Drought and Hydrological Variability in Southern Somalia

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The Snake and the Soothsayer

On the second visit, the snake said to the soothsayer:

"Tell the sultan who sent you that a wasting drought will come.
Tell him that the dihi, maajeen and duur grass will wither away altogether.
Tell him that of the groves and of the great trees standing alone, some will die.
Tell him that all the weak and poor and all the flocks will perish.
Tell him that the strong camels and black-headed sheep will remain.
Tell him that men who are enterprising and industrious will survive."

The soothsayer set off in a great hurry and after some time he came to the assembly. He recited the poem and when he had finished, the people ran towards him and lifted him from the ground in their joy. The sultan, very pleased, got up, shook hands with him, patted his head and blessed him. Then the people paid him great honour, entertained him, and made a riding display for him.

Next day the sultan assembled his clan. "It has been foretold for us that a time of drought is approaching. Everyone must store away something for himself", he told them. So every man made a storage place with racks, on which he placed such food as would keep.

After some months the drought began. The autumn rains did not come and there was no rain during the following spring.

All over the country clouds of dust were blown about by the wind, the land became bare, the trees withered, the ponds dried up, and all the shallow wells and water-holes were exhausted, except for the deep spring-fed wells. All those animals which cannot live for a long time without water, and all the animals with horns, died, and no livestock could be found except for the big strong camels. Other people were not prepared for the drought and they and their animals perished, but the sultan and his clan turned to their stores and survived the hard times.

(From a traditional Somali legend)

Abstract

Somalia, located in the Horn of Africa, is a country constantly at risk of drought. Annual rainfall varies from less than 100 mm up to approximately 600 mm. There are two rainy seasons, which are controlled by the movement of the Inter-Tropical Convergence Zone (ITCZ) over the country. The Juba and the Shabelle, both of which originate in the eastern Ethiopian highlands, are the only perennial rivers.

The basic characteristics of rainfall and runoff in Southern Somalia are defined, including the seasonality, temporal and spatial variability, and flow and rainfall frequencies. Autocorrelations of annual time-series show evidence of a six-year cycle in the runoff of both rivers. This is thought to be dependent, at least in part, on the Southern Oscillation Index (SOI). However the cycle is amplified in runoff in comparison to rainfall, suggesting additional influences which could include vegetation cycles, temperature variability, or variations in abstractions from the river.

The problem of defining "drought" is considered, including the difficulties of determining appropriate scales of time and space, and deciding on a threshold to use in the analysis of runs. Drought is really a demand-driven concept, although it is rarely treated in this way by meteorologists or hydrologists. A complete definition of drought should thus take in to account the requirements of water users. Detailed knowledge of water use was not available in this study, so thresholds have been assumed.

Due to the variability of rainfall and runoff, and the various definitions of "drought" which could be adopted, no single period could be found in the historical record that represents the most extreme drought for the whole of Southern Somalia. However, despite this variability, there have been some occasions where severe, widespread drought has been evident in both rainfall and runoff. This includes the early 1970s and mid-1980s.

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Abbreviations

ARIDA	Assessment for Regional Indicators of Drought in Africa
ASL	Above Sea Level
BB	Bulo Burti
BW	Belet Weyne
CCD	Cold Cloud Duration
CEH	Centre for Ecology and Hydrology
CRU	Climate Research Unit, University of East Anglia
DEM	Digital Elevation Map
ENSO	El Niño- Southern Oscillation
FAO	Food and Agriculture Organisation of the UN
FEWS-NET	Famine Early Warning System, USGS
FSAU	Food Security Assessment Unit
GEV	Generalised Extreme Value distribution
IH	Institute of Hydrology
IOA	Indian Ocean temperature anomaly
ITCZ	Inter-Tropical Convergence Zone
MW	Mahaddey Weyne
NDVI	Normalised Difference Vegetation Index
PDSI	Palmer Drought Severity Index
SOI	Southern Oscillation Index
SST	Sea Surface Temperature
TEJ	Tropical Easterly Jet
UEA	University of East Anglia
UNDP	United Nations Development Programme
USGS	United States Geological Survey

A note on spellings

The spelling of place names and seasons in Somalia is very variable. Attempts have been made to use the same spelling throughout, but there may be discrepancies! The phonetics are usually similar even if the spelling differs, although it can sometimes take some thought. H and X may be used interchangeably, as in Haggai/Xaggai, and Huddur/Xuddur. H and J are also interchanged, for example Jilaal/Hilaal. Baidoa is often spelt Baidhabo. Luuq is variously referred to as Luuq Ganane, Lug Ganana, or some such combination. Balcad may be spelt without the c. Jowhar may be spelt Jawhar or Johar. Kismayo can be spelt Chismayu. Hopefully most of the discrepancies have been removed, although some may remain in maps from other sources.

Chapter 1: Introduction

1.1. Objectives

This thesis has been carried out with the Food and Agriculture Organisation (FAO) of the United Nations, who are in the process of developing a GIS-based "Land and Water Information System for Somalia". It is hoped that this thesis will provide some contribution to their work.

Water resources in Somalia must be understood in the most detail, and in the most practical manner, by the Somalis themselves. However, there has been only limited formal characterisation of those water resources, and as a result, this thesis is designed in part to provide a comprehensive overview of the surface water resources of Somalia, particularly the south of the country. This includes analysis of the basic characteristics of both rainfall and streamflow.

The focus of the thesis is on drought, which is an inescapable problem in a climate such as that of Somalia. Various aspects of drought must be considered, and further objectives could thus be outlined as follows:

- To consider the problem of drought definition, and put this in the context of water availability in Southern Somalia
- To investigate the techniques available for drought analysis and apply these to Somalia
- To understand the influences on climatological and hydrological variability in Somalia, and thus the factors contributing to drought

Characteristics of rainfall and runoff will be considered independently. Similar techniques will be used for both, although some differences exist since rainfall is an intermittent process while the rivers in question are permanent. Analyses of the two water sources will then be compared in order to provide a more complete description.

1.2. Introduction to Somalia: Geographical and social aspects

1.2.1. General physical characteristics

Somalia is situated in the Horn of Africa, the location of which is shown in figure 1.1. It has to its east the Indian Ocean, with the Gulf of Aden to the north. It is bounded on its western side by Ethiopia, with Kenya to the southwest and Djibouti to the northwest. It extends approximately from 1° south of the equator to 12° north. The elevation varies from sea level to 2,416 m at the highest point. A map of Somalia itself is shown in more detail in figure 1.2.

Most of Southern and Central Somalia is low-lying with only gentle topography, with the exception of the coastal belt, which is hilly with sand dunes (Faillace, 1987). There is a general dip to the southeast towards the Indian Ocean (Kammer, 1989). This continues from the Ethiopian highlands, where the elevation can exceed 4000 m.

Northern Somalia differs significantly from the south in respect of topography. It is characterised by the Northern Plateau and significant mountain ranges. The slopes are incised with "togga" (seasonal water courses), and the highest elevations are over 2000 m.

The Ethiopian highlands themselves are igneous, and have at their centre the Rift Valley. Within Somalia, the geology is predominantly limestone and gypsum with some sandstones, and basement rock is exposed on the Buur area in the south of the country. This covers most of the Bay Region, and consists of outcrops of granite and schists, marble and other metamorphics.

1.2.2. Political and social situation

The Somali people are organised by clan, and this organisation is the source of much conflict in the country. The Somali people themselves extend in to the Ogaden region of southeast Ethiopia and are found through most of Somalia. In the south and along the coast are people of Bantu and Arab origin, who look dissimilar from the Somalis and are treated distinctly.

Somalia was first colonised by the Portuguese in the 19th Century, and was then ruled by the Italians and the British until the 1960s. Southern Somalia was controlled by the Italians, while the British ruled over the northern part of the country (British Somaliland). Both territories became independent in 1960, and the two were joined to form the Republic of Somalia (UN Somalia, 2002).

The presence of Somali peoples in Ethiopia and Kenya has caused conflict with those two countries, and internal conflicts have also been severe. The country was ruled under the military regime of Siad Barre until he was ousted at the outbreak of civil war in 1991. Since then there has been no internationally recognised government in Somalia, although a Transitional National Government was formed in 2000. The Puntland State of Somalia, in the north of the country, is semi-autonomous and remained relatively peaceful through much of the 1990s (UN Somalia, 2002).

Figure 1.1. The Horn of Africa, including Somalia and Ethiopia
Source: University of Texas at Austin, http://www.lib.utexas.edu/maps/africa/

Figure 1.2. Somalia.
Source: University of Texas at Austin, http://www.lib.utexas.edu/maps/africa/somalia_pol02.jpg

1.3. Introduction to Somalia: Climate and water resource issues

1.3.1. Climate and meteorology

Somalia has an arid to semi-arid climate. Rainfall is the defining characteristic of the climate, and this has great spatial and temporal variability. The highest rainfall (an average up to 600 mm rain per year) occurs in a band in the south just inland from the coast, and also in small pockets on the northern plateau. In contrast, further inland in Southern Somalia, close to the Ethiopian border, only about 2-300 mm rain is expected in a year. On the northern coast and in the northeastern-most part of the country, there is less than 100 mm rain per year.

Rainfall is primarily controlled by the movement of the Inter-Tropical Convergence Zone (ITCZ) across the country, which creates two rainy seasons. These are the Gu season in April-May, as the ITCZ moves to the north, and the Deyr season in approximately October-November, as it moves back to the south. The gap between seasons is shorter in the north.

The Deyr season is less well-defined than the Gu, and total rainfall is usually lower in the Deyr, with the result that the Gu is generally treated as the main cropping season for agriculture.

The main dry season is the Jilaal, from about December-March, when the ITCZ is far to the south. The Haggai is a minor dry season that occurs between the Gu and Deyr. Some parts of the country, particularly the southern coastal areas, experience significant rains during the Haggai.

Movement of the ITCZ also causes distinct changes in wind direction through the year. When the ITCZ is to the south, the winds are from the northeast, while when it is to the north, the winds are from the southwest. This 180-degree shift to the southwest occurs gradually as the ITCZ passes over, spanning approximately March-July, and then returning to the northeast winds by December. While there are some regional variations, this pattern is dominant across the whole country. Sea breezes can be significant, and cause strong southwest winds off the north coast during June-August, which are known as the Kharif.

Wind speeds average between 3-11 m/s, with the highest winds occurring on the Northern Plateau. The weakest winds generally occur as the ITCZ passes over, with the strongest between June and August (Hutchinson and Polishchouk, 1989).

Luuq, in the Gedo region near the border with Ethiopia, has the highest mean temperature in the country, at over 30°C. Most inland areas of Southern Somalia are only slightly cooler, and the north coast can also have similar temperatures. Temperatures along the southern coast are lower than those inland. In the north, temperature is well correlated to altitude, with a lapse rate of 6.4°C per 1000m (Hutchinson and Polishchouk, 1989).

Average monthly temperatures reach as high as 41°C in March around Bardheere and Luuq.

Greater contrasts between daily maximum and minimum temperatures occur inland compared to on the coast, but these contrasts are generally small in comparison to those which might be expected for desert environments. Hutchinson and Polishchouk (1989) explain this by the relatively high humidity across the whole country.

Humidity is highest in the coastal areas, with the main source of moisture being the Indian Ocean. The humidity is lowest furthest inland, in both Southern and Northern Somalia. Average annual humidity varies between 75% to 45%, with the lowest humidity occurring during the Jilaal season.

There are few records of evaporation, and the values which have been reported in various studies vary between about 1500-3000 mm per year. There is little doubt at least that evaporation is considerably greater than precipitation over a year in all parts of the country. There are localised areas in Southern Somalia, centred around Jilib and Baidoa, where a few months of the year experience higher rainfall than evaporation. This occurs at the beginning of both the Gu and Deyr seasons, allowing crop growth to commence (Hutchinson and Polishchouk, 1989).

Total evaporation generally increases from south to north, with the highest annual evaporation on the north coast. The time of greatest evaporation also varies across the country, being the middle of the year in the north, and the beginning of the year in south and central regions (Hutchinson and Polishchouk, 1989). The contrast is, however, greater in the north, with only minor changes in evaporation through the year in the south.

1.3.2. Surface hydrology

Somalia has two perennial rivers, the Juba and the Shabelle, both of which originate in the Eastern Ethiopian highlands. The Juba flows approximately south, entering Somalia near Dolo Odo and reaching the Indian Ocean near Kismayo. The Shabelle flows east from the highlands and then south through Ethiopia to enter Somalia near Ferfer, where it continues with its approximate southward flow until Balcad. At that point, the river turns to the southwest and flows parallel to the coast, before dissipating in the Lower Shabelle swamps between Hawaay and Homboy. The Shabelle itself has no outlet to the ocean, but under exceptional flood situations, flow can reach the Juba near Homboy, so in a strict sense it is a tributary of the Juba.

The catchment area of the Shabelle is significantly larger than that of the Juba, yet the average annual flow of the Juba is approximately three times greater than the flow in the

Shabelle. This is attributed to the greater proportion of exposed impermeable baserock and the higher rainfall in the Ethiopian part of the Juba catchment, as well as greater abstractions and overbank flow along the Shabelle.

The rivers do not often run dry higher in Somalia, but the Shabelle frequently does so in its lower reaches. River flows can be highly variable from year to year and are almost entirely dependent on the rainy seasons in the Ethiopian highlands. As much as 95% of annual flow originates from Ethiopia. Some flow may enter the rivers within Somalia, particularly during significant rainfall events in the upper Somali reaches. Similarly to the rainfall, two seasons are experienced each year, the Gu and the Deyr. However in contrast to rainfall, the Deyr flow season tends to be larger than the Gu. The Shabelle shows a more defined distinction between seasons, while high flows are often retained on the Juba right through from approximately April to November.

Both rivers are used extensively for irrigation, and the Shabelle has a number of barrages in its lower reaches for controlling flow. In addition, a large offstream reservoir was constructed on the Shabelle at Jowhar in 1980, which significantly impacted the downstream flow regime. The lower reaches of both rivers have been heavily modified for flood control and irrigation. Small-scale irrigation is widely carried out in the flood plains. Flood-recession irrigation is common in natural depressions (desheks) adjacent to the riverbanks. Large-scale irrigation projects exist on both rivers, particularly the Juba. A number of large irrigation canals were constructed before the war, but some never became fully operational.

Changes to the flow regime since the start of the civil war in 1990 would be expected, since large-scale irrigation projects have been abandoned and irrigation canals and flood relief channels have fallen in to disrepair. However the extent of these changes is not currently known in detail, and will not be until the gauging network has been fully reinstated and a longer period of reliable post-war data collection has occurred.

As a result, this study can be concerned only with the state of the rivers as they were before the war. Predominance will be given to the most upstream gauging stations, which represent the closest approximation of the natural flow regime possible. The amount of development on the rivers in Ethiopia is not exactly known but is thought to be minor in comparison to that within Somalia. As a matter of interest, it appears that this situation is currently changing, with lower than normal flows at Jowhar being attributed to increased irrigation on the Shabelle within Ethiopia (Chris Print, personal communication).

Away from the two perennial rivers, significant flows can occur in togga, particularly in the north of the country. Some also exist off the southeast of the Buur escarpment in the south.

The togga are seasonal watercourses (wadis), which can hold considerable flood flows where bedrock is exposed. However they rarely reach the sea due to overflow, evaporation, and infiltration in the sandier coastal areas (Kammer, 1989). The largest of the togga are the Tug Der and Tug Nugal, in North-Central Somalia.

1.3.3. Groundwater

In many parts of Somalia, groundwater is relied on for domestic and livestock purposes. This is obtained mainly from shallow hand-dug wells, although boreholes are also used and are often relied on by large numbers of people during the dry season. However, the quality of the groundwater is variable and at times unacceptable.

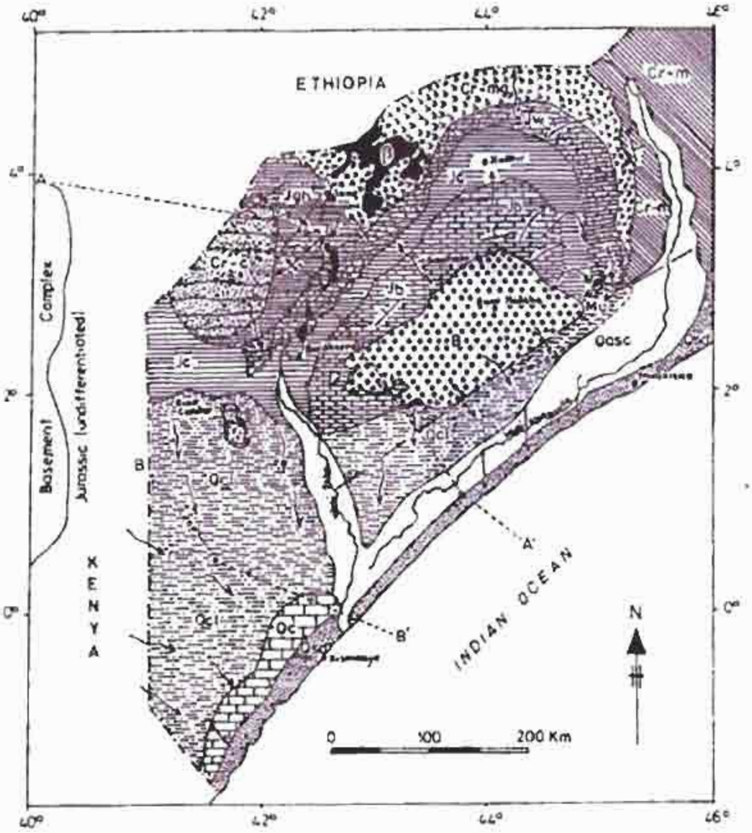
In Southern Somalia, there is a significant groundwater divide along the Buur escarpment. To the southeast of this, the groundwater system slopes similarly to the surface topography, towards the Indian Ocean, while flow on the other side of the uplifted complex is northwest towards Huddur and Bardheere. This results in areas of discharge (springs) further inland. Karstic systems exist in some areas of Southern and Central Somalia. Shallow aquifers exist in the alluvial deposits of the Shabelle and Juba rivers, along the coast, and beneath togga on the Buur escarpment (Faillace and Faillace, 1987). The hydrogeology of Southern Somalia is shown in figure 1.3.

