Institute of Hydrology

Natural Environment Research Council

Review of the Water Resources Division

Institute of Hydrology
Wallingford, U.K.

Final Report
January 1993

Report to the
Lesotho Highlands Development Authority

CONTENTS

DISCLAIMER

During this review it has been necessary to carry out some hydrological analysis to identify issues and to test alternative ideas of the appropriate hydrological strategy to follow. It should be understood that these analyses, some of which are presented in this report to illustrate the points made, do not imply acceptance of the data used, nor should they be regarded as exhaustive or preferred forms of analysis for the project.

EXECUTIVE SUMMARY

We have carefully reviewed the history of hydrological analysis for the Lesotho Highlands Water Project (LHWP) over the six years since the publication of the feasibility study report in 1986. We have had valuable and wide-ranging discussions with all parties involved in data collection and analysis for the project, and we are grateful for the open expression of views on the matters of common interest. In addition we have carried out some additional analysis to understand better the fundamental issues involved, and to be sure that our recommendations are soundly based and viable.

It is undisputed that the main problems have arisen because of the quality and availability of rainfall data. Records from the existing stations cover different periods, they contain many gaps, and there are some obvious, and many less obvious, errors in the monthly series. Furthermore, there are few rainfall stations within the basins to be modelled. Unfortunately, the analytical strategy based on the use of the Pitman model to hindcast river flows for the period up to 1967, when there were no gauging stations, requires good rainfall data for each of the river basins.

This has led to an excessive emphasis on rainfall analysis. WRD and DWA(RSA) have evolved different positions with regard to the data and methods that should be used to improve them. As a result, relations between the parties have deteriorated to the point where future progress is stalled unless a radical initiative is taken.

We have given priority to the definition of a programme that could ensure that this impasse is broken and that a revised hydrology could be prepared before the end of 1993, indeed it was suggested by the RSA representatives to the JPTC that hydrological flow series should ideally be available by the latter part of 1993 for design of Phase 1B of the project. At the centre of our conclusions is the belief that the analytical strategy should be changed. This is partly because the rainfall data are relatively weak, but also because we believe that stochastic modelling of river flows directly will give a more reliable basis for design than the existing strategy based on the Pitman model, especially now that 25 years of river flow data are available. Rainfall data can be used to add information through a stochastic model, but the need is for more general, regional rainfall data, not the detailed basin by basin data. Also the primary time-scale of the analysis should be annual rather than monthly, although the use of disaggregation techniques will result in monthly series for design and royalty computation.

We are concerned that cycles in the historical rainfall and river flow data could represent a significant underlying component of the series. These cycles are a feature of the historical data and the question is whether they are likely to persist in the future. Some additional work on this issue would be necessary whether or not the analytical strategy is changed. However, the use of stochastic modelling would mean that the issue could be dealt with explicitly, and its impact on the project assessed directly.

We have assessed the logistical needs of WRD in terms of our recommended programme of work to complete the revised hydrology within 1993 and reached the conclusion that the most cost-effective solution would be for WRD to be supported by consultants with a specific terms of reference to complete the immediate analysis. We believe that their involvement would need to amount to 16 man-months and cost about R 800,000.

Finally we summarise here our main recommendations covering the range of issues facing WRD.

1 A closer working relationship must be established between WRD and DWA(RSA) as a matter of urgency, to rebuild confidence and to re-establish an agreed methodology for completion of the database and derivation of reservoir inflow sequences for engineering design and for computation of the Royalties. This can be achieved through regular meetings providing that an open approach to ideas, aims and interchange of results is practised by all parties.

2 WRD should adopt quality assurance procedures for their reports. These procedures should trap errors and check that the results presented accord with the agreed programme of analysis. They should also ensure that unforseen results that do not truly represent successful application of the methods are rigorously checked..

3 Wholesale gap-filling and extension of rainfall records should be discontinued. The better placed and most reliable records (say about 40 stations) should be screened with reference to the daily records, corrected where possible, and used to support the revised analytical strategy.

4 Checking of all hydrometric data and continued monitoring of rating curves at each gauging station should be continued. In particular, the theoretical ratings for each of the three Crump weirs should be carefully checked by whatever current meterings are available, although this may not be possible in the case of Marakabei, where the cableway has been removed.

5 Flow series for both engineering design and for estimation of Royalties should be based principally on a statistical description of the recorded annual flows. Disaggregation techniques should be used to divide the annual flows into a monthly series for subsequent analysis. Selected rainfall data should be used to provide information on the long-term stability of rainfall and runoff, and to assist in the transfer of the flow sequences at gauged sites to the reservoir sites.

6 This modelling should follow a review of the annual response of the different basins to re-examine and explain the variation in specific runoff between basins taking account of basin morphology, possible forms of the mean annual rainfall distribution, evaporation losses and how they might relate to rainfall. This review could usefully include comparisons of flow duration curves and other flow statistics to highlight differences that there might be between basins.

7 The longer and more accurate of the rainfall records should be used to examine the significance of cycles of about 18 year period in the historical period. The stochastic

model should, if these cycles are shown to be statistically significant, contain components that will deal with this cyclical pattern so that its impact on the hydrological analysis can be examined explicitly.

8 A rainfall radar system should not be established at this late stage of the hydrological investigations, since the problems of calibration and interpretation of data would compound rainfall issues. Data from the new rainfall stations should be incorporated into the general hydrological analysis as soon as possible.

9 In view of the uncertainty in transferring flows to dam sites, stations (rated sections) should be established at selected sites. The need for up-grading of flow measuring stations should be re-examined when the historical flow data have been carefully reviewed.

10 LHDA should employ a team of consultants to undertake the tasks necessary to produce a revised hydrology that would form the basis for agreement.

11 A Liaison Committee should ideally be established, comprising representatives from both LHDA and DWA(RSA) to monitor the progress of further hydrological studies. This committee should meet frequently to discuss work progress with the consultants. A brief report could perhaps be made by representatives from this committee to the regular meetings of JPTC.

12 The head of WRD should continue to be an expatriate, professionally qualified, water resources engineer/hydrologist to manage the division and to undertake tasks such as the hydrological analysis necessary for operation and management of the reservoirs. In addition, WRD should recruit a degree or diploma level hydrometeorological technician to undertake some of the routine data processing and verification. There is also a case for recruitment of a water resources engineer, probably an experienced expatriate hydrologist/engineer, who should be responsible for assisting with the establishment of reservoir operating procedures and for management of reservoir releases in order to optimise hydro-power production whilst meeting the water transfer targets.

1 HISTORICAL BACKGROUND

Rainfall over the Lesotho Highlands is abundant compared with much of southern Africa, ranging from 1000 to over 3000 mm, and drains into the upper reaches of the Senqu/Orange River. In contrast the area of the Republic of South Africa to the north of Lesotho, drained by the Vaal River, contains around 60% of the Republic's industrial production but lacks sufficient water resources.

Since the early 1950s, the Governments of Lesotho (then the Basutoland Protectorate) and South Africa have considered the possibility of diverting the headwaters of the Senqu into the upper reaches of the Vaal River. In 1978 the two countries agreed to fund a feasibility study into the Lesotho Highlands Water Project (LHWP). This was undertaken by two engineering consortia: Lahmeyer MacDonald Consortium (LMC) and Olivier Shand Consortium who reported in April 1986. They recommended that the project, which would include several high dams and diversion tunnels, should be constructed in four phases over a period of 25 years. During its transfer, the water would also be used to generate hydro-electric power for Lesotho.

1.1 AIMS OF THE HYDROLOGICAL ANALYSIS

Hydrological and meteorological data are required for a number of purposes within the LHWP. They are required for storage-yield analyses, that is determination of the capacity of the reservoirs in various phases of the scheme, for estimation of floods for design of spillways and temporary works during construction, and they comprise a vitally important component in the calculation of Royalty payments by a procedure defined by the Treaty.

To a large extent, the data required for the main tasks of reservoir design and for computation of the Royalties are broadly identical; they both require that flow series be derived for a number of actual or potential dam sites. However, there are some subtle differences in the data requirements of each task.

1.1.1 Hydrology for the calculation of Royalties

In October 1986 the Kingdom of Lesotho (KOL) and the Republic of South Africa (RSA) signed a treaty which approved implementation of the Project. The Treaty included specification of how the level of Royalties to be paid by South Africa to Lesotho for the diverted water would be calculated. The Royalties will be computed using a computer program developed by LMC during the feasibility studies, which will compare the costs of one variant of the LHWP (many possible transfer schemes were studied during the feasibility studies) with that of the alternative Orange-Vaal Transfer scheme. All the key variables within the Royalty calculation program have already been fixed except for the hydrology, which both parties agreed should be updated to take account of all available data prior to the calculation in 1994. The Treaty therefore requires that the reservoir inflows and rainfall onto, and evaporation from, the reservoir surface be derived and agreed by both parties before the Royalty computation program is run in 1994.

The Treaty specifies that reservoir inflows and rainfalls for a pre-determined period, 1930-31 to 1982-83, shall be used in the program, but does not state how such series are to be derived. The position on reservoir evaporation is unclear, as it would seem to be difficult to derive a representative historical evaporation series, particularly for the earlier years, because of the lack of suitable data. It seems probable that a fixed mean monthly evaporation would have to be used for all years. These series of inflows, rainfall and evaporation have been termed the royalty hydrology.

1.1.2 Hydrology for the engineering design

The design of the engineering works for the project also requires hydrological records for estimation of the storage and yield of the various reservoirs, and for estimation of floods for spillway design and for construction purposes. This has been termed the design hydrology. The Treaty does not specify the hydrological data that should be used, or the analytical methods that should be employed for the design studies, which will take place over a period of time to cover the various phases of the LHWP. However, it was always envisaged by both parties that all available hydrological data would be utilised during the design of each phase. Consequently, the design hydrology will not necessarily be the same as the royalty hydrology, with different periods of data being used in each, and possibly different methods being used.

1.2 ANALYTICAL APPROACH ADOPTED

During the feasibility study it was recognised that the historical flow data available within the LHWP area are not sufficient by themselves to determine either the design or the royalty hydrology since recording only began in the mid 1960s. However, rainfall records for Lesotho and within the neighbouring areas of South Africa extended back to 1930. It was decided that the these rainfall records could be used to extend the flow data back to at least 1930. This was achieved by calibrating a conceptual rainfall-runoff model for each basin, using the available concurrent monthly flow and rainfall data in each case. The monthly rainfall data for the period from 1930 to 1983 were then applied to the model to generate a long series of flows. The Pitman model was adopted for the study since it had been used widely in southern Africa and was felt to be appropriate to the river basins in the Lesotho Highlands.

This use of the Pitman model and historical rainfall led to the decision to specify within the Treaty the use of reservoir inflows for the period 1930-31 to 1982-83 for the derivation of the royalty hydrology.

Two main problems were encountered with this methodology. First, the rainfall data contained many gaps. In the feasibility study these were infilled using regression techniques. Second, there were very few rain gauges within the basins to be modelled; hence derivation of basin average rainfalls for input to the rainfall-runoff model was difficult.

As will be seen in the remainder of the report, overcoming these two problems has been a major preoccupation of the LHDA Water Resources Division, and the bulk of the division's efforts over the past few years have been directed towards derivation of suitable rainfall series for input to the Pitman model.

1.3 PRESENT POSITION AND DIFFICULTIES ENCOUNTERED

LHDA has responsibility for updating the project hydrology which must be agreed with DWA(RSA), through the Joint Permanent Technical Commission (JPTC), who must be consulted on both the raw data to be used and on the methodologies to be applied. In order to meet these obligations, LHDA established a Water Resources Division (WRD). Initially it was envisaged that WRD would merely have the task of updating the preliminary hydrology by analysing recently collected data using a methodology defined in the LHWP feasibility study (LMC/OSC, 1986). Additionally, WRD would have the task of providing hydrological information required for the LHWP in support of other divisions within LHDA, such the Engineering and Construction Division and the Environmental Division, and for providing data and analytical advice on hydrology and water related matters to all consultants and contractors working for LHDA.

Substantial progress has been made by WRD towards database definition, field hydrometry and the development and programming of analytical software. Both WRD and DWA(RSA) have questioned aspects of LMC/OSC's methodology, but issues identified have not always been widely discussed and the agreed methodology remains that defined in the feasibility study with the exception of methods used to infill rainfall data. Nevertheless an agreed hydrology is still some distance away. There appears to be several reasons for this.

First, the analytical methodology adopted in the feasibility study is heavily dependent on good rainfall data, particularly within the highlands of Lesotho. Analysis undertaken since that study has shown that historical rainfall data generally are of lower quality than was originally recognised in contrast to the flow data which are reasonably good. While DWA(RSA) has consistently pointed to some clearly erroneous rainfall data, WRD has demonstrated that there is a much wider problem of data reliability which will remain even when the most serious errors have been corrected using techniques proposed by DWA(RSA) and their consultants, BKS.

Second, the work-load and scope of WRD has increased considerably since its inception as it has rightly decided it must take on responsibility for the collection and processing of all river level, flow and water quality data within the LHWP area. Responsibility for the collection and quality of rainfall data has remained with WEMMIN, yet WEMMIN has not been able to provide historical data of sufficient quality to produce an acceptable hydrology, due to shortage of suitable staff. Consequently a large proportion of WRD staff time - which has increased as awareness of errors in the data has grown - has been devoted to checking rainfall data to the detriment of other stages of the analysis. It is understood that a WRD request for additional, specialised help to carry out the considerable work-load of data checking has not been supported. This laborious task is essential to the achievement of an acceptable project hydrology and our recommendations concerning the effort that should be devoted to this are included in our review of the work programme.

Third, liaison between WRD and DWA(RSA) has been allowed to deteriorate to the point where it is counter-productive. There are misunderstandings about the true situation and the intentions of both parties. Consequently, the central issues are not being addressed effectively. Questions have quite rightly been raised concerning the effectiveness of WRD, its failure to meet agreed work programmes, and its scheduling of activities. These questions are inextricably linked to relationship between WRD and WEMMIN and to the level of staffing of WRD which we shall address later in the report.

1.4 LIAISON BETWEEN LHDA AND DWA(RSA)

DWA(RSA) believes that agreements reached at meetings have been disregarded, both in terms of methodologies to be adopted, acceptance of data, and target dates for completion of elements of the analysis. In part this follows from differences of approach to the hydrological problems, although WRD must be criticised here for failing to follow agreed work programmes on a number of occasions and for its reluctance to change the data base when obvious errors have been pointed out to them.

For example with regard to rainfall data, DWA(RSA) takes an orthodox, practical approach in which some, partly subjective, adjustment of the data precedes an agreed process of analysis. WRD on the other hand, in order to avoid subjective judgements, has tended to take a more analytical approach in which errors in the data are not corrected (assuming they can be defined) if they are not seen to be statistically significant to final results. There is some merit in both of these positions, but these differences of view can be insurmountable without a closer working relationship between the parties than presently exists.

The procedure of passing reports for comment, supplemented by occasional meetings is inadequate to deal with the complex problems of the LHWP database and programme of analysis. It is particularly ineffective when, as has happened, reports are not properly reviewed before circulation and contain errors that were intended to be corrected from previous reports. WRD has certainly been guilty of releasing reports containing some erroneous, or implausible, data which should either have been commented on, or corrected. This problem stems in part from the fact that WRD only has two professional staff, and consequently has limited resources for undertaking the basic tasks of analysis and reporting, so that the important task of checking reports before they are released has on occasions been omitted.

The result is a growing mutual suspicion where both parties begin to question the motives of the other. Minor decisions, which should be resolved simply on hydrological grounds, are exaggerated out of proportion in the light of their impact on the dam size or Royalties issues. If matters do not improve, it is likely that the hydrology will have to be decided by arbitration. This can be avoided if steps are taken now to redefine the programme of work and to bring appropriate resources to bear on it, so that the work can be completed effectively and on time.

Despite these suspicions, we find no evidence that either party is attempting to produce biassed results. On the contrary, both parties show a genuine desire to reach an objective resolution of the problems on purely hydrological grounds.

1.5 PURPOSE OF THIS REVIEW

The immediate needs of the LHWP require a rapid convergence to a new agreed project hydrology. There is not much time before the Royalty hydrology must be available, and design of further stages of the project is already under way. Our primary concern is to recommend a way forward that will achieve these immediate objectives rather than to dwell on the history of the hydrological studies and the relations between the parties. For background information, we have reviewed the history of the project in terms of the published work and meetings that have taken place over the past five years, and these are presented in Annexes B and C. However, in order to address the important question of the effectiveness and productivity of the Water Resources Division, or WRD, of LHDA and of the Department of Water Affairs of RSA, or DWA(RSA), and their consultants, a brief review of the role of each is included below.

None of the hydrological problems is insurmountable, but a fresh start is clearly necessary if future progress is to be assured. We have therefore given primary emphasis to a review of the hydrological issues as a whole without pre-condition, except insofar as the availability of data is always an important constraint. This review is structured to define the analytical options, assess the knowledge gained from the analyses carried out so far, and to recommend the most promising analytical strategy. Because rainfall data are a severe constraints we have carried out some exploratory analysis to look at cyclical patterns and the gap-filling problem.

Following this analysis we have addressed the logistical and institutional arrangements that are needed to carry out the programme of work and achieve agreement in an acceptable time-scale.

1.6 THE EFFECTIVENESS AND PRODUCTIVITY OF WRD AND DWA(RSA)

The consultants were charged with assessing the results which have been achieved by WRD and by DWA(RSA) towards successful implementation of the LHWP and for assessing the quality of these results. They were similarly asked to assess the productivity and effectiveness of WRD and DWA(RSA).

The role of WRD has shifted in recent years because of the need for it to take over responsibility for primary collection of hydrological data within the LHWP area, and the changes caused by this to the division's staffing and workload are discussed. A list of the current staff together with job descriptions and responsibilities is given in Annexe D.

The responsibility for the provision and maintenance of a suitable data base of hydrological data for the planning, design and operation of the various phases of the LHWP rests with the WRD, although they are not primarily responsible for the collection of the bulk of the rainfall data, and have only in recent years become responsible for collection of hydrological data throughout the highlands area. Whilst other parties, such as consultants, may be responsible for the application of these data for the design of particular phases of the scheme, these other users of the data must rely upon the data series maintained by WRD.

One point which surprises the consultants is that WRD has only two professionally qualified staff, and in view of the inevitable administrative burdens on these two senior staff, their output of useful technical work will inevitably be limited. The Senior Hydrologist has limited experience of advanced analytical hydrological techniques and can therefore provide the Water Resources Manager with only limited advice and support in this area. This is largely because it has never been convenient for the Senior Hydrologist to be sent to RSA, or somewhere similar, to undertake appropriate training due to the work load of the WRD. He is however receiving on-the-job training. The Water Resources Manager must therefore rely primarily on his own capabilities and resources as he has no experienced colleague to discuss difficult technical problems with. On occasions the efforts of WRD have been directed towards unproductive areas of work, mainly because there was no opportunity for the Water Resources Manager to talk through technical matters with a peer. One solution might be for LHDA to engage consultants to provide short term advice and guidance to WRD to avoid efforts being unwisely directed in future, although of course we can only with the benefit of hindsight now recognise that some areas of work undertaken by WRD have been less productive than they might have been. Alternatively, WRD might usefully be strengthened by recruitment of a water resource engineer/hydrologist, probably at expatriate level, who would be primarily responsible for development and operation of management tools for optimising water transfer. This additional professional would also serve to boost the analytical capabilities of WRD and would allow the work programme to be more effectively discussed in future.

WRD has established a very complete and efficient data base system within LHDA, based primarily upon the HYDATA software system. They have entered all historic data onto the computer system and have developed routine procedures for the capture and processing of the new river level and flow data within the LHWP area for which they have now assumed primary responsibility. The majority of the existing staff complement works primarily upon the development and maintenance of this data base.

It is unfortunate that this data base is obviously flawed in that analyses of the data, particularly the rainfall data, have shown that there are serious errors in the monthly rainfalls at some sites. It could be argued that these errors are not the fault of WRD as they are not responsible for primary collection of the data. However, the faults in the rainfall data base have been recognised for several years now, and whilst a great deal of effort by WRD staff has been directed towards the resolution of the problems, it is regrettable, and disappointing, that the data base has not been more effectively upgraded over the past few years.

We have commented on the reasons for the slow progress in the resolution of this problem elsewhere in the report, and pointed out the different philosophies adopted by WRD and DWA(RSA). Whilst we accept the reservation held by WRD over the somewhat empirical, subjective approach proposed by DWA(RSA), and respect the aims of WRD towards correction of problems by unbiased, analytical methods, we believe that the progress of WRD towards an improved data base has been disappointingly slow. Whilst WRD are rightly reluctant to change the data base in an arbitrary, ad hoc manner, particularly as the primary national data base is the responsibility of the GOL through WEMMIN, progress on the LHWP has remained stalled because of the slow progress on correcting the data. The Kriging technique adopted by WRD is attractive as an objective means of filling gaps in the rainfall data base. However, because experts in France advised that all available data should be used, regardless of the quality of the data or the length of record, the results of the gap-filling exercise using this technique have been unconvincing. A great deal of time and effort has been expended on Kriging, yet the results, particularly where individual months are concerned, remain suspect.

It might be argued that over emphasis on individual suspect monthly totals is less important that getting reliable estimates of catchment rainfall, and certainly many of the comments produced by BKS, consultants to DWA(RSA), have concentrated on anomalies in the monthly rainfalls at particular gauges. Whilst there is little doubt that these 'rogue' months can affect the output from the Pitman model, their real significance may be small. It is regrettable that so much emphasis has been directed towards individual errors in the data base, when a more innovative overview of the problem might have helped to resolve the underlying hydrological problems. It is also regrettable that DWA(RSA) and their consultants have not yet reached agreement with WRD over how the Crump weir data at Marakabei and other sites should be used to correct flows.

It is certainly true that progress towards an acceptable hydrology for engineering design and for computation of the Royalties has been very much slower than it should have been. We have pointed out that this is in part because of the very limited number of professional staff within the WRD having analytical capabilities, and it is regrettable that repeated requests by WRD for additional professional staff have not been supported. However, consultants might perhaps have been brought in at an earlier stage to strengthen the capabilities of the WRD, although the cost of this support might well have been broadly similar to that of strengthening the division's permanent staff.

2 DATA COLLECTION AND PROCESSING

2.1 THE ROLE OF LHDA AND OTHER ORGANISATIONS

Responsibility for the collection, processing and publication of meteorological and hydrological data within the Kingdom of Lesotho rests with the Ministry of Water Energy and Mines, or WEMMIN. Its has two separate departments responsible for the task; the Department of Meteorology (DoM) responsible for meteorological and climate data collection, and the Department of Water Affairs (DWA) responsible for river flow data. However, in recent years the Water Resources Division of LHDA has also become involved in data collection and processing within the area of the highlands of interest for the LHWP.

The relationship between WRD and the two executive agencies within WEMMIN is discussed in Annexe F, where the role of DoM and DWA is described. When considering the present availability of hydrological data for planning and execution of the LHWP, it is important to note that the bulk of the historic data was collected by WEMMIN before the WRD came into existance.

A review of the present data base and its potential impact upon the water resources objectives of the LHWP is given below.

2.2 RIVER FLOWS

2.2.1 Historical data

The historical river flow data at all gauging stations within the highlands of Lesotho have been checked on a number of occasions by both WRD and DWA(RSA), assisted by their respective consultants. A summarised chronology of the events concerning the derivation of river flows is presented in Annexe B. There seems to be broad agreement between the two parties on the rating curves to be used for conversion of stage data to flows at the various rated sections, and these were largely established by the LHDA, assisted by consultants, in 1987 and reported in Interim Hydrology Report No 2 (LHDA, April 1987).

We have devoted some time to a review of the quality of the historical flow data, but concentrated mainly on reviewing the rainfall data, about which the two parties expressed most concern. However, some checks on the internal consistency of the flow data were undertaken and these are reported on in Chapter 3, Section 3.2.3, where the flow records are shown to be spatially consistent, particularly when the flow data from the new Crump weirs are incorporated into the analysis.

During our review, we noted that there was agreement between the two parties that the quality of the flow records is undoubtedly better than that of the rainfall series. It was also clear that both parties appear to be very much closer to agreeing the series of daily and monthly flows at the various river flow gauges than is the case with rainfall records. Indeed, there appears to be broad agreement that the flow data available from each gauge are as good as can be achieved given the historical stage data and current meter measurements.

Whilst some minor additional checks on the flow data should be undertaken before they are used for the Royalty calculation, such checking represents a very minor task when compared with that involved in checking the validity of the historical daily and monthly rainfall data which would necessary for use with the Pitman model. Given the very limited time now available before the Royalty issue must be resolved, it would seem sensible to concentrate efforts on obtaining an agreed series of historical flows at each site as quickly as possible. Discussions on how these flows might be used for computation of the Royalties and for engineering design of reservoirs for later phases of the scheme are presented later in the report. Even without considering how the flow data are finally to be used however, it is clear that they must lie at the centre of any form of hydrological analysis used, and it would seem to be essential for both parties to agree that the historical flow series at each gauging station are as good as can be achieved given the data available. We strongly recommend that discussions be held between technical staff of the two parties in order that an agreed set of historical flows be produced as soon as possible. These flows will lie at the heart of any form of hydrological analysis and must therefore be prepared as a matter of some urgency.

