published elsewhere (Farquharson *et al.*, 1992), and the present report only summarises the main findings and the recommended approach. The region was defined as having average annual rainfall of 600 mm or less, but cold or sub-arctic areas and catchments where the flood response is dominated by snow-melt are excluded. In addition, anomalous catchments which, for instance, have average rainfall of less than 600 mm but where the flood response is determined by a part of the total basin which is much more humid, are also not covered by this study.

Data were assembled for a total of 162 stations in appropriate parts of the USA, Morocco, Algeria, Tunisia, South Africa, Botswana, Jordan, Saudi Arabia, Iran, Russia and Australia, as well as single stations in a few other countries. Catchment areas ranged from about 1 to 360,000 km^2, and annual rainfall from 50 to 600 mm with a median of 405 mm.

Both the MAF prediction equations and the flood frequency curves were similar across the whole data set, and it was considered that the group could be treated as single region with a single MAF equation and regional curve. The MAF equation includes AAR as well as the catchment area, although including rainfall brings only a minor improvement, perhaps because of the narrow range of AAR values available. At 2.85 the factorial standard error of the MAF equation is higher than found in most country groupings, and thus the method has a fairly high level of uncertainty. Nevertheless, as arid and semi-arid areas are extremely difficult to gauge and often have very sparse station networks with short or broken records, the method provides a means of making preliminary flood estimates in a situation where, often, no other methods are available.