In Central Somalia, deep water-bearing formations extend from southeast Ethiopia. A significant aquifer is found in the basalt formation. Shallower groundwater is recharged through togga, sand dunes and karst areas (Louis Berger International, 1985).

A significant groundwater divide also occurs in northern Somalia as a result of the coastal mountains. There are numerous hotsprings along the north coast, originating from deep fractures. Infiltration occurs through alluvial deposits as flood flows pass down togga from the mountains, and shallow aquifers also exist along the coast (Faillace and Faillace, 1987).

Water table depth is highly variable. Water is tapped within five metres of the surface by shallow hand-dug wells in alluvium and coastal dunes. At the other extreme, in some north and central areas, water may not be found until hundreds of metres below the ground surface.

Much of the groundwater quality is poor, except in near-surface lenses which are regularly recharged by rain or river water. The low quality is due to the predominance of gypsum and gypsiferous formations throughout the country. In addition, sulphate levels are often high enough to cause quality problems (Faillace and Faillace, 1987).



TIME UNITS	BASINS AND AQUIFERS	SYMBOL
	Coastal Basin Aquifers	
Quaternary	Alluvial deposits of Shabeelle & Juba	□ Qosc
Quaternary	Sand dunes	▨ Qsd
Quaternary-Pleistocene	Coral limestone	▨ Qc
Quaternary - Pleistocene	Fluvio-lagunal deposits	▨ Qcl
Miocene	Mudug - Marka	▨ Mu
	Kuddur-Bardheere Basin Aquifers	
Tertiary	Basalt	■ β
Upper Cretaceous	Mustaxiil - Fer Fer - Belet Weyn	▨ Cr-m
Lower Cretaceous	Main Gypsum	▨ Cr-mg
Lower Cretaceous	Cambar	▨ Cr-c
Upper Jurassic	Garbahaarrey	▨ Jgn
Upper Jurassic	Waajid	▨ Jw
Upper Jurassic	Canoole	▨ Jc
Upper Jurassic	Baydhabo	▨ Jb
Pre-Cambrian	Basement Complex	▨ B

Syncline *Anticline* A------A' *Cross-section* *Fault*

Dip *Assumed general direction of underground flow*

Figure 1.3. Hydrogeology of Southern Somalia

Source: Faillace and Faillace, Water Quality Databook of Somalia (1987).

Chapter 2: Literature review

2.1. The problem of definition

Drought is inherently one of the most difficult hydrological phenomena to define. This is in part because it is characterised by non-events rather than by events (e.g. Hershfield *et al*, 1972). A single definition of drought is in effect impossible to obtain, since it is highly dependent on the region and time-period in question, as well as on the water resource and water users under consideration. It is a demand-driven phenomenon, since drought is only perceived to be occurring once people are being affected by some kind of reduction in water availability.

Definitions of drought are generally based around an inadequate supply of water for some purpose, such as in Palmer's (1965) definition:

> "An interval of time, generally of the order of months or years in duration, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply"

This is an easily understood concept but not one that is simple to define in such a way as to allow a quantitative analysis to be carried out.

2.1.1. Types of water deficiency

Common drought classifications include meteorological, hydrological, agricultural and economic.

In the most basic terms, a meteorological drought would be defined as a period of below-normal rainfall. This is closely tied to agricultural drought, since crops may be adversely affected by short-term deficits in rainfall. However, agricultural drought would be more usefully defined using effective rather than total rainfall, and ideally it should be defined by soil moisture and incorporate evapotranspiration.

The majority of studies of drought have defined the phenomenon based on rainfall alone. This is largely because long-term rainfall records tend to be more widely available than any other type. Studies of this type have been carried out, for example, by Herbst *et al* (1966), who considered rainfall data in a study of South African drought, and by Sichingabula (1998) in a study of drought in Zambia.

The dominant method of analysis of meteorological drought in the agricultural context is that developed by Palmer (1965). The Palmer Drought Severity Index (PDSI) and other related indices are widely applied to agricultural purposes in the US (Tate *et al.*, 2000), but the method is complex and has intensive data requirements, and as a result it is difficult to apply in most other countries (Bonacci, 1993). Rangeland studies in South Africa using the PDSI had poor results, so the use of the Palmer method in this environment has not been advocated (du Pisani *et al*, 1998).

A definition of agricultural drought is complicated by the varying needs of the different crops and animals involved (Hershfield *et al*, 1972), and additionally by the heterogeneity of soil physical characteristics and soil moisture. The relative impact of a soil moisture deficit also depends on the timing in relation to the growing season(s). Water requirements are greatest during early stages of growth, level off at maturity, and start to decrease again late in the season.

Complex definitions of rainfall drought were used by Subrahamanyam (1967). Meteorological, climatological, atmospheric and agricultural droughts were all given different definitions, depending on the extent of meteorological data which was available. In addition, hydrological and water management droughts were considered, where the latter is concerned with the failure of management practices in addition to hydrological and meteorological aspects.

Hydrological droughts most commonly consider streamflow, but for a comprehensive study should also be concerned with groundwater levels or storage in other types of reservoir. While these are intrinsically linked to rainfall, the complexities involved in the conversion of rainfall to runoff or groundwater mean that a hydrological drought may not always coincide with or share the same characteristics as a meteorological drought.

Hydrological droughts are usually considered over a longer time period than meteorological droughts due to the dampening of response and the time delay between rainfall and runoff. In addition, streamflow or groundwater at a location is not necessarily derived from rainfall at that same point, in which case meteorological and hydrological anomalies at any particular location will not necessarily coincide (Hudson and Hazen, 1964).

Hydrological drought will also differ from meteorological drought in terms of impact. While a rainfall deficit can have an almost immediate influence on agriculture, hydrological drought will not necessarily have the same effect except in cases where crop growth relies on irrigation. Hydrological drought is often of more significance for domestic or industrial water supply, which is usually dependent on stored water. Depletion of water storage due to a continued deficit of infiltration or runoff would require a longer time period than that of concern for most agricultural purposes.

Studies of streamflow drought have included Woo and Tarhule (1994) in a study of northern Nigeria, Tallaksen and Hisdal (1997), and Clausen and Pearson (1995).

As Beran and Rodier (1985) point out, a quantitative description of a groundwater drought can be difficult to obtain, since the lowering of the water table is caused not only by a lack of recharge, but is also influenced by the over-abstraction of groundwater if a surface water drought is also occurring.

It should be noted that while hydrological drought is generally concerned with streamflows or groundwater, the classification has also been used in discussions of rainfall deficiency, which further complicates the issue of definition. An example of this is the 1993 study of Bonacci, which is entitled "Hydrological identification of drought" but goes on to analyse rainfall time-series.

Most studies consider only one type of drought, as in those mentioned above. However in order to gain a comprehensive view of drought, a combined study of all types of drought is desirable. This could be achieved by separately considering meteorological and hydrological variables for a region, and then comparing the results. It should also be possible to integrate the effects of a rainfall deficiency with other types of drought through the aid of rainfall-runoff modelling (e.g. Burnash and Ferral, 1972).

2.1.2. Timing and duration of drought

The time period over which below-normal rainfall or runoff becomes significant varies depending on location and climate. In the UK, a drought is defined as a period of at least 15 consecutive days with less than 0.01in rain in any one day (Shaw, 1994). In Bali, six days without rain constitutes a drought (Hudson and Hazen, 1964). However in many climates it is normal for months or even years to pass without rainfall. In these regions, seasons where rainfall is not expected would not normally be referred to as droughts since lifestyles are adapted to this variability in the climate. Drought would be more appropriately defined as a rainy season that is less rainy than usual, or in the case of longer-term anomalies, as a reduction in annual rainfall below the norm. However, maintenance of river flows and groundwater supplies during the dry season in these environments can be critical, and so in this sense the dry season must also be considered when characterising drought.

Concern may lie mainly with a reduction in water availability over a single season, or with the compounding effects of a multi-season or multi-annual drought. These in general must be considered separately, further complicating the definition of a drought.

It is common for time series of monthly data or longer to be used for drought analysis, and for multi-year droughts only annual totals would usually be considered. However for short-term agricultural drought it may be necessary to consider daily rainfall.

2.1.3. Further defining aspects of drought

Drought analyses often involve the use of a "threshold" or "truncation" level. When the rainfall or runoff (or the level of any other water source) falls below this limit, drought is said to be occurring. A complete definition of drought thus requires selection of a suitable threshold level. The technicalities of this are discussed further in section 2.3, but at this point it should be noted that choice of an appropriate threshold level depends on the water user. While "normal" conditions, taken as the mean or the median of the time series, are often chosen, some activities may function without difficulty at lower levels than this, in which case a lower threshold would be more appropriate.

Regionalisation of drought is another complicating issue, since drought cannot be said to occur at only a single point, but must extend over some area which is not necessarily pre-defined. In some cases the region of interest may already be known, but in others it may be necessary to determine the areal extent of drought. The drought characteristics would not be expected to be constant across the region.

2.2. Drought: Causes and effects

The primary cause of drought can be considered to be inadequate rainfall. This may result in reductions in soil moisture, streamflow, groundwater availability or other water storage.

Climatological causes of drought have been widely studied, and differ fundamentally between the tropical and temperate zones. In temperate zones, drought is often caused by a 'blocking' effect, resulting in persistent subsidence of an air mass over a region (Beran and Rodier, 1985). In contrast, in tropical regions, rainy seasons are well-defined, and controlled by movement of the inter-tropical convergence zone (ITCZ). Failure of rains is generally considered to be the result of anomalous movement of the ITCZ. Studies in the West African Sahel have shown that in fact in that region, while shift of the ITCZ can be a contributing factor, it is not a prerequisite for the occurrence of drought. There the characteristics of the equatorial westerlies which blow in from the Atlantic are considered much more important in causing drought conditions (Grist and Nicholson, 2001). However, the movement of the ITCZ is much more pronounced over East Africa in comparison to the west, since there is land rather than ocean to both the north and the south (Nieuwolt, 1977). Thus the ITCZ may have more effect on rainfall variability in East Africa.

Unfortunately, the situation is rarely so simple that drought can be attributed solely to a lack of rainfall. This is partly due to the hydrological and hydrogeological factors which interlink with the climate and meteorology. In addition, the management of water can have a significant impact on its availability. This includes management of storage reservoirs and groundwater and of surface water abstractions. The severity of drought is also related to agricultural practices, particularly the efficiency of irrigation and control of salinisation.

Famine in developing countries, often attributed to drought, is compounded by many different factors. This complicates the search for a useful definition of drought, since the impacts of a drought and the wider causes of famine may become indistinguishable. Economic, political and social factors will be significant in determining the eventual impacts of a famine. In addition to a lack of rainfall, crop failure can be caused by flooding and pests, and the problem may be exacerbated by misuse of land, for example by the disturbance of pastoralist lifestyles or growth of inappropriate crops for the climate.

While the complexities of famine can make it difficult to determine the exact impacts of drought alone, it should be clear that the knock-on effects of drought can be many. Crop yields (both subsistence and commercial) will be the first to suffer. Livestock are often more resistant to short-term deficiencies in water availability, and effects are often delayed. Over time, industrial and domestic water supply may be reduced, which can eventually impact on the economy. Water quality problems and the spread of disease can also result.

The expected impacts of drought differ across the regions of the world. In the UK, concern lies mostly with depleted public water supplies. In contrast, in developing countries which are dependent on crop growth and livestock health, the primary concern will most likely be in food security.

In understanding the effects of a climatological, meteorological or hydrological drought, consideration of timing is crucial. If only annual rainfall totals are considered in an analysis of drought, this may result in the loss of valuable information concerning the characteristics of rainfall. For example, the start of the wet season may be delayed far beyond that expected so crop growth is unsuccessful. Then it is possible that a large amount of rain falls at a late stage in the season, causing flooding, and destroying any crops that have been able to grow. This could have severe consequences for agriculture, while not being registered at all in the annual rainfall total.

As another example, if rainfall has been light during most of a wet season but enough to wet the soil, and then heavy rainfall occurs at the end of the season, a high proportion of runoff will occur due to the wet antecedent conditions. As a result, there may have been below-average rainfall, but its characteristics have resulted in average or above-average runoff (Beran and Rodier, 1985).

The impact of drought on the economy is difficult to quantify since it affects varying aspects of both production and consumption. Impacts are most significant on the smaller scale (Millan, 1972). Drought directly influences actual users of water, but this also filters through to those who buy or sell services or goods which are dependent on water. The effect of drought alone on economy cannot be determined, but must be considered in the context of the performance of the economy otherwise. Such impacts will not be considered directly here.

2.3. Drought analysis

It is clear that the accepted definition of drought will affect the choice of analysis technique. A statistical analysis of some aspect of water balance may be suitable, for example through the use of rainfall, runoff, soil moisture or groundwater level time series. This gives an understanding of drought simply as a hydrological or meteorological phenomenon. In other cases it will be the impacts of hydrological or meteorological deficits that are of importance. While these can be supposed through the analysis of rainfall or runoff, the impacts of such deficits vary depending on their timing, and due to other external factors discussed previously (section 2.2). The areal extent of a drought is also important in terms of its overall impact. The relative significance of these various factors cannot be fully understood unless the drought is considered in the context of the activities and people that are being affected.

2.3.1. Setting a threshold

Studies of hydrological and meteorological droughts have most commonly been concerned with the use of threshold (or truncation) levels and the theory of runs. Dracup *et al.* (1980a) state that the choice of a threshold level is necessary for a complete definition of drought. The theory of runs has been applied to both rainfall and streamflow situations, so the two will be discussed interchangeably.

On the premise that "natural vegetation and the agriculture of any region are more or less adjusted to the normal rainfall of that place" (Havens, 1954), the threshold is commonly taken as some measure of "normal" meteorological or hydrological conditions. This could be the mean or the median, and should allow for the standard deviation. The threshold level is defined by Bonacci (1993) as:

$$t = \bar{x} - n\sigma$$

where $\bar{x}$ is the mean, σ the standard deviation and n is a scaling factor.

However, Havens' (1954) statement is general and does not account for the varying water requirements of different users. Thus the use of a number of different threshold levels may be necessary for a complete investigation of impacts (Woo and Tarhule, 1994). These thresholds can be defined as a percentile flow (e.g. Q_{95}) or as a percentage of mean flow (Tallaksen *et al.*, 1997). Shaw (1994) suggests that either the Q_{95} percentile or a quarter of the mean would be suitable thresholds, although the choice will vary depending on the climate.

In arid climates the rainfall frequency distribution is usually skewed, so the use of the mean in defining a threshold may be inappropriate. In this case the median or mode should be used instead as a better approximation of "normality" (Beran and Rodier, 1985). In temperate climates, the normal distribution is often acceptable in which case the mean could be used.

Choice of an appropriate threshold level depends on the climate characteristics and on the purpose for which "drought" needs to be defined. If a monthly time series is being considered then choosing a threshold can be difficult, except in a climate where rainfall is similar year-round. In climates where there are distinct contrasts between wet and dry periods, use of a single threshold would result in determination of "drought" periods every year, while this in fact is a natural seasonal variability which often causes little or no problem in terms of impact. To remove this effect, different threshold values could be used for every month, as suggested by Griffith (1990), who uses the median values for each month individually. However in some cases the length of the dry seasons is of importance, in which case use of a single threshold would be appropriate.

2.3.2. Run analysis

Once a threshold has been defined it can be used in drought analysis by the statistical theory of runs (Yevjevich, 1967). A run is defined as a "succession of the same kind of observations preceded and succeeded by at least single observations of different kinds" (e.g. Yevjevich, 1972 and Sen, 1976), for example a negative run of runoff is a period of below-threshold streamflow preceded and succeeded by periods of above-threshold streamflow. Runs can be characterised in terms of time of occurrence, duration and severity (Tallaksen *et al.*, 1997). The duration is defined as the time between onset and termination of the run, and is also referred to as the run-length (positive or negative run length depending on whether it is above or below the threshold). The run-sum is the total cumulative surplus or deficit during the duration, and in the case of a negative run-sum is referred to as drought severity. Tallaksen *et al.* (1997) define the time of occurrence as the mean of the onset and termination dates, while other analyses retain separate variables for the start and end dates of drought.

While it is expected that a longer duration will give rise to a large run-sum, the longest duration droughts are not necessarily those of greatest severity. In this case the relative importance of these two variables will depend on the water use in question (Sen, 1980a). For example, the total deficit (negative run-sum) will be of most significance for reservoir design, but for agriculture the duration and timing are often more important. The latter point is not considered by Bonacci (1993), who states, "Undoubtedly, severity is the most comprehensive characteristic…"

It is possible to combine the two parameters and consider drought in terms of a single characteristic, magnitude, which is equal to the severity divided by duration (Dracup *et al.*, 1980b).