Over the past few years, an inordinate amount of time has been devoted to the rainfall issue, and in attempting to derive a complete set of monthly rainfall data at each gauge for the period 1930/31 to date. There has been disagreement over how this objective should best be achieved, and as the exercise has progressed, more and more doubts have been raised about the quality of the underlying data. The fundamental disagreements over methods of analysis and over which data series to start any analysis with have seriously damaged working relationships between the two parties and has led to deep mistrust. This situation is deplorable and is discussed elsewhere in our report. The point that we would wish to make is that if analytical efforts were concentrated less upon the contentious, and dubious quality rainfall data, but more upon the seemingly better quality, and largely agreed, river flow data, it might be possible to reach a series of hydrological data which could be acceptable to both parties before the 1994 Royalty deadline.

2.2.2 Revision of data

At three sites, Paray and Whitehills on the Senqu, and Marakabei on the Senqunyane, Crump weirs were built some years ago in order to check flows at these stations where historical data from the rated sections were suspect. Since 1985/86, level data has been recorded at both the new Crump weir and at the original rated section at each of these sites. At these three stations both the WRD and DWA(RSA) have level recorders on both the original rated sections and also on the new Crump weirs. This unfortunate duplication of effort is a sad reflection of the deep mistrust that has grown up between the two parties. The duplication of level recording does however ensure that complete flow records are available for these important sites during recent years; if a recorder on the Crump weir breaks down data should be available from the second recorder, or in extremis, from the rated section.

The data from the Crump weirs should be intrinsically more reliable than that from the rated sections because of the stability of the section and because a theoretical rating curve may be applied. There should be no problems caused by shifting control of the rating curve. Thus, both parties intended that the new flow data from the weirs should be used to obtain a better indication of basin runoff in each case, and the intention was that historical flows would be adjusted using data from the weir and rated section during the concurrent period of record.

In June 1991 LHDA published a report which presented a methodology for correcting the historical flow data at Marakabei using the recent Crump weir data. On the whole this report was objective, and scientifically sound, however, it unfortunately concluded with some very provisional, and unsubstantiated estimates of how such revised flows might affect Royalty payments. This rather emotive conclusion rather clouded the earlier, valid findings of the report, and once again raised the highly contentious issue of the validity of the rainfall data used together with the Pitman model in flow extension.

In response the consultants to DWA(RSA), BKS, agreed in September 1991 that data from the weir indicated that basin flows were higher than had been believed previously. However, they drew attention to a period of apparently poor level data at the LHDA gauge during the period November 1987 to July 1988, and suggested that RSA records be substituted. Although the WRD responded in December 1991 with a report detailing differences between the two level records and suggesting periods when either the WRD or DWA(RSA) data should be used, because of the growing antagonism between the parties, the consultants are not aware that this important issue has yet been resolved.

It is important that the parties agree flow series at each of the three sites having both a weir and an original rated river section as soon as possible. Until such agreement has been reached, no sensible adjustment of the historical flow series is possible. The consultants believe that agreement between the two parties could be achieved fairly quickly, provided that both sides approach the exercise with open minds and with integrity. The impression gained during the consultants' visit was that both parties are much closer to agreement on this issue than they are over the rainfall data, and it should be possible to agree on flow series at each site without too much difficulty.

2.3 RAINFALL

WRD has spent considerable time reviewing the rainfall data, both assessing the quality of the raw data, and using techniques to estimate missing data. Each new endeavour finds more errors, such as inconsistencies between daily and monthly data, which suggests that errors are widespread and not easily identifiable by quick and simple forms of data screening. DWA(RSA) and their consultants BKS have also spent time appraising the various data sets as they are made available by WRD, although they have not had the opportunity to carry out a thorough data validation.

Before attempting a detailed appraisal of this work, we should consider the objective of the rainfall analysis given that the rainfall records constitute the longest hydrological series available.

In the current hydrological strategy, historical rainfall data are used to extend the shorter flow record to give a series of flows at gauging stations more representative of the long-term regime. Flow series at potential dam sites can be estimated from these flows. This procedure can be successful only if the rainfall data correctly indicate the long-term features of the climate, and if they reasonably represent rainfall on the basins of interest. Thus the first objective must be to define the long-term features of the rainfall both at individual stations, and more generally across the region.

In addition, it is desirable to map mean annual rainfall so that differences in the response of the different basins can be explained rationally. Furthermore, if the Pitman model is used to extend the flow record, it is desirable to obtain time-series rainfall data for each of the basins that accord with knowledge of the overall long-term features of the climate.

This presupposes an accurate and spatially representative rainfall database, but several aspects of the data have been controversial over the past few years. One is the identification and elimination of monthly values in the database that are clearly implausible; the other concerns the techniques that should be used for gap-filling and extension of station records to a common period. This latter issue is further complicated by apparent non-stationarity of the rainfall series from some stations. In terms of the LHWP objectives, non-stationarity, including that due to errors in the data, could be the most far-reaching problem posed by the data.

In order to assess the scale and effect of these issues and to reach some recommendations as to the way forward, we have used monthly data from the current LHDA database[1]. These checks cannot be exhaustive in the time available, but they illustrate the issues that remain to be resolved.

---

1 We have used data from file RAIN.DAL dated 29 April 1992.

2.3.1 Historical data

The database includes records from 80 stations situated in Lesotho and the neighbouring areas of the RSA for the hydrological years 1930/31 to 1989/90. It comprises 4800 station-years of monthly data of which only about 54% are observed data even when about 40 additional stations with short records have been omitted. The remaining 46% of the data are infilled values; currently these result from use of the Kriging procedure. While these figures alone give an impression of poor records, the view is more disturbing when it is appreciated that the longer observed records are generally from the least relevant stations.

We have summarised the availability of rainfall data in Table 2.1 in which we have defined four classes of data based on the extent to which the data are observed values over each hydrological year as follows:

- class A - wholly recorded,
- class B - recorded except for one month in the period October to May or any month in the period June to September,
- class C - wholly or largely infilled,
- class D - years when some or all infilled values have been rejected.

The difference between classes B and C is arbitrary, but it allows us to distinguish between cases when there are no observed records and cases when only one or a few months are missing. In Table 2.2, the stations have been grouped geographically to distinguish between those stations that are important to the LHWP and those that are indirectly useful.

Many of the stations with long observed records are those in areas outside the watershed of the basins in the project, or in the west of Lesotho and the neighbouring part of the RSA. The network is sparse in the central, mountainous area of Lesotho where most of the headwater basins are situated. Only five stations are at an altitude of more than 2440m (8000 feet). This contour on the physical map indicates that most of the area of the headwater basins is at a higher altitude. These five stations contribute a total of 91 station-years of observed record in the 4800 station-year database, a mere 1.9%.

LMC and WRD report little correlation of rainfall with altitude. This is not surprising; the altitude range is not well sampled and those stations that are in the headwater basins tend to be in the valleys where the rainfall recorded may be more typical of the surrounding higher ground. Until more records are available from the new stations, installed by WRD to remedy the poor distribution of stations with altitude, it will not be possible to draw up a reliable isohyetal map of mean annual rainfall.

Application of the Pitman model to the headwater basins must rely on a poor estimate of the spatially averaged, monthly rainfall for each basin. Any bias in the estimation of the mean annual rainfall can be corrected by including a parameter in the model to scale

Table 2.1 Summary of the data available in the rainfall database

Station	Altitude m	Years of record in class: A	B	C	D	Break ?	Station	Altitude m	Years of record in class: A	B	C	D	Break ?
2	1575	40	11	8	1	no	79	2290	15	2	43	0	no
3	1910	22	3	35	0	no	83	1800	17	3	37	3	1938
5	1490	10	12	38	0	no	84	2270	20	2	38	0	1970
8	1680	48	3	9	0	1954	85	2350	16	2	42	0	no
9	1770	41	7	12	0	no	86	2180	12	2	46	0	no
11	1830	35	6	19	0	1952	87	1650	39	7	14	0	no
15	1970	29	6	25	0	1962	88	1680	37	5	18	0	no
18	1700	14	2	44	0	no	89	2250	19	1	40	0	no
20	1750	29	2	29	0	no	101	1539	52	6	2	0	no
21	2240	18	4	38	0	no	102	1645	20	3	37	0	1974
22	2160	39	6	15	0	no	103	1524	40	4	16	0	1948
23	2250	22	4	34	0	1984	104	1463	38	9	13	0	1972
25	1830	41	9	10	0	1943	105	1661	47	2	11	0	no
26	2440	16	1	42	1	1939	106	1610	51	4	5	0	no
31	1690	34	6	20	0	no	107	1550	43	14	3	0	1965
32	2040	17	4	39	0	no	108	1486	29	12	19	0	no
35	1177	15	5	39	1	1943	109	1478	29	4	27	0	no
41	2040	27	5	27	1	no	110	1676	42	3	15	0	1952
42	2010	39	4	17	0	no	111	1454	55	4	1	0	no
43	2060	19	2	39	0	no	112	1370	32	2	26	0	no
44	1740	53	5	2	0	no	113	1676	40	4	16	0	no
45	1680	13	8	39	0	1963	114	1905	56	3	1	0	no
47	1640	10	7	42	1	no	115	2286	59	0	1	0	no
48	1860	17	5	38	0	1981	116	1951	37	4	19	0	1959
59	2600	26	4	30	0	no	117	1830	28	0	32	0	1952
60	1740	53	4	3	0	1960	118	1449	29	0	31	0	no
61	1530	52	3	5	0	1978	119	1524	26	2	32	0	no
62	1780	36	5	17	2	no	120	1676	47	6	7	0	no
63	1970	50	5	5	0	1958	121	1750	19	1	40	0	no
64	1770	53	4	3	0	1963	122	2055	20	1	39	0	no
65	2600	14	7	39	0	1984	123	2210	9	7	44	0	no
69	1980	17	0	43	0	no	124	1981	41	1	18	0	no
70	1610	51	5	4	0	1979	125	1530	27	0	33	0	no
71	2200	55	2	3	0	1955	126	1448	47	4	9	0	no
72	1600	57	2	1	0	no	127	1219	29	3	28	0	1972
73	1750	51	6	3	0	1980	128	1490	30	3	27	0	1978
74	2458	19	1	40	0	1977	129	1829	41	0	19	0	1964
75	3050	16	2	42	0	1972	130	1951	41	3	16	0	no
76	2250	27	5	28	0	1943	131	1769	48	4	8	0	no
77	2300	6	9	45	0	no	132	1676	49	7	4	0	no

Notes:

The data have been classified in terms of the completeness of annual records viz:

A - complete year of recorded data

B - completely recorded except for one month (Oct-May) or any month (Jun-Sep)

C - wholly or largely infilled data

D - year when some infilled values have been rejected

Table 2.2 Geographical classification of rainfall stations

Stations in or near the headwater basins

3	25	41	59	71	79	86	122	126	
21	26	42	62	75	83	87	123	128	
22	31	43	65	76	84	89	124	129	
23	32	48	69	77	85	121	125	130	*(36)*

Stations further outside the headwater basins (or alternates)

47	60	64	120	127	131	132			*(7)*

Stations in the middle basin

8	11	20	44	63	74	118			
9	15	35	45	72	117	119			*(14)*

Stations in the lower Senqu basin

5	102	104	106	108	110	112	114	116	
101	103	105	107	109	111	113	115		*(17)*

Stations well outside the Senqu basin

2	18	61	70	73	88				*(6)*

the estimated monthly series. However, any bias in the seasonal distribution or random errors in the monthly series could have a substantial effect on the simulated and hindcast flows unless there is a strong spatial coherence of rainfall.

2.3.2 Stationarity of the rainfall series

The analysis and use of rainfall series in southern Africa poses particular problems because of the appearance of cycles of alternating high and low rainfall through the length of the available record. This is a pervasive issue. It can affect the way in which records are tested for consistency; it affects the estimation of station mean rainfall when incomplete records are available. It therefore affects gap-filling and record extension and, ultimately, it affects the process by which the shorter runoff record might be extended with reference to the longer rainfall records.

Figure 2.1 shows the standardised[2] annual rainfall series for station 115 (the most complete record in the database) both as individual annual values and as a 5-year moving mean. The smoothing in time shows a clear cyclical pattern of about 18 years interval. Figure 2.2 shows a similar result; this time from the standardised mean of the data from nine stations[3] selected because of their good record length and distribution across the region. Again a strong cyclical pattern is seen with peaks in the same years as for station 115. There is also good correspondence at the annual time-scale. The apparent stability of inter-annual variation in rainfall is supported by the annual variation in flows. Figure 2.3 compares the 5-year moving mean of rainfall for the nine-station average to the 5-year moving mean of annual standardised flow at Seaka.

While the appearance of cycles is enhanced by the averaging procedure used in these Figures 2.1 to 2.3, we can reasonably conclude that the cycles are a discernable feature underlying the rainfall series at these and, by inference, most of the rainfall stations. Flows at Seaka are the integrated response of rainfall on the whole Senqu basin in Lesotho and they support the evidence of the sample of rainfall series used in the illustrations. We can also conclude that rainfall appears to be spatially coherent, at least on an annual time-scale. It remains to be demonstrated by statistical tests whether the cycles are a significant inherent feature underlying the annual rainfall process and whether they are a real feature of the climate in this part of the world to the extent that they can be expected to continue into the future. We have to say that such cycles are not often seen so clearly in hydrological series from other parts of the world and belief in their continuity would have to be supported by some evidence of a physical cause or a much longer geophysical series.

Consider the graph in Figure 2.4. It appears to show a similar pattern to the rainfall

---

2 Standardisation of a series means subtraction of the sample mean and division by the sample standard deviation.

3 Data from stations 9, 44, 72, 111, 115, 120, 124, 126 and 132 were used in this analysis.

Figure 2.1 Standardised annual rainfall for station 115 Funnystone

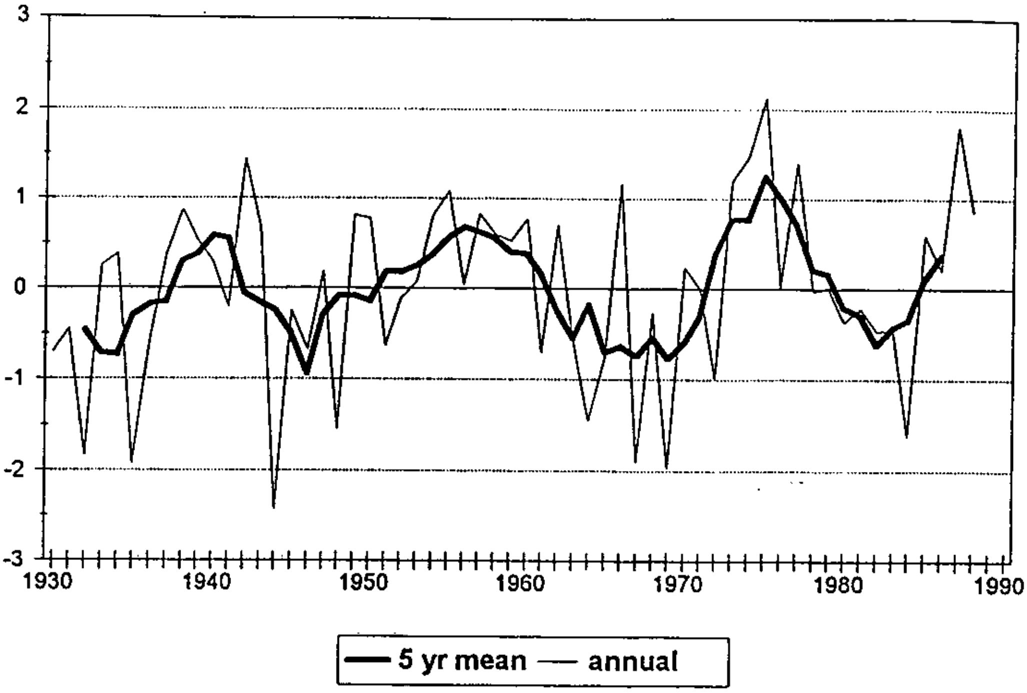


Figure 2.2 Mean standardised annual rainfall from 9 selected stations

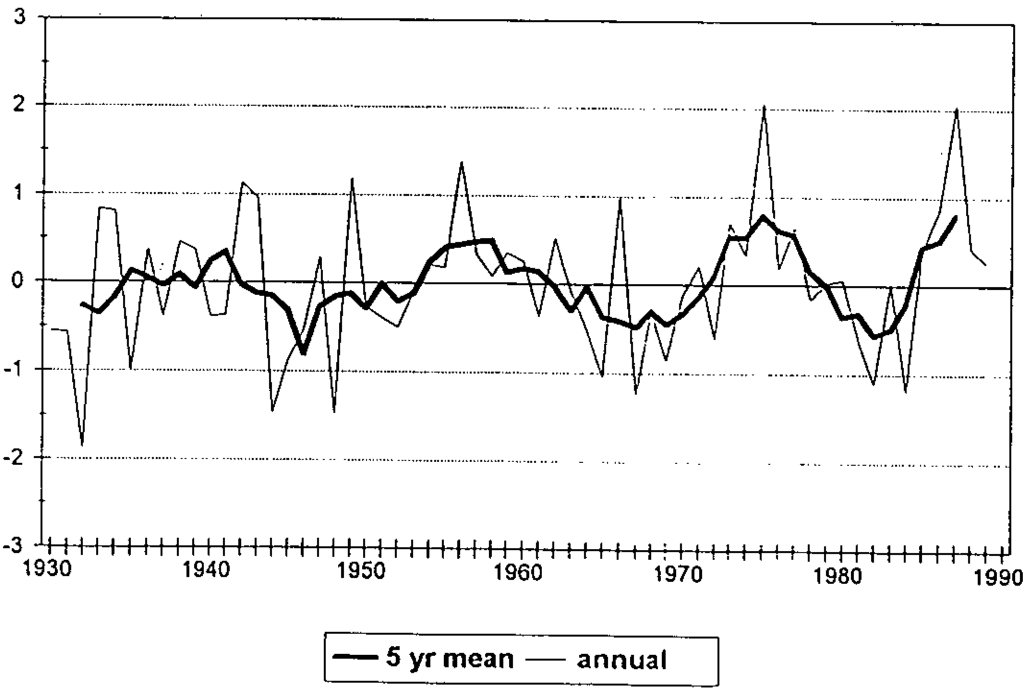


Figure 2.3 Standardised runoff at Seaka compared with mean standardised rainfall from 9 stations

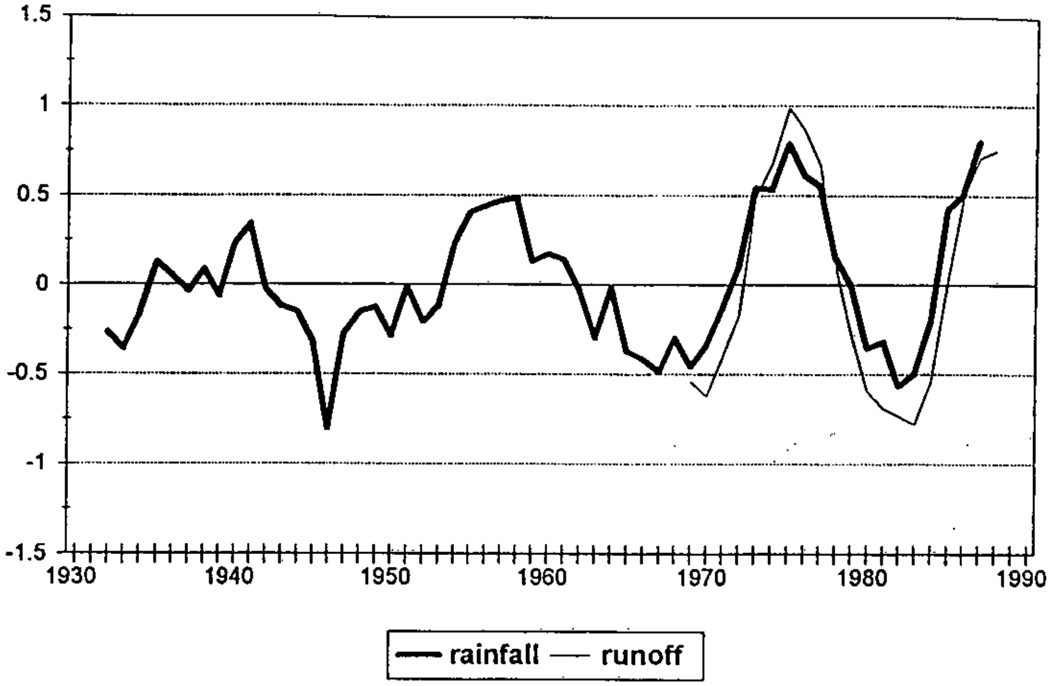
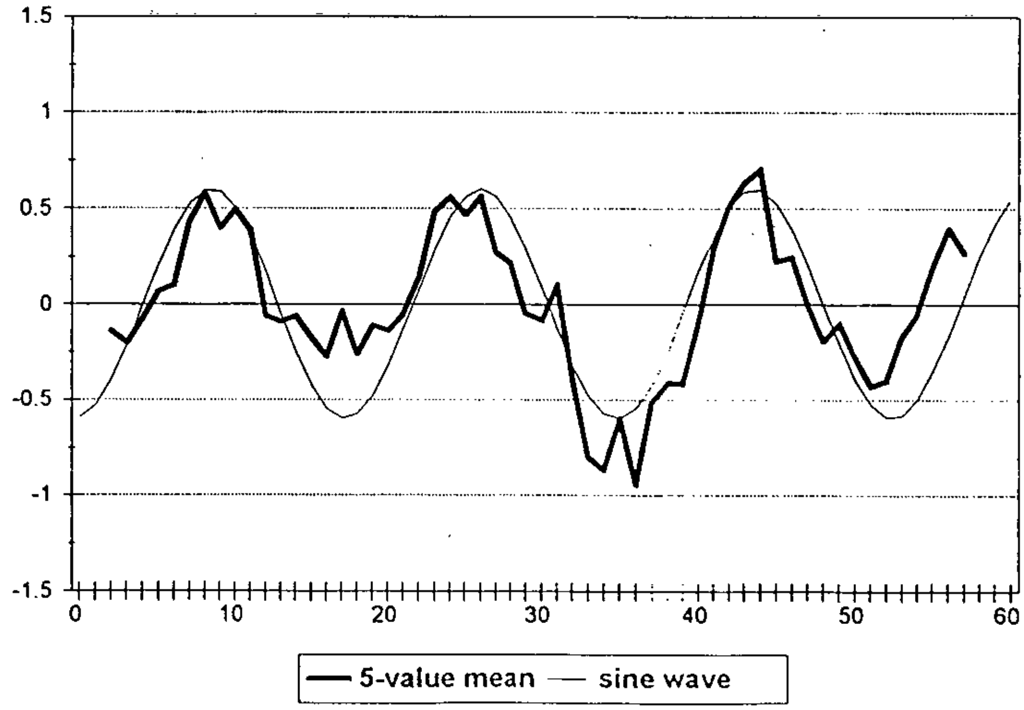


Figure 2.4 Cycle produced from a moving average of normally distributed random numbers



series illustrated above. Yet this cyclical pattern with similar departures from zero has been generated by taking a 5-value moving mean of a series of numbers drawn independently from a normally distributed variate of zero mean and unit standard deviation with no underlying cycle. Admittedly, such a pattern does not occur very frequently; most of the randomly generated samples produce a featureless sequence with no identifiable cyclical pattern.

The question therefore becomes: can a cyclical pattern emerge sufficiently frequently that there is a reasonable degree of confidence that the pattern observed in the rainfall data has occurred only by chance and hence there is no cyclic behaviour in the underlying rainfall generating process?

Because of the fundamental importance of this question, we have carried out a range of statistical tests to assess whether the cyclical pattern in the rainfall data could be expected to have occurred by chance. The detail of this analysis is given in Annexe G where we show that there is evidence that the cycles in the data from some stations and in the areal average series could be significant and not just a chance occurrence. Further analysis is needed on screened data to establish the credibility and generality of this preliminary finding and this is discussed in the context of the analytical strategy in the next chapter. It will not be possible to say whether or not any cycles detected would continue into the future unless some plausible causative linkage to another geophysical process, such as sea-surface temperatures, sunspots, or variations in the southern oscillation could be demonstrated.

Before going on to review the WRD rainfall analysis, it is worth discussing a working definition of stationarity in time-series as the term is widely used by WRD to indicate changes in the mean rainfall at some stations. Broadly speaking, an annual series can be regarded as stationary if there is no systematic change in the mean (no trend), if there is no systematic change in the variance, and if periodic variations have been removed. We have shown in Figure 2.4 that cycles over a period of 60 values (years) can be derived occasionally from a stationary process such as random sampling of a normal distribution. Therefore it is perhaps too constraining to declare a record non-stationary if it contains cycles of similar magnitude, especially if the record is short. In such cases it would be wrong to suspect the data quality, but it could be desirable to take account of the timing of the record relative to the cycles when estimating the long-term mean. We shall therefore try to distinguish between non-stationarity caused by changes in the mean (probably resulting from errors in the data) and the effect of cycles alone.

2.3.3 Identification and correction of errors

WRD and DWA(RSA) agreed as long ago as 1987 that the rainfall data used in the LMC report were of uncertain quality and that an agreed set of rainfall data is a prerequisite to flow generation using the Pitman model. It was also agreed that a full review of the rainfall and flow data would be undertaken before the Royalties are calculated.

Now in 1992, there is still no agreed rainfall database and arguments have developed over the methods of data appraisal and error correction, and the procedure to be used to fill gaps in the data. This is a long and sorry story and we set out the chronology of events in Annexe B insofar as they can be derived from reports, minutes of meetings and letters between the parties.

It is unprofitable to try to follow the detail of all these developments and we shall try to concentrate on the essential issues in order to reach conclusions as to the best way forward bearing in mind the urgency of reaching an agreed hydrology. It is also relevant to bear in mind that not all the data are directly relevant to the hydrology of the project, some stations are included only in the expectation that they might provide information of indirect value, perhaps in the gap-filling procedure.

The main manifestations of possible errors have been identified as follows:

- outliers defined as unrealistic-looking values,
- changes of slope in cumulative mass plots at some stations,
- inconsistencies between the observed and infilled or extended records,
- differences between one station and the regional trend in known wet or dry years.

Outliers have been found to arise from a number of causes including:

- factors of 10 arising from reading tenths of a millimetre as millimetres or vice-versa,
- factors of 2.54 arising from confusion between British and metric units,
- errors in transcription when data are entered into the computer database,
- unknown causes when outliers are seen in the infilled records.

The larger errors, either numbers much higher than reasonably expected or zero in a month when there is always some rainfall, are readily identifiable by eye. But there are likely to be errors of less obvious magnitude which cannot be detected by eye or even by a computer program. DWA(RSA) and their consultants BKS have offered to provide software primarily to identify outliers and to carry out cluster analysis to assist with error detection. This software has not been used by WRD who believe that a comparison of monthly and daily data offers a more thorough review of the basic data.

Changes in slope of cumulative mass plots usually indicate some change in the circumstances of a rainfall station, such as relocation or change in exposure of the rain gauge, or a new observer, which results in a different average rainfall than previously observed. WRD has developed a program which objectively identifies the break year in a series that has a change of slope, and applies a number of statistical tests to determine whether the change in slope is significant. Their report on this work notes that 1943 and

1963 are the prominent break years for most stations and that the non-stationarity of the annual series can be attributed to the suspected cycles of about 18-20 years on average.

This requires some elaboration. The technique used in the WRD study to define the break point was based on a graph showing the cumulative departure of the annual series from the running mean. By definition, this graph starts and ends at zero. It is very similar to a graph of cumulative departures of the series against the sample mean (the mean for all the years) which is often useful in rainfall data appraisal. If the annual series is perfectly cyclic, say with a period of 18 years, the cumulative departures graph will also appear cyclic with the same periodicity. But the cumulative departures graph will show peaks and troughs out of phase by a half cycle relative to the original data.

This is why WRD report that the frequent finding of break years at 1943 and 1963 follows from the existence of cycles in the rainfall pattern. Review of the list of apparent break years suggests that something over half the stations have apparent breaks in years that would be expected from the cycles. Whether the statistical tests defined by WRD show that a break point is significant or not is not helpful. In some circumstances a perfectly accurate record could be declared as having a significant break just because of a coincidence of timing of the fragment of record with the cyclical pattern.

Thus there is real difficulty in separating the effect of cycles from real errors in the data. This is particularly true for stations whose records are of the same order of length as the cycles. However, the cumulative graphs from which DWA(RSA) form their judgements are seen to be much less affected by the cycles; the cycles are not strong enough relative to the mean to influence the shape of the cumulative line.

We illustrate some of these problems in Figures 2.5 and 2.6 which show both cumulative and cumulative departures series for three stations. These graphs show only the observed data; infilled data have been omitted. The cumulative graph for station 115, Funnystone, is almost straight and there is only slight evidence of the cycles. Lines for the other stations, 60 Leribe and 129 Matsoakeng, show some curvature around in the early 1960s and are otherwise fairly straight. The cumulative departures graph magnifies the departures from a straight line seen in the previous graph and illustrates why 1960 and 1964 were identified as break points in the WRD analysis for stations 60 and 129 respectively. These breaks were found to be significant in the statistical tests, unlike the putative break in 1948 for station 115.

The breaks, and the significance of them, are reasonably clear from Figure 2.6. But the difference between the three stations is not what happens between about 1950 and 1975 when rainfall at all three stations follows the same pattern. The main difference lies in the divergence in 1930 to 1950. The breaks identified by WRD appear to be caused by cycles in this case; they do not appear to be indicative of errors in the data.

While it is likely that there are some breaks that are not influenced by cycles in the rainfall, it is clear that the WRD analysis is not sufficiently robust to identify them. More powerful techniques are needed if they are to be found objectively. This begs the question: should subjective methods be used similar to those of DWA(RSA)/BKS in which putative breaks could be identified, those shown to be due to cycles could be

Figure 2.5 Cumulative annual rainfall at selected stations (observed data only)

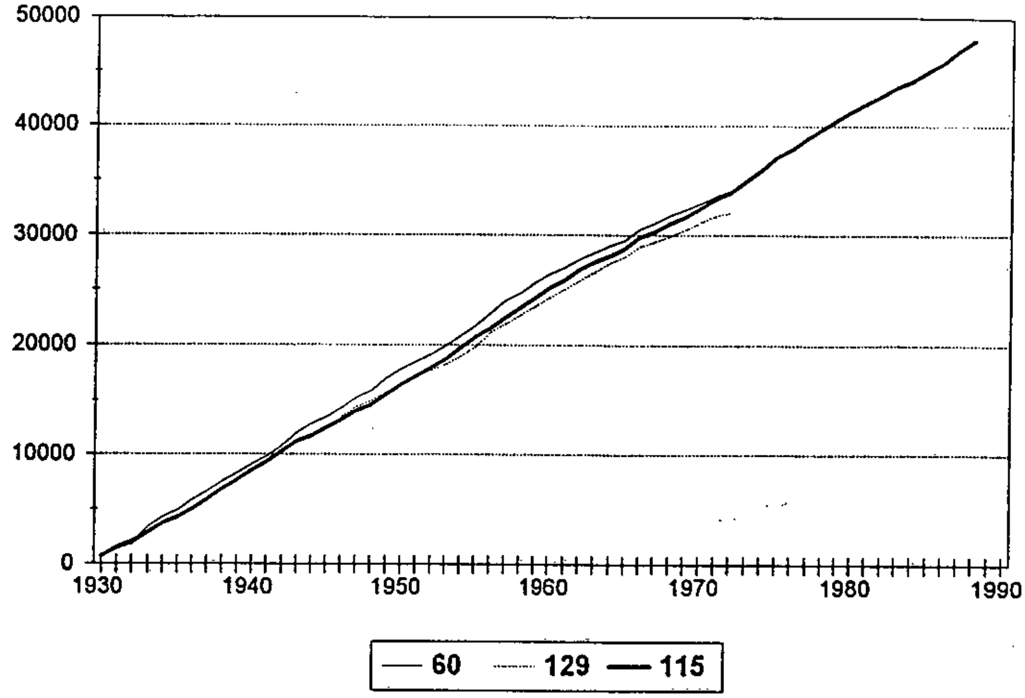
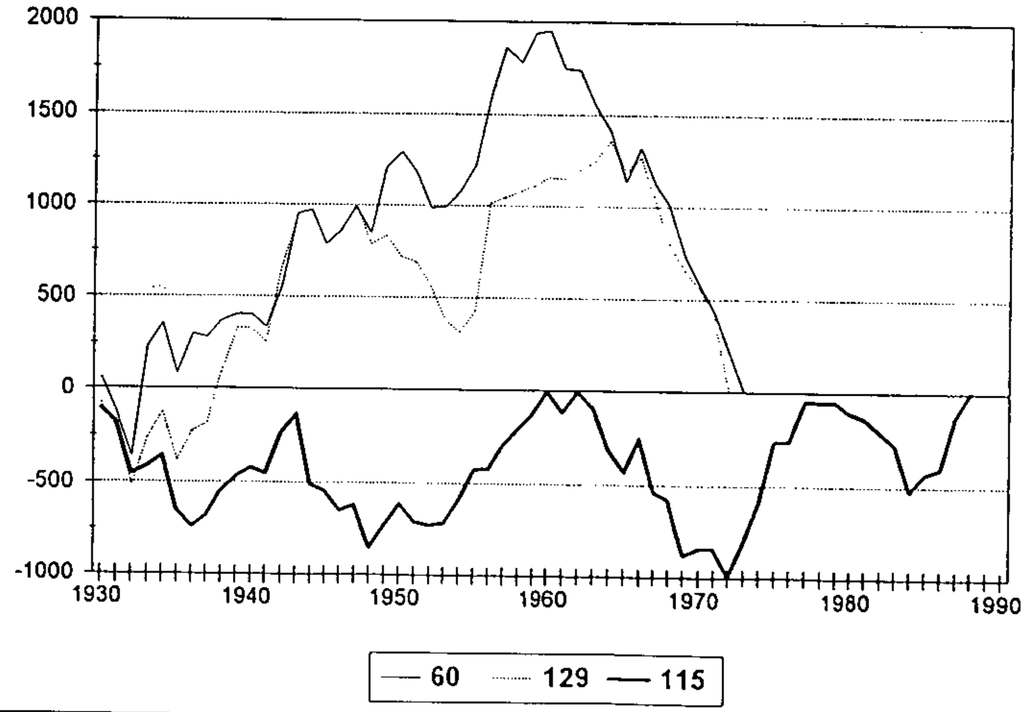


Figure 2.6 Cumulative departure from mean annual rainfall at selected stations (observed data only)



ignored, and those remaining could be investigated in terms of the history and operation of the station.

2.3.4 Filling gaps in the data

LMC, in the feasibility study, set the strategy of rainfall gap-filling and extension with the objective of producing a complete record at all of the 76 stations used. With the short flow records available at that time (17 years up to 1983/84) they had little choice but to extend the flow record using the longer rainfall data.

LMC tested the acceptability of records from the 76 stations against the mean of 11 long-term stations split into an eastern and western group. Some records were rejected but no adjustment was made to those exhibiting marked variation from the control groups. The remaining records were filled to give a complete monthly record for the period 1930/31 to 1983/84 using multiple linear regression.

Their regression technique derived missing data for a station with reference to the three nearest stations with the proviso that at least one of the neighbouring stations had to have largely recorded data. Some other constraints were applied, for instance the regressions which defined the relationship between stations were based on seasonally grouped data to ensure at least 30 observed values in each regression.

There are a number of drawbacks to this method when the proportion of missing data is high and there is evidence of cycles or possible non-stationarity in some of the records. The method progresses through the data so that missing values in the record of the current station are derived in part from previously in-filled values at other stations. Thus any bias in the estimation of missing values is propagated through the data in a way that cannot be defined from the results alone. Any non-stationarity in the records used in a regression equations, including any bias in the sample means due to cycles, is passed into the gap-filling process and propagated through the data set. Finally, regression in-filling will tend to reduce the variance of the rainfall record unless some random error is added bach into the generated data.

Kriging, the method implemented by WRD, is a spatial interpolation technique that works with standardised data. It does have theoretical advantages over the regression techniques that were used in the feasibility study. Kriging is essentially a surface fitting procedure whereby data are infilled with reference only to contemporary records at other stations without reference to the time-series dimension. As such it should be less sensitive to errors in the data and properties of the series, such as non-stationarity or cycles, than alternative regression techniques. Nevertheless the results contain some values that clearly fall outside a reasonable range. It is difficult to define why such values have occurred and suspicion arises that the method cannot improve the database unless the problems of the recorded data are addressed first.

WRD used data from 130 stations in their Kriging exercise, inevitably including stations with short records. This was in line with expert advice they received at the time. With hindsight, WRD accepts that little benefit was gained by using the additional data which might have contributed to some of the peculiarities found in the results. An example which follows from our review of the effect of cycles in data assessment is shown in Figure 2.7. This graph shows the cumulative departures of the observed and infilled data taken together for the same three stations used in Figures 2.6 to which it should be compared. While the Kriging procedure has reduced the apparent non-stationarity for station 129, it has markedly exaggerated it for station 60.

It is a difficult topic to review thoroughly and we have had to rely on the statistical data provided by WRD (LHDA, March 1990). One feature of these statistical summaries merits careful review, namely, the averages across stations for each hydrological year. These averages are calculated separately for the stations with observed data in that year, for the infilled stations alone, and as an overall average for all stations whether infilled or not. Figure 2.8 shows the time-series for the three averages, and Figure 2.9 shows the difference between the infilled average and the observed average over the years.

It is striking that the infilled average is markedly higher than that of the observed data in the first half of the record, and markedly lower in the second half. This could be because the infilling was predominantly for the higher-rainfall stations in the first half of the record and for the lower-rainfall stations later. While this seems to be true to some extent, a rapid appraisal of the tabulated data suggests that it accounts for no more than about 30mm of the difference. We cannot see any theoretical cause for this result, but would add that results for station 60, illustrated in Figure 2.7, would contribute to it.

Kriging is an internationally respected technique and much work has been done by WRD to adapt it to the problems posed by the rainfall data in this region. This work has included reviews of standardisation techniques, anisotropy in the spatial distribution of rainfall and methods of weighting the stations used to provide an infilled value. Some of the results which are seen as unrealistic or unacceptable have probably arisen from the use of unscreened data. We do not believe that Kriging or any other procedure can substitute entirely for techniques of data quality control and screening.

This uncertainty about the results of Kriging in the time dimension has a direct bearing on the extension of flow records using the Pitman model. Differences of the magnitude illustrated would lead to the hindcasting of much higher flows for the early years. It is clearly necessary to substantiate the results of the Kriging procedure if flow extension using rainfall is to be part of the continuing analytical strategy.

2.3.5 Conclusions

The techniques for identifying potentially erroneous data and for gap-filling and extension of incomplete rainfall records remain controversial. Our sample analysis has shown that many of the fears expressed by DWA(RSA) are well justified; there is yet no

Figure 2.7 Cumulative departure from mean annual rainfall at selected stations (observed and infilled data)

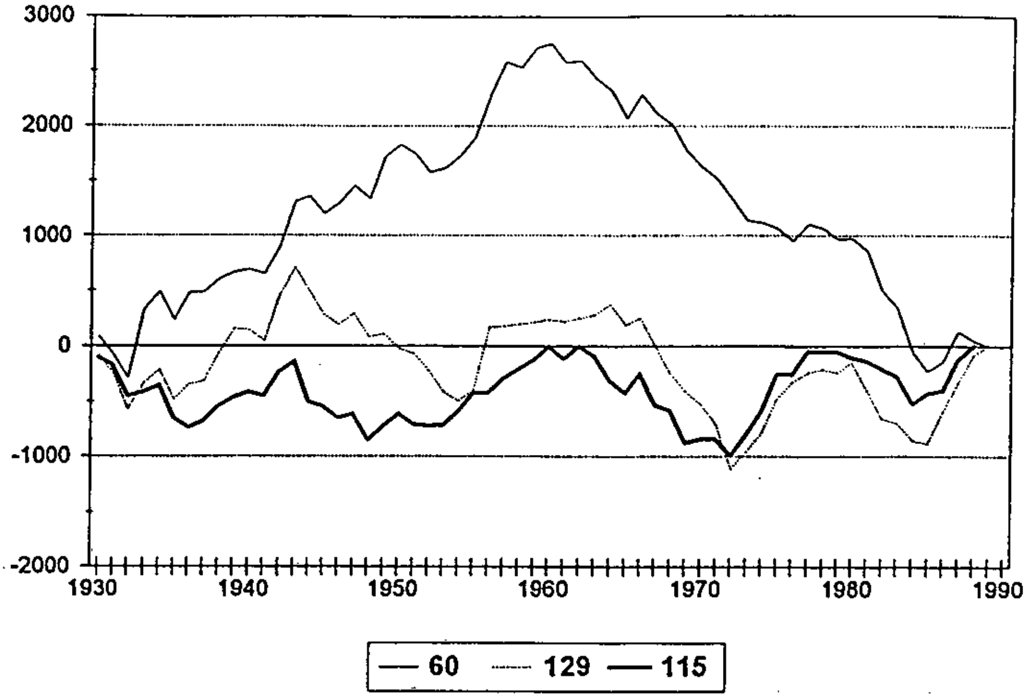


Figure 2.8 Comparison of average annual rainfall across stations according to source of data

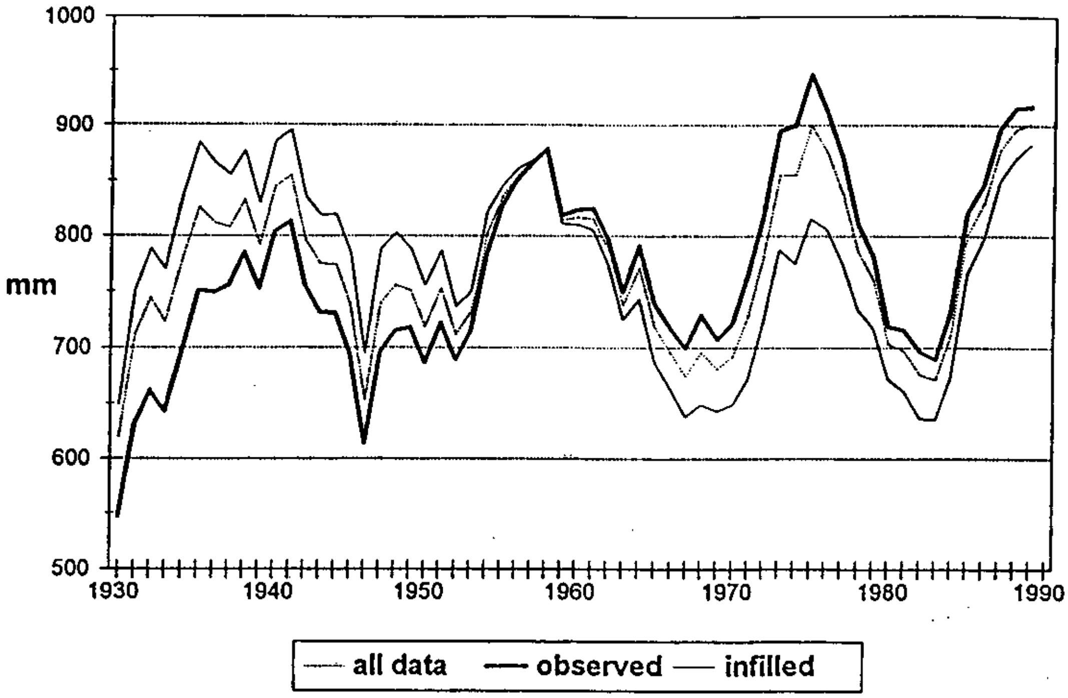
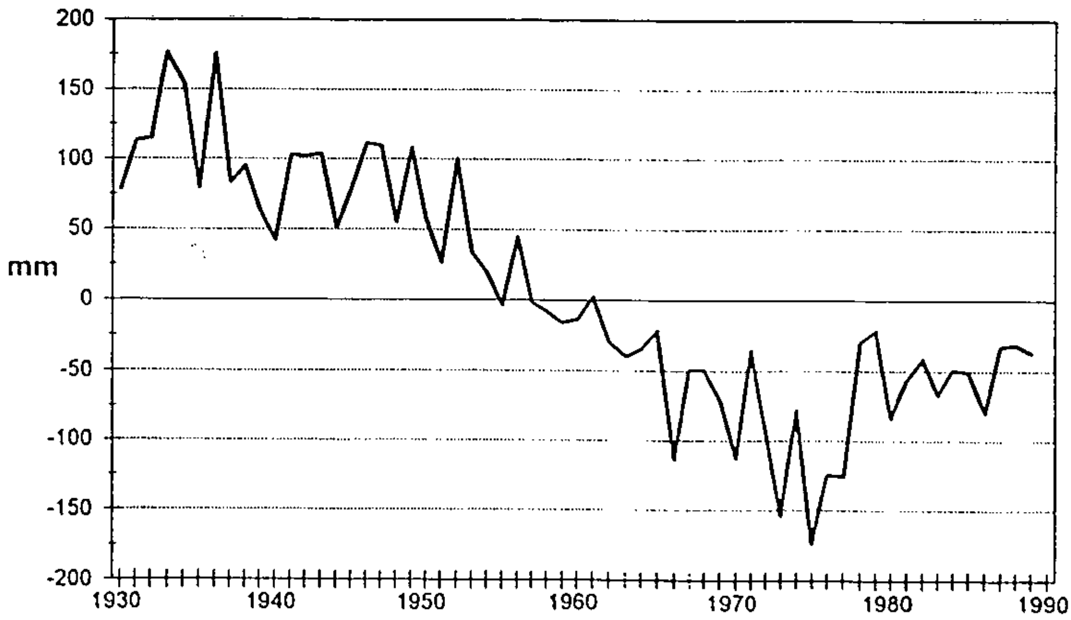


Figure 2.9 Difference between infilled and observed average annual rainfall across stations



basis for belief that the rainfall database is much stronger than it was after the feasibility report.

There appear to be four main reasons for this.

a The data provided by WEMMIN are not of consistent quality. There are discrepancies between manuscript and compMwer-based data, and between daily and monthly data. WRD have provided some assistance to WEMMIN to expedite checking procedures, but the combined resources available to check the data thoroughly are insufficient to the scale of the task.

b The existence of an apparent, underlying cyclical pattern in annual rainfall over the 60 year record makes it difficult to identify potentially erroneous data in an objective way.

c WRD has not adjusted their strategy to allow for these problems. Too great a reliance has been placed on wholesale numerical analysis when a more pragmatic, partly subjective, approach would have been more effective initially..

d The rainfall database includes far more stations than are strictly necessary even for the existing analytical strategy.

There is now an urgent need for a change of strategy for rainfall data processing and analysis, and for techniques and available resources to be adjusted to expedite the achievement of an effective, agreed rainfall database. The options open are inextricably linked with the choice of an overall analytical strategy and are discussed in this context in the next chapter.

Our exploratory analysis has shown that the cyclical pattern in annual rainfall could be a significant feature of the climate and not just a chance occurrence in the period covered by the historical rainfall record. But the tests that we have been able to carry out on a sample of the data do not lead to a completely unambiguous conclusion. Further analysis of the data should be made when an agreed rainfall database has been achieved.

3 ANALYTICAL STRATEGY

3.1 DEFINITION AND IMPLICATIONS OF THE OBJECTIVES

The hydrological objectives include the derivation of storage-yield statistics for one or more reservoirs, aMw the description of inflow series into a defined reservoir system for the computation of Royalties by a procedure defined by treaty. For practMwal purposes these objectives are the same; they both require that flow series be derived for a number of actual and potential or hypothetical dam sites. The flow series should be representative of the long-term flow regime at the sites, although for Royalty computations the series has been defined specifically as the flow series from 1930/31 to 1982/83.

A less immediate objective is the preparation of a procedure for operational analysis of the system, but this will also be based on an analysis of flow series representative of likely future inflows. Operational decisions will be depend on knowledge of the system state (current reservoir contents) and expected inflows.

Two characteristics of the LHWP have an important bearing on the strategy that should be adopted to meet these objectives. A high degree of security of supply is required; failure to meet demand is expected to occur in no more than two years out of a hundred on average. The reservoirs are large in terms of the mean annual inflow from their basins; cumulative active storage is two or three times the mean annual inflow from basins above the reservoirs.

While the scale of the reservoirs follows from the demand for a very high security of supply, the two characteristics together imply that the critical period of deficient flows between occurrences of failure must be very long, fifty years on average. The inflows are seasonal following the monthly variation in rainfall, but seasonal effects are small compared to the fluctuations over years and decades that, in practice, will govern the storage required to meet a given yield.

The implications for the analytical strategy are clear. It is the longer term variation in annual flows that will be the main determinant of storage requirements. Seasonal variations will need to be known to a lesser order of accuracy. Thus the primary analysis could use annual flows with some disaggregation into monthly flows for final detailed analysis.

A second implication is cause for greater concern. If critical periods in the reservoir analysis are of several decades duration, the accurate description of flows over such periods (and the reliability associated with them) requires flows records of a century or more. Historical flow records cover only 25 years; some historical rainfall records cover 61 years. Thus the emphasis on trying to extend the flow records with respect to the longer rainfall records is understandable and soundly based. Even so, an extended flow record will cover only 61 years, and we can expect it to define no more than one manifestation of a critical period of flows. It would be impossible to estimate directly whether the critical period flows defined by an extended record truly represent the probability ascribed to them. But it does suggest that alternative techniques that describe the underlying statistical structure of the flow series could have a part to play in defining a representative critical flow sequence by simulating many different series all equally likely to represent future flows.