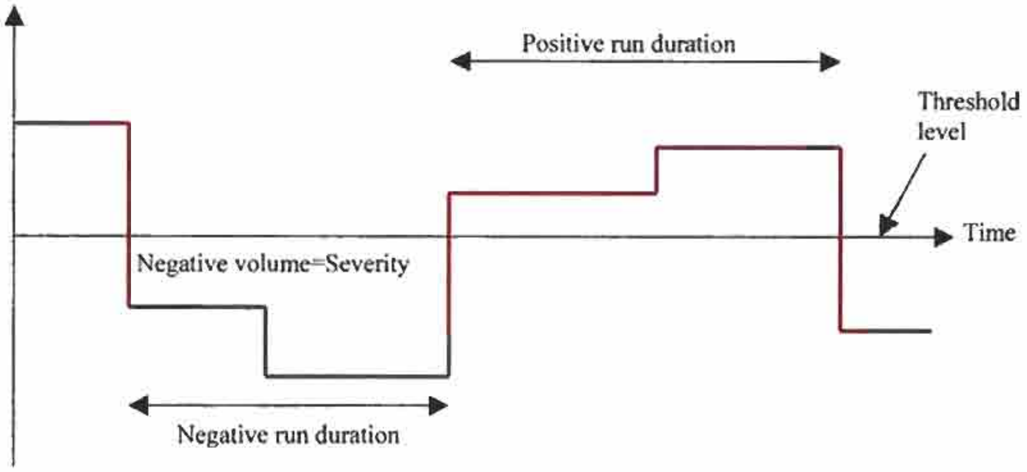


Figure 2.1. Characteristics of runs

Dracup *et al.* (1980b) suggest the use of annual flows in comparison to a long-term annual mean for run analysis, and Sen (1980a) also considers annual flow series. However Herbst *et al.* (1966) and others have applied the method to monthly time-series.

At a fine temporal resolution there may be complications in analysis due to mutually dependent droughts (Tallaksen *et al.*, 1997). This occurs when the threshold is exceeded only for a short time, which in effect divides one long drought in to a number of shorter but dependent droughts. Tallaksen *et al.* (1997) suggest that pooling of shorter drought periods could be carried out based on either the time lapsed or the surplus volume between droughts. A critical time (t_c) or critical volume (v_c) is defined, and droughts separated by less than the critical value are pooled to give a pooled drought of total duration d_{pool}, and total severity s_{pool}. This method has been applied to drought studies using the model ARIDA (Assessment of Regional Indicators of Drought in Africa), which was developed by CEH for operation in Southern Africa (Tate *et al.*, 2000). Short periods above the threshold could also be removed using a moving average procedure to smooth the time series (Tallaksen *et al.*, 1997).

Herbst *et al.* (1966) used the theory of runs on a modified monthly time series for the analysis of rainfall drought. Actual rainfall from the previous month was used to calculate effective rainfall, using a separate weighting factor for each month. This allowed some consideration of soil moisture storage so that the onset and termination of a drought were adjusted from that which would be expected if actual rainfall were used. The method also developed tests for the onset and termination of drought, rather than relying on the common assumption that a drought is occurring at any time where the time series falls below the threshold. The onset of drought was determined using a sliding scale based on the mean monthly rainfall, and the termination of drought depended on the occurrence of multiple months above the threshold.

The same method was used by Mohan and Rangacharya (1991), although they found that it did not adequately represent known historical periods of drought in India. They suggested that the method could only be applied to trend-free series with low standard deviation. In cases of high rainfall or runoff variability, the threshold level can be reduced according to the standard deviation, and is then defined as:

$$T(t) = \overline{Q}(t) - {\sigma_t^2}\big/{\overline{Q}(t)}$$

where T(t) is the threshold level for month t and $\overline{Q}(t)$ is the mean flow. However, they did not explain how this could be applied where the coefficient of variation is greater than one, which results in a negative threshold.

Dracup *et al.* (1980b) suggest various statistical analyses to better understand the characteristics of drought. These include tests for the stationarity and randomness of the time series in question, and correlations between parameters (duration, severity and magnitude) for single events and successive events. Relationships between successive drought events are considered, along with the relationship to the intervening surplus periods.

Investigations of the correlations between drought parameters (e.g. Bonacci, 1993) have shown that the strongest correlation exists between duration and severity. Since severity is the cumulative deficit, it is sensible that this would become larger over a longer period of accumulation. Magnitude was found to be insignificantly correlated to duration and only weakly correlated to severity. This suggests that while magnitude would be expected to be a useful summary of the characteristics of a drought, it may lose the defining features of a particular drought period and will not directly reflect either the duration or severity.

Dracup *et al.* (1980b) found that drought periods had a stronger correlation to the preceding surplus period than the succeeding one. They explained this using the streamflow regression study of Orsborn (1974) which showed that high flow periods are more strongly affected by the inputs to the system (rainfall), while low flows depend on the previous high flow period.

2.3.3. Distribution of run parameters

Two types of probability can be utilised when considering the occurrence of droughts (Yevjevich *et al.*, 1983). One is the probability that the next negative run will have a certain duration or magnitude. The other is the conditional probability that a negative run of a particular magnitude or duration will occur in a sample of size n.

A number of studies have been carried out in to the distribution of the drought parameters determined by the theory of runs, and various different distributions have been proposed. The distribution of the parameters is dependent on the distribution of the time series in question (Yevjevich *et al.*, 1983).

The occurrence of droughts is generally assumed to be represented by a Poisson distribution. This was used by Zelenhasic and Salvai (1987) in a study of instantaneous river discharges, which was concerned with droughts of duration less than a year. The Poisson distribution was also used by Gupta and Duckstein (1975) to consider point rainfall events.

For an independent series, the probability of a drought of duration m years occurring is given by the geometric distribution:

$$f(m) = q^m p$$

where q is the probability of deficit, and p the probability of surfeit, with $p=1-q$. The value of p and q can be estimated from historical time series (Yevjevich, 1972). For a dependent series, there is no exact expression for the frequency distribution of drought duration, and it must be obtained by approximation from power series expansion (Yevjevich *et al.*, 1983).

The geometric distribution was assumed by Hershfield *et al.* (1972) to be appropriate for the frequency of dry-day sequences of varying duration. Similarly, Zelenhasic and Salvai (1987) assumed an exponential distribution for drought duration (and also severity), which is the continuous form of the discrete geometric distribution.

The most suitable distribution may depend on the cause of the drought. For example, in a study of Nigerian rivers, Woo and Tarhule (1994) defined two types of droughts. The duration of short droughts which occur within the rainy season was best represented by the Weibull distribution, while the duration of the dry season was more appropriately represented by the normal distribution.

The distribution of the severity and magnitude can also vary depending on location, and on the type of run under consideration. For a study of rainfall runs in Croatia, Bonacci (1993) determined that the gamma distribution was most suitable for describing the severity or magnitude of negative runs, while the Weibull distribution was used for positive runs.

Griffiths (1990) formulated a joint probability density function (pdf) for the number of runs, run length and severity. This used the density function for the number of runs (r_d) developed by Mood (1940):

$$f(r_d) = \binom{np-1}{r_d-1}\binom{nq+1}{r_d-1} \bigg/ \binom{n}{np}$$

where p is the probability of deficit, q the probability of surplus, and n the total number of months. For run length (duration, m), the geometric distribution $f(m)$ is assumed. Since the total rainfall depth per run is expected to increase as run length increases, the distribution of severity (h) is conditional on run length. The distribution of monthly rainfall is assumed to be exponential and as a result the total run-sum (severity) is gamma distributed:

$$f(h|m) = h\gamma^{-1} e^{-h/\beta} / \beta^{\gamma}\Gamma(\gamma)$$

where h is the severity and γ and β are the shape parameters. The joint distribution of r_d, m and h is then defined by assuming that $f(r_d)$ and f(m,h) are independent, resulting in:

$$f(r_d, m, h) = \left[\binom{np-1}{r_d-1}\binom{nq+1}{r_d} \bigg/ \binom{n}{np}\right]\left\{qp^{m-1}\left[h\gamma^{-1} e^{-h/\beta} / \beta^{\gamma}\Gamma(\gamma)\right]\right\}$$

It is potentially also possible to consider runs of bivariate or multivariate processes (Yevjevich, 1972). For a bivariate process, four types of runs could then be defined: joint negative run; joint positive run; run with x negative and y positive; run with x positive and y negative. This would be useful for considering the state of multiple storage reservoirs or more than one river.

2.3.4. Extreme drought analysis

The maximum run duration or magnitude is dependent on the distribution of the variable in question, on the sample size, and on the sample variation (Yevjevich *et al.*, 1983). Duration or magnitude of extreme events may be overestimated if high sample variance is not taken in to account (Beran and Rodier, 1985).

In order to assess the representative extreme drought from a sample, it may be necessary to model the time-series process and generate a large number of samples, from each of which the extreme drought can be extracted. It cannot be assessed from a single sample in case an extreme drought has occurred which is not representative of a sample of that size (Yevjevich *et al.*, 1983).

Extreme droughts were studied by Gupta and Duckstein (1975) in terms of the maximum period without rainfall. Analytical expressions for the distribution function of maximum duration could not be found for most cases and it was suggested that the distribution may have to be generated by process simulation.

2.3.5. Other methods of meteorological and hydrological drought analysis

Studies into the distributions of other aspects of drought and low flow have also been carried out. The classical study of this type is that of Gumbel (1958), which considers, along with other analyses of extremes, the distribution of annual minimum streamflows. The Extreme Value Type I (EVI) distribution, also known as the Gumbel distribution, is commonly applied to flood flows. The same distribution can also be used for minima according to the principle of symmetry, but may not always adequately represent streamflows (Kottegoda and Rosso, 1997). The Extreme Value type III (EVIII), which has an upper (or lower) bound, is generally more appropriate for the representation of low flows. In the case of minima, the EVIII is known as the Weibull distribution.

Low flow analysis is useful for water resource planning, but a drawback of its use is that it provides no information about the duration or timing of the low flows (Sen, 1980b). In this sense, low flows are not necessarily indicative of drought. Low flow studies are mainly concerned with the expected periods of low flow in each year, while drought suggests a period of abnormally low flow.

Drought was considered by Joseph (1970) to be the consecutive 14-day period of each year with the lowest mean discharge. This would generally be considered a low flow study as opposed to drought. The gamma distribution was found to be most suitable for representing these 'droughts', but the Weibull and log-normal distributions were also acceptable.

2.3.6. Analysis of agricultural drought

Agricultural drought may be measured in terms of crop yields, or alternatively from a meteorological point of view, in which case primary consideration is given to evapotranspiration and soil moisture anomalies. Agricultural drought has been widely studied in Australia, and analysis has also been well developed in the US through use of the Palmer drought indices. As mentioned previously, use of the PDSI has not always been successful outside the US. Other agricultural drought indices have been developed, including that of Meyer et al (1993), and the STIN agro-climatic stress index model as discussed by Stephens (1998). The STIN model is a combination of an FAO crop monitoring method with a soil water balance model. It accounts for rainfall, evaporation, drainage and crop water requirements and allows multi-year droughts to be considered. Rangeland drought indices used in South Africa include the ZA Shrubland Model and the PUTU Suite of Plant Models, all of which consider rainfall and temperature, and some also take in to account soil characteristics (du Pisani et al, 1998).

2.3.7. Regionalisation

Some account must be taken of the regional extent of a drought. As discussed in section 2.1, drought is not a point process, but unfortunately, the characteristics of a drought do not remain constant across a region. This can make regional studies complicated. Streamflow analyses are useful in regionalisation as they provide an integrated view of rainfall (and potentially groundwater) deficits across a catchment.

If there is a suitably dense network of rainfall or streamflow gauging stations, a contour map showing the variation of drought severity, duration or magnitude can be produced. This is similar to an isohyetal map of average rainfalls, except showing the rainfall deficit at a particular time. Since the time of occurrence of a drought may differ between locations, production of such maps will not always be an easy task. It is even more complex if considering a streamflow drought, due to the complexities in conversion of rainfall to runoff, and the varying density of stream networks.

Correlations of rainfall deficiencies between stations can be useful in determining the spatial extent of a drought. If a particular location is taken as the centre of a drought, then it may be possible to determine a relationship between the distance to satellite stations and the correlation of rainfall at those stations to the central station (Beran and Rodier, 1985).

Regional characteristics of drought, including the deficit area, the total areal deficit, and the maximum intensity, were considered by Sen (1980b). A truncation level can be used, similarly to the point processes discussed earlier in this section, but in this case there is a truncation plane across a whole catchment, dividing it in to areas of surplus and deficit. The distribution functions of the surplus and deficits can be calculated.

2.4. Drought persistence

2.4.1. Studies of persistence

Various studies have been carried out considering the phenomenon of drought persistence. That is, the perpetuation of droughts over a longer duration than can be considered chance. This is mainly concerned with a multi-year time scale, and within-year persistence seems to be a less contentious issue. According to Beran and Rodier (1985), most of the persistence studies have been of two types. Firstly, using the study of runs (section 2.3), and secondly, through consideration of first order autocorrelation coefficients. The results of these studies have been somewhat conflicting, with few studies finding significant serial correlations, despite the presence of a number of extremely long runs of below-average conditions (for example in the Sahel through the late 1960s and the 1970s). It was suggested by Beran and Rodier (1985) that this conflicting evidence could be explained if the persistence applied mainly to extreme years. This would cause correlations to be lower while still allowing runs of more extreme values to occur.

It also seems feasible, particularly for rainfall, that persistence is more likely to be displayed if average values over a region are considered rather than individual stations. This is because local, small-scale variations are dampened out in the averaging process. However the question then arises as to whether a drought is really occurring, if it cannot be distinguished at individual locations. This will depend on the spatial scale in question, and on the degree of variability. If large variations in rainfall occur in a small space then point readings would not be expected to give a good indication of drought conditions. In this case, spatial averaging would be preferable although the high variability actually makes this a difficult task unless there is a very dense network of raingauges.

The lifestyle of the people in the region also affects the suitability and scale of averaging that should be carried out. Settled, small-scale agriculture is actually dependent on point rainfall and thus from the individual point of view, averaging may be un-necessary. In contrast, the pastoralist lifestyle is specifically adapted to rainfall variability and allows migration to areas where water is available. In this case, while a regional deficit is definitely a much more severe problem, the variation which is lost in the regionalisation process is crucial for determining actual impacts. For water supply deficits which are dependent on stored water, regional averaging would be expected to be an integral part of the management process.

Simple tests for persistence have been carried out by ranking sample values and dividing them in to equal classes, such as quartile or quintile classes. A contingency table (transitional matrix) can then be formed showing the number of times that a value in class *i* is succeeded in the time series by another value of the same class. If a value in class *i* is more commonly followed by another value in the same class than any other, then it may be concluded that some persistence is occurring. This could also be carried out using only two classes, wet and dry, if the sample size is small (e.g. Gommes and Petrassi, 1994).

In the case of persistence being evident more in extreme years, the transition matrix would have its largest values in the highest and lowest classes (Beran and Rodier, 1985).

In contrast to the conclusions of Beran and Rodier (1985), Nicholson (1983) determined that the lag-1, -2 and -3 autocorrelations for annual rainfall in the West African Sahel did show evidence of persistence. This was also suggested by the presence of extremely long runs, particularly the continuation of below-normal rainfall in the Sahel throughout the 1970s and 1980s.

This persistence was later quantified by Long *et al* (2000) using the correlation scale of fluctuation, expressed as:

$$\theta = \int_0^\infty \rho(\tau)d\tau$$

where $\rho(\tau)$ is the autocorrelation. The scale of fluctuation θ is expressed in units of time, with a larger θ indicating more persistence.

2.4.2. Potential causes of persistence

Possible causes of multi-year drought persistence and cyclicity have been widely contemplated in climatological studies. A popular theory has been association of droughts with the 11-year sun-spot cycle, although conclusions have been conflicting.

A number of positive feedback mechanisms have been proposed which could contribute to the perpetuation of droughts. These are primarily related to the effects of decreasing surface vegetation. Firstly, reduced vegetation can increase the surface albedo, which causes a local heat deficit, and the resulting temperature gradient induces subsidence (Beran and Rodier, 1985). Secondly, in regions where internal recycling is important for the occurrence of precipitation, the removal of vegetation could potentially decrease the moisture available for rainfall by reducing evapotranspiration. This was investigated by de Ridder (1998) for Sahelian West Africa, and it was discovered that evaporation from vegetated surfaces became significantly greater than that from bare soil within three days of rainfall. This was due to rapid drying out of the surface, with the resulting decrease in diffusivity preventing further capillary rise. In contrast, vegetation is able to withdraw water from deeper below the surface so evapotranspiration could be sustained for longer. It was found that this was particularly significant in West Africa where convective precipitation is induced by easterly waves which have a period of 3-5 days. Thirdly, reduction of vegetation may increase dust in the atmosphere, which could increase atmospheric albedo and so induce subsidence (Beran and Rodier, 1985). These feedback mechanisms have been tested by theoretical climate models for the Sahel (Nicholson, 1983).

It is important to note that Nicholson (1983) considered drought in the Kalahari in addition to the Sahel. While the two regions share many characteristics, as they are both influenced by the ITCZ, are at similar latitudes (although on opposite sides of the equator), and often experience similar rainfall anomalies, no significant persistence in the Kalahari was detected. It was proposed that this is because synoptic disturbances in the Kalahari are less sensitive to surface boundary conditions than those of the Sahel. Thus such feedback mechanisms may not be worldwide phenomena but could exist only under specific conditions.

Anomalies in sea-surface temperature (SST) are known to be important in influencing climate, and these effects tend to perpetuate due to the high storage capacity of the oceans, resulting in slow temperature changes. This is an important contributing factor to both within-year and multi-year droughts.

Persistence of hydrological drought is in principle easier to explain than meteorological drought due to the inertia involved in the release of water from storage (Beran and Rodier, 1985). This inertia does not apply to the same extent to a meteorological or climatological drought.

2.5. Drought prediction and monitoring

The monitoring and prediction of drought can be divided into the consideration of cause and of effect. Consideration of cause involves climatological forecasting, ultimately the long and short-term forecasting of rainfall, temperature and other climatic variables. The second option is more concerned with the impacts of drought, and uses observed and forecasted climatic data to predict the effect on crops, livestock or water supply.

An alternative approach is to consider the probability of drought occurrence based on its statistical characteristics, independently of meteorological forecasting.

2.5.1. Probabilistic forecasting

The theory of runs, discussed in section 2.3, has been adapted by Moyé *et al.* (1988) to be of use for drought likelihood estimation. In any year, the occurrence or non-occurrence of drought is determined by the success or failure of a Bernoulli trial, i.e. the annual rainfall lies either above or below a threshold, but the magnitude is not considered. The average drought duration for the next n years is determined based on knowledge of the distributions of duration and the expected number of droughts. The probability of occurrence of a run of length K could be determined for any probability of failure (q), run length (K) and number of years (n).

2.5.2. Climate prediction

Meteorological forecasting techniques are beyond the focus of this study, particularly for the short range. Long-range forecasting is concerned with the wide-scale atmospheric and oceanic circulations that have been discussed previously. Sea surface temperature anomalies are invaluable for this type of forecast, and can give indications of likely meteorological conditions months in advance. This is particularly the case for the Southern Oscillation Index and El Niño (SOI and ENSO), the development of which in the Southern Pacific is now carefully monitored. The resulting variations in SST can be tracked around the world.

Ropelewski and Halpert (1989) found 12 regions across the world where rainfall anomalies were associated with the Southern Oscillation Index (SOI), including the West Pacific, Australia, Indian sub-continent, eastern South America and parts of North and Central America. The relationship of rainfall to SOI is not constant between regions, with some experiencing increased rainfall during high SOI while other regions will have reduced rainfall.

Other teleconnections, such as the relationship between East African winds and Indian monsoons, can also be useful for forecasting (Beran and Rodier, 1985).

The potential for using El Niño developments to forecast drought in Botswana was considered by Nicholson *et al.* (2001). Drought in Botswana is known to be closely associated with ENSO events, although if the SOI anomaly is relatively weak and short-lived then drought conditions will not necessarily ensue. It was determined that rainfall variability was dependent on wide-scale spatial patterns of SST in the Atlantic and Indian Oceans, but that local SST anomalies alone would be inadequate for forecasting.

Seasonal forecasting incorporates historical time series. The state of the climate at the start of the season is considered, and years from the historical time series which began the season in a similar state are extracted. The changes through the year are examined, and a probability of below-normal, normal or above-normal rainfall is determined based on this history.

2.5.3. Prediction and monitoring of drought impacts

A number of drought monitoring systems have been developed, most of which are regionally specific. Impacts on agriculture, particularly crop yields, and the monitoring of public water supplies are two common concerns.

Wide-scale models have been developed for the prediction of drought impacts on crop yields, often incorporating remotely sensed data. This is, for example, the case for the USGS Famine Early Warning System (FEWS) crop model for sub-Saharan Africa, which is a GIS-based system incorporating remotely sensed imagery in the form of rainfall estimates and the normalised difference vegetation index (NDVI), along with variable soil type. Rainfall estimates (RFE) are made using cold-cloud duration (CCD) and microwave sounding. Ground stations are used as much as possible to calibrate such estimates, and the validity of RFE where ground data is sparse may be questionable. The spatial resolution of the data is coarse (eight kilometres in the case of the USGS model), but it has been argued that this is adequate for a continental or regional-scale early warning system, which is then backed up by ground monitoring (Gideon Galu, personal communication).

Agricultural monitoring systems should be crop-specific and take in to account differing water requirements through growth stages (Lourens and de Jager, 1996). This is a limitation of the USGS model, which while considering both maize and sorghum, takes no account of sub-species, and crop water requirements have only been verified for West Africa (this limitation is discussed further in chapter 3).

The success of remotely sensed imagery in predicting crop yields was investigated for southern Africa by Unganai and Kogan (1998). This involved the use of NDVI and Brightness Temperature (BT), adapted for each grid cell to give vegetation and temperature condition indices (VCI and TCI respectively). Historical records of the VCI and TCI were correlated against actual meteorological conditions in terms of 500mbar geopotential height anomalies, and also against actual crop yields. Good correlations were found in both cases, and as a result corn-yield models were developed based on regression relationships to remotely sensed data. The model adequately predicted crop yields approximately six weeks in advance of harvest, and it was thought that this could be applied successfully across most of southern Africa.

Chapter 3- Rainfall analysis

Somalia has an arid to semi-arid climate, which is influenced predominantly by the Inter-Tropical Convergence Zone (ITCZ) and the Somali Jet. Orographic and coastal influences are also significant and cause a high degree of variability across the country.

3.1. General climatology

The ITCZ represents the boundary between the Hadley cells of the northern and southern hemispheres (Nieuwolt, 1977). Convergence of the northeasterly and southeasterly trade winds creates a region of uplift and instability positioned approximately over the equator. This zone moves north and south of the equator through the year according to the relative position of the sun. Equatorial climates are dominated by the movement of the ITCZ. Regions close to the equator generally have two rainy seasons, as the ITCZ passes north and south, while those at the northern and southern extremes of its passage have only one. Movement of the ITCZ is affected by the oceans and topography, and so the movement across Somalia is affected by the African and Asian landmasses, by the Arabian Peninsula, and by the Western Indian Ocean (Hutchinson and Polishchouk, 1989).

The climate in Somalia is also influenced by the low-level Somali Jet, which is of significant extent between May and September. East-southeasterly flow is present to the east of Madagascar year-round, but from October to April its extension to the African coast is prevented by strong northeasterly flow from the Arabian Sea. When this flow weakens in March, the flow off Madagascar strengthens and by May the southeasterly jet reaches equatorial East Africa. It is deflected by the Kenyan-Ethiopian highlands to curve in to a southwesterly flow, which passes across the length of Somalia and exits the African landmass across the Horn, where it extends towards the Indian subcontinent. The flow is disrupted later in the year as the ITCZ moves back towards the south, pushing the Somali Jet with it. The jet has average wind speeds of up to 35 knots (Hutchinson and Polishchouk, 1989).

Most studies of the Somali jet have been concerned with its influence on the Southeast Asian monsoons. The exact impacts on Somali rainfall are not known, but it is known to be the cause of the intense aridity of northern and northeastern Somalia. The north coast is unique among coastal regions in having an onshore to offshore wind, which is dry as it has already lost its moisture over Madagascar and Equatorial East Africa (Nieuwolt, 1977 and Hutchinson and Polishchouk, 1989).

3.2. Data

3.2.1. Data sources

There is little good quality data, or at least data of known quality, for Somalia. The primary source of rainfall data still in existence is often unknown. However data collection activities are known to have been carried out by:

- Somalia Government Food Early Warning System (FEWS)
- Fantoli, "Contributo alla climatologia della Somalia", Rome 1965
- Large-scale agricultural projects, e.g. J.S.P Sugar Project
- Civil Aviation Service
- Short periods of data collection by various consultants
- Current data collection by Food Security Assessment Unit (FSAU) and FAO

Secondary data sources include:

- Hutchinson and Polishchouk, "Agroclimatology of Somalia", FEWS, 1989
- FAO
- University of East Anglia, Climate Research Unit (CRU)
- Australian National University
- USGS/FEWS NET
- British Meteorological Office

Fantoli (1965) is the most comprehensive source of pre-1965 data, with daily rainfall records extending back to the early 20th century. Unfortunately the location of this publication is now unknown. The appendices of Hutchinson and Polishchouk (1989) also contained extensive time series, but only the main text of this document has been located.

The data used in this analysis was made available by the FAO and the CRU, who have accumulated data from various sources. In some cases the primary source of the FAO data has been recorded, but the source of CRU data is unknown.

Most of the available data is monthly, although the FAO also has 10-day (decadal) time series. The FAO have monthly data for approximately fifty 55 stations across Somalia. Much of this is intermittent and has not been quality checked. For some stations the records are as short as two years, but there are records extending back to 1894 for Mogadishu and Kismayo. A number of other stations have records back to the early 20th century.

The period from 1963-1990 has been concentrated on in the analysis, as this is the time during which streamflow data is available. This will allow comparison between the two water sources.

Station name	Station number	Latitude	Longitude	Elevation (mASL)	Known sources
Kismayo	SO02CHSM	-0°22'S	42°26'E	8	BMO, CA, Fantoli, WB
Bardheere	SO22BRDR	2°21'N	2°18'E	116	Fantoli, BMO, CA, FEWS
Iscia Baidoa	SO33SCBD	3°08'N	43°40'E	487	Fantoli, ACARS, CA, BRADP
Mogadishu	SO25MGDS	2°02'N	45°21'E	9	Unknown
Afgoi	SO25FG00	2°08'N	45°08'E	83	Fantoli, CARS, LAHM, FEWS
Belet Weyne	SO45BLTN	4°42'N	45°13'E	173	Fantoli, BMO, CA
Galcayo	SO67GLKY	6°51'N	47°26'E	302	Fantoli, BMO, Hunt, CA, FEWS

Table 3.1. Main rainfall stations used in analysis.
Sources: British Meteorological Office (BMO), Civil Aviation Service (CA), "Contibuto alla climatologia della Somalia" by Fantoli, World Bank Sector Review (WB), Somali Government Food Early Warning System (FEWS), Afgoi Central Agricultural Research Station (ACARS), Baidoa Regional Agricultural Development Project (BRADP), Central Agricultural Research Station (CARS), Lahmeyer International (LAHM), General Survey of Somaliland (Hunt

Analysis has focussed mainly on seven stations in Southern and Central Somalia which have the most complete records for 1963-1990. These are shown in table 3.1. The records for Belet Weyne and Galcayo are complete, while the others have data missing from between 1-6 years.

3.2.2. Data quality

Both the FAO and CRU have data for all the seven stations given in table 3.1. As would be expected, in most cases the data sets were identical. This is reassuring but is not conclusive evidence that the data is of high quality. It is probable that the data is all from the same primary source, and the consistency and reliability of sampling and recording methods from this source have to be assumed.

For some stations, there were months or years of data which were present in one data set (FAO or CRU) but not the other. Since the data was identical through the rest of the time-period, it was assumed that the two sets could be combined, in order to have the most complete time series possible.

Unfortunately, comparison of the data sets for Mogadishu and Kismayo revealed significant differences between the two sources throughout most of the 27-year period of 1963-1990. It was speculated that the data could have been obtained from different rain gauges near the same town, but since the differences were not consistent (e.g. sometimes they were the same, and sometimes had hundreds of mm difference) this was thought unlikely.

Since the primary sources of the two data sets were unknown, assumptions about the reliability of the sources could not be made. However, it was still possible to determine with some degree of certainty which was correct, by using a number of different methods.

The acceptability of the FAO data set was first considered. Time-series of annual totals were derived from the monthly data, and the resulting annual series for all stations were plotted together. Due to the great spatial and temporal variability of rainfall in Somalia, it was not possible to determine visually any constant relationships between stations, and so no conclusions could be drawn from this exercise.

All seven data sets were tested for outliers using cumulative plots. Plots were produced showing the monthly time-series of the station in question, against the average of the remaining six stations. This type of plot is generally expected to produce an approximately straight line, and any abrupt changes in slope or unusual discrepancies can be taken as an indication of errors in the data.

For most cases a relatively straight line was obtained, although there were a few exceptions, which are shown in figure 3.1. Rainfall at Galcayo appears to decrease relative to the other stations for the last three years of the record. This could be a result of a change in the siting or the type of rain gauge. Anomalous jumps in the plots occur for Belet Weyne, Mogadishu and Kismayo. Since rainfall events are often heavy and localised, this could be the result of genuinely large events at individual locations. However, if the rest of the graph is a fairly straight line, it may also be an indication of sampling or recording problems.

Cumulative plots of the CRU and FAO time series for Mogadishu and Kismayo are compared in figure 3.2. The CRU plots appear more linear, suggesting that the FAO data is incorrect, although it is still difficult to draw conclusions based on this analysis.

Ten-day time series later became available from the FAO. These were converted to monthly rainfall by addition of the 10-day periods in groups of threes, and the resulting time-series were identical to the CRU data. This requires that either the 10-day or monthly FAO data sets must be incorrect. If the 10-day data were incorrect, this would indicate that the CRU must have had the same incorrect 10-day series and cumulated it to monthly. It seems more likely that a mix-up of the FAO monthly data has somehow resulted in incorrect time-series being recorded for Mogadishu and Kismayo.

On this basis, backed up by the cumulative plots, it was decided to use the CRU time series for both Mogadishu and Kismayo in the analysis.

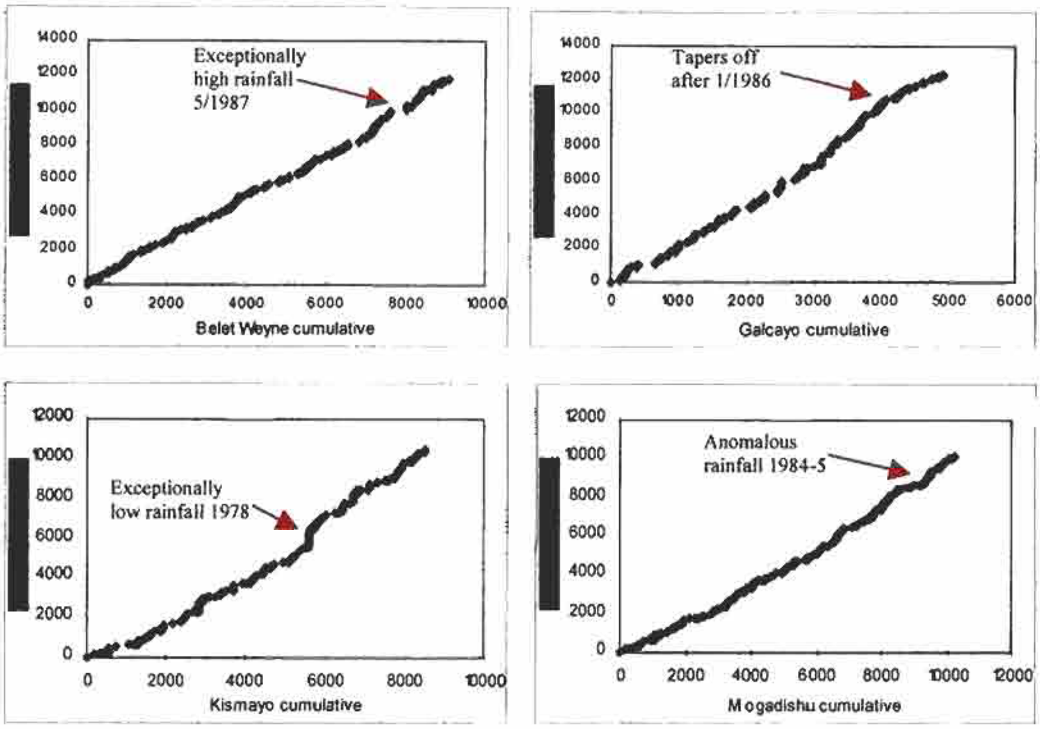


Figure 3.1 Cumulative rainfall plots to test for outliers. a) Belet Weyne b) Galcayo c) Kismayo d) Mogadishu

3.2.3. Attempts at data infilling

It is desirable to have a complete time-series so as to be able to consider the cumulative changes over time, and to aid in comparison between locations. It was proposed that infilling of data for incomplete time-series could be carried out by correlation to other stations.

Unfortunately, the rainfall in Somalia is highly variable in both time and space, and most stations are located hundreds of kilometres apart. In addition, zero monthly rainfall is frequently recorded in the dry seasons. This truncates the frequency distribution and distorts correlation or regression analysis. For correlation to be carried out, a normal distribution is usually assumed, but rainfall in arid climates tends to be highly skewed, particularly over shorter time-periods (Maidment, 1992). Removing the zeros reduces the skewness, but the pattern of zero-rainfall months must then be considered separately.

Comparison of monthly rainfall (with zeroes removed) between the seven main stations resulted in correlations of less than 0.6. This was not acceptable, particularly when scatterplots of one station against another were considered (one of the more successful examples is shown in figure 3.3!).