In the rest of this Chapter, we review the application of the Pitman model and its place in the present analytical strategy, before discussing the options open to LHDA given the present position and these general objectives. Special attention is given to the constraints imposed by the quality of the different kinds of data that have been discussed already.

3.2 CONTINUATION OF THE PRESENT ANALYTICAL STRATEGY

The present strategy is essentially that developed by LMC in its feasibility study of the LHWP. It included patching and extension of the rainfall series at each station with reference to records from other neighbouring stations, and use of the Pitman model to convert the historic rainfall to runoff. While WRD and DWA(RSA) have questioned parts of this strategy and experimented with a stochastic modelling approach, there has not been wide discussion of their views even within LHDA, and the LMC strategy remains the basis of the hydrological programme agreed with DWA(RSA).

3.2.1 Application of the Pitman model

Deterministic rainfall-runoff models, of which the Pitman model is an example, aim to represent the physical processes underlying the transformation of rainfall into runoff. Thus they need to operate on a short time-base; a month may be too long in some environments, particularly if rainfall tends to occur in short periods, erratically distributed in time, or if there is little natural storage in the basins.

The model is calibrated by fixing values of parameters that control thresholds, rates or storage capacities within the model so that simulated flows resemble closely those observed in the calibration period Subsequently, the parameters are held constant while historical flows are simulated from the longer rainfall series. When, as is the case in Lesotho, average rainfall on the river basin is not known accurately, a multiplying factor on rainfall may be included as a further parameter in the model.

The Pitman model is non-linear in the sense that it allows more runoff for a given rainfall if the basin is already wet than if the basin is dry when some of the rainfall is used to replenish soil storage. This is a simple and obvious example of several non-linearities inherent in most conceptual, deterministic models. Non-linearity is necessary if we are concerned with describing the short-term response of a basin. The question is whether the longer term response, say the simulation of annual runoff, also requires such an elaborate scheme.

If rainfall is seasonally distributed and the seasonal pattern is stable, a basin will return to fairly dry conditions at the end of each hydrological year (September in Lesotho). Annual runoff will be a summation of short-term, say monthly, responses to rainfall, and the response might be expected to follow a reasonably regular seasonal pattern. In the early months of the rainfall season, runoff will remain low as the basin soil storage is replenished; later in the year runoff will increase as rain falls on a wetter basin. As rainfall dies away, runoff will decay slowly and the basin will dry out as evaporation continues to use the stored moisture. By the end of the hydrological year conditions will be similar to those at the start of the year. Overall, we might expect annual runoff to be reasonably well related to annual rainfall.

Figure 3.1 shows annual runoff in terms of annual basin rainfall predicted by the Pitman model for the basin above Pelaneng (G45)[4]. It illustrates that on an annual (hydrological year) basis, the basin response is broadly linear. Variation about the linear regression line of annual runoff on rainfall results, in part, from variation in the distribution of rainfall through the year that the Pitman model has accounted for. But some of the variation must derive from the uncertainty of estimation of rainfall over the basin given the sparse coverage of rainfall stations and the variation in rainfall over the higher altitude, predominantly ungauged, parts of the basin.

Figure 3.2 shows that actual evaporation losses increase with rainfall as one would intuitively expect. More rainfall, perhaps over a longer wet season, ensures that soil storage are maintained for longer providing a source for evaporation. Also the annual loss is a realistic proportion of the potential evaporation estimated from Symonds pan data.

Figure 3.3 compares annual simulated runoff with observed values for the model calibration period (1967/68 to 1984/85). The model is evidently reasonably good at predicting annual runoff, at least over the calibration period, but there is a tendency for runoff in dry years to be underestimated and for runoff in wet years to be overestimated. Thus the variability of annual runoff is increased in the simulated series, and presumably in the extended period. This could have important implications for the LHWP where the long-term variability of runoff is a major factor in reservoir sizing.

The purpose of this illustration is not to show that the Pitman model is deficient, but to indicate that it is not necessarily appropriate to the problem given its inherent need to operate on a shorter time scale than is relevant. We are concerned that a great deal of time and effort might be spent on continuing this form of modelling which could produce flow series that are flawed at longer time scales.

Once calibrated, a deterministic model can produce only one historic series of flows from

---

4 The data used in these illustrations are taken from the LHWP Feasibility Study, Preliminary Draft, Supporting Report A - Hydrology Studies, LMC, June 1985.

Figure 3.1 Annual runoff and rainfall from the Pitman model for basin G45 Pelaneng

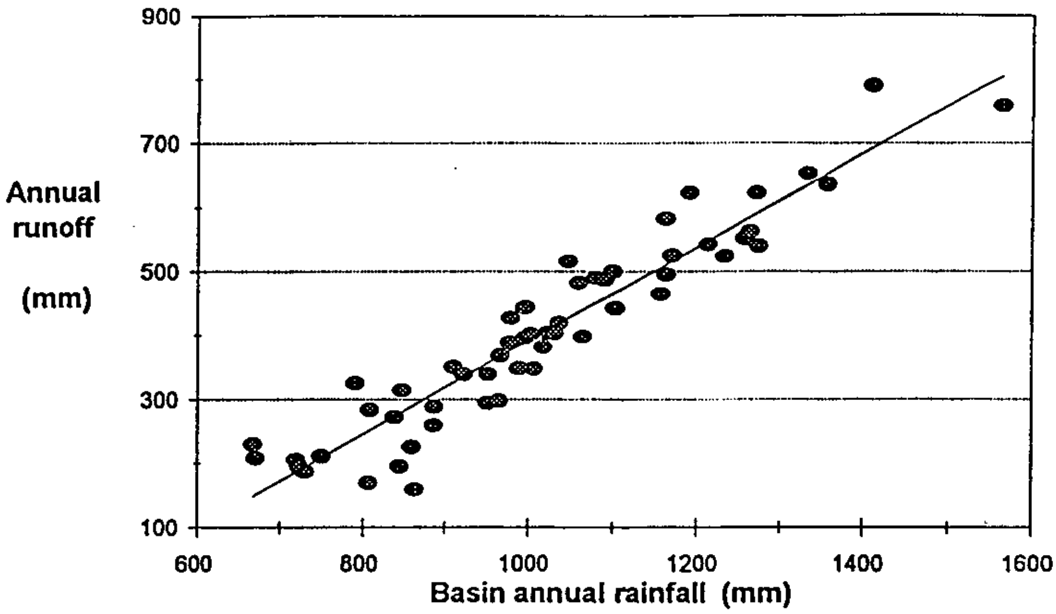


Figure 3.2 Implied annual losses and rainfall from the Pitman model for basin G45 Pelaneng

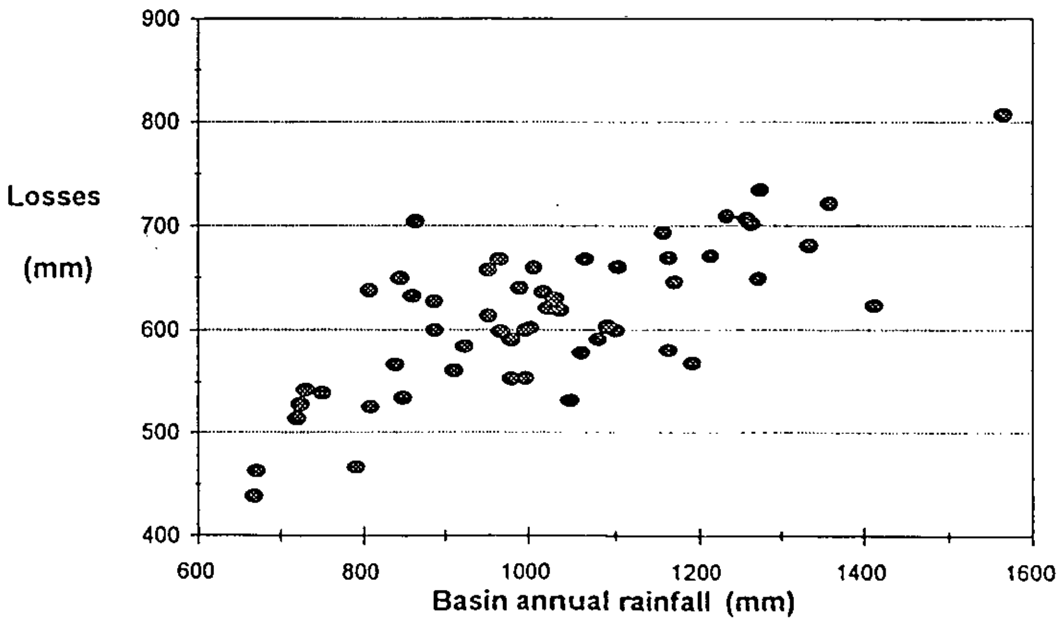
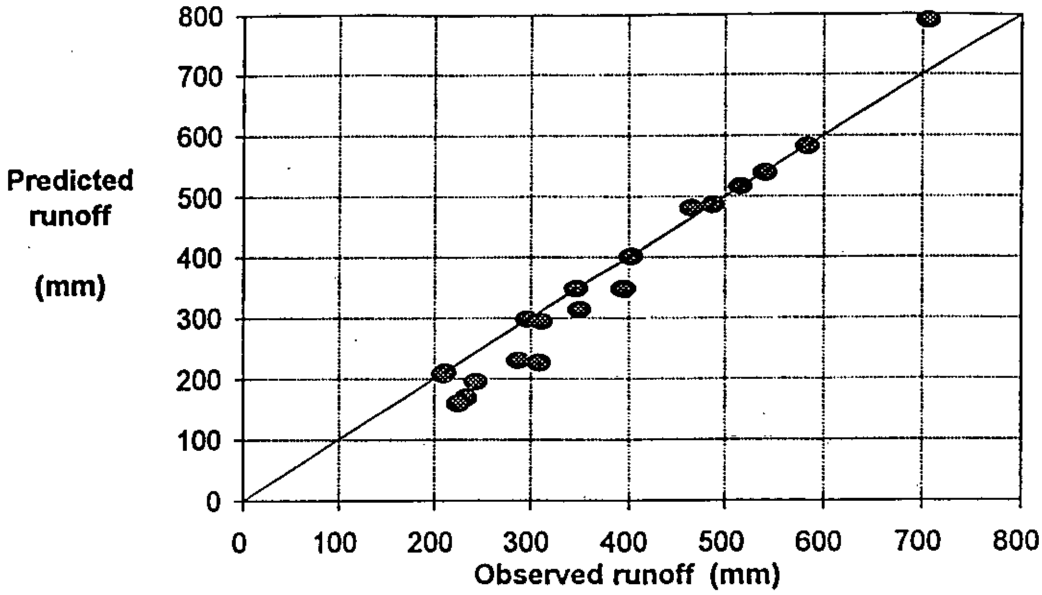


Figure 3.3 Comparison of predicted and observed annual runoff for basin G45 Pelaneng (Pitman model)



a given rainfall series. Although there are techniques for adding uncertainty to the predictions, the underlying statistic of the predicted flows follow from the statistics of the historical rainfall. Thus any reservoir design based on the predicted flows 'sees' only one or perhaps two manifestations of a critical period of deficient flows.

There are some other issues relating to the application of the Pitman model during the feasibility study that merit discussion. The modifications made by LMC appear to be soundly based and comparative tests indicated that they improved the simulation. But most of the tests were concerned with short-term model performance.

The estimation of monthly basin rainfall was done using a procedure that LMC called 'correlation weighting'. This gave more weight to stations whose record is well correlated to the flow record. It is not clear whether this correlation used monthly, seasonal or annual data. If a station was very poorly correlated, it was omitted from the analysis. Occasionally this produced the bizarre result that a rainfall station outside the basin would be preferred to one within the basin. In this procedure, regression analysis is likely to show poor correlation because of a few outliers (possibly errors) in the data. However, there is no reported work on identifying the reasons for rejection of stations in the basin area.

A further issue is the use of constant, regional parameter values over the range of different basins modelled. There is no intrinsic reason why the hydrological response of basins should be the same. It depends on many factors, such as soil characteristics, geology, basin slope, and vegetation among others. There is no analysis reported in the feasibility study to support the assumption of uniform parameter values; all inter-basin variation was attributed to errors in the estimation of basin rainfall and countered by introducing a rainfall scaling factor as a parameter.

3.2.2 Completion of the data processing

It was clear from our review of the data processing in the previous Chapter, that much work remains to be completed, particularly on the rainfall data, before modelling can be resumed. Continuation of the present strategy using the Pitman model requires considerable effort on rainfall analysis to produce consistent rainfall series for each of the basins modelled. An alternative strategy based on stochastic modelling requires much less detailed work on the rainfall but perhaps demands greater emphasis on the appraisal of the flow data.

In either case it is necessary to reject aspects of the data preparation that are not worthwhile and which do not add significantly to the sum total of relevant hydrological knowledge, given the objectives of the analysis.

Rainfall Data

The long-term variation in rainfall (and therefore in runoff) governs the design, operation and performance of the reservoirs in the LHWP. Therefore, the major effort should be put into the derivation of a rainfall database that accurately represents the longer term features of the rainfall records. Less emphasis need be placed on the precise monthly distribution.

The first priority should be to identify the most useful stations in this regard, and to check their daily and monthly records to achieve a consistent and realistic set of data. Much of this work has been done by WRD for 20 selected stations.

Further tests on inter-station consistency are necessary, probably using annual data, but these tests must take account of the underlying cycles in the records. Any departures from a consistent pattern should be checked against the station history to identify possible changes in station position or operation. Inconsistent records should be rejected or corrected if feasible. It is important that a comparison of the long-term statistics over the model fitting and extending periods are within a reasonable and justifiable range.

While it is more convenient to work with rainfall records of equal length, we believe that the true information content of the rainfall data is not expanded significantly by the different procedures of gap-filling and extension used by LMC and subsequently by WRD. It is difficult to assess the extent to which several factors contribute to this conclusion. They include: the underlying unreliability of the records; the unrepresentativeness of the rainfall station network (poor coverage of the high-altitude, high rainfall areas); and the high proportion of gaps in the record. All contribute to make estimation of rainfall over the headwater basins particularly difficult and susceptible to different, subjective, interpretation.

We therefore conclude that wholesale gap-filling and extension of rainfall records has little overall benefit and should be discontinued. A better strategy is to concentrate on a reasonable selection of stations that provide spatial coverage and have the most reliable records. Referring back to Table 2.1, we recommend that the records from no more than 20 stations should be screened with reference to the daily records, corrected where possible, and used primarily to define the long-term climate series. The choice of stations should be made according to a number of criteria among which we recommend the following:

- at least 30 years of record preferably without long gaps,

- uniform spatial coverage; stations close to another should not be included, stations outside the effective basin area should be included only where there is no alternative inside the basin area,

- good quality of record, initially by subjective appraisal including the results of past analysis, later on the basis of consistency between daily and monthly data and revised tests.

If the strategy using Pitman model is continued some additional stations will need to be screened, bringing the total number to no more than 40 stations. Areal average rainfall on the headwater basins should be estimated by averaging the standardised series from each rainfall station. Rescaling the average standardised values could be done using a mean annual rainfall derived from the isohyetal map, as before, disaggregated into a monthly values from the average distribution from the stations used. The standard deviation appropriate to areal estimates can be derived from a separate study using the best data.

Flow Data

The main task remaining with the flow data is the correction of the historical flow series at the three sites having Crump weirs, Paray, Whitehills and Marakabei. In all three cases, flows for the Crump weirs are higher than those from the corresponding rated river sections, although the exact magnitude of this increase has yet to be agreed by both parties. Nevertheless, in broad terms the Crump weir flows appear to be higher than the rated section flows by some 4 to 5% at Paray, by about 14% at Marakabei, and possibly by as much as 20% at Whitehills.

Because two sets of river level recorders exist at both the rated section and the weir at each site, one pair operated by staff of WRD and the other by DWA(RSA), it should be relatively simple for agreed flows to be computed for the weir and rated section at each site for the concurrent period of record in each case.

However, slightly different methods of chart digitisation are used by each party, which may lead to some debate as to which flow series should be used. The WRD use fixed period digitisation, where river levels are taken from the chart at fixed times, normally 15 minutes. The DWA(RSA) use the "change-point" method, where river level is digitised only were necessary to define adequately the shape of the level hydrograph. Both methods are hydrometrically perfectly acceptable and neither data set could be thought of as intrinsically better than the other. The change point method is normally used in order to minimise the volume of data necessary for definition of the record, and is sometimes believed to be require slightly less disk space for data storage, particularly during periods of low flows. However, hard disk capacities of modern PCs have increased dramatically in recent years, and such considerations are now of only minor significance. Because flows are ultimately required at fixed time intervals, be it 15 minutes, hourly or even daily, there is merit in the fixed time digitisation used by the WRD.

The two data processing techniques employed are both equally valid, and for most of the period of record processed flows from each agency should be within a few percent of one another. There will be some occasions where one or other recorder has not operated correctly, and the data should be taken from whichever recorder was operational. During any periods of significant discrepancy in the processed records, it should be fairly easy for staff of the two organisations to agree which record is most accurate, particularly as the rated section levels and processed flows are also available. Unfortunately, because of the mistrust that has developed between the parties, agreement may be slightly more difficult to achieve for some periods of doubtful record. If the two parties are unable to agree on the data series, perhaps the disputed data could be reviewed by independent consultants.

Once agreed concurrent flow series have been produced for the Crump weir and for the rated section at each site, the historical rated section flows for earlier years should be adjusted. The methods of adjustment put forward by the WRD in their June 1991 report on "Methodology for correcting historical flows for the Senqunyane River @ Marakabei" seem to offer a valid approach. The regression approach proposed seems to offer the best adjustment technique, although the equations derived in the report would need revision once flow series have been agreed by the two parties. Similar regression models should be developed for Whitehills and Paray.

The work could be completed fairly rapidly by staff of WRD, provided there are regular liaison meetings with DWA(RSA) to ensure that mutually agreed flow series are being used in the adjustment exercise.

3.2.3 Other hydrological analysis

Throughout this project WRD have tended to look for objective, numerical techniques of analysis to solve problems with the data that would have benefitted from simpler, perhaps subjective, analysis first. It is always important to look at the records for hydrological insight and to see whether they are consistent, before embarking on time-consuming analysis. If these simpler forms of analysis are overlooked, it is difficult afterwards to discover why the results do not accord with expectations.

Disagreements have arisen about issues such as precisely which rainfall stations should be used as input to the Pitman model for this or that incremental area, before there is a realistic appraisal of more fundamental questions, such as why runoff on the Mohale basin should be substantially higher than that recorded at Seshotes. It is as though the hydrological knowledge has been deliberately constrained by the belief that the Pitman model truly represents basin response and that some regional coherence of parameter values in the model should be expected. We believe that all the data now available should be used to look afresh at the actual hydrological response of the basins with emphasis on defining their similarities and their differences so that models (of any kind) can be properly structured to represent the true relationship of runoff to rainfall.

Tables 3.1 and 3.2 illustrate a simple annual analysis which tests the consistency of the runoff data for all the basins. In Table 3.1 we have used the mean annual flow data from the rated sections to estimate runoff from the ungauged (incremental) areas in each major reach of the Senqu above Seaka. These estimates are compared with those resulting from a correction applied to the sections at Paray, Marakabei and Whitehills as a result of the new data available from the Crump weirs. The correction at Paray is small (4%), but that at Whitehills is substantial (20%). Both corrections markedly improve the validity of the runoff from incremental areas and appear to provide a more balanced pattern of runoff. However, the correction at Marakabei (15%) appears to worsen the estimate of incremental flows above Nkaus, but not substantially.

In Table 3.2 we have estimated mean annual rainfall from the runoff data using the regression equation illustrated in Figure 3.1. Comparison of this implied rainfall with the isohyetal map allows the tentative identification of possible high or low values given our limited knowledge of the spatial distribution of mean annual rainfall. Initial indications are that flows at Koma-Koma might be underestimated, but that the balance overall looks good. We would stress that more detailed balances should be examined before firm conclusions are reached.

However, this preliminary balance does illustrate that the flow data based on rated sections alone were bound to cause problems in the analysis; they are basically inconsistent. Flows adjusted by the new information from the Crump weirs generally appear better balanced. The analysis should be extended to test the consistency of monthly flows, specifically to look for any drift in the ratings of the sections, and unexpected changes in the seasonal distribution of runoff. If the flow records are to be used directly in a stochastic flow generation model, it is vitally important that all possible tests are carried out to show that the basic data are consistent and correct. Otherwise the model will propagate errors into the simulated series.

It is unlikely that there will be enough data from the new rainfall stations to improve the water balance analysis for individual basins, but every effort should be made to use the data to validate or improve the isohyetal map. The regression equation derived from the Pitman model output, and used above, does not necessarily represent the true relationship between mean annual rainfall and runoff. The rainfall estimated is a index of the true rainfall that is unknown. It is possible that true rainfalls on some headwater basins are significantly higher than presently estimated.

3.3 AN ALTERNATIVE STRATEGY BASED ON STOCHASTIC MODELLING

Rather than relying on a single historical hydrological record, the design and operation of water systems has often been undertaken using synthetic streamflow series. These synthetic series are generated by stochastic models which are calibrated using historical records. The stochastic models are able to reproduce the underlying hydrological process in general terms. The generated series vary randomly from the calibration data but their statistics such as the mean and variance are preserved. They therefore represent a range of possible scenarios for a given period.

3.3.1 Appropriate models

Various types of model of different levels of complexity have been developed for synthetic streamflow generation, particularly in the last 20 years with advances in digital computing. The simplest models assume monthly or annual river flows are normally distributed independent random variables. Long sequences of synthetic flows may then be generated by sampling randomly from a normal distribution whose mean and variance are derived from historical data. Clearly the flow in one month may be related to the flow in the previous month, thus more sophisticated models allow for serial correlation between successive flows. A further refinement might be to allow modelling of non-normal flow data, for example, by applying a logarithmic transformation, or use of a different distribution form.

The Thomas-Fiering model is one of the most well known of the basic models. This is an autoregressive model of order 1, or AR(1), which relates flows in one period to flows in the previous period. Moving average models of order q, or MA(q), which represent the behaviour of data averaged over duration q are also widely used, as are combinations of the two called ARMA(p,q).

The majority of models operate only at a single site. However, for many applications, such as in the LHWP, several concurrent records of streamflow exist for neighbouring basins. The Spigot model developed by Grygier and Stedinger (1990) allows explicitly for the correlation between flows at a number of sites within a region. Spigot is based on a hierarchy of disaggregation models which can be operated within several schemes. Each scheme has several steps, for example, in the first step the model generates aggregate annual flows for the region as a whole using an AR(1) model. In the second step each annual flow is disaggregated to produce an aggregate flow for each month. In the third step, these aggregate monthly flows are disaggregated to flow sites preserving the cross correlation between them.

3.3.2 Advantages of stochastic modelling

Use of a stochastic model has several advantages over the current methodology. First, because the generated series vary randomly from the calibration data they represent a range of possible scenarios for a given period and therefore provide information about the likelihood of future droughts and wet periods not present in the historical data. It is possible to generate long series that contain several manifestations of the kind of critical periods of interest in the LHWP, so that reservoir trials are not constrained by a single sample of inflows, and such that reservoir reliability may be determined.

The second advantage is that annual flows are modelled explicitly. This is particularly important for large reservoirs such as in the LHWP where annual flows are the critical measure of water resources. In contrast, annual flows resulting from application of the Pitman model are not constrained since only monthly flows are modelled explicitly. Use of a temporal/spatial stochastic model, such as Spigot, offers the further benefit that simultaneous modelling of flows from a number of basins within a region produces a more stable model and allows modelling of the water resources project as a whole.

3.3.3 Dealing with cycles in the record

Despite the large number of gaps and poor quality of many of the records, the historical rainfall data provide valuable information about the longer term hydrological characteristics of the Lesotho Highlands. These data also contain substantially more

Table 3.1 Mean annual runoff balance for the Senqu basin above Seaka

River reach	Area km2	Data from rated section Flow mcm	Data from rated section Runoff mm	Data from Crump weir where available Flow mcm	Data from Crump weir where available Runoff mm
Balance to Paray					
41 Bokong	403	107	266	107	266
42 Seshotes	652	108	166	108	166
45 Pelaneng	1157	480	415	480	415
Sum of gauged tributaries	2212	695	314	695	314
Implied flow from ungauged areas	1028	88	86	119	116
8 Paray	3240	783	242	814	251
Balance to Koma Koma					
8 Paray	3240	783	242	814	251
36 Tlokoeng	852	168	197	168	197
6 Mokhotlong	1660	309	186	309	186
Sum of gauged tributaries	5752	1260	219	1292	225
Implied flow from ungauged areas	2198	270	123	238	108
5 Koma Koma	7950	1530	192	1530	192
Balance to Whitehills					
5 Koma Koma	7950	1530	192	1530	192
7 Tsoelike	797	156	196	156	196
Sum of gauged tributaries	8747	1686	193	1686	193
Implied flow from ungauged areas	2253	5	2	343	152
2 Whitehills	11000	1691	154	2030	185
Balance to Nkaus					
17 Marakabei	1087	322	296	370	340
Sum of gauged tributaries	1087	322	296	370	340
Implied flow from ungauged areas	2393	364	152	315	132
32 Nkaus	3480	685	197	685	197
Balance to Seaka					
32 Nkaus	3480	685	197	685	197
2 Whitehills	11000	1691	154	2030	185
Sum of gauged tributaries	14480	2377	164	2715	187
Implied flow from ungauged areas	5395	1334	247	996	185
3 Seaka	19875	3710	187	3710	187

Notes: **Implied flows are the difference between flow at the primary station in the reach less the sum of flows from the gauged tributaries.**

It has been assumed that Crump weir flows exceed rated section flows by 4% at Paray, 15% at Marakabei and 20% at Whitehills.

Table 3.2 Implied mean annual rainfall for the Senqu basin above Seaka

River reach		Area km2	Runoff mm	Implied rainfall mm	Comment
Balance to Paray					
41	Bokong	403	266	828	
42	Seshotes	652	166	691	
45	Pelaneng	1157	415	1032	
	Sum of gauged tributaries	2212	314	894	
	Implied flow from ungauged areas	1028	116	623	
8	Paray	3240	251	808	
Balance to Koma Koma					
8	Paray	3240	251	808	
36	Tlokoeng	852	197	734	low?
6	Mokhotlong	1660	186	719	
	Sum of gauged tributaries	5752	225	772	
	Implied flow from ungauged areas	2198	108	613	low?
5	Koma Koma	7950	192	728	low?
Balance to Whitehills					
5	Koma Koma	7950	192	728	low?
7	Tsoelike	797	196	733	
	Sum of gauged tributaries	8747	193	728	
	Implied flow from ungauged areas	2253	152	673	high?
2	Whitehills	11000	185	717	
Balance to Nkaus					
17	Marakabei	1087	340	930	
	Sum of gauged tributaries	1087	340	930	
	Implied flow from ungauged areas	2393	132	645	
32	Nkaus	3480	197	734	
Balance to Seaka					
32	Nkaus	3480	197	734	
2	Whitehills	11000	185	717	
	Sum of gauged tributaries	14480	187	721	
	Implied flow from ungauged areas	5395	185	717	
3	Seaka	19875	187	720	

Notes: Runoff is that given in Table 3.1 using Crump weir data where available.

Implied rainfall is estimated from the regression equation shown in Figure 3.1 viz: runoff = 0.73 * rainfall -339 unit: mm.

information about the possible cyclical behaviour in the hydrological series, although, as yet, the significance of the cycles is not adequately demonstrated.

Spigot, and most other stochastic models, assume that the underlying flow generating process is stationary. That is, the probability of experiencing a given annual flow is the same for any year. Clearly, if it can be demonstrated that the underlying process is cyclical, these cycles must be included in the model. Even if the cycles are not shown to be statistically significant and therefore part of the underlying process, they appear to be sufficiently evident in the historical data to require modelling for derivation of the royalty hydrology, since this is to be based on the flow data derived for the specific period 1930-1983.

The cycles can be removed from the flow and rainfall data before a stochastic model is calibrated by using a simple representation, such as a sine wave. Flows can then be generated using a stationary stochastic model based on the transformed, stationary data. After generation, the cyclical component is re-introduced to synthetic flow sequences generated.

Whether or not the cycles are shown to be statistically significant, it would be worthwhile to test the influence of the cycles on the design of the system. Two models could be formulated, one incorporating the cyclical behaviour and one without it, which would allow the influence of cycles on the design of the system to be evaluated in a tangible way. It seems unlikely that judgements about the significance of cycles based on the results of statistical tests on the data series will be unequivocal. Nor is it entirely clear whether an assumption of stationarity would lead to a more or less conservative design. Given the long critical period of the reservoir system, it is possible that the effect of cycles is small, but this remains to be demonstrated.

3.4 CHOICE OF A MODELLING STRATEGY

A switch of strategy away from the Pitman model and towards the stochastic generation of flow series is a major step which requires careful consideration. It is useful to review the pros and cons of the alternative strategies in the light of the objectives of the analysis that we outlined at the beginning of this chapter. We concluded that it is the long-term variability of flow that is important in addition to the correct estimation of the mean. The underlying cyclical pattern of rainfall is another complicating factor that should be considered.

3.4.1 Deterministic modelling (Pitman)

The advantages include:

- the ability to deal with different seasonal patterns of rainfall in different years,

- the method is easy to understand, and has some credibility in southern Africa where it has been used on other projects,

- the model will extend the flow series to give a combined simulated and observed series that is related to real years, and therefore it provides the flow series envisaged by the Royalty Treaty,

- the model directly represents the physical response of a basin, although in a simplified, conceptual way.

The disadvantages are:

- model fitting is subjective and apparently similar results can be obtained for different sets of parameter values,

- when rainfall data are poor, it is not easy to distinguish between errors in rainfall estimation and real differences in response between basins,

- the model has to use monthly rainfall data even though the short-term response of the basins is less important than the long-term annual variation in flows,

- there is no direct control of the variability of annual flows simulated by the model,

- only one hindcast is possible based on the historical rainfall which will determine the main features of the extended flow series,

- cycles in the rainfall data will be reproduced in the extended flow series even if there are grounds for believing that the cycles in the rainfall record could have occurred by chance and may not recur in the project lifetime,

- it is difficult to estimate uncertainty in the simulated series and to link this uncertainty to the hindcast series.

3.4.2 Stochastic modelling

The advantages include:

- the underlying statistical structure of the flow data is described directly and preserved in the generated series,

- the stochastic model is less dependent than the deterministic model on the rainfall data,

- the longer rainfall series can be included in the model to allow the additional information to be built into the generating process,

- the model can be based on annual total flows, using a disaggregation technique to produce monthly flows for reservoir studies,

- the underlying cyclical features in the rainfall series can be ignored or included, depending on the consensus of opinion as to their likely persistence,

- unexplained variation in flows is defined directly during the model fitting and can be used to generate an unlimited number of manifestations of possible flow series,

- use of a number of possible flow series can improve the reservoir analysis by providing many manifestations of possible critical sequences of flow.

The disadvantages are:

- stochastic models are more difficult to understand and use,

- it can be less easy to control the inter-relationships between flows from different basins, and thus to transfer results to ungauged sites,

- any bias in the flow records will be reproduced in the generated flow series,

- the model does not directly generate the historical flows envisaged by the Royalty Treaty, although a central estimate could be derived.

3.4.3 Conclusions

In our judgement it is unlikely that the Pitman model offers any advantage over statistical models in defining the annual flow series, given the unreliability and general unrepresentativeness of the rainfall record. As much information could be gained from a statistical model of annual rainfall and runoff, with the advantage that the uncertainty in the generated flows could be quantified and carried forward to the reservoir analysis.

We are particularly concerned that the variability of annual flows cannot be directly controlled by the Pitman model and that this is a serious disadvantage of the technique in this project. However, use of a stochastic model does place much more emphasis on the accuracy and internal consistency of the flow records which emphasises the need for the simpler preliminary analyses discussed above.

The flow records appear to be nearly consistent and are now of sufficient length, 25 years, to allow stochastic modelling a good chance of success. Rainfall information, albeit of a regional kind, can still add to the total information available to the model, which is equivalent to having a flow record of longer duration.

We are further persuaded that the considerable effort still needed to produce the detailed rainfall data for the Pitman model is a heavy drain on WRD resources. This is time that could be better spent on the basic hydrological analysis and stochastic modelling. We believe that it is possible to complete a revised hydrology within six months if consultants are used to carry out a revised strategy based on stochastic modelling. It is not possible to foresee results in that time frame using the existing strategy based on the Pitman model.

4 IMPLEMENTATION OF THE HYDROLOGICAL ANALYSIS

4.1 PREFERRED ANALYTICAL STRATEGY

There appear to be two parallel requirements for an agreed hydrology, one for engineering design of Phase 1B of the LHWP, and a second for establishment of rainfall and reservoir inflow series for the Royalty calculations. Whilst the precise hydrological data requirements of each task are slightly different, we recommend that the same methods of analysis be used in order to achieve the objectives.

It is suggested that annual flow series be derived from a stochastic model based on a statistical description of the recorded flow data. Disaggregation techniques should be used to divide the annual flows into a monthly series for subsequent analyses. Rainfall data from selected stations should be used to provide information on the longer term variability of runoff and to assist in the transfer of flow sequences from gauged site to the dam sites.

This modelling should follow a full review of the flow data and of rainfall records at a selection of gauges having the longest, and most reliable records. The annual runoff response of the various basins should be checked in order to ensure internal consistency in the flow series used for the stochastic modelling. Comparisons between the specific runoff of the various catchments should be undertaken, taking into account basin morphology and mean annual rainfall, existing maps of which should be carefully checked and updated as necessary. The flow data review might usefully include comparison of flow duration curves and other simple flow statistics to highlight whatever differences there might be between the basins. The objective would be to highlight regional runoff patterns in order to assist in estimation of flow series at the ungauged dam sites.

The records from those rain gauges having the longest, and most reliable data should be used to examine the significance of the cycles apparent in the historical data. Longer rainfall records from other adjacent parts of southern Africa should be included in this analysis in order to determine whether the detected periodicity in the data are truly representative of the longer term data. Should periodicity in the underlying rainfall records be proved by this analysis, this periodicity would have to be built into the stochastic flow generation model.

This would not pose any special problems, and any underlying periodicity which could be proved in the rainfall data could be used to assist in the flow generation process. In Figure 2.3, it was shown that standardised flow records at Seaka demonstrated the same cyclical pattern as the rainfall, and in Figure 3.1 it was shown that the relationship between annual rainfall and runoff was essentially linear for the Pelaneng catchment. It is probable that a fuller analysis of the data than was possible in this review study would show that these findings held true for the bulk of the catchments within the Highlands, and hence transferring any proven rainfall periodicity into the flow generation model should be feasible.

A preliminary briefing note on how this proposed stochastic modelling strategy might operate has been written in response to comments made on the Draft Report, and this is included as Annexe H. It should be noted that this briefing paper has been prepared as an extra item beyond the original terms of reference of the review consultancy and that consequently the strategy outlined should only be regarded as the consultants' preliminary thoughts on the subject. The note cannot be regarded as a definitive statement of our proposed modelling strategy.

4.1.1 Time constraints

The Royalty hydrology must be defined by the end of 1994, as fixed by the Treaty. Ideally, an agreed set of hydrological data should be produced by the beginning of that year to allow time for discussion on the various issues. The data required for the Royalty calculations are inflows for the period 1930-31 to 1982-83 to the reservoirs, and rainfalls onto, and evaporation from each reservoir.

The data required for engineering design of the next construction phase of the LHWP, Phase 1B, are similar to those needed for the Royalty calculations, but the period of data to be used is not fixed by the Treaty. All data available at the time of the analysis should be used. Furthermore, the series of design inflows and other variables needed for engineering design purposes are not necessarily restricted to a fixed historical period. Alternative, stochastically generated, flow series may be more appropriate for optimisation of reservoir size and transfer tunnel capacity. The consultants understand that hydrological data will be required for the engineering design studies during the latter part of 1993, and ideally results should be available by the middle of the year.

Although the hydrological analyses and data requirements of each task are different in some respects, it would be sensible to carry out both studies simultaneously, and a programme of work is proposed below which allows for this. The programme aims to produce engineering hydrological results and a set of hydrological data for computation of Royalties before the end of 1993. This timetable should allow both Parties adequate time to consider the results of the analysis before the Royalty calculation is actually made. The hydrological inputs to the computer program which will actually compute the Royalties must be agreed by both Parties, and time must be allowed for adequate consultations on this point. The computer program itself will take no significant time to run.

4.1.2 Manpower constraints

The programme of hydrological analyses outlined in the preferred analytical strategy above could be undertaken by staff of the WRD if there were no time constraints and provided that the head of the WRD is an experienced expatriate hydrologist. The local staff would not in the consultants' view be able to undertake the complex stochastic analysis alone; only the expatriate head of the department has sufficient experience and ability to carry out such a task.

Regrettably, the slow progress towards the achievement of a revised hydrology over the last several years has resulted in a lack of confidence by DWA(RSA) in the staffing and conduct of WRD. While the consultants recognise this position, we must say that does not appear to follow from any lack of analytical ability, leadership, energy or determination on the part of WRD, rather it has demonstrated that the tasks of data collection, of assembling and checking the quality of the basic data take up the full time of almost all the local staff, leaving only the head of the department to deal with the analytical problems, along with his managerial and other duties.

Given that our review of these analytical aspects of the work calls for some major changes in strategy, we believe that the existing staff complement of WRD is insufficient to meet the demands of the analytical programme while maintaining the existing workload of primary data collection and processing for the flow stations within the highlands, and for the hydrological support of other divisions of LHDA. It is clear that whilst staffing levels in WRD should be significantly augmented, specific tasks should be sub-contracted to a firm of consultants.

4.1.3 Conclusions

Within the limited timescale available for completion and agreement of the design and Royalty hydrology, we believe that it would be appropriate for the LHDA(WRD) to be strengthened through provision of support by a suitably qualified consultancy firm, who should be able to mobilise quickly the experienced professional staff necessary to complete the work. The consultants should work independently of WRD, but should draw upon the data base and expertise of WRD as necessary in order to ensure that the best use is made of existing resources.

There are a number of advantages in this course of action:

- a consultant could deploy quickly sufficient staff of appropriate experience and qualifications to provide a team that is able to meet the demanding time-scale and demanding hydrological problems,

- use of the consultant would be limited to the period of particular need, leaving WRD to be staffed appropriately for its important long term role.

In the remainder of this chapter we have assumed that this conclusion is accepted and we define the activities of the consultants and the longer term role of WRD in the event that consultants are commissioned to carry out the immediate analysis.

4.2 THE USE OF CONSULTANTS

4.2.1 Scope of the consultants contract

The objective is clear: the consultant should prepare a revised hydrology for the Royalty calculations and for design purposes. In practice, the consultant's task will fall naturally into three main elements:

- continuation and completion of the review of the rainfall data in order to define regional rainfall series for calibration and later as input to the multi-site stochastic model,

- review and revision of the flow data, taking account of the records from the Crump weirs, and by other methods of regional hydrological analysis,

- development of one or more stochastic generation models to produce quasi-historical flow series at the sites of interest for the two main objectives.

Because of the unsatisfactory state of relations between WRD and DWA(RSA), it is desirable that the consultant be instructed to provide independent solutions to the hydrological issues. This can be achieved if the consultant is responsible to LHDA directly and if the consultant is required to produce working papers on the main issues so that all parties can be aware of progress and can discuss any differences of fact or opinion throughout the period of the consultancy.

Naturally, the most fruitful outcome will be achieved by effective liaison between the consultant and WRD. There is much knowledge and experience of hydrological issues already gained by the data processing and analyses carried out by WRD. Indeed it is often through examination of methods that have not worked that progress can be made more effectively. Thus it is vital that WRD continue to have a limited part to play in the analysis in support of the consultant. The experience gained will be of value in the proper development of its long term role.

4.2.2 Monitoring progress

In view of the importance of these proposed hydrological studies to the LHWP, it is essential that both parties have every opportunity to monitor the progress of the work throughout the study. Regular bi-partite liaison meetings should be held, probably every six to eight weeks, to review progress and to allow problems to be discussed and to guide those working on the study. Brief progress reports should be produced a few days before each meeting, and the meetings might usefully start with a short presentation of results to date and include discussion of work planned for the following weeks. The liaison meetings should be thought of more as seminars where the work is discussed openly by all parties in order to avoid the confrontational style of meeting that seems to have evolved over recent years. Such confrontation has arisen partially because of frustrations over the slow progress of work to date, and the ever growing recognition of the limitations of the rainfall database upon which the Pitman model depends.

The intention must be to agree each step of the analytical methodology as the study progresses, and to agree the results of each key phase of the study before progressing on to the next step. Provided both Parties have every opportunity to monitor progress throughout the study, there is every chance that the resulting hydrological results can form the "agreed hydrology" called for in the Royalty Treaty.

4.2.3 Presentation and agreement of results

It is suggested that results of the study should be presented as a series of working papers on completion of the various tasks outlined in the work plan below. Thus working papers would be produced on each of the following topics.

- Results of the review of rainfall at selected stations and the derivation of regional rainfall series,
- Results of the review of flow data at all stations, and of inter-station comparisons and possible adjustments,
- Discussion note on the form of the stochastic flow/rainfall generation model(s).

A final report would be required on completion of the study, and this report should give full details of the work carried out leading to the final rainfall and flow series recommended for computation of the Royalties and for engineering design studies. The report would be based on the working papers as accepted during the study.

4.2.4 Estimated costings and manpower inputs

We provide below provisional estimates of the inputs of manpower, air fares, living expenses and so on necessary to complete the programme of hydrological work leading to the derivation of hydrological series for both engineering design and for calculation of the Royalty Payments, acceptable to both parties. It is assumed that staff of WRD will provide data and local knowledge, but, in view of their other commitments, it has been clear that the bulk of the work should be undertaken by staff of the consultants.

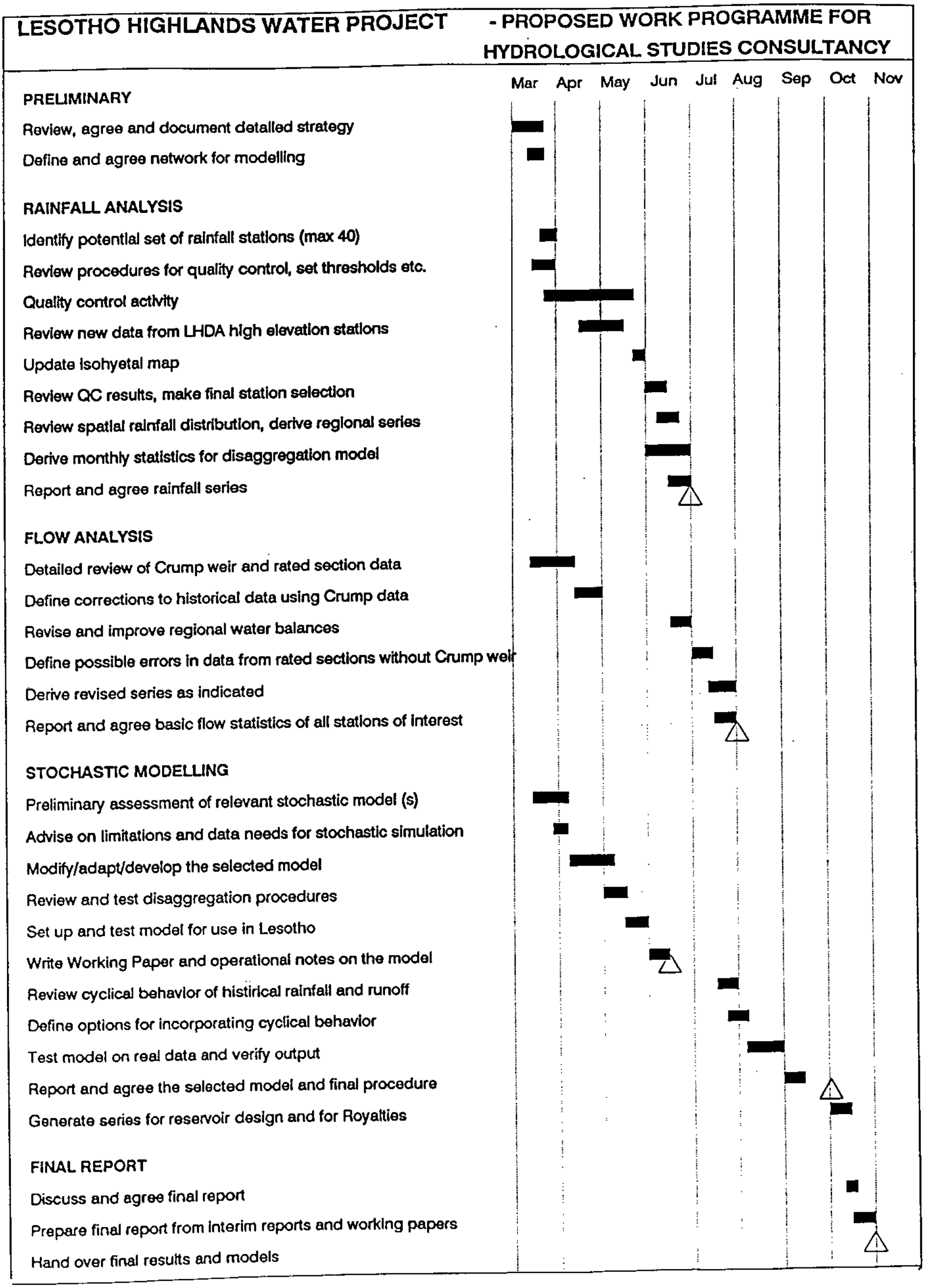

LESOTHO HIGHLANDS WATER PROJECT - PROPOSED WORK PROGRAMME FOR HYDROLOGICAL STUDIES CONSULTANCY
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
PRELIMINARY
Review, agree and document detailed strategy
Define and agree network for modelling
RAINFALL ANALYSIS
Identify potential set of rainfall stations (max 40)
Review procedures for quality control, set thresholds etc.
Quality control activity
Review new data from LHDA high elevation stations
Update isohyetal map
Review QC results, make final station selection
Review spatial rainfall distribution, derive regional series
Derive monthly statistics for disaggregation model
Report and agree rainfall series
FLOW ANALYSIS
Detailed review of Crump weir and rated section data
Define corrections to historical data using Crump data
Revise and improve regional water balances
Define possible errors in data from rated sections without Crump weir
Derive revised series as indicated
Report and agree basic flow statistics of all stations of interest
STOCHASTIC MODELLING
Preliminary assessment of relevant stochastic model (s)
Advise on limitations and data needs for stochastic simulation
Modify/adapt/develop the selected model
Review and test disaggregation procedures
Set up and test model for use in Lesotho
Write Working Paper and operational notes on the model
Review cyclical behavior of histirical rainfall and runoff
Define options for incorporating cyclical behavior
Test model on real data and verify output
Report and agree the selected model and final procedure
Generate series for reservoir design and for Royalties
FINAL REPORT
Discuss and agree final report
Prepare final report from interim reports and working papers
Hand over final results and models

Figure 4.1

Input	Cost (£ Sterling)	Equivalent Cost (Maluti/Rands)
(i) STAFF TIME	£ 117,400	(558,800)
(ii) AIR FARES	£ 19,600	(94,300)
(iii) LIVING EXPENSES	M 94,200	
(iv) CAR HIRE	M 16,500	
(v) COMPUTER HIRE / SOFTWARE PURCHASE	£ 9,000	(35,700)
OVERALL TOTAL	£ 146,000 plus M 110,700	Maluti/Rand Equivalent Approx M 799,500

4.3 THE CONTINUING ROLE OF WRD

4.3.1 WRD role in data collection

It is regrettable that the responsibility for all data collection and processing within Lesotho has not remained within WEMMIN. The best long term solution for Lesotho would certainly be a strong, well trained and motivated WEMMIN, with staff of DWA and DoM being wholly responsible for national data collection, processing, quality control, archiving and publication for all hydrometeorological data, for whatever purposes the data may be required. However, given that neither DWA nor DoM currently have the resources to achieve such an ideal, the present arrangement involving WRD may offer the best short term solution. A fairly radical improvement in the resources and personnel of WEMMIN would be required by the Government of Lesotho before WRD could relinquish their role as primary river flow data collectors within the highlands area. The present data collection system probably provides the best means of ensuring that the good-quality data required for the LHWP is obtained.

Given that WRD has, and will continue to have, a wider role in data collection, checking and processing than was envisaged originally, we suggest that some strengthening of the staff complement is required. Particularly, there is a strong case for the recruitment of a diploma level hydrometeorological technician to assist with the processing and analysis of the rainfall data in view of the difficulties experienced in obtaining data that are substantially error free.

With data being collected by staff of three separate organisations, it is important to ensure that there is no duplication of effort, and even more important to ensure that no vital task is ignored under the assumption that somebody else is responsible. Therefore we believe that regular liaison meetings should be held between managers of each of the three agencies. The existing informal working relationships between senior staff of the three agencies is already good, and has worked well to date. However, it would be wise to instigate a more formal series of meetings, possibly on a bi-monthly basis.

It is understood that the custom in the Lesotho is that staff should be paid an attendance fee for such meetings, which are often held after normal office hours. This practice is definately not condoned by the consultants, but we recognise the desired liaison meetings might not be attended regularly by the intended participants without this incentive. Thus it may be necessary for the LHDA to provide a budget for such attendance fees as it is unlikely that any other agency within the Government of Lesotho would be able, or willing, to provide funding.