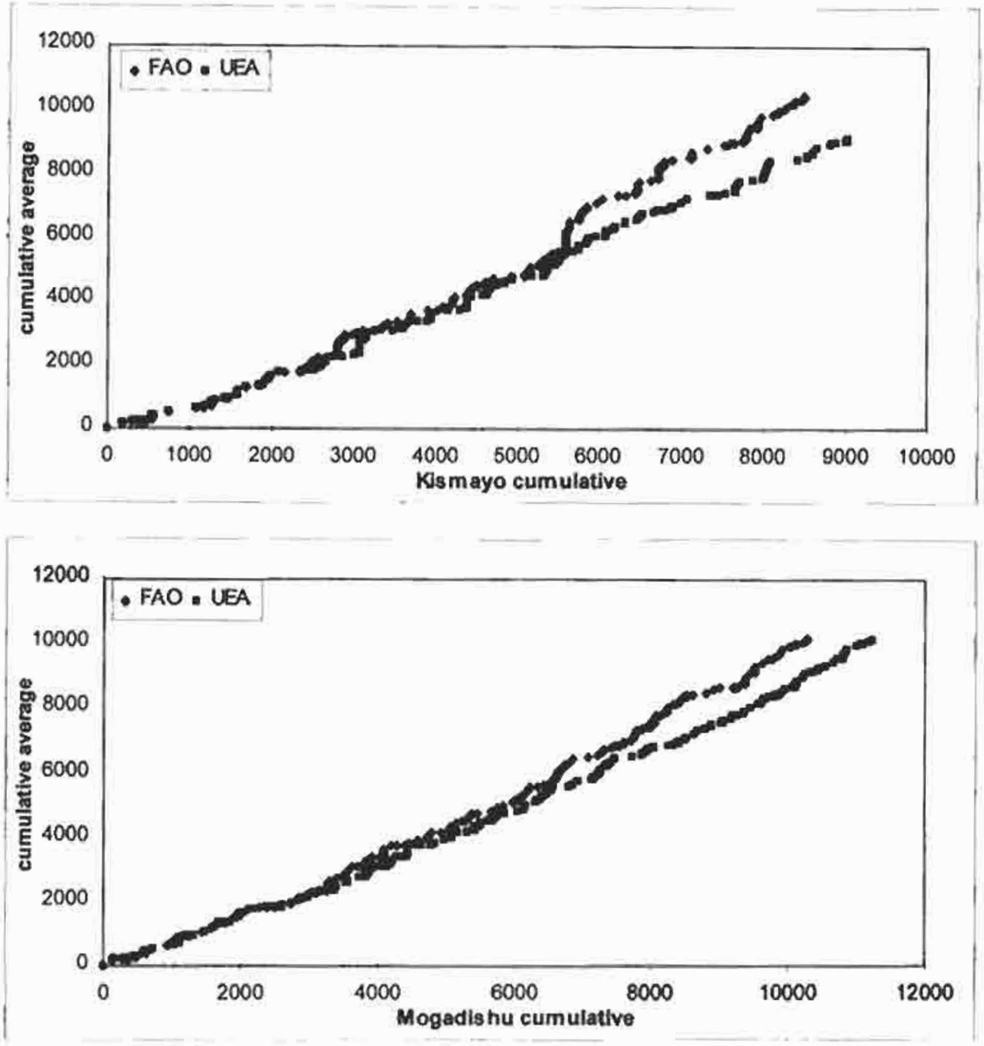


Figure 3.2. Comparison of FAO and CRU rainfall data sets for Kismayo and Mogadishu

It is possible that the correlation would be more successful if each month were considered separately. It also seems likely that stations could be better correlated based on annual data as opposed to monthly since the time-step is longer, and use of annual data also removes the problem of zeroes. However it transpired that even when using annual data, the only pair of stations with correlation exceeding 0.6 was Mogadishu-Afgoi.

It was then proposed that it might at least be possible to determine whether annual rainfall was above or below average based on comparison to other stations. Even this proved unsuccessful, with only 1968 and 1989 recording above-average rainfall at all stations, and only 1974 recording all below-average rainfall. If Galcayo is excluded (on account of its northern position and drier climate), the number of years being all above or all below average rises only to seven out of 27.

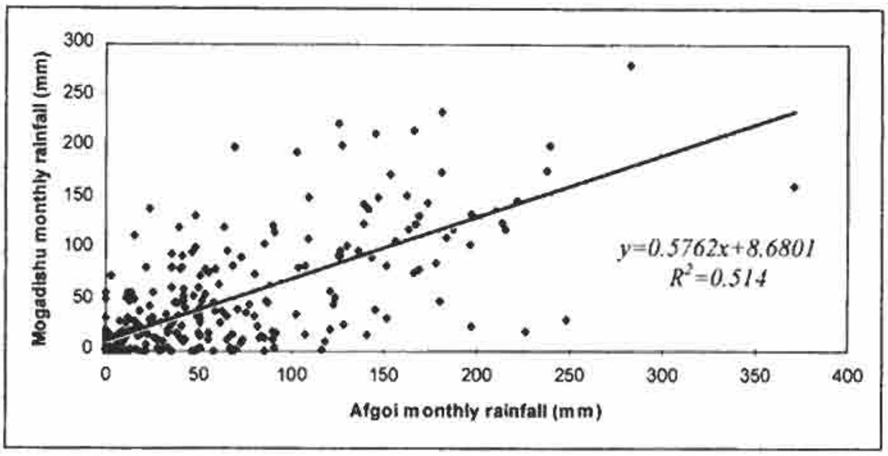


Figure 3.3. Example of an attempt at regression between rainfall stations (monthly data)

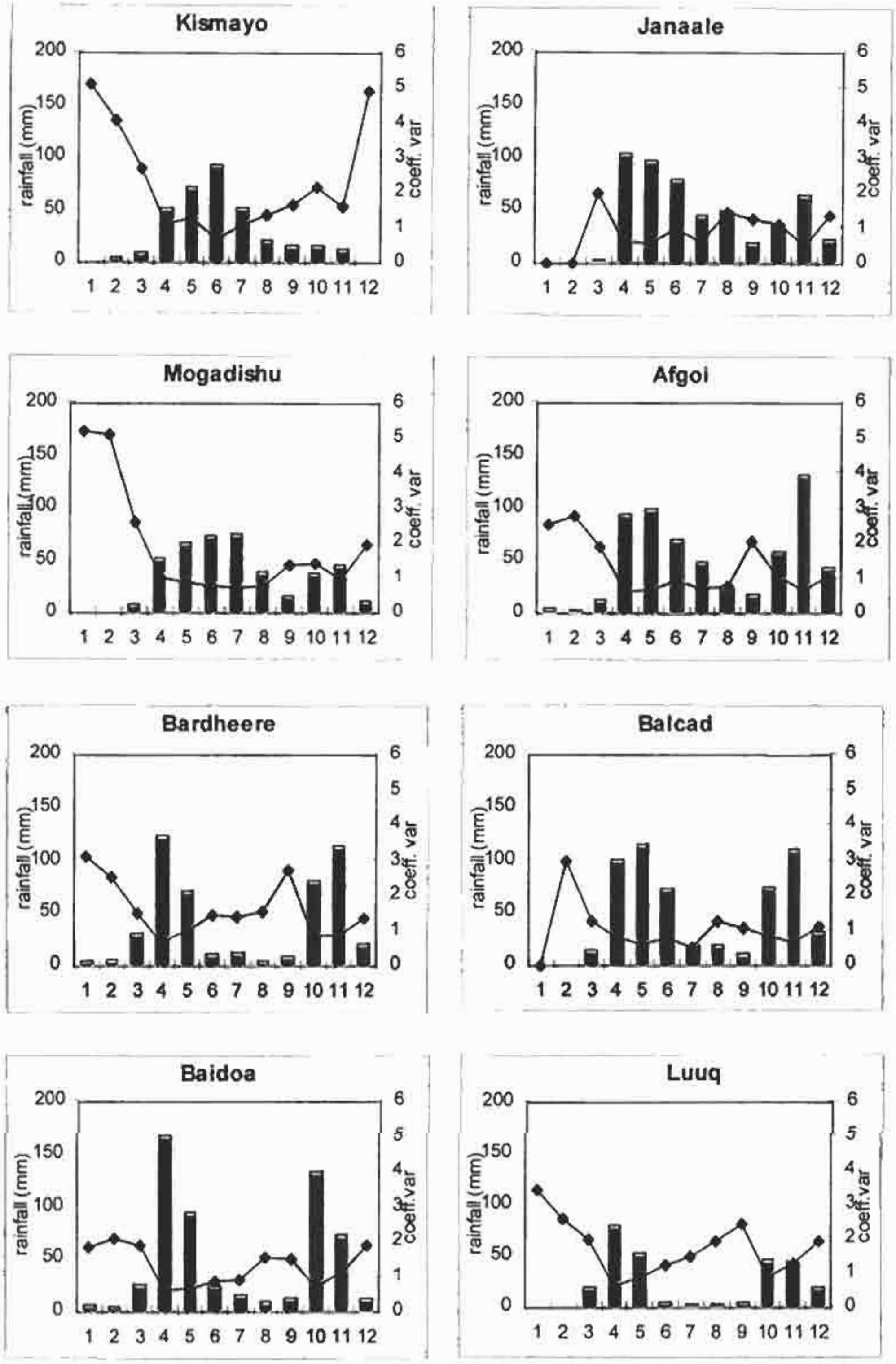
It had to be concluded that infilling data in an arid environment such as Somalia, where rainfall variability is so high and rainfall gauging stations are so widely spaced, is impractical. Thus analysis was carried out as far as possible without infilling, except where the FAO and CRU data were combined.

3.3. Temporal and spatial rainfall variability

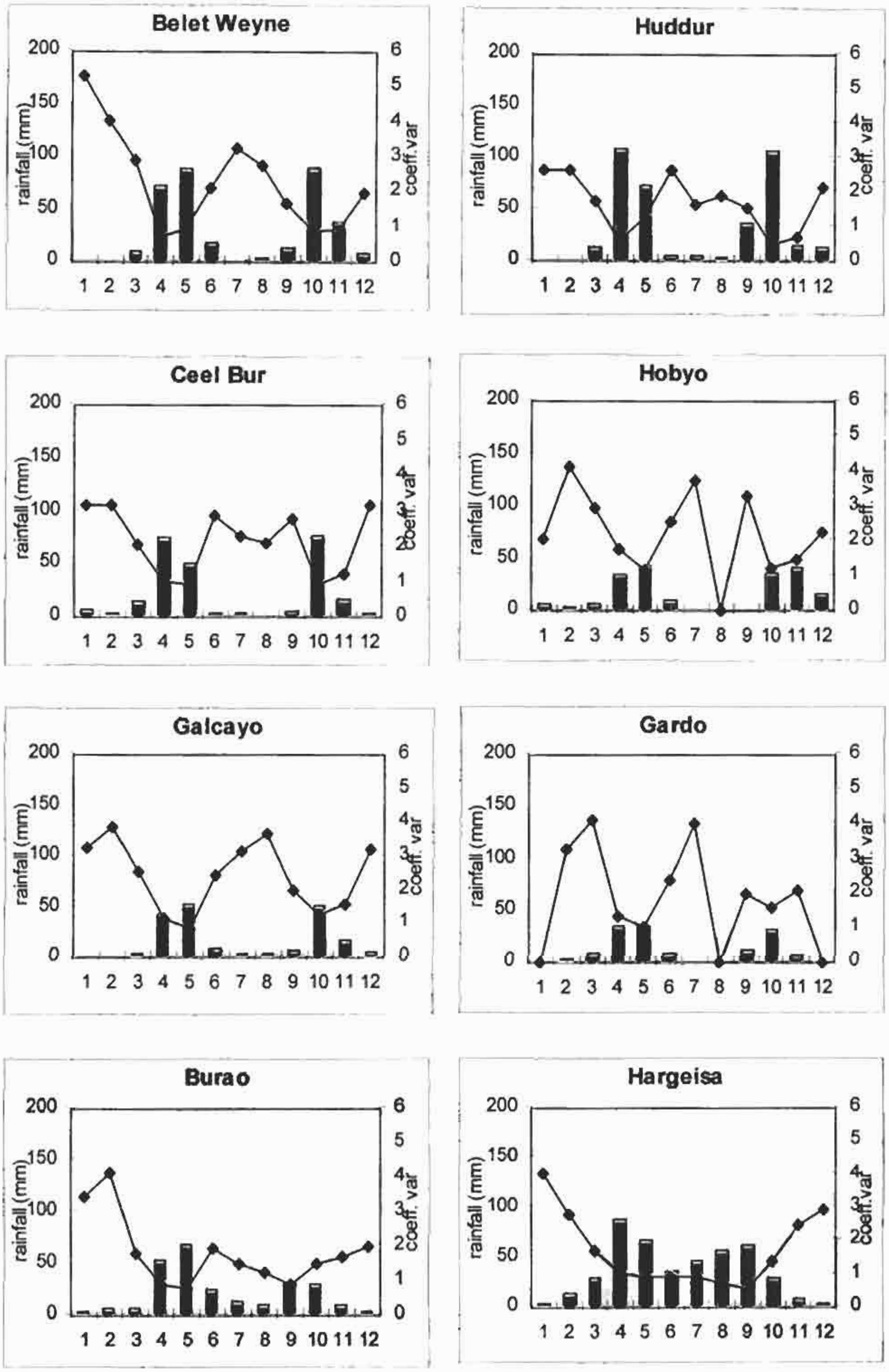
3.3.1. Within-year rainfall variability

The average annual distribution of rainfall is shown for various stations across Somalia in figure 3.4. Additional stations other than the main seven have been used in this figure to give a firmer idea of the spatial variability across the whole country. The locations of the stations are shown in figure 3.4.a. Northern Somalia is shown for comparison to the south, although this has not been considered in subsequent analyses. The averages were calculated using all available data between 1963-1990, although in some cases this amounted to as few as ten years.

Somalia has two rainy seasons. The timing of the seasons varies across the country, but the *Gu* can be approximately defined as extending from March-July, and the *De*yr from August-November. The highest rainfall months are generally April-May and October-November. The Gu season dominates over the Deyr (usually in quantity, but also in reliability) and is treated as the primary cropping season.


Kismayo
Janaale
Mogadishu
Afgoi
Bardheere
Balcad
Baidoa
Luuq
rainfall (mm)
coeff. var
0
50
100
150
200
0
1
2
3
4
5
6
1 2 3 4 5 6 7 8 9 10 11 12

(Figure 3.4)



(Figure 3.4 continued)

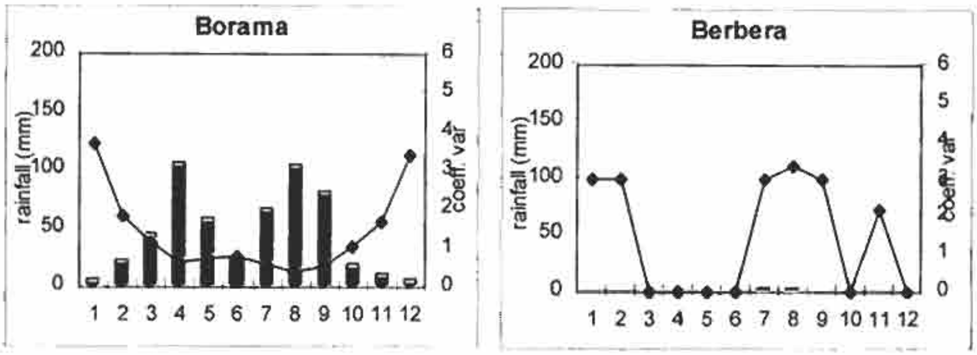


Figure 3.4. Rainfall distributions across Somalia. Figures arranged approximately from south to north.

The main dry season is the Jilaal, occurring between December-March, when the ITCZ is far to the south. The secondary dry season, the Haggai, occurs between the Gu and Deyr rainy seasons. It extends from approximately July-September, but this varies across the country and significant rainfall occurs during this period along the coast. This makes the distinction between seasons less defined on the coast. The Deyr rains are much smaller on the coast, particularly in the southernmost part of the country around Kismayo, where there is no reliable increase in rainfall at the time of the Deyr. The Deyr season is also minor at Janaale and Mogadishu.

There is much more distinction between seasons inland, particularly close to the Ethiopian border, where rain rarely falls in January, February or June-September. Rare but heavy rainfall events can however occur during these months, resulting in a high coefficient of variation.

Afgoi and Mogadishu are less than 50km apart and generally show similar rainfall patterns. The exception to this is November, where the average rainfall for Afgoi is twice that of Mogadishu. Since Mogadishu is coastal, and Afgoi some distance inland, differences would be expected between the two. However the magnitude of the difference in November is still somewhat surprising given the small distance of separation. Rainfall in November at Afgoi is similar to that of neighbouring Balcad, but much greater than at Janaale. Janaale is located a similar distance inland to Afgoi but its rainfall patterns are more coastal. The differences are most likely to be due to the position of the Somali Jet and localised coastal effects.

Rainfall in Northern and Central Somalia is considerably lower than in the south, with the exception being the Northern Plateau. There is a marked contrast in rainfall between the plateau (Borama and Hargeisa) and the north coast (Berbera). Rainfall is rare at Berbera, but occurs more commonly during the Deyr than the Gu.

The pattern of rainfall is similar in Northern Somalia to the south, but there is a shorter gap between the Gu and Deyr seasons. The timing of the start of the Gu season is variable, being earlier on the plateau due to topographic influences. The Deyr season starts earlier across the whole of northern Somalia in comparison to the south as a result of the movement of the ITCZ from the north.

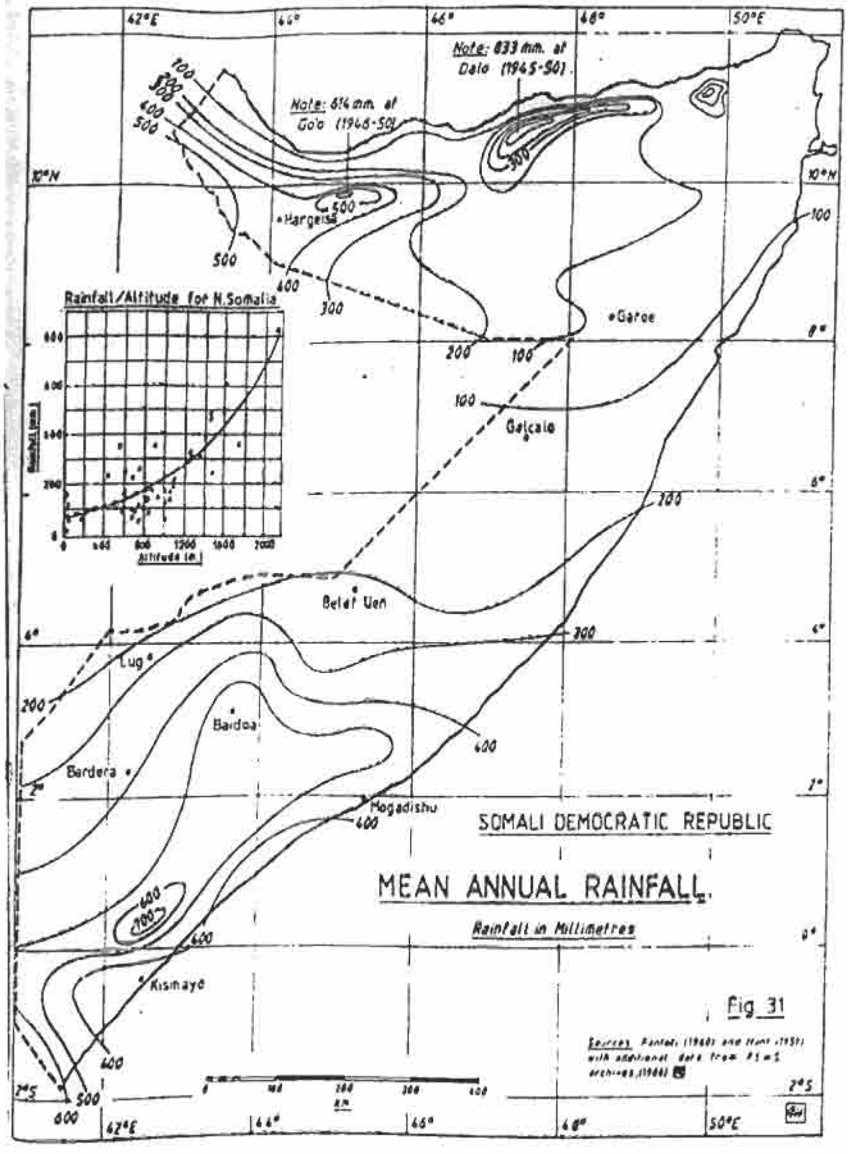


Figure 3.5. Spatial distribution of rainfall across Somalia. Source: Hutchinson and Polishchouk, 1989

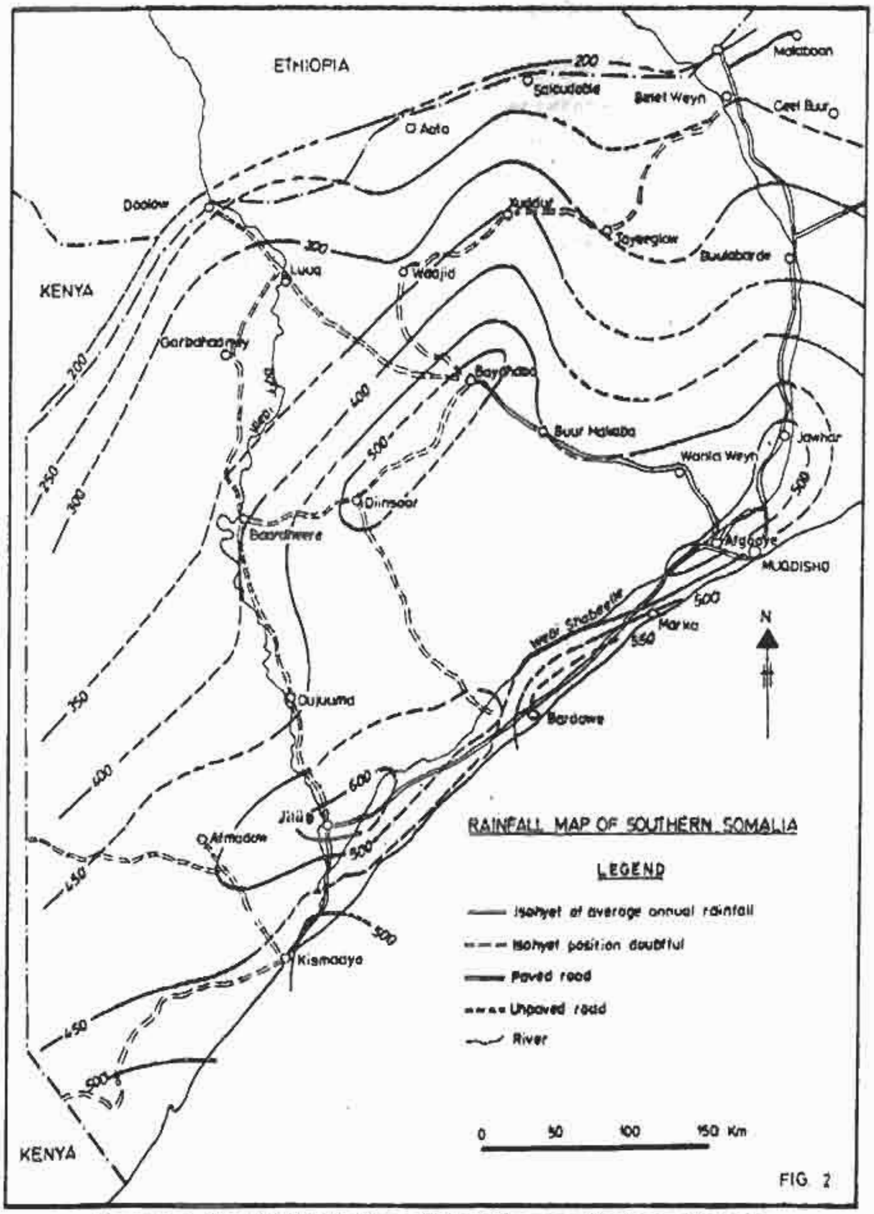


FIG 2

Figure 3.6. Spatial distribution of rainfall across Southern Somalia
Source: Hunting Technical Services, 1977

3.3.2. Spatial variability in annual rainfall

A number of maps have been produced showing the distribution of annual rainfall across Somalia. These include Hutchinson and Polishchouk (1989), Fantoli (1965), Kammer (1989) and Hunting Technical (1977). Examples are shown in figures 3.5 and 3.6. The maps from the various sources differ somewhat depending on the interpolation technique used.

The accuracy and value of these maps is questionable due to the sparse gauge network and the high inter-annual variability in rainfall. In addition, the use of annual totals alone may not be very useful since there are two cropping seasons, and since the intensity, duration and timing of rainfall can be more important than the total amount. Nevertheless, this is a simple way to express the limited knowledge about the spatial variability of the rainfall.

Rainfall is well correlated with elevation in Northern Somalia, but this is not the case in the South of the country. There is generally little topography across Southern Somalia, although elevations are higher in the inter-riverine area. Elevation increases towards the Ethiopian border, but this does not correspond to an increase in rainfall. In fact, rainfall is lowest near the border with Ethiopia, while the highest rainfall occurs in a band parallel to the coast (although slightly inland), which is centred over Jilib and reaches Baidoa at its northern extent. It has been suggested by Hunting Technical (1977) that high rainfall over Baidoa is a result of topographic effects, while localised atmospheric instabilities due to swamp areas contribute to the high rainfall at Jilib.

Hutchinson and Polishchouk (1989) produced isohyetal maps for Gu and Deyr seasons individually. These showed similar patterns to the annual total but with the highest rainfall concentrated around Kismayo during the Gu. Rainfall is generally much lower and more patchy during the Deyr.

3.3.3. Characteristics of rainfall events

Some consideration of rainfall intensities and frequency of rain-days was carried out by Hutchinson and Polishchouk (1989), using daily rainfall data.

Rainfall is generally localised. According to Hunting Technical (1977), rain occurs mostly in isolated storm-cells, and rainfall intensities of greater than 75 mm/ hour have been known to occur in Southern Somalia. Williams (1996) stated that in the Gedo region, more than half the annual rainfall can fall in two hours during the Gu season. However Hutchinson and Polishchouk (1989) did not find any "very heavy" rainfalls in the records, with daily rainfall never reaching 200 mm.

3.3.4 Rainfall frequency analysis

The distribution of rainfall in arid climates is usually positively skewed, with the greatest skewness occurring when shorter time-periods are considered.

Histograms for each of the seven main stations were produced, and are shown in figure 3.8. The distribution of decadal rainfall is clearly highly positively skewed. The mode is zero at all locations, and the median is always less than one. Galcayo has the most highly skewed distribution, as expected since it is the driest of all the stations under consideration.

The characteristics of the decadal rainfall are summarised in table 3.2. The highest recorded rainfall in a 10-day period is 360mm, recorded at Baidoa in April 1981. No other stations had their maxima at the same time, illustrating the localised and variable nature of rainfall events. Both Afgoi and Mogadishu had their highest recorded 10-day rainfall in May

1964. For the other stations, the highest rainfalls were recorded at Bardheere during May 1972, at Belet Weyne during May 1987, at Galcayo during October 1965, and at Kismayo during June 1983. These all occurred during the Gu season, with the exception of Galcayo.

The distribution of annual rainfall totals is much less skewed than the decadal rainfall, with the annual mean and median being similar for all stations. The characteristics of the annual rainfall are shown in table 3.3. Cumulative frequencies for the annual rainfall were calculated and are shown in figure 3.7. This clearly shows that rainfall is lowest at Galcayo, while Afgoi and Baidoa have the highest annual totals. The cumulative curve for Afgoi is steeper than most others, with annual rainfall below 400 mm being rare.

Afgoi and Baidoa recorded the same year of minimum rainfall (1983), while Afgoi and Mogadishu had the same maximum (1967). Even over an annual scale it is clear that spatial variability in rainfall is an important issue. It appears that Mogadishu and Afgoi have the most similar rainfall, due to their close geographic position, at least when considering maxima. However there are still notable differences between the two with a significantly higher mean annual rainfall at Afgoi, which is reflected in the cumulative frequency curves.

The year of maximum decadal rainfall and maximum total annual rainfall coincides for Baidoa, Bardheere and Galcayo. This would appear to suggest that there may be more intense rainfall but fewer rain-days at these stations in comparison to the others. However this does not conform with the Hutchinson and Polishchouk (1989) study, which found Baidoa to have on average 14 rain-days per month, while Galcayo has only three. Thus single rainfall events would be more likely to have a significant impact on the annual total at Galcayo, while the high decadal rainfall at Baidoa in 1981 may have been an exception rather than the rule.

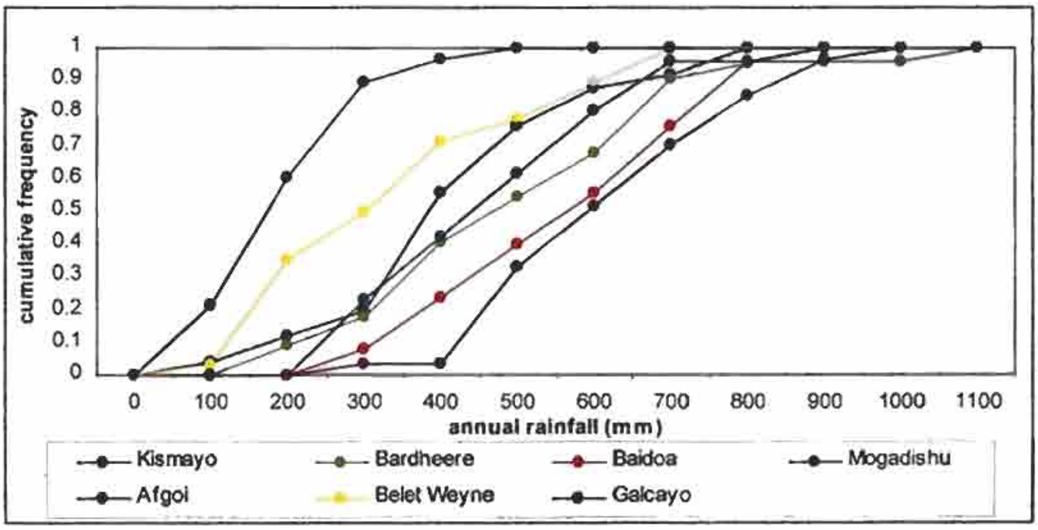


Figure 3.7. Cumulative frequency analysis for annual rainfall in Southern Somalia

	Kismayo	Bardheere	Baidoa	Mogadishu	Afgoi	BW	Galcayo
Mean (mm)	10.7	13.2	15.8	12.7	16.0	8.7	5.0
Median (mm)	0.0	0.0	0.0	0.7	0.1	0.0	0.0
Mode (mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Standard Deviation	26.5	30.3	35.2	25.8	31.6	23.4	17.7
Skewness	4.1	3.4	4.3	3.4	3.0	4.6	6.3
Kurtosis	22.3	13.8	27.2	16.1	10.4	29.1	55.8
Minimum (mm)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Maximum (mm)	229.0	230.0	360.4	251.9	241.0	274.8	232.0
Year of max.	1983	1972	1981	1964	1964	1987	1965

Table 3.2. Characteristics of decadal rainfall across Southern Somalia

	Kismayo	Bardheere	Baidoa	Mogadishu	Afgoi	BW	Galcayo
Mean (mm)	401.1	469.5	561.5	455.4	598.3	323.6	176.4
Median (mm)	379.6	433.0	556.0	455.3	585.0	290.5	169.5
Standard Deviation	173.3	183.2	187.7	169.4	162.4	173.8	90.6
Skewness	0.4	0.0	0.4	0.6	0.2	0.4	0.6
Kurtosis	0.1	-0.6	0.7	0.0	-0.7	-1.0	0.2
Minimum (mm)	77.7	116.0	205.0	214.0	293.0	55.0	33.0
Year of min.	1969	1970	1983	1978	1983	1974	1980
Maximum (mm)	769.7	813.0	1063.0	889.4	911.0	651.0	406.0
Year of max.	1981	1972	1981	1967	1967	1977	1965

Table 3.3. Characteristics of annual rainfall across Southern Somalia

3.4. Rainfall requirements

Rainfall is a crucial source of water supply in Somalia. This is particularly so away from the two main watercourses, and where groundwater is unreliable or of poor quality. Rainwater storage is common, in smaller domestic tanks known as ballis and berkads, and in large community stores called wars. Wars are water-storing depressions usually located in togga, which may be as deep as 2m but are usually unlined and uncovered and as a result can suffer high losses (Williams, 1996).

Rainfall is necessary for domestic requirements, crop growth, and livestock watering. Stored rainwater sustains pastoralists through the dry season, and when the stores become depleted, it is necessary to move to the rivers or borehole supplies. This can place pressure on groundwater supplies and may create tension between river-users.

Except for along the banks of the Juba and Shabelle, all crops are rain-fed. Rain-fed cropping is practiced particularly in the Bay and Bakool regions, centred around Baidoa, which has some of the most fertile soils of the country. Sorghum generally requires at least 300mm rain in a growing season, although some yield may be obtained with as little as 175mm rainfall (Hunting Technical, 1977).

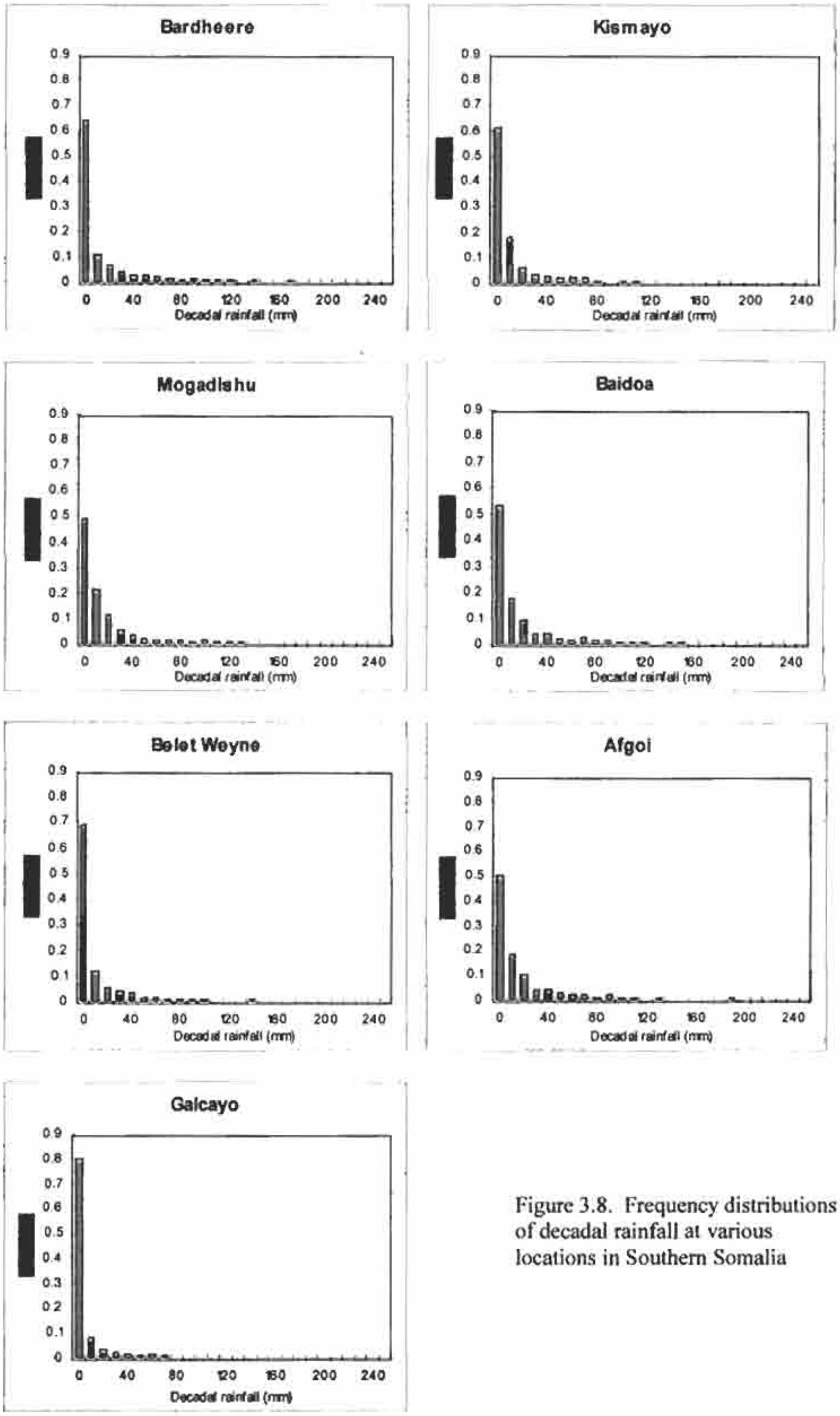


Figure 3.8. Frequency distributions of decadal rainfall at various locations in Southern Somalia

Timing of the rains is crucial for agriculture, as the seasons are short and unpredictable. Early starts can catch farmers unprepared, but at the other extreme, if planting goes ahead and the rains then cease, the season's crops may be lost. Total rainfall volume will not always be adequate for determining the success of a cropping season, as a single large storm can result in a high season total, while also causing flooding and wiping out crops.
(Water requirements are discussed further in chapter 6.)