4.3.2 Scope of WRD activities and manpower needs

The range of activities covered by WRD should remain although the emphasis should be different in view of a consultancy to prepare the hydrology for Royalty calculation and design. The most time-consuming tasks will continue to be data gathering, quality control and review, and the continuing development and enhancement of the computerised data base. While these activities can be managed and implemented by the local staff of WRD supported by the modest enhancement described above, the development of models for operation and management of the system to optimise water transfer and hydropower production and the response to needs for other analyses, such as flood estimation, cannot.

Annexe D sets out the responsibilities and activities of the existing staff of WRD supplemented by the addition of a hydrometeorological technician, and possibly a water resource engineer/hydrologist, as discussed above. We believe that the Head of WRD should continue to be an expatriate hydrologist/engineer with sufficient knowledge and experience to provide overall management to the division and to carry forward the operational modelling tasks into the future, possibly supported by consultants.

In Annexe E we outline the responsibilities and activities of WRD, and identify the immediate as well as the longer term programme. This assumes that the work programme will be adapted to complement the activities of the consultants, while providing a solid basis for a continuing hydrological service to the project.

4.3.3 Relations between WRD and DWA(RSA)

It is difficult to see a significant improvement in relations between the parties without some major change in attitudes. There are sincerely held philosophical differences between DWA(RSA) and the Head of WRD and there are no regular channels of communication that would allow differences of analytical approach to be discussed as a matter of routine. Use of consultants at this juncture could have the benefit of reestablishing trust if the consultants are instructed to rebuild communications and confidence as a subsidiary objective of their consultancy. The benefits would be considerable in view of the many other issues to be addressed as the LHWP develops. Not least would be the considerable waste of time that has been spent on going over the same ground time and again in the case of the rainfall data.

5 REFERENCES

BKS *Comments on proposed LHDA work plan.* October 1987

BKS *Comments on LHDA report "Processed raw rainfall data".* April 1989.

CNS Scientific & Engineering Services *The use of precipitation measuring radar in Lesotho.* September 1988

CNS Scientific & Engineering Services *Preparatory mission for weather radar in Lesotho.* November 1989

Crygier, J.C. & Stedinger, J.R. *SPIGOT - a synthetic streamflow generation software package. Technical description verion 2.6.* Cornell Unversity, New York. 1990.

DWA(RSA)/BKS. *Analysis of the Lesotho Highlands Hydrology.* June 1987

DWA(RSA)/BKS. *Analysis of the Lesotho Highlands Hydrology.* July 1987.

DWA(RSA)/BKS. *Analysis of the Lesotho Highlands rainfall data.* November 1988

DWA(RSA)/BKS. *Review of LHDA report "Stationarity of the raw rainfall data in the LHWP area", March 1990,* July 1990.

DWA(RSA)/BKS. *Evaluation of the LHDA report titled "Geostatistical approach for estimating the missing monthly data of the rainfall network".* November 1990.

DWA(RSA)/BKS. *Review of the LHDA report titled "Geostatistical approach for estimating the missing monthly data of the rainfall network - release 2".* March 1991.

DWA(RSA)/BKS. *Comments on LHDA report titled "Methodology for correcting historical flows at Sequnyane River at Marakabei.* September 1991

DWA(RSA)/BKS. *Evaluation of the LHDA report "Revised monthly raw rainfall data of the LHWP - January 1992".* March 1992.

Ecole Nationale Superieure des Mines de Paris. *Estimation of the rainfall in Lesotho.* November 1990.

Institute of Hydrology. *Proposal for the Review of the Water Resources Division.* June 1992

Kingdom of Lesotho and Republic of South Africa. *The treaty on the Lesotho Highlands Water Project.* October 1986

Lahmeyer MacDonald Consortium/Olivier Shand Consortium. *Lesotho Highlands Water Project Feasibility study*, April 1986

LHDA *Proposals for the assessment of tolerance of hydrometric data*. June 1986

LHDA *Interim hydrology progress report no 1*. April 1987

LHDA *Interim hydrology progress report no 1 - release 2*. April 1987

LHDA *Interim hydrology progress report No 2. Rating curves*. April 1987

LHDA *Interim hydrology progress report No 3. Processed 1983-1986 flows*. May 1987

LHDA *Interim hydrology progress report No 4. Flow sequences at dam sites*. June 1987

LHDA *Hydrology Work Plan*, October 1987

LHDA *Assessment of uncertainties in the hydrometric stations*. October 1987

LHDA *A manual on hydrological field data collection procedures in Lesotho*. June 1988

LHDA *Work plan for 1989*. February 1989.

LHDA *Evaluation of the observed rainfall data*. February 1989.

LHDA *Processed raw rainfall data*. March 1989.

LHDA *Grouping of rainfall stations in Lesotho for infilling missing monthly data*. November 1989.

LHDA *A comparison between the infilled monthly rainfall by LMC and infilled using the RSA EM algorithm*. January 1990.

LHDA *Stationarity of the raw rainfall data in the LHWP area*. March 1990.

LHDA *Operation and management of the reservoirs and hydro-electric facilities*. Prepared by Charles Howard & Associates Ltd. June 1990.

LHDA *Geostatistical approach for estimating the missing monthly data of the rainfall network*. October 1990.

LHDA *Geostatistical approach for estimating the missing monthly data of the rainfall network - Release 2*. February 1991.

LHDA *Methodology for correcting historical flows of Sequnyane River at Marakabei*. June 1991

LHDA *Review of flow data for Sequnyane River at Marakabei G17.* December 1991.

LHDA *Revised monthly raw rainfall data of the LHWP.* January 1992

LHDA *Draft report on DWA/BKS Comments on* Revised monthly raw rainfall data, 1992.

LHDA *Request to IH for a proposal to review the work of the LHDA Water Resources Division.* May 1992.

SAS Institute Inc. 1988. *SAS/ETS User's Guide*, Version 6, First Edition. Cary,NC:SAS Institute Inc., 560p.

Tyson, P.D. *Climatic Change and Variability in Southern Africa.* Cape Town: Oxford University Press, 220p. 1986

Young, P. and Benner, S. *microCAPTAIN 2 User Handbook.* Centre for Research on Environmental Systems, Lancaster University. 1991

ANNEXE A

GLOSSARY OF ABBREVIATIONS

KOL	Kingdom of Lesotho
GOL	Government of the Kingdom of Lesotho
RSA	Government of the Republic of South Africa
LHWP	Lesotho Highlands Water Project
LHDA	Lesotho Highlands Development Authority
JPTC	Joint Permanent Technical Commission
WRD	Water Resources Division of LHDA
DWA(RSA)	Republic of South Africa Department of Water Affairs
WEMMIN	Ministry of Water, Energy and Minerals GOL
DoM	Department of Meteorology
DWA	Lesotho Department of Water Affairs
LMC	Lahmeyer MacDonald Consortium
OSC	Olivier Shand Consortium
BKS	Bruinette Kruger Stoffberg
CNS	CNS Scientific & Engineering Services
ENSMP	Ecole National Superieure des Mines de Paris

ANNEXE B

CHRONOLOGY OF EVENTS CONCERNING THE DERIVATION OF FLOW DATA

April 1986 LMC/OSC published report: *Lesotho Highlands Water Project Feasibility study*

This report provides the basic hydrological methodology to provide inflow series at each reservoir for the period 1930 to 1983. The Pitman rainfall-runoff model was calibrated using rainfall and flow data for the period 1967 to 1983. Rainfall data for 76 gauges from 1930 to 1966 were used to generate synthetic flows for the this earlier period.

25 July 1986 LHDA published report: *Proposals for the assessment of tolerance of hydrometric data*

This report considers the procedures for assessing the tolerance of the flow gauges and the methodology for quantifying the errors.

24 October 1986 KOL and RSA published report: *The treaty on the Lesotho Highlands Water Project*

In this treaty it was agreed that the design of the project and the calculation of Royalties would be based on the flow sequences 1930-to date ???

24 April 1987 LHDA published report: *Interim hydrology progress report No 2. Rating curves*

This report present an assessment of rating curves for 10 of the 12 gauging stations analyzed in the feasibility study by LMC. The two other stations were closed in 1983. It also provides the rating equations for the two new Crump weirs.

6 May 1987 LHDA published report: *Interim hydrology progress report No 3. Processed 1983-1986 flows*

This report describes LHDA's assessment of the water level and associated daily flow data for the period October 1983 to September 1986 at 10 of the 12 gauging stations analyzed in the feasibility study by LMC.

11-12 May 1987 Meeting between LHDA and DWA(RSA)/BKS, held at BKS offices, Pretoria

It was agreed that the Interim hydrology flow data would be used for the reservoir optimisation study but that a full review of both the rainfall and flow data would be undertaken before the Royalties were calculated.

3 June 1987 LHDA published report: *Interim hydrology progress report No 4. Flow sequences at dam sites*

This report describes the work undertaken to produce flow sequences at each dam site for the period 1930 to 1986. This used the runoff data for the period 1967 to 1986 in the calibration of the Pitman model. Up to 1983 all monthly data (flow and rainfall) were those produced by LMC/OSC except for the flows at Marakabei where the river level charts were redigitised. In addition a revised rating curve was used for Oranjedraai. Data for 1983 to 1986 were those given in LHDA's report *Interim hydrology progress report No 3. Processed 1983-1986 flows.*

June 1987 DWA(RSA)/BKS published report: *Analysis of the Lesotho Highlands Hydrology*

This report contained listings of raw and infilled flow data for each gauging station and for each dam site produced separately by LHDA and by DWA(RSA)/BKS up to September 1986. There was generally good agreement on these data.

DWA(RSA)/BKS reported that the MAR for the period 1930-1983 at Marakabei using the extended data is 10% lower than the original LMC phase 2B estimates.

They concluded that because the rainfall data were unreliable, the extended synthetic flows generated using the rainfall data must also be unreliable.

9 October 1987 Meeting between LHDA and DWA(RSA)/BKS, held at LHDA offices, Maseru

At this meeting LHDA put forward its new Hydrology Work Plan which included proposals for three new gaugings stations at the Malatsi, Ntoahae and Mohale dam sites to aid transfer of data and new station at Koma-Koma as current stations did not provide good data. In addition proposals for a flood warning system were put forward and for generation of stream flow by stochastic modelling.

28 October 1987 BKS published report: *Comments on proposed LHDA work plan.*

BKS agreed that the Koma-Koma station was unreliable but indicated the need to build a new weir closer to dam site at Mashai.

It was concluded that the responsibility for flood warning lay with the Water Transfer consultant.

BKS recommended that methods of stochastic stream flow generation should be explored.

October 1987 LHDA published report: *Assessment of uncertainties in the hydrometric stations*

This report provides measures of the uncertainties in the flow data due to uncertainties in the stage estimation and in the rating curves.

June 1988 LHDA published report: *A manual on hydrological field data collection procedures in Lesotho.*

This report provided an agreed methodology for measuring river flows.

25 June 1990 LHDA published report: *Operation and management of the reservoirs and hydro-electric facilities*

This report describes a system for operating the system efficiently using the derived flow series.

29 June 1990 Meeting between LHDA and DWA(RSA)/BKS at BKS offices, Pretoria.

This meeting focused on problems with the rainfall but, since these data were of poor quality, LHDA suggested that an alternative approach involving stochastic flow modelling should considered.

16 May 1991 Letter sent by LHDA to JPTC

This letter requested a review of the LHDA Water Resources Division to be undertaken by consultants and included draft Terms of Reference.

June 1991 LHDA published report: *Methodology for correcting historical flows at Sequnyane River @ Marakabei*

This report compares the flow data from the rated section with that from the Crump weir at Marakabei. For the overlapping period 1985-1990, the flows from the weir were greater than from the rated section with the difference in mean flow given as 2.9 m^3s^{-1}.

It was concluded that if the design calculations were repeated on the basis of the revised flows would make of saving on the costs of Phase IA of 1.165 billion Maluti.

September 1991 DWA(RSA)/BKS published report: *Comments on LHDA report "Methodology for correcting historical flows at Sequnyane River @ Marakabei"*

This report indicates that the recorded flows on the rated section and at the Crump weir obtained by DWA(RSA) and LHDA for the period 1985 to 1990 were very similar apart from the weir flows for November 1987 to July 1988. DWA(RSA)/BKS concluded that flows measured by the weir were 21.8% (LHDA) and 14.3% (DWA(RSA)/BKS) higher than those of the rated section. It was concluded that since the rainfall used to extend the flows was wrong, when corrected, the MAR to the Mohale dam is unlikely to be significantly different than seen in the previous studies.

December 1991 LHDA published report *Review of flow data for Senqunyane River @ Marakabei G17.*

This report on the review of the Marakabei flow data for the period November 1987 to June 1990.

10 May 1992 Letter sent by LHDA to IH

This letter was a request for a proposal to review the work of the LHDA Water Resources Division and included the Terms of Reference for the study.

June 1992 IH published proposal: *Review of the Water Resources Division*

This document gives details of the proposed review of the LHDA Water Resources Division.

8 October 1992 Meeting between JPTC and IH held at JPTC offices, Maseru

8-20 October 1992 Various meetings between WRD and IH held at LHDA offices, Maseru

12 October 1992 Meeting between DWA(RSA)/BKS, LHDA and IH held at BKS offices, Pretoria

20 October 1992 Meeting between WEMMIN (DWA and MoS) and IH at LHDA offices, Maseru

ANNEXE C

CHRONOLOGY OF EVENTS CONCERNING THE DERIVATION OF RAINFALL DATA

April 1986 LMC/OSC published report: *Lesotho Highlands Water Project Feasibility study*

This report provides the basic hydrological methodology to provide inflow series at each reservoir for the period 1930 to 1983. The Pitman rainfall-runoff model was calibrated using rainfall and flow data for the period 1967 to 1983. Rainfall data for 76 gauges from 1930 to 1967 were used to generate synthetic flows for this earlier period.

24 October 1986 KOL and RSA published report: *The treaty on the Lesotho Highlands Water Project*

In this treaty it was agreed that the design of the project and the calculation of Royalties would be based on the flow sequences 1930-to date.

2 April 1987 LHDA published report: *Interim hydrology progress report no 1*

This report contained listings of rainfall data from 76 gauges for the period 1930-1983 used by LMC/OSC to produce the hydrology for phase 2B. These data were used in all subsequent feasibility and design work.

LHDA added a further two years of data 1984 and 1985 to each gauge using observed data or by infilling using regression analysis.

23 April 1987 Meeting between LHDA and DWA(RSA)/BKS at LHDA offices, Maseru

Dr Pitman (SSI) and Dr McKenzie (BKS) expressed doubts about the quality of the rainfall data published by LHDA in *Interim hydrology progress report no 1* and highlighted errors in both the original LMC/OSC data as well as the two years provided by LHDA.

It was agreed that these errors would be corrected but that there was little time to undertake a full review of all the data as they were required urgently for hydropower design.

30 April 1987 Meeting between LHDA and DWA(RSA)/BKS, at LHDA offices, Maseru

LHDA published report: *Interim hydrology progress report no 1 - release 2*

In this report the errors in the infilled data highlighted at the meeting of 23 April 1987 had been corrected and were accepted by DWA(RSA)/BKS.

The errors in the original LMC/OSC data had not been addressed.

6 May 1987 Letter sent by DWA(RSA)/BKS to LHDA

This letter contained details of the errors in the original LMC/OSC raw and infilled data. It indicated that agreement on the rainfall data was required before the generated flow data could be considered.

11-12 May 1987 Meeting between LHDA and DWA(RSA)/BKS, at BKS offices, Pretoria

LHDA acknowledged the errors in the data indicated in the DWA(RSA)/BKS letter of 6 May 1987.

It was agreed that the Interim hydrology flow data would be used for the reservoir optimisation study but that a full review of both the rainfall and flow data would be undertaken before the Royalties were calculated.

17 July 1987 DWA(RSA)/BKS published report: *Analysis of the Lesotho Highlands Hydrology*

This report contained listings of raw and infilled flow data for each gaugings station and for each dam site produced separately by LHDA and by DWA(RSA)/BKS. There was generally good agreement on these data.

DWA(RSA)/BKS concluded that because the rainfall data were unreliable, the extended synthetic flows generated using the rainfall data must also be unreliable.

8 September 1987 Letter sent by LHDA to JPTC

This letter contained comments on the DWA(RSA)/BKS report *Analysis of the Lesotho Highlands Hydrology*. LHDA agreed that the raw rainfall at all 76 gauges should be checked and the infilling exercise repeated. A work plan was proposed which included infilling and catchment rainfall using kriging.

1 October 1987 Letter sent by JPTC to LHDA

This letter indicated that JPTC was not convinced of the need to use kriging particularly as it was expensive and time consuming.

9 October 1987 Meeting between LHDA and DWA(RSA)/BKS, at LHDA offices, Maseru

At this meeting LHDA put forward it new Hydrology Work Plan which included proposals for new rainfall stations with telemetry.

DWA(RSA)/BKS reiterated their reservations about the use of kriging and felt that it would cause unnecessary delay to the project at great expense.

It was agreed that Dr Chetboun would obtain expert advice on kriging by the beginning of March 1988 and that DWA(RSA)/BKS might consult Professor Krige on the results. It was also accepted that agreement need to be reached at each step in the validation procedure and the subsequent application of the kriging technique before moving to the next step.

28 October 1987 BKS published report: *Comments on proposed LHDA work plan.*

In this report BKS recommended the investigation of methods of stochastic stream flow generation and gives approval of funds for five rainfall stations and telemetry. [However, final approval to install stations was not given until 1990.]

October 1987 LHDA published report: *Assessment of uncertainties in the hydrometric stations*

This report considers the effects of uncertainties in the rainfall data, due to infilling and catchment averaging, and in the flow data due to the flow transfers from gauges to dam sites.

16 March 1988 Letter sent by LHDA to WEMMIN

This letter requested the Meteorological Service to undertake a review of its daily rainfall data to resolve problems with the monthly data.

11 May 1988 Meeting between LHDA and WEMMIN, at LHDA offices, Maseru

At this meeting a work plan was proposed to resolve the problems of the rainfall data.

25 May 1988 Meeting between LHDA and DWA(RSA)/BKS, at JPTC offices, Maseru

At this meeting LHDA reported that problems with the monthly data could not be resolved without referring to the daily data and that this had led to delays. Dr Chetboun suggested that four months would be required to collate the raw daily rainfall data and that agreement should be reached on these before additional techniques could be addressed.

It was agreed that the daily rainfall data would be collated by the end of October 1988. DWA(RSA)/BKS would infill the missing data using regression analysis and LHDA would use kriging and other multi-variate analysis techniques. The results would then be compared.
Since the kriging software would not be available before December 1988. It was accepted that the infilling studies could not be completed before February 1989.

7 July 1988 Meeting between LHDA and WEMMIN, at LHDA offices, Maseru

At this meeting progress on the collation of the daily rainfall data was discussed. By this time, raw data for 32 stations were available in a computerised form, but there were gaps in the records.

WEMMIN reported that a shortage of meteorological staff might mean that the exercise would not be completed within LHDA's specified schedule. Dr Chetboun stressed the important of meeting the schedule and LHDA staff were provided to assist with data entry to the computer.

A request for a hydrometeorologist to work for LHDA was made in the budget proposals for 1989/90. This was not approved by JPTC.

27 September 1988 CNS published report: *The use of precipitation measuring radar in Lesotho.*

This report gives details of a pre-feasibility study on the use of weather radar in Lesotho and concluded that it could overcome the problems of areal rainfall estimation in the highlands.

18 November 1988 DWA(RSA)/BKS published report: *Analysis of the Lesotho Highlands rainfall data*

This report contains mass plots of the monthly rainfall data provided by LHDA in its *Interim hydrology progress report no 1 - release 2* on 30 April 1987 despite a previous agreement that they would wait for the daily data to be analyzed.

26 January 1989 Meeting between LHDA and DWA(RSA)/BKS, at LHDA offices, Maseru

At this meeting the DWA(RSA)/BKS report *Analysis of the Lesotho Highlands rainfall data* published on 18 November was discussed.

LHDA indicated that this report was premature because neither the raw daily data nor the methodology for analysis had been agreed which was a prerequisite to considering the monthly data as discussed at the meeting of 9 October 1987.

LHDA reported that 80% of the raw daily rainfall data had been transfer from WEMMIN. As these data were the responsibility of WEMMIN, LHDA could not guarantee delivery by a certain date, but agreed to provide a work plan for 1989.

February 1989 LHDA published a work plan for 1989

As agreed at the meeting of 26 January 1989, a revised work plan was submitted to JPTC by LHDA. The main aspects were as follows:

Task	Completion date
Check raw daily rainfall data	28 February
Discuss discrepancies with DWA(RSA)/WEMMIN	17 March
Comparison of new monthly data with Interim data	30 March
Analysis of monthly data	15 April
Establish and update database	30 April
Definition of unreliable data	30 May
Agree monthly raw data with DWA(RSA)	30 June

February 1989 LHDA published report: *Evaluation of the observed rainfall data*

This report contained listings of the raw rainfall data obtained from WEMMIN and results of initial quality control including consistency of station location and assessment of record lengths and annual totals.

March 1989 LHDA published report: *Processed raw rainfall data*

This report contained details of analysis of the raw rainfall data obtained from WEMMIN including mass plots for the 76 gauges used to derive the phase 2B hydrology. The mass plots differed from those published by DWA(RSA)/BKS in *Analysis of the Lesotho Highlands rainfall data* on 18 November 1988 as the data used for the DWA(RSA)/BKS plots contained infilled data.

LHDA indicated that these data were preliminary since further checking was required.

26 April 1989 Letter sent by BKS to DWA(RSA) with: *Comments on LHDA report "Processed raw rainfall data"*

This report indicated that the preliminary raw data received from WEMMIN and contained many errors and inconsistencies.

6 July 1989 Letter sent by JPTC to LHDA

This letter gave approval for the purchase of 10 tilting syphon rain gauges with monthly charts, but no heating elements were approved. The gauges were not installed until 1990 because of lack of an engineer.

19 October 1989 Meeting between LHDA and DWA(RSA)/BKS, at LHDA offices, Maseru

At this meeting errors in the raw data provided by WEMMIN and published in *Processed raw rainfall data* in March 1989 were discussed. The Meteorological Service was not able to address these problems promptly so LHDA had begun its own data validation, however this had been hampered by the lack of meteorologist within LHDA.

LHDA agreed to try BKS software to aid in the data validation.

November 1989 CNS published report: *Preparatory mission for weather radar in Lesotho.*

In this report Blue Mountain pass is identified as the best site in Lesotho for a possible weather radar.

November 1989 LHDA published report: *Grouping of rainfall stations in Lesotho for infilling missing monthly data.*

This report gives details of the use of cluster analysis for grouping rainfall gauges to extend and infill missing monthly data.

23-24 November 1989 Meeting between LHDA and DWA(RSA)/BKS, held at the BKS offices, Pretoria

At this meeting the remaining areas of disagreement concerning the consistency of the rainfall records were discussed and agreement was reach on each.

January 1990 LHDA published report: *A comparison between the infilled monthly rainfall by LMC and infilled data using the RSA EM algorithm.*

This report has very little text and no summary statistics. The plots suggests that the two methods give similar results.

March 1990 LHDA published report: *Stationarity of the raw rainfall data in the LHWP area.*

This report contained results of statistical techniques for identifying discontinuities in the data from the original 76 stations. LHDA concluded that these were superior to the tests based on visual inspection adopted by BKS.

29 June 1990 Meeting between LHDA and DWA(RSA)/BKS, at BKS offices, Pretoria

At this meeting broad agreement was reached on which of the 78 stations could be used without further attention and which exhibited non-stationarity which needed correcting or rejecting analysis. How the correction might be achieved was not agreed.

LHDA stated that the rainfall data were the responsibility of WEMMIN and since these data were of poor quality an alternative approach such as stochastic flow modelling might be considered.

July 1990 BKS published report: *Review of LHDA report titled "Stationarity of the raw rainfall data in the LHWP area", March 1990*

This report indicated that there were very few areas of disagreement and recommended that where breaks in continuity were recognised one portion of the record should be adjusted or rejected. No agreement was reached on the validity of the raw rainfall.

22 August 1990 Letter sent by LHDA to JPTC

This letter request funds to employ a computer specialist for the Water Resources Division. This was not approved.

October 1990 LHDA published report: *Geostatistical approach for estimating the missing monthly data of the rainfall network.*

This report contained details of the method used to infill the monthly rainfall data by applying the kriging technique. However, 120 gauges had been used in the analysis rather than the 76 presented in previous reports. The extra 44 gauges had not been agreed with DWA(RSA)/BKS.

November 1990 ENSMP published report: *Estimation of the rainfall in Lesotho.*

This report gives details of the methodology developed at the Centre de Geostatistique, Fontaineblue, to infill the missing monthly data.

November 1990 BKS published report: *Evaluation of the LHDA report "Geostatistical approach for estimating the missing monthly data of the rainfall network".*

BKS found a large number of serious errors in the data published by LHDA some of which had been identified in April 1987 and concluded that the results were completely unacceptable.

February 1991 LHDA published report: *Geostatistical approach for estimating the missing monthly data of the rainfall network - Release 2.*

In response to the comments on the first release of this report, LHDA produced a revised edition (release 2) which contains data from 101 rainfall gauges.