3.5. Within-year runs and dry season duration

The success of crop growth and the replenishment of water storage depend on the duration of both the dry and rainy seasons, and on the intensity and duration of individual rainfall events. The timing of the start of the rainy seasons is crucial for the successful establishment of crops.

3.5.1. Defining the start of the season

The United States Geological Survey (USGS) has developed a Famine Early Warning System (FEWS-NET) which is in operation across much of Sub-Saharan Africa This includes a crop-specific model for predicting crop yields, as discussed in chapter 2. However, although it is crop-specific, the model only considers maize and sorghum, and does not take in to account the various sub-species, such as those which may be quick-growing or drought-tolerant. The model determines the date at which crop growth starts and uses this along with subsequent rainfall to predict crop yield. The full details of this model and their merits or disadvantages will not be discussed here, but of particular interest is the definition used for the start of the season.

The start of the season is defined by FEWS-NET as a decade with at least 25mm rain, followed by two decades each with at least 20mm rain. The first occurrence of this is taken to be the start of the season, and if this does not occur at all then it is assumed that crops will fail. These quantities are based on water requirements for seed germination, which have been verified for a single species of maize or sorghum, growing in West Africa (Gideon Galu, personal communication). Use of this criterion in the model assumes that it will adequately represent growth of any variety of these crops across the varying climates of Sub-Saharan Africa.

It is accepted that the FEWS definition for the start of the rainy season is not entirely satisfactory. However, for want of a better definition, it has been used here to determine the most likely start times of the cropping seasons across Southern Somalia. The problems associated with this are discussed in more detail following the analysis.

(In a previous study in to the duration of rainy seasons (Hunting Technical, 1977), the start and end of the season were defined as the first and last days experiencing at least 10 mm rainfall).

3.5.2. Analysis of rainy season timing

The timing of the start of the rainy seasons, as defined by USGS, was examined for each of the seven main stations in Southern Somalia. The whole period of record for each station was used, resulting in some different record lengths, but no change in the average start-time was noticed.

The results of the analysis of start time are shown in table 3.4. The decade given is the first of the 3-decade period over which the start is observed. As expected, the provided definition for start of season results in a high probability of failure. Probability of failure was defined as the percentage of years in which the requirements for the start of season were not met.

For the Gu season, the start time varies between decade 10 (first 10 days of April) and decade 17 (second 10 days of June). A sequence of rains conforming to the definition for start of season has been known to occur as early as the end of March in Bardheere, and as late as the end of August in Mogadishu.

The most obvious difference in the Gu seasons between locations is the later start along the coast (Mogadishu and Kismayo). The rains start earlier inland due to the interaction of the ITCZ with the Kenyan-Ethiopian highlands (Hutchinson and Polishchouk, 1989).

The probability of failure is lowest for Baidoa, which lies within the band of highest annual rainfall and is known to be the most suitable area of the country for rain-fed cropping. The highest probability of failure occurs in Galcayo, which is expected as this is further north than the other stations, and has significantly lower annual rainfall. Belet Weyne also has a very high probability of failure, being in the area of low rainfall close to Ethiopia.

	Gu		**Deyr**	
Location	Most probable start time (decade)	Probability of failure (%)	Most probable start time (decade)	Probability of failure (%)
Belet Weyne	11	83	28	73
Bardheere	10	65	30	74
Baidoa	10	33	29	56
Galcayo	10	91	-	100
Afgoi	11	61	30	77
Mogadishu	17	55	28	73
Kismayo	15	54	-	100

Table 3.4. Start of rainy seasons across Southern Somalia

With the exception of Baidoa, all locations have a probability of failure greater than 50%. According to this analysis, Gu crop failure may be expected at Baidoa on average one year in every three.

Probability of failure for the Deyr using the given definition is extremely high, with 100% failure at Galcayo and Kismayo. It is clear from the annual rainfall distribution at Kismayo (figure 3.4) that the Deyr season does not really occur in this area, and it is assumed that no attempts would be made to plant crops there at this time of year. The same could be said for Galcayo, which in any case depends more on pastoralism than agriculture (FSAU, 2001).

There are no obvious spatial patterns in the start time of the Deyr season, which is not surprising given the known variability and patchiness of these rains. There is much less variation in the start time than for the Gu (if the start occurs at all), with the season almost always beginning in October (decades 28-30). At Mogadishu, Belet Weyne and Baidoa, the season may start as early as the last week of September, and in Baidoa and Bardheere as late as the beginning of November.

The high probabilities of failure give an indication of the inadequacy of the definition for start of season. There may be some truth in the results, as it has been estimated that both Gu and Deyr rains will fail on average once in three years (Hunting Technical, 1977 and Hutchinson, 1992). However those estimations are considerably smaller than the probabilities of failure determined here (with the exception of Baidoa). The water requirements for crops assumed by the FEWS/NET model are not necessarily correct for the Horn of Africa since cropping patterns are adapted to the climate and it is known, for example, that fast-growing sorghum and cowpeas are grown in the Hiraan region (ICRC). Thus it is concluded that the definition for start of season and the crop water requirements assumed by the FEWS/NET model may not be adequate for predicting crop yields in Somalia.

3.5.3. Within-year drought durations

Within-year droughts were defined as periods during which no rain fell. This seems reasonable given the results of the decadal rainfall frequency analysis in section 3.3.4, which showed that zero rain occurs during at least 50% of the time for all stations. Zero-rain has previously been used as a threshold for drought analysis by Gupta and Duckstein (1975), although they were using daily data.

The duration of all zero-rain periods was considered, along with the maximum duration from each year.

The distribution of zero-rain periods (within-year droughts) is shown for each station in figure 3.9. Mogadishu has the highest proportion of short-duration "droughts", but when considering the longest dry spell from each year (figure 3.10), it actually appears to have a longer dry season than Afgoi, Bardheere and Baidoa. This corresponds to the smaller Deyr rains and later start time for the Gu season at Mogadishu compared to stations inland, which causes the Jilaal to be longer.

Galcayo, at the other extreme, has far fewer short spells without rain, but more long periods, with its longest dry period being 10 decades longer than at any other station. During 1975-6, 1978-9 and 1986-7, periods of no rainfall lasting over thirty decades (10 months) were recorded at Galcayo, including one spell of 34 decades (only two decades short of a year). The drawn-out S-shape of the cumulative distribution of annual maxima at Galcayo shows that these long-duration droughts occur only infrequently. The maximum duration dry spell for each location is shown in table 3.5. (It should be kept in mind that data quality is always an issue, and it is possible that dates where rainfall was not measured were just recorded as zero, resulting in very long periods with apparently no rain.)

Most of the annual maximum droughts occur during the Jilaal (December-March), although Belet Weyne suffered an extreme 16-decade drought mid-year in 1985, beginning at the end of May. This indicates vulnerability for agriculture, since this would be at the peak of the growing season.

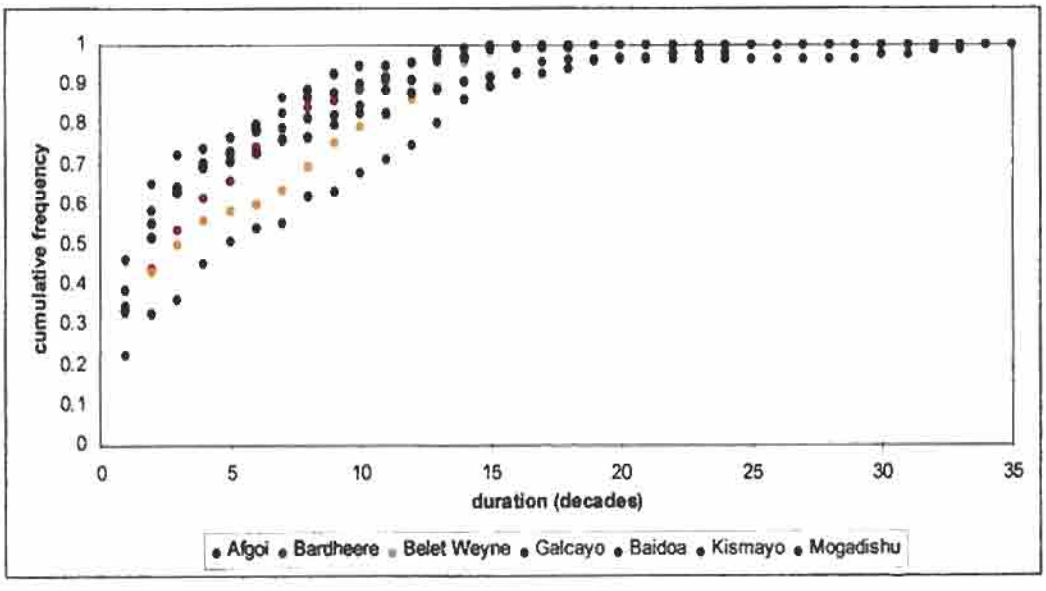


Figure 3.9. Cumulative distributions of durations of zero-rain episodes

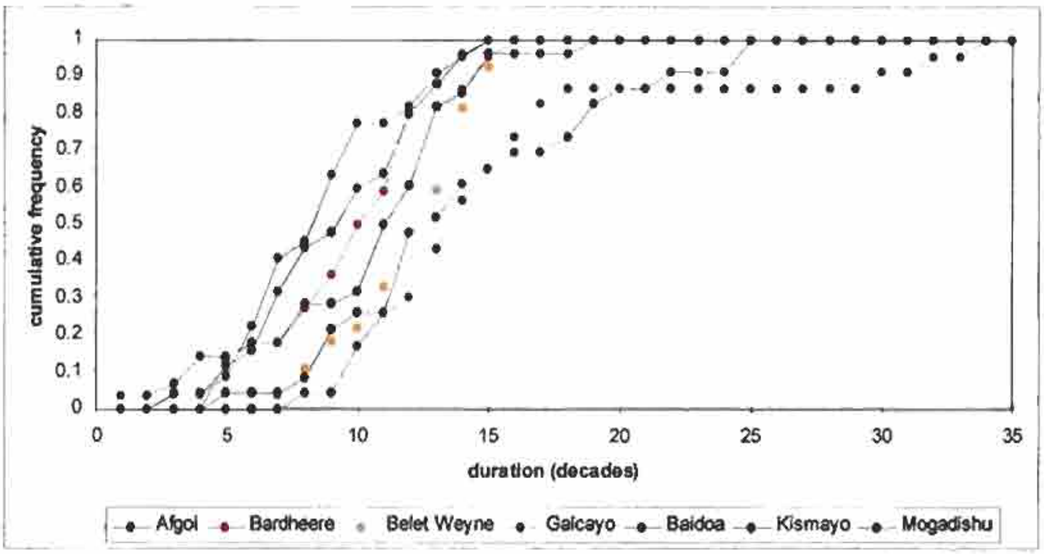


Figure 3.10. Duration of zero-rain spells: cumulative distributions of annual maxima

Station	Maximum drought duration (number of decades)	Time of occurrence
Kismayo	25	1968-9 and 1987-8
Mogadishu	19	1970-1
Afgoi	15	1971-2
Baidoa	15	1970-1
Bardheere	16	1964-5
Belet Weyne	16	1979-80 and 1985
Galcayo	34	1986-7

Table 3.5. Maximum duration of zero-rain episodes

3.6. Analysis of multi-year runs

Multi-year runs have been considered using annual data. This is the easiest and most practical time-period to use since it incorporates a whole hydrological cycle in to each point of a data series. However, in a climate with two rainy seasons, it is possible that valuable information will be lost by lumping the Gu and Deyr seasons together. For example, failure of rains for a single season may not be reflected in an annual total, although it can be argued that this kind of failure would be identified more appropriately by analysing within-year runs. Another problem with the use of annual data is that it ignores the extremely important aspect of the timing of the rains, and the characteristics of individual rainfall events.

The mean annual rainfall for each station has been used as a threshold, so that a drought is said to be occurring when rainfall is below average. Where the rainfall distribution is positively skewed, the average may be an unsuitably high limit. However, it was shown in table 3.3 that skewness of annual data is minor and as a result there is little difference between the mean and median at any station, so it was thought acceptable to use the mean.

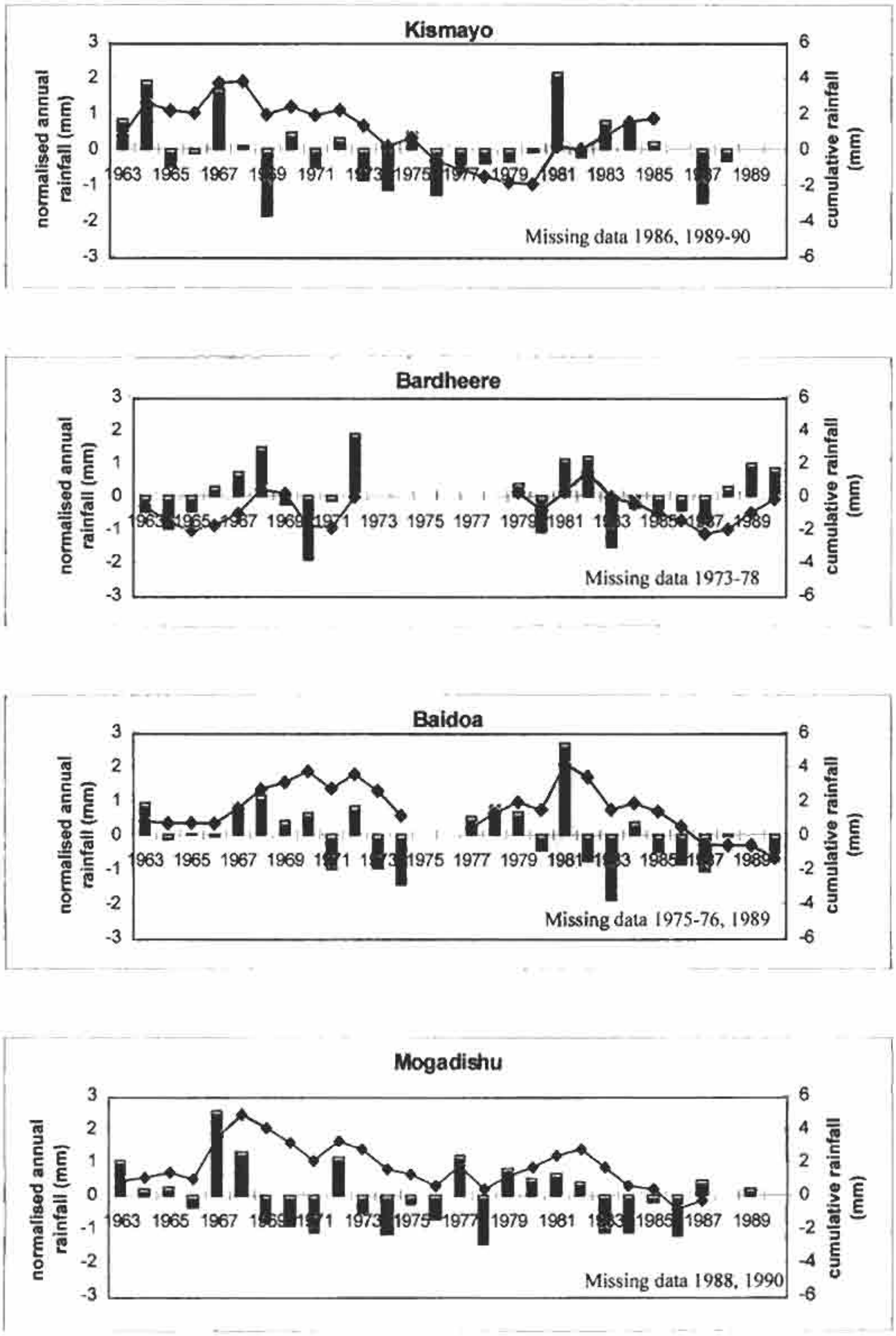
In some cases the rainfall for a particular year may lie only just below the mean, and caution must be taken in including this as a drought period, in part due to the differences between the mean and median, but also because of the questionable data accuracy.

All drought periods were classified by duration, severity and magnitude (as defined in chapter 2). Table 3.6 shows that periods of drought have differed across Southern Somalia, and that the various classifications result in different drought periods being the most extreme.

Standardised time series for each of the seven stations are shown in figure 3.11 (the annual rainfall has been standardised by subtracting the mean and dividing by the standard deviation). This also helps to show the patterns in inter-annual rainfall across Southern Somalia. Despite the apparently high spatial variability in rainfall, the patterns of excess and deficit between locations are often similar. This is the case for Mogadishu, Afgoi, Baidoa, Bardheere and Belet Weyne, although Kismayo and Galcayo show fewer similarities to the other stations.