March 1991 BKS published report: *Review of the LHDA report "Geostatistical approach for estimating the missing monthly data of the rainfall network - release 2".*

In this report BKS compared the use of kriging to infill missing data with regression techniques. It was concluded that they provide equally realistic results. However, use of erroneous raw data would mean that the infilled data would be unreliable.

16 May 1991 Letter sent by LHDA to JPTC

This letter requested a review of the LHDA Water Resources Division by consultants and included draft Terms of Reference.

Unknown date Lesotho Highlands rainfall: impact of data errors on hydrology.

Paper to the Fifth South African National Hydrology Symposium, R.S.McKenzie, P.G.Van Rooyen and F.Cornelius. This paper pointed out that there were fairly major problems with the rainfall data base for Lesotho, and demonstrated the effects of these errors on modelled flows.

4 December 1991 Letter sent by Dr Chetboun (LHDA) to Dr Shand.

This letter provides comments on the paper by McKenzie, Van Rooyen and Cornelius titled *Lesotho Highlands Rainfall; Impact of data errors on hydrology*, presented to the Fifth South African National Hydrological Symposium. Four types of error are discussed: (1) measurement errors; (2) database entry errors; (3) spatial interpolation errors; and (4) temporal infilling errors.

February 1992 The authors of the paper responded to the letter from Dr Chetboun. Neither Dr Chetboun's comments or these responses were ever published.

4 February 1992 A letter was sent from Dr Mckenzie of BKS to Dr Chetboun commenting on the paper, and Dr Chetboun's comments. No reply appears to have been sent.

January 1992 LHDA published report: *Revised monthly raw rainfall data of the LHWP.*

This report gives listings of monthly data. The raw data had undergone revision but the infilled data remained unchanged.

March 1992 DWA(RSA)/BKS published report: *Evaluation of the LHDA report titled "Revised monthly raw rainfall data of the LHWP - January 1992"*.

The results presented in this report were based on visual inspection. It was concluded that although many errors identified previously had been corrected, further errors remained.

Undated LHDA prepared: *Draft report on DWA(RSA)/BKS Comments on Revised monthly raw rainfall data*

In this report LHDA stated it had provided a computer disc of the data to avoid visual inspection, but some of the data were still provisional and the subject of discussions with WEMMIN.

10 May 1992 Letter sent by LHDA to IH

This letter was a request for proposals to review the work of the LHDA Water Resources Division and included Terms of Reference for the study.

June 1992 IH published proposal: *Review of the Water Resources Division*

This document gives details of the proposed review of the LHDA Water Resources Division.

8 October 1992 Meeting between JPTC and IH at JPTC offices, Maseru

8-20 October 1992 Various meetings between WRD and IH held at LHDA offices, Maseru

12 October 1992 Meeting between DWA(RSA)/BKS, LHDA and IH at BKS offices, Pretoria

20 October 1992 Meeting between WEMMIN (DWA and MoS) and IH at LHDA offices, Maseru

ANNEXE D

JOB DESCRIPTIONS OF THE STAFF OF THE WATER RESOURCES DIVISION

Introduction

The following job descriptions are a combination of those listed in LHDA files and of the ideas the consultants have on the responsibilities and duties that existing staff should have in order to provide the required support of the LHWP. Because we have suggested that the role of the Water Resources Manager should change, two job descriptions are given; one for the present post, and another to cover the suggested new role. We envisage that for the foreseeable future, the role of Water Resources Manager should continue to be held by a widely experienced expatriate hydrologist/engineer.

The change in the status of the Water Resources Manager is suggested partly in recognition of the suggestion that the bulk of the hydrological analyses will now be undertaken by consultants in order to meet the needs of the Royalty hydrology and for derivation of design flows for the next phases of the LHWP. These changes also reflect how the work load of the WRD will shift in the next few years more towards the development and operation of water transfer and hydro-power management models.

We also give job descriptions for the two new staff suggested in the main report, the hydro-meteorological technician and the water resources engineer/hydrologist.

Water Resources Manager (Existing Role)

Responsibilities

Responsible for the direction of all LHDA hydrology and water resources activities, and for management of the Water Resources Division. Responsible for coordinating LHDA activities with the hydrology divisions of the GOL and RSA.

In the short-term, the main task should be preparation of hydrological data for use in the various design contracts.

Duties

- Developing the hydrology programme and task definitions.
- Defining the technical terms of reference for hydrology and water resources contracts.
- Direction of hydrology and water resources contracts.
- Undertaking training programmes for WRD staff.
- Overall responsibilities for developing methodologies and procedures for processing, analysing and extending hydrological data.

- Overall responsibility for developing mathematical models for utilising hydrological data (mainly river flow sequences) for use in the various Phase 1A design contracts.
- Developing technical inputs for the terms of reference of design contracts.
- Providing input into the development of the technical library.
- Overall responsibility for the development of a water resource management model for reservoir operation and maintenance rules.
- Overall responsibility for the hydrological inputs into the Royalty manual.

<u>Suggested new Job Description for Water Resources Manager/Engineer/Hydrologist</u>

Responsibilities

Responsible for the direction and management of all LHDA hydrology and water resources activities, and for management of the Water Resources Division. Responsible for coordinating LHDA activities with the hydrology divisions of the GOL and RSA. Responsible for supervising the work of consultants working for LHDA on hydrological and water resources topics.

Duties

- Managing the Water Resources Division.
- Supervising the maintenance of a computerised data base of hydrological data for the LHWP area.
- Overall responsibility for developing mathematical models for utilising hydrological data (mainly river flow sequences) for use in the various Phase 1A design contracts.
- Overall responsibility for the hydrological inputs into the Royalty manual.
- Operating and maintaining the planned/envisaged reservoir operation and management model for the various Phases of the LHWP in order to optimise reservoir operation as far as water transfer and HEP generation are concerned.
- Checking the sensitivities of the hydrological inputs/yields into the water resources management model.
- Determining monthly release patterns from the reservoirs in order to best meet the schedule of water transfers whilst maximising HEP production.
- Assessing the economic impact of reservoir operations in relation to the overall objective of the LHWP.
- Checking the design and operation of the various hydraulic structures such as weirs and hydrometric installations within the LHWP area.
- Defining the technical terms of reference for hydrology and water resources contracts.
- Supervising all hydrology and water resources contracts.
- Planning and undertaking training programmes for WRD staff.

Senior Hydrologist

Responsibilities

Overall water resources data collection, processing and analysis activities and programmes within the LHWP.

Coordinate all field activities and programmes with the involved parties, ie with the GOL and RSA.

Advise and provide briefs on the hydrology/water resources data for the LHWP activities related to design, environment and infrastructure.

Duties

- Monitor and schedule the primary hydrometric data collection programmes in order to establish a long term water resources database for the LHWP.
- Plan the establishment of the meteorological and hydrological networks within the LHWP in order to develop a long term water resource data monitoring programme.
- Check the overall reliability of the data for use in the development and calibration of the water resources model.
- Coordinate and supervise the processing and analysis of both meteorological and hydrological data to provide quality control, and to develop the methodologies of refining the water resources data for the development of models that support water decisions.
- Prepare and review the hydrological/water resources data for use within the LHWP for design and environmental matters.
- Monitor the process of establishing and updating the water resource database systems.
- Provide and check the hydrological/water resources data as an input into the overall development of the water resource management model for reservoir operations and maintenance.

Hydrological Analyst

Responsibilities

Adopt, develop and improve the software packages of hydrological models (i.e. mathematical, statistical, stochastic and deterministic), water resources management and reservoir operation models, and the existing computerised hydrological database,mainly through the use of FORTRAN.

For analysis of the hydrological data output according to the objectives of determining the water resources potential of the LHWP.

Duties

- Write, adopt, improve and document all the software packages/computer programs in the WRD using FORTRAN and BASIC languages.
- Involvement in the process of developing hydrological, water resources management and reservoir operation models etc. for use in assessment of the water resources of the LHWP.
- Review and identify the statistical parameters/characteristics of the water resources data series for research, operation and forecasting purposes.
- Improve the performance of the existing computerised hydrological database systems in the processing, storage and retrieval of water resources data.
- Maintain an inventory and library of all hydrological software in the WRD.
- Ensure proper operation and use of all hydrological software within the WRD.
- Coordination of all activities related to the computer needs of the WRD with the Information system of the Computer Services Division.
- Provide support to WRD staff on general information technology applications.

Hydrological Technicians (Field) (2)

Responsibilities

Collection, compilation, processing, storage and retrieval of the primary raw river flow, current meter, sediment and water quality data within the LHWP area using internationally recognised field processes and computerised systems.

Duties

- Collection of water resources data using international standard procedures of stream gauging and sediment sampling from the existing network within the LHWP area.
- Check and compile field data into standardised paper formats.
- Check and adjust the water resources data for field errors.
- Repair and maintain hydrometric equipment and stations so that accurate data are collected.
- Undertake regular fieldwork to assess the status of hydrometric stations and check the reliability of field observers and hydro-sediment observers.
- Retrieve the water resources data from the computerised database system as necessary.
- Be actively involved in the construction of hydrometric stations and in the installation of hydrometric equipment.

Hydrology Technician (Office) (2)

Responsibilities/Duties

- To digitise field charts from river level and automatic rainfall gauges.
- Assist in the establishment of a computerised database by entering the data onto

a computer. Keep this database up-to-date.
- To assist in the maintenance of the hydrometric database.
- To assist with the data checking and quality control tasks in order to ensure that the database contains the best possible data.
- Retrieve the water resources data from the computerised database system as necessary.
- Prepare data for publication and use by the Parties involved in the LHWP.

Meteorological Instrument Technician

Responsibilities/Duties

- Repair and service meteorological equipment and instruments installed at automatic weather stations, seismic stations and radio repeater stations within the LHWP area.
- Retrieve and interpret on site data received from the network and weather stations within the LHWP area.
- Monitor the status of the existing hydrometric network and weather stations within the LHWP area.
- Install instruments and equipment for the rainfall gauges (automatic and manual) and weather stations within the LHWP area.
- Any other duties that are related to the weather stations and rainfall network within the project area.

Computer Operator

Responsibilities/Duties

- Start up the computers and auxiliary equipment each day.
- Entry of basic data for computerisation.
- Report on any system errors at the start of any day to the system supervisor (hydrological analyst).
- Periodically collect jobs submitted to the data control supervisor.
- Passes all input data and computer output to the system supervisor for checking.
- Operation of the water resources system database.

Secretary and Driver (1 of each)

Responsibilities/Duties

Provide general support to the remainder of the division

Hydrometric Field Observers (18)

Responsibilities/Duties

To collect field data on a day-to-day basis and to provide the data to the hydrometric technicians during their regular visits.

NEW STAFF REQUESTED BY WRD

Hydro-meteorologist (1)

Responsibilities/Duties

- Provision of hydro-meteorological data to the consultants for engineering design, planning and implementation of subsequent phases of the LHWP, e.g., Phase 1B.
- Coordinate the overall hydro-meteorological data collection, analysis and processing activities of the WRD.
- Process and analyse the raw rainfall data of the LHWP for all stations which are the LHDA have responsibility.
- Monitor and update the rainfall and climatic database of the LHDA by acquiring and checking data from DWA/WEMMIN in accordance with agreed work plans.
- Undertake quality control of all rainfall data within the LHWP area.
- Supervise the operation and maintenance of the LHDA raingauges, and the work of the meteorological technician.

Water resorces engineer/hydrologist

Responsibilities/Duties

- Operating and maintaining the planned/envisaged reservoir operation and management model for the various Phases of the LHWP in order to optimise reservoir operation as far as water transfer and HEP generation are concerned.
- Checking the sensitivities of the hydrological inputs/yields into the water resources management model.
- Determining monthly release patterns from the reservoirs in order to best meet the schedule of water transfers whilst maximising HEP production.
- Assessing the economic impact of reservoir operations in relation to the overall objective of the LHWP.

ANNEXE E

RESPONSIBILITIES AND WORK PLAN OF THE WATER RESOURCES DIVISION

E.1 Introduction

The general objectives of the Water Resources Division (WRD) of the LHDA are as follows;

1. To collate all of the information necessary to negotiate and agree a hydrology for the computation of the water transfer Royalties.

2. To collate the water resources data necessary for the implementation of further Phases of the LHWP.

3. To provide hydrological and water resources data and advice to other divisions with LHDA and to consultants and contractors as necessary in order to provide general support to the various activities of the LHWP.

4. Develop or adapt existing models for the operation and management of the reservoirs of the LHWP for optimising water transfer and hydro-power production.

E.2 Detailed work plan for 1993

1. Operation and maintenance of 14 hydrometric stations and 10 recording raingauge stations within the LHWP area.

2. Data capture, and data processing of the raw field data.

3. Maintenance of a computerised data base of all data of interest for hydrology and water resources (rainfall, river level, current meterings, river flow, sediment and water quality).

4. Provide advice and data on all water related matters to the various divisions of the LHDA.

5. Supply hydrological data, advice and results of hydrological analyses to the various consultants and contractors working on the LHWP.

6. Initiate the development of a model for optimising the operation and management of the water transfer and hydro-power components of the LHWP, possibly with support from consultants.

7 Continue establishing a library of hydrological and water resources software within the WRD of LHDA.

8 Coordinate, support and supervise all of the LHDA consultancies dealing with water.

E.3 Tasks and Objectives for the Medium-term

1 To maintain a full, checked, computerised data base of rainfall, climate, river flow, water quality and sediment data for the area of the LHWP.

2 To liaise with other hydrological and meteorological agencies within the KOL and RSA in order to obtain and collate the data required for task (1).

3 To undertake basic data collection tasks within the LHWP area in order to collect rainfall, climate, sediment and river flow data where it is apparent that other agencies are not adequately undertaking such a task. Maintenance of all hydrometric stations within the LHWP area and for newly installed recording raingauges.

4 To provide hydrological data and limited analytical assistance to other divisions within LHDA on all matters related to hydrology and water.

5 To provide hydrological data and assistance to any consultants employed by the LHDA for the planning and design of subsequent Phases of the LHWP and for derivation of hydrological series for the Royalty calculations.

6 To develop a short-term flow forecasting model as an input to the models for operation and management of the reservoirs.

7 To develop control procedures for the water transfer component of the scheme in order to meet the requirements of the Treaty whilst optimising hydro-power production.

WRD may require support from consultants in implementing items (6) and (7), although the Water Resources Manager may be capable of undertaking such work alone.

ANNEXE F

THE RELATIONSHIP BETWEEN WRD AND WEMMIN

In this Annexe we summarise the responsibilities that LHDA, through its WRD, has assumed in recent years, and describe how WRD interacts with the two primary data collection agencies of WEMMIN. Our findings are based on relatively brief meetings with senior staff of the different departments to ascertain their responsibilities, their interactions with other departments, and to establish the essential features of the data collection system. We are grateful to the staff of WEMMIN for freely expressing their views.

F.1 Department of Meteorology

The Department of Meteorology, or DoM, is structured primarily for synoptic weather forecasting, consequently collection and archiving rainfall data for engineering purposes is of low priority. Whilst on paper this department appears to be adequately staffed, with a total of 51 staff, only six of these are professionally qualified, 18 are concerned solely with forecasting and many of the remainder are full-time observers. There are 12 staff based at the headquarters office in Maseru and these are responsible for publication of monthly weather and climate bulletins for the whole of the KOL and must meet the needs of a wide variety of users, agriculture being the largest group. In addition they contribute to the FAO Food Early Warning bulletin, which is produced either monthly or bi-monthly according to the season.

Computers are extensively used and computer literacy within the department is believed to be reasonably good. Data are stored on a computer database using the WMO CLICOM software. However, it is clear that the quality of the computerised and published rainfall data is very poor, and not enough effort has gone into verification and quality control of these data before publication. The poor quality of the rainfall data is a matter of great concern for the LHWP, and the significance of rainfall data to the project is discussed in Section 2.4 of the main report. However, some comments on why the data are of such poor quality should be given here.

There appears to be a number of reasons why the rainfall data are of poor quality. In general, the observers are very poorly trained and do not understand either the techniques involved in successful data collection, or equally importantly, why the data are being collected at all. They are also very poorly paid, receiving only M 25 or 50 per month. Because observers are inadequately trained and remunerated, the data that they collect are often of doubtful quality.

In recognition of this, a five day training seminar was held for observers in Maseru during which staff of WEMMIN and WRD explained not only how data should be collected, but also why it was being collected. By explaining to the observers the importance of good quality data for a range of purposes, including the LHWP, it was hoped that observer motivation could be improved. A regular newsletter for observers has also been started which allows DoM to keep observers informed, and to which the observers themselves are encouraged to contribute anecdotes and ideas. Since this training scheme, the observers have been much better motivated and the quality of the data returned to Maseru has apparently shown a marked improvement, although we did not have the time or opportunity to check this claim. Those involved in organising the training scheme are to be commended for their efforts, and such training should become a regular event, despite the additional cost.

Vandalism of equipment is another reason why there are so many gaps in the recorded data; many gauges are either stolen or badly damaged. As the observers are poorly paid and motivated, they have no incentive either to explain to local people why data collection is beneficial to the people of Lesotho, nor to attempt to stop vandalism. This problem is not unique to Lesotho, but other countries have managed to control the problem, sometimes by providing really effective fencing around equipment compounds, but also by better education of both observers and local people as to the reasons for data collection. The recently introduced programme of observer training is therefore to be welcomed.

However, one of the main shortcomings in the present data collection, archiving and publication procedures must be that of limited quality control of the data when they reach the headquarters at Maseru. This may be explained partly by the limited staff resources of the department, particularly at the professional level, although it is not part of our brief to investigate the workload and commitments of DoM in detail. Nevertheless, as has been demonstrated in a number of reports in recent years, there are very grave doubts over the quality of the bulk of the rainfall data.

F.2 Department of Water Affairs

The Department of Water Affairs, or DWA, within WEMMIN has responsibility for the collection, processing and publication of hydrological data at all stations within Lesotho, although WRD has taken over responsibility for the 16 key flow gauging stations within the highlands. Three major problems in collecting and processing data were reported to the consultants; manpower, equipment and transport.

There are only three professional staff within the department, and one of these is reported to be only partially effective. There appears to be a shortage of professionally trained staff, which echoes the situation in DoM. Consequently, staff are not able to undertake basic data processing and quality control tasks as rigorously as they might like to. In addition, there are no training schemes for technicians, who are poorly paid, inadequately trained and whose productivity and effectiveness is low. The department does not have a budget for training, which is the responsibility of the Ministry of Planning, Economic Affairs and Manpower Development, from whom WEMMIN must negotiate funds. However, there is no suitable Technical college or similar secondary education establishment within the Lesotho, and provision of suitable training could only be provided through on-the-job training, by sending staff outside the country for training, or by bringing in training staff from elsewhere to run a suitable course. With so few professionally trained staff, there seems little scope for effective on-the-job training. Sending staff outside of the country could be effective if suitable training courses could be identified, but the use of external trainers is probably the most cost effective solution, and a series of training courses could probably be provided through a consultancy with an appropriate international organisation with experience of technician training.

The second problem is that of frequent vandalism of equipment. This problem could be reduced by more effective fencing of installations and by using really secure instrument houses. Improved staff training and education of the local population would not be as effective as in the case of meteorological sites, where an observer visits the gauge daily.

Finally, problems with transport were mentioned as being a constraint upon data collection. All of the department's vehicles are more than 5 years old, which is not a great age provided that vehicles are regularly serviced and provided that spare parts are available within Lesotho. However, at present only 9 out of 15 vehicles are operational for various reasons, the situation being made worse by the department's limited budget. Seven new vehicles were ordered last May and should be delivered early next year, although delivery has been delayed by a strike at the Toyota plant in South Africa. It should be possible for the department to keep more of its vehicles operational in future, and the task of data collection should not be unduly interrupted by problems with the vehicles if sufficient funds are available for vehicle servicing and maintenance.

The data collected are processed and archived on computer using some bespoke software written a few years ago by consultants. Whilst the system operates satisfactorily, it does not appear to be as flexible and user-friendly as the HYDATA software currently used by the LHDA, and DWA may be about to change to using HYDATA.

F.3 The Water Resources Division of LHDA

In view of the importance of good quality rainfall and river flow data to the LHWP, the WRD has over the past few years assumed ever greater responsibility for data collection and processing within the Lesotho Highlands. They have recently installed 10 new recording rain gauges at high elevation sites within the highlands to supplement the existing DoM stations, and these new data will be extremely useful once sufficient data have been collected. Vandalism has been a major problem with these new sites, with several sets of equipment being damaged during the first year of operation; indeed one site has effectively been closed due to persistent vandalism.

In the case of river flow data within the highlands area, WRD has agreed with DWA to take over full responsibility for data collection and processing. The DWA has limited resources and has tended to concentrate on data collection within the western parts of Lesotho where water supply for domestic purposes and for irrigation are important. The remote stations within the highlands are of less importance to DWA and consequently data collection within this area was given lower priority.

WRD recognised the unsatisfactory river flow data collection situation within the LHWP area, and realising that DWA were in no position to improve the situation given their limited staff and transport resources, decided that reliable data collection could best be achieved by LHDA. Thus technicians were employed and trained by WRD to collect and process river flow data from the 16 key flow gauging stations within the LHWP area. Many of these technicians came from DWA within WEMMIN due to the better salaries offered by the LHDA and required minimal training. From our observations these staff are very competent and well motivated and the recently collected river flow data appear to be as good as can be expected given the inevitable difficulties of hydrometric work in remote mountainous regions.

F.3.1 Staffing and budget of WRD

The total budget of the LHWP for the year to 31/3/92 was R 747,367,000. Of this, R64,290,000 was allocated to engineering aspects of the project including the Water Resources Division which received R 626,475 directly. This includes salaries for local staff, equipment, travel and subsistence, training, books and stationery. In addition to this LHDA provides WRD with office accommodation and vehicles. The department is led by an expatriate Water Resources Engineer, whose salary and living allowances approximately double the total budget figures for the WRD given above.

This budget is small given the central rôle of hydrology to the LHWP and the total costs of the project. Of the R 626,475 direct budget, some R 452,475 covers the salaries of the local staff of the Division, which has the following staff.

Senior hydrologist	1
Hydrological analyst	1
Hydrological technician	4
Meteorological Instrument Technician	1
Personal Secretary	1
Computer operator	1
Secretary	1
Driver	1
Hydrometric observer	14
Meteorological observer	4

A brief job description for the various staff within WRD has been compiled by the consultants and is given in Annexe D. These job descriptions are a compilation of duties and responsibilities documented in LHDA files and of the consultants' views on what the various staff duties should be in order to achieve the objectives of the WRD most effectively.

It is suggested that the division should be strengthened by a hydrometeorological technician trained to diploma level at least, although a graduate might be preferable.

ANNEXE G

STATISTICAL ANALYSIS OF ANNUAL RAINFALL SERIES FROM SELECTED STATIONS

This annexe describes the results of a range of statistical tests on the rainfall series discussed in Chapter 2, where we show that some or all the series have evidence of an underlying cyclical pattern of about 18 years period.

Data available from stations 9, 44, 72, 111, 115, 120, 124, 126 and 132 were collated and because of many gaps the infilled data were included as well as the recorded values. Data from each station were standardised by subtraction of the sample mean and division by the sample standard deviation. A standardised regional rainfall series was produced by averaging the annual rainfall across these nine stations. A five year moving average was constructed to smooth the series and hence show the underlying characteristics of the rainfall data.

Quantifying the cyclical behaviour

The preparatory analysis indicated cyclic behaviour in the data which can be modelled and quantified using the microCAPTAIN 2 time series analysis package.

The data sets were smoothed using microCAPTAIN's Integrated Random Walk (IRW) model. This method involves the selection of a single parameter value, the Noise Variance Ratio (NVR), which determines the range of frequencies over which noise is eliminated (Young and Benner, 1991). The series of mean rainfall along with four of the individual station series (44, 111, 115 and 124) exhibited strongly defined 18 year cycles when smoothed by this technique (using an NVR of 0.01) as shown in Figures G.1 and G.2. This accords with previous work in southern Africa which indicated the occurrence of 18 year periodicity in the region's rainfall (Tyson, 1986). Of the remaining five stations this 18 year cycle is defined reasonably well in the data of station 72 but poorly elsewhere.

Another facility in the microCAPTAIN 2 package investigates periodic behaviour; the auto-correlation option. It identifies the spectral characteristics of a time series through decomposition of the data into component sine and cosine waves of varying amplitude and wavelength. The end product of this analysis is a 'periodogram' which describes the relative importance of each of a set of cycles in terms of the height of the peak corresponding to each periodicity identified.

The dominant peak accords to an 18 year cycle in the regional rainfall series and in three of the individual station series (44, 111 and 115) as shown in Figures G.3 and G.4. The analysis of the data series from station 124 resulted in a periodogram in which the 18 year peak is second only to that of a 2 year cycle, but in all other cases the periodograms are multi-peaked and an 18 year cycles are far from dominant.

Overall this analysis indicates that an 18 year rainfall cycle is important in less than half of the data series considered. However, the cycle is apparent in the regional series derived from annual rainfall at the nine stations.

Significance of the cyclical behaviour

Cyclic behaviour has important implications for derivation of the hydrological aspects of the study. For the Royalty hydrology in particular it is necessary to identify whether cyclic behaviour is a facet of the historical records since the Royalty calculations will use reservoir inflow and rainfall series for the period 1930/31 to 1982/83. Its importance for the engineering design hydrology may be slightly different if a stochastic model is used as discussed in Chapter 3. The important question in this case is whether the cyclic behaviour is a facet of the underlying rainfall process. To determine this, it is necessary to test whether the cycles observed in the historical data could have arisen by chance.

The microCAPTAIN 2 package does not include the capability to conduct significance testing and therefore the analysis was continued using the SAS/ETS package, which runs on the IH IBM mainframe. Its contains a collection of techniques grouped together as the SPECTRA procedure which allows for more sophisticated spectral analysis than that described above. The most important aspect of this is the output of two separate test statistics which allow the significance of cycles occurring within a data series to be assessed.

SPECTRA first computes the periodogram for a given data series. The ordinates of the periodogram are then used to calculate the Fisher's Kappa statistic, which is the ratio of the value of the largest ordinate to the average of all ordinates values. This provides a test for the existence of a sinusoidal component of unknown period. However, the individual periodogram ordinates themselves can be used to test for a pre-specified period, such as 18 years.

The second statistic computed by SPECTRA forms the basis for a test which essentially seeks to determine whether a series can be considered as white noise. Bartlett's Kolmogorov-Smirnov statistic is defined as the "maximum absolute difference of the standardized partial sums of the periodogram and the CDF of a uniform (0,1) random variable" (SAS Institute Inc., 1988).

An important point is that the significance of these test statistics is based on analysis of discrete cycles. Therefore SPECTRA only considers explicitly periodicities which correspond to a complete number of cycles within the timespan of the data series. The number of possible periodicities tested for is thus limited, although it is expected that cycles with slightly different periodicities would be revealed since the periodogram ordinates will not be independent.

Analysis of each rainfall series produced no significant test statistics at the 10% level. In other words, the set of cycles apparent in the data could be the result of chance sampling from a population with no cyclic behaviour: in more than 1 out of every 10 instances a sample from such a non-cyclic population would show stronger apparent cyclic behaviour at the same period.

The major peaks on the periodograms produced from this analysis tend to correspond to short wavelengths (< 4 years) or with periodicities of 15 and 20 years. These latter peaks could be interpreted as a crude indication of the existence of an 18 year cycle in the data. Since the data series are of 60 years in length, SPECTRA does not include a periodicity of 18 years. One simple way of forcing significance tests to be carried out explicitly on the existence of an 18 year cycle is to remove the last 6 years of data, thereby producing a data series 54 years long and divisible by 18. It is recognised however that such a step leads to a degree of bias in the significance testing.

The last 6 years of data were removed from the rainfall series of each station and of the 9 station average and SPECTRA rerun to test specifically a set which includes the 18 year cycle. It should be noted that this test focuses only on an 18 year periodicity if it represents the dominant cycle within the data series. The test should not therefore be confused with one which tests specifically and solely for an 18 year cycle.

The results of this analysis, shown in Table G.1, are somewhat different to those from the complete 60 year data set. In five of the rainfall series, including the 9 station average, the dominant peak corresponds to a periodicity of 18 years. Of the remaining data series, two stations show an 18 year cycle coloured by noise of period two years, whilst three stations are dominated by high frequency noise. Although the 18 year cycle is clearly evident in six of the data series it is statistically significant in only three of them (Fisher's Kappa test), most noticeably in the rainfall series of station 111. However, using the Kolomogorov-Smirnov test statistics, the series could well be described as white noise in all but two cases.

Table G.1 Results of SAS/ETS SPECTRA Analysis (54 Data Points).

Rainfall Station	Dominant Peak (years)	Fisher's Kappa	Significance	Kolmogorov-Smirnov	Significance
9	2 & 18	2.5979	N/S	0.1368	N/S
44	18	5.3981	10%	0.1694	N/S
72	18	3.9018	N/S	0.1254	N/S
111	18	8.0845	1%	0.2748	5%
115	18	6.6651	5%	0.2230	15%
120	2 & 18	3.5444	N/S	0.1493	N/S
124	2.35	4.9029	N/S	0.1497	N/S
126	several <5	3.5722	N/S	0.2077	N/S
132	several <5	3.5677	N/S	0.1225	N/S
Mean	18	5.0824	N/S	0.1424	N/S

To test that the precise six years of data removed were not biasing the result, the analyses were repeated for station 115 after removing the first six years rather than the last. The results were very similar.

The rainfall series of the mean of the 9 stations does not, according to these tests, exhibit a significant 18 year cycle at the 10% level. For that to be the case Fisher's Kappa must be greater than 5.130 and the Kolomogorov-Smirnov statistic must be greater than 0.234. It is the case, however, that with a Fisher's Kappa of 5.0824, the 18 year cycle is 'almost significant' in the regional data series.

The analysis outlined above indicates the occurrence of an 18 year cycle in several of the data series. However, the interpretation of the combined results for individual stations is not straightforward since neighbouring stations will experience similar patterns of rainfall and thus their data will be not be independent.

It is recommended that a full study of cyclic behaviour is undertaken. To test for all possible cycles in the data, rather than the subset of discrete cycles tested by SPECTRA, simulation experiments would need to be undertaken to define the distribution of the test statistics.

Tests for trend in the data

A further characteristic apparent in the data is the general increase in the mean with time. It is usually referred to as trend, but this tends to imply an infinite increase over time. Perhaps a better way of viewing the increase is that it is part of a cycle whose frequency is so long that the portion of the cycle displayed appears straight. To test whether this increase is significant, for each gauge and for the regional average, the annual rainfalls were regressed against time. If the exponent of the regression equation is significantly different from zero, the increase can be said to be significant. Table G.2 gives the coefficient and the standard error for each data series. Only for station 111 is the coefficient greater than two standard errors from zero, which is broadly equivalent to the 5% significance level.

These preliminary trials indicate that, although there is some indication of a slight upward trend in the data, the trend may not be statistically significant. Some further work to confirm these initial results should form part of the studies of cycles outlined above.

Figure G1 Mean annual rainfall and IRW trend from 9 selected stations

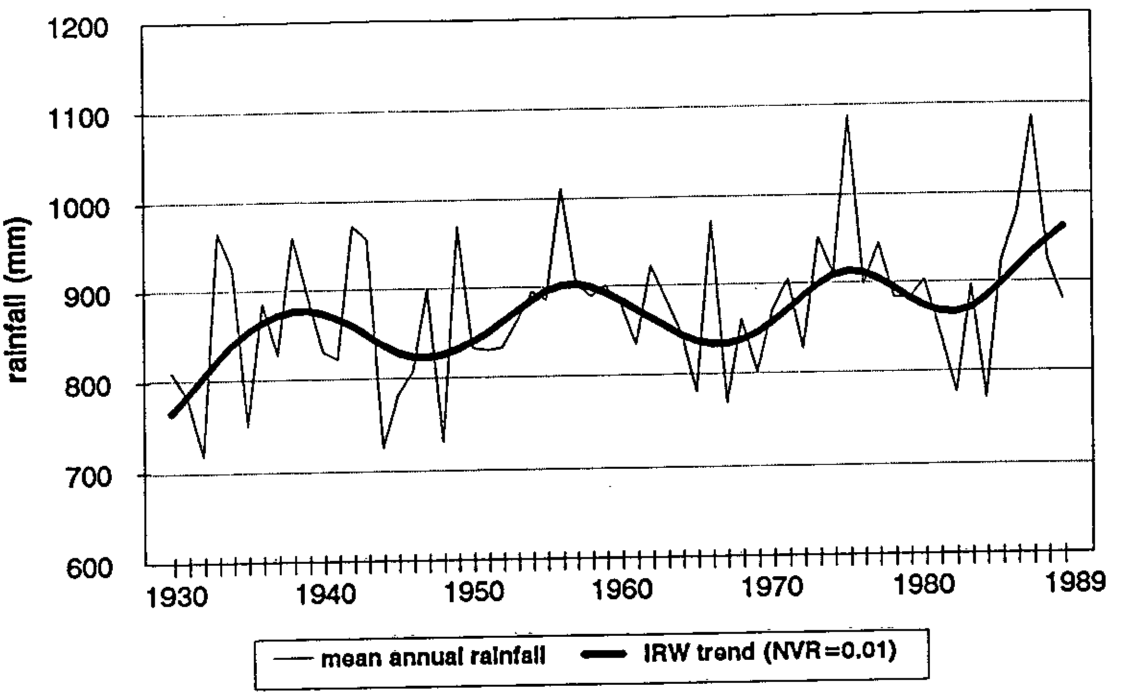


Figure G2 Annual rainfall and IRW trend, Station 115

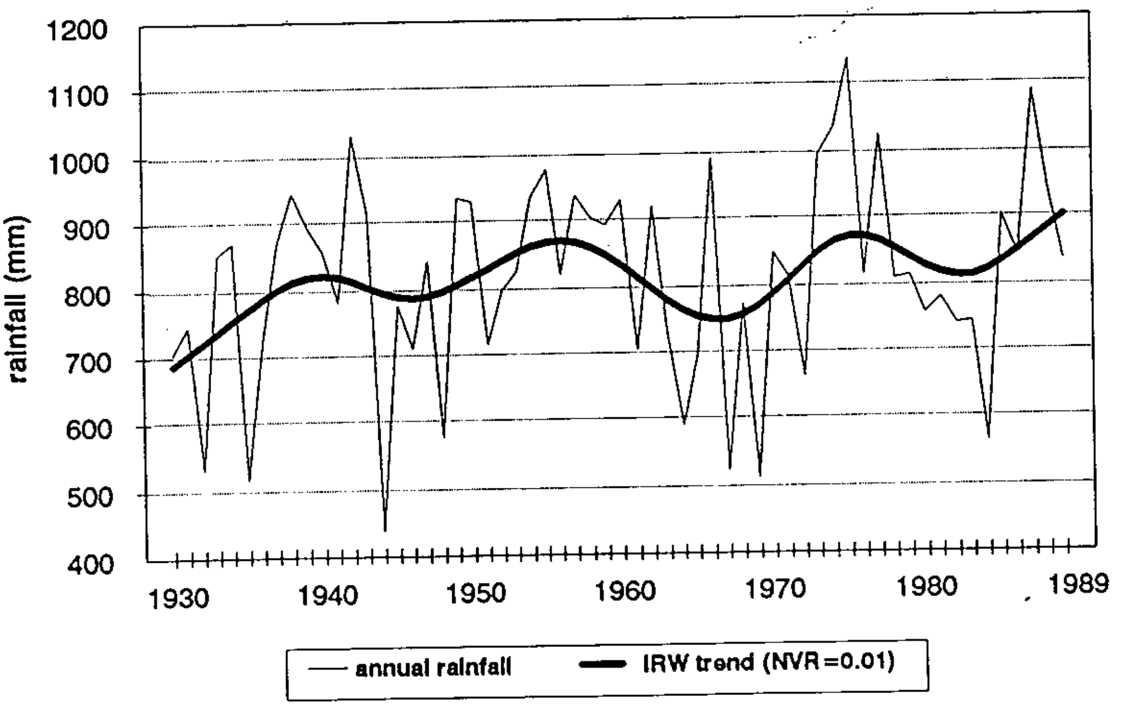


Figure G3 - Periodogram of mean annual rainfall from 9 selected stations

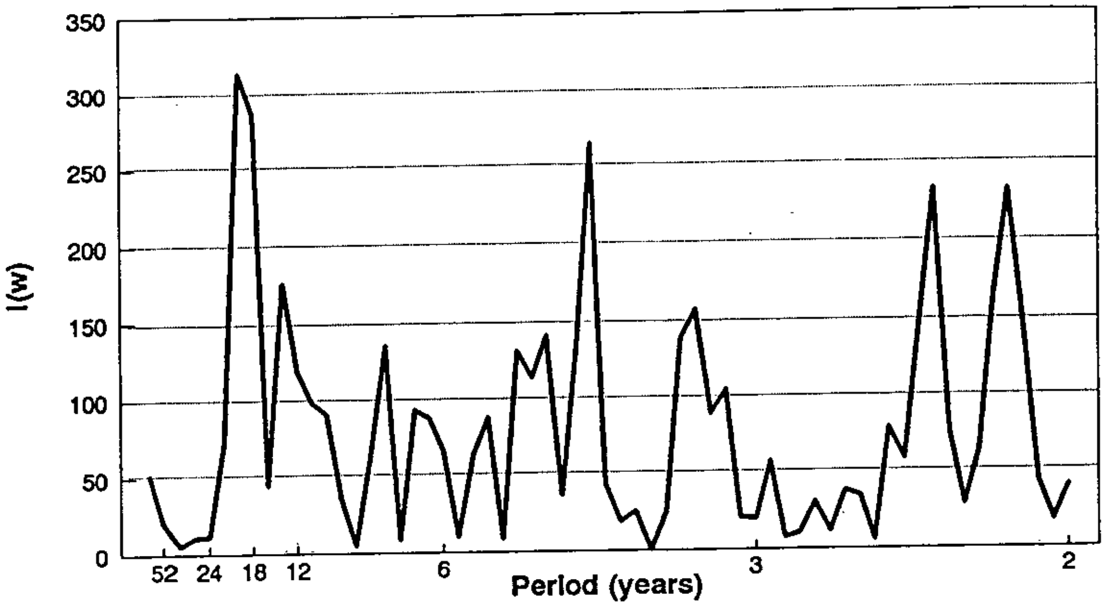


Figure G4 - Periodogram of annual rainfall. Site 111

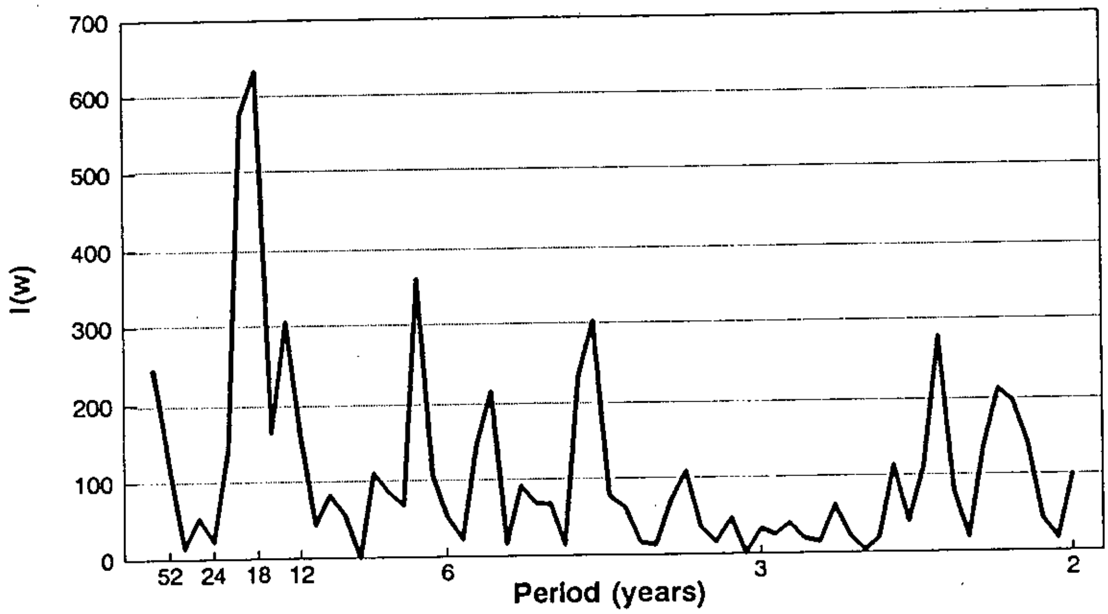


Table G.2 Test for significance of increasing mean

Station	Coefficient	Standard error
9	-0.52	1.02
44	0.66	1.26
72	0.56	1.24
111	2.89	1.22
115	1.42	1.12
120	-0.31	1.70
124	1.78	1.33
126	3.02	1.95
132	2.74	1.26
mean	1.36	1.08

ANNEXE H

A NOTE ON POSSIBLE STOCHASTIC MODELLING PROCEDURES

1 BACKGROUND AND GENERAL OBJECTIVES

Flow records cover about 25 years at a number of stations, none of which coincide exactly with the sites at which knowledge of flows is required for Royalty or design purposes. Rainfall records cover a period of 60 years or more at many more stations, but no single record is complete over the whole period, and the area is not covered uniformly.

The Treaty requires a Royalty hydrology being defined as a historical series of flows (and net rainfall) at the dam sites for a specified period (1930 to 1983). The flows will comprise those observed since the mid 1960s and those derived by modelling for the earlier years. The design hydrology requires representative flow series at combinations of sites, but there is no prior constraint on the form of these series in terms of length or historical association.

2 GENERAL PRINCIPLES

We believe that there are three main principles that should underlie the choice of modelling approach needed to achieve the objectives in an unbiased way, viz:

a the longer rainfall series can provide much more information on the long-term variability of flows than the flow series alone, providing flow is well related to rainfall say on an annual basis. Thus any modelling procedure should be able to handle series of different length and to be driven by the longer series.

b project design should be based on a wider range of possible flows (critical periods) contained in a longer series series than is available in the historical flow record even when it is extended by reference to the historical rainfall. Stochastic models can generate longer series, representing the range of flows that could occur in the future, based on the statistics of the observed record. These longer series can provide a range of periods of deficient inflow so that the storage required to meet the target yield can be estimated more reliably.

c the relationship between rainfall and runoff should be statistical rather than conceptual (as in the Pitman model) to avoid the subjective decisions involved in the derivation of individual basin rainfall and in the derivation of model parameters. The within year variation in flow is not critical to the analysis: the reservoirs are large compared to their annual inflows, and the overall reliability of the project is high. Thus a statistical description of annual flows is likely to be more stable than one based on conceptual modelling at much shorter time scales.

d the benefit of providing reservoirs on different basins lies partly in the extent to which flows on the different basins are not fully correlated. Thus accurate estimation of the total storage required to meet the target aggregate yield depends on preserving the correct cross-correlation structure between the several inflow series.

3 SELECTION OF DATA

Once an agreed set of observed flow data is derived from the rating curves and stage measurements made since the mid 1960s, there is no further manipulation required except the interpolation procedure used to transfer flows to ungauged sites discussed below.

The precise choice of rainfall series is less clear. We anticipate that the rainfall data will be used to guide the flow generation. In the case of the Royalty hydrology, rainfall over the historic period will be used directly to derive the flows. In the case of the design hydrology, it is better to base the generation of long flow series primarily on the generation of long rainfall series, than it is to use the statistics from the shorter observed flow series alone. This is because the longer rainfall record provides a stronger basis for a description of the statistics underlying the long term hydrological fluctuations.

Because of deficiencies in rainfall station coverage it is not possible to derive rainfall estimates for individual sub-basins with sufficient accuracy. Therefore we envisage deriving regional or sub-regional rainfall series that will reflect any strong differences across the region but will not be linked directly to each flow station or site of interest. The number will depend on the areal differences of annual rainfall across the region, and whether these differences are significant between major basins. We anticipate that standardised annual rainfalls differ more from year to year than they do from place to place.

4 SELECTION OF THE MODEL ELEMENTS

We need model elements to carry out the following tasks:

a transfer flows at gauging stations to the (ungauged) dam sites of interest,

b define the relationship(s) between annual rainfall and annual flow,

c generate long series of annual rainfalls,

d define the stochastic generating structure for multi-site flow sequences,

e disaggregate annual flows to monthly flows.

Transfer of data to the sites of interest is an interpolation problem guided by ideas of the hydrological response of basins. We have shown in our recent report how a basin-wide analysis of the data might usefully be developed. The illustration based on average annual data will be developed to look at the consistency of response of all the sub-basins on an annual time-series basis from which it will be possible to determine whether the uncertainty in the interpolation is sufficiently large to warrant modelling it. If possible we would prefer to transfer the observed data series to the sites of interest initially, before the rest of the modelling takes place, on grounds of simplicity.

The statistical relationship between runoff and rainfall will be some form of regression equation that can handle any differences between the form of the statistical distribution of the two variables, such as transformation of one or both of the series. Estimates of the uncertainty in the relationship due to errors in both data sets, and due to variation in the true relationship over time, can be calculated directly during the model fitting.

Well established and widely used methods of time-series analysis will be used to define a stochastic model to generate long series of annual rainfalls based on the observed series. The method will be more complicated if several sub-regional rainfall series are used rather than a single regional rainfall series. In this case it will be necessary to preserve the cross-correlation structure between the series as well as the time-series features. The specific question of cycles in the rainfall series will be addressed as part of the derivation of a time-series model of rainfall alone. As far as the historical period is concerned, the cycles will be present to the extent that they are seen in the historical rainfall data. Any bias caused by these cycles in the central estimate of quasi-historical flows over the period can be noted.

5 USE OF COMMERCIALLY AVAILABLE MODELS

We require a model structure that will handle data streams of different length. The observed flow records are of different length and we want to use the longer rainfall series - either the historic or extended series - to drive the flow generation.

The commercially available models such as the SPIGOT or NATAL package do not handle this situation explicitly and we envisage using a hybrid model element tailored to suit the particular objectives of this project. Some aspects of the SPIGOT or similar packages could be used, such as the disaggregation components which derive monthly from annual series, but the statistical/stochastic elements used to derive the generating functions will need to be developed separately.

The SPIGOT model is divided into stages so that the annual aggregate flow series is generated first and then disaggregated to sites and from years to months in subsequent stages. Thus it is possible to use parts of the SPIGOT package for this application However, further study is needed to decide whether the SPIGOT procedure of using aggregate flow generation is appropriate in this project.

The question concerning the use of aggregate flows is less clear. If flows can be considered satisfactorily as aggregates over stations (or sites of interest), the generation process can be simplified, but a layer of disaggregation (between sites) has to be used to reduce the aggregate to components that retain the correct inter-station variability. The difference in approach lies in whether the generating process acts on all sites simultaneously or on the simpler aggregate flow. Aggregation implies an over-riding strong relationship between regional rainfall and aggregate runoff which holds satisfactorily at sub-basin level. This is not a necessary condition of the standard SPIGOT package which is designed to extend flow series without reference to rainfall.

Some preliminary analysis will be necessary to resolve this issue. At present we doubt whether an aggregation procedure will be helpful particularly because dealing with separate flow series directly will allow differences in the rainfall-runoff response of sub-basins to be handled explicitly in the flow generation process.

Further study of the flexibility of the SPIGOT and NATAL packages will be made before final decisions on their use in this application. It is possible that we shall seek the advice and assistance of Professor Pegram in the case of the NATAL package.

6 MODELLING THE ROYALTY FLOWS

Even direct use of the historical rainfall series can not produce an unambiguous flow series due to uncertainties in the rainfall data and in the rainfall- runoff relationship. This uncertainty can be built into the flow generation process stochastically but this results in an infinite number of possible flow series, each of which is equally likely to have occurred.

A central estimate will be defined for use in the Royalty calculation and this can be redefined (truncated) to cover the period specified in the Royalty Agreement. This series will be directly comparable to one that would have been derived using the Pitman model. The difference being that statistical relationships of wider generality will have been substituted for supposedly physically-based deterministic relationships derived for each basin, although in practice the independence of estimation for each basin in the Pitman model is thwarted by lack of detailed knowledge of rainfall.

Determination of the central estimate can be made in a number of ways. The choice depends on the linearity of the relationship between the result (in money terms) and the statistics of the many different flow series that could be produced. If the relationship is linear, it will be necessary to produce only one flow series using the model in which most sources of uncertainty have been removed. If the relationship is non-linear, the best central estimate of Royalties would be derived from the average Royalty from a range calculated separately from each of the alternate generated flow series. The approach taken will depend on the flexibility, if any, allowed in the Treaty.

7 MODELLING THE DESIGN FLOWS

A time-series model of the regional rainfall series alone can be derived and used to generate stochastically a very long rainfall series which contains features that can identified in the historic record. Fragments of this long record can be used with the model to estimate new, and wider ranging, flow series than those derived purely from the historic rainfall series.

The variation of the many possible flow series about the central estimate, provided by stochastic generation, will give a measure of the uncertainty in the flow series due to uncertainty in the relationship between rainfall and runoff. It does not include a measure of uncertainty due to the representativeness of the reference period (largely in terms of rainfall) or indeed the flow data period (in terms of possible changes in the rainfall runoff regime) to the future response of the basins. Of these, the first can be estimated, the second can only be guessed at.

These wider-ranging flow series should be used for design purposes. Given the very severe failure criterion (the system shall fail only once in 50 years on average) a long flow series for design, say 500 or 1000 years, will be generated using both the rainfall model and the multi-site model together. This procedure should give reasonably stable estimates of reservoir storage required to achieve the design objective. There are still uncertainties remaining, but they are limited to those that are unquantifiable.

Natural
Environment
Research
Council