Gauging station	Start year	Duration (years)	Severity (mm)	Magnitude (mm/year)
Kismayo	1965	2	-104	-52
	1969	1	-323	-323
(Annual mean 401 mm)	1971	1	-82	-82
	1973	2	-351	-176
	1976	5	-449	-90
	1982	1	-36	-36
Mogadishu	1966	1	-61	-61
	1969	3	-480	-160
(Annual mean 455 mm)	1973	4	-444	-111
	1978	1	-241	-241
	1983	4	-607	-152
Afgoi	1964	1	-71	-71
	1971	1	-196	-196
(Annual mean 598 mm)	1973	4	-478	-119
	1978	2	-78	-39
	1983	4	-737	-184
	1988	1	-111	-111
	1990 (end of data period)	1	-178	-178
Baidoa	1964	1	-24	-24
	1966	1	-8	-8
(Annual mean 562 mm)	1971	1	-188	-188
	1973	2	-455	-288
	1980	1	-86	-86
	1982	2	-497	-249
	1985	4	-459	-115
Bardheere	1963 (start of data period)	3	-357	-119
(Annual mean 470 mm)	1969	3	-426	-142
	1980	1	-200	-200
	1983	5	-686	-137
Belet Weyne	1963 (start of data period)	2	-96	-48
(Annual mean 324 mm)	1966	1	-158	-158
	1969	1	-221	-221
	1971	1	-141	-141
	1973	3	-426	-142
	1979	2	-237	-119
	1983	4	-593	-148
	1988	1	-178	-178
Galcayo	1964	1	-106	-106
	1966	2	-4	-2
(Annual mean 176 mm)	1969	4	-96	-24
	1974	2	-174	-87
	1978	1	-98	-98
	1980	2	-180	-90
	1983	5	-336	-67

Table 3.6. Multi-year droughts in Southern Somalia from 1963-1990


Kismayo
normalised annual rainfall (mm)
cumulative rainfall (mm)
Missing data 1986, 1989-90
Bardheere
normalised annual rainfall (mm)
cumulative rainfall (mm)
Missing data 1973-78
Baidoa
normalised annual rainfall (mm)
cumulative rainfall (mm)
Missing data 1975-76, 1989
Mogadishu
normalised annual rainfall (mm)
cumulative rainfall (mm)
Missing data 1988, 1990
3
2
1
0
-1
-2
-3
6
4
2
0
-2
-4
-6
1963
1965
1967
1969
1971
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1977
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1981
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1985
1987
1989

(Figure 3.11)

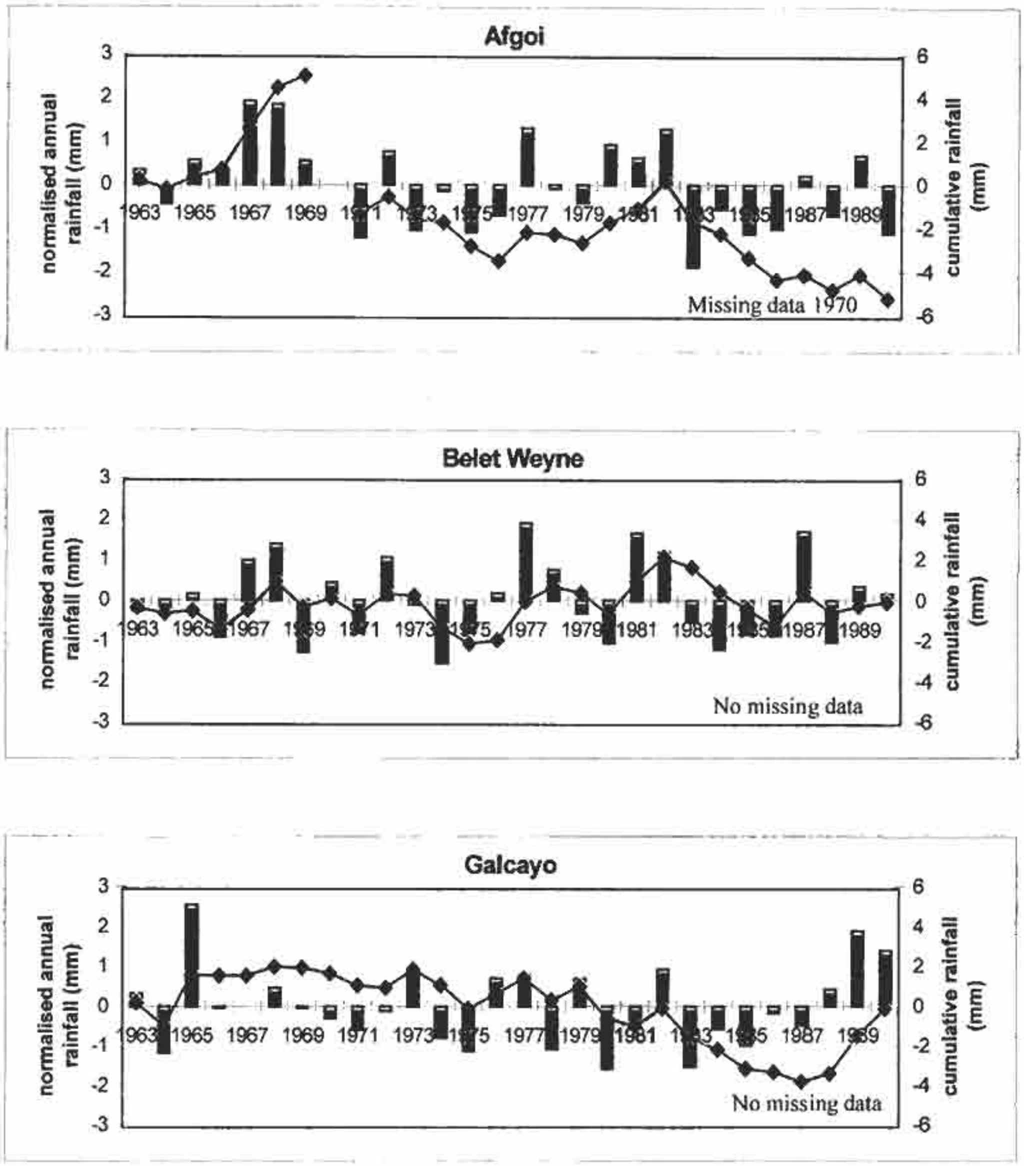


Figure 3.11. Annual time series of standardised rainfall across Southern Somalia

Across most of Southern Somalia, significant periods of rainfall deficit occurred in the early 1970s and mid-1980s. The most significant and widespread periods of excess rainfall occurred in the late 1960s, and the late 1970s-early 80s (excepting 1980).

The deficit of the early 1970s occurred at every station. This is concurrent with the widespread drought in West Africa. The deficit of the mid-1980s was evident at six of the stations and lasted for 4 or 5 years in all cases, but there appears to have been high rainfall during this time at Kismayo.

The most lengthy period of rainfall deficit in Kismayo occurred in the late 1970s, when the rest of the region was experiencing at- or above-average conditions. Since Kismayo is situated in the extreme south of the country, away from the other stations, and it is possible that this area is affected differently by the ITCZ and Somali Jet. However, as some studies (e.g. Hutchinson, 1992) have found Southern Somalia to behave similarly to the Kenyan coast, the discrepancy is somewhat surprising.

3.7. Consideration of trends and persistence

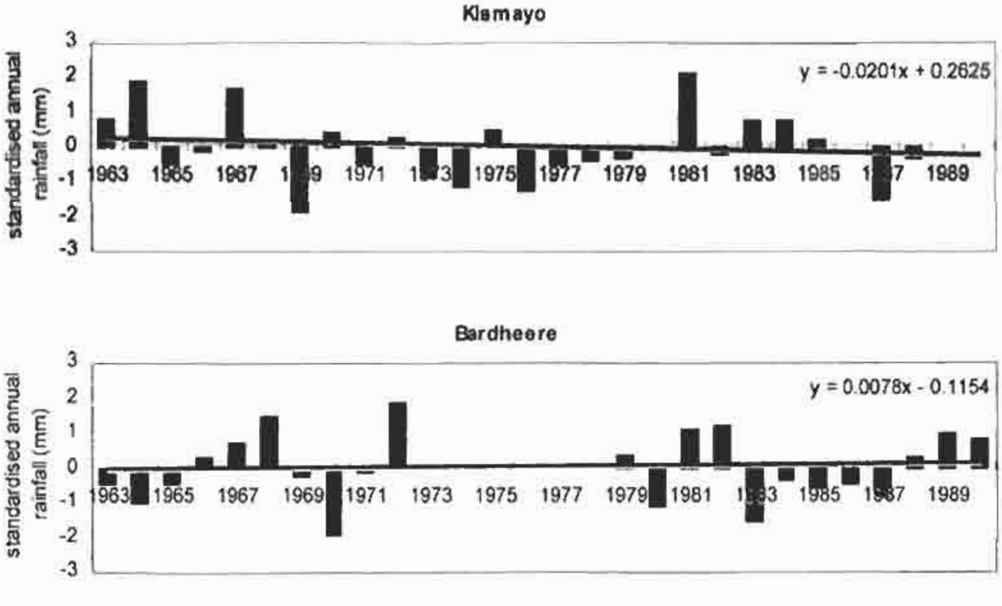
3.7.1. Evidence of trends

As shown in figure 3.12, there is evidence of a slight downward trend in rainfall at the coastal stations (Kismayo and Mogadishu) and at two interior stations (Afgoi and Baidoa). The other three stations, however, have no discernible trend. The "trend" may be caused by the prolonged period of below average rainfall in the 1980s.

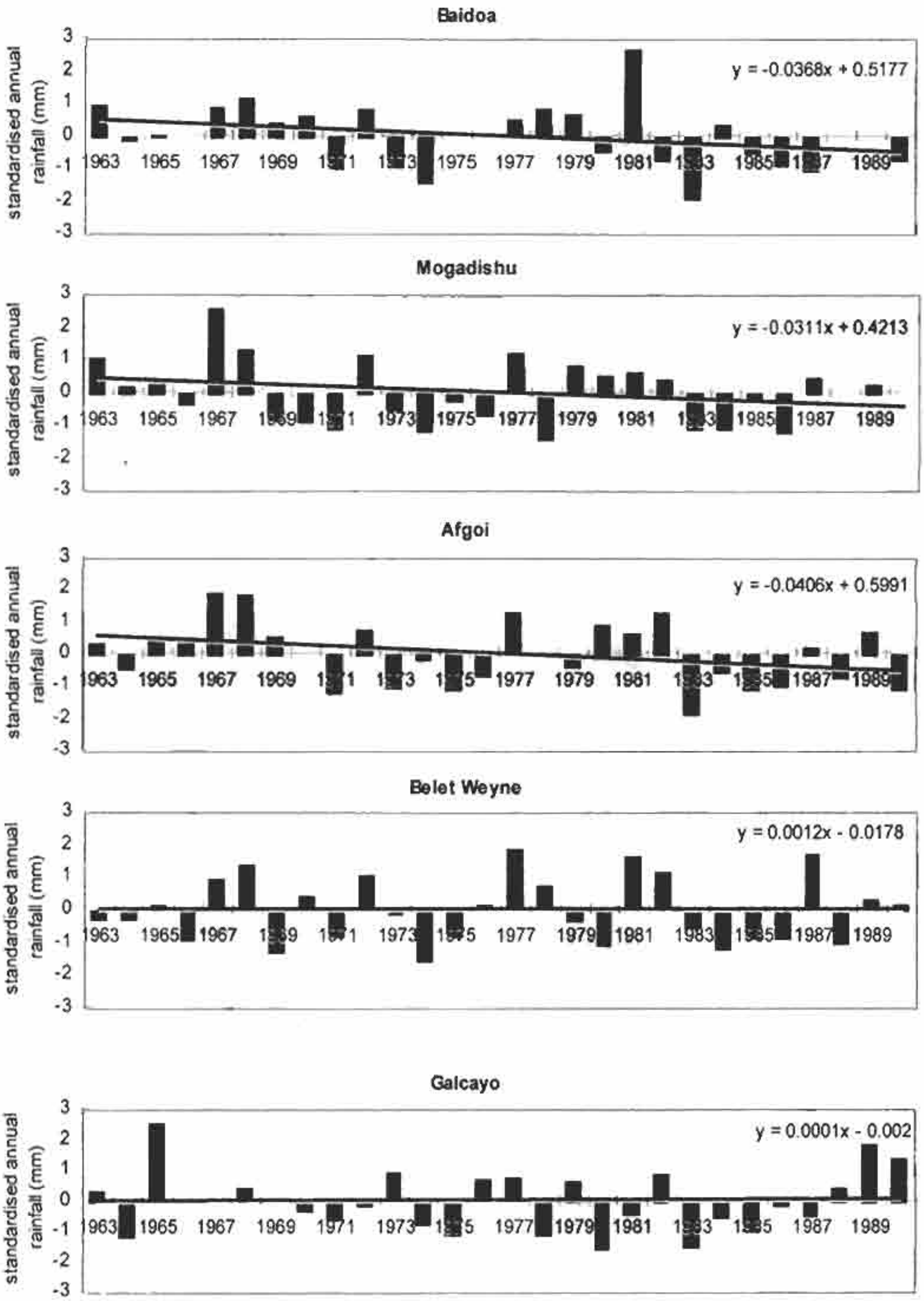
These apparent trends contrast with the study of Gommes and Petrassi (1994), which indicated an increase in rainfall over time in Somalia. However this was a wide-scale study of Sub-Saharan Africa, and as no particular attention was paid to Somalia, the validity of such a trend and the area over which it applies cannot be confirmed.

3.7.2. Autocorrelation of inter-annual time-series

Autocorrelations were calculated for each of the seven stations, and the correlograms are shown in figure 3.13. There were no significant correlations, but for the low correlations that did exist, the results were very variable between stations. There do seem to be some similarities between Mogadishu and Baidoa, and between Kismayo, Afgoi and Belet Weyne. Galcayo shows no evidence of autocorrelation at any lag. However, no obvious spatial variations can be distinguished.



(Figure 3.12)


Baidoa

Mogadishu

Afgoi

Belet Weyne

Galcayo

Figure 3.12. Evidence of linear trends in rainfall in Southern Somalia

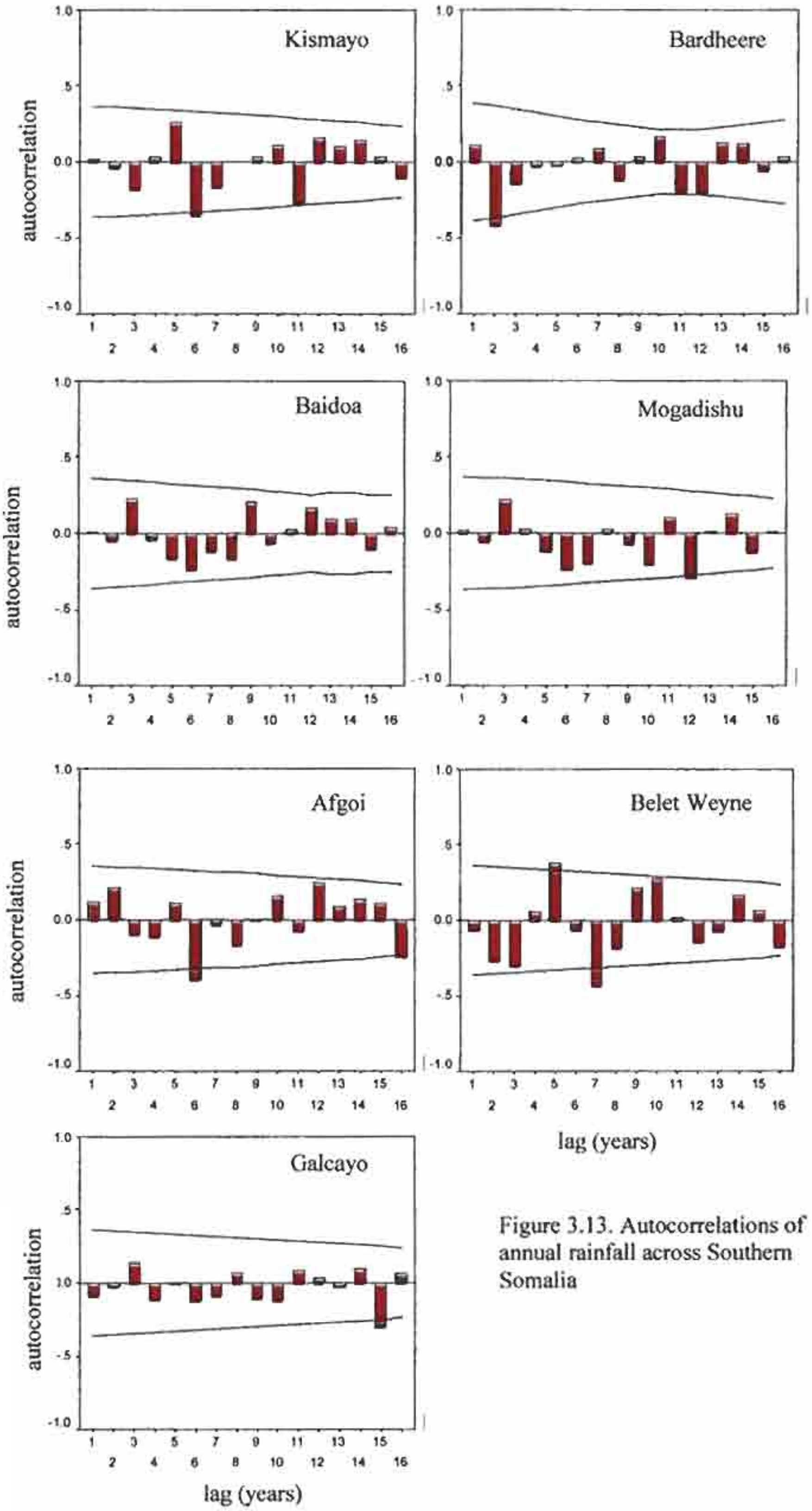


Figure 3.13. Autocorrelations of annual rainfall across Southern Somalia

3.7.3. Consideration of persistence

Contingency tables were produced for the annual time series of each of the rainfall gauging stations. For a single station, each year can be classified as either wet or dry, depending on whether it has above- or below-average rainfall. The classes can be further divided depending on whether the following year is wet or dry. A predominance of wet years being followed by wet years, and dry being followed by dry, would suggest some degree of persistence.

The contingency tables in figure 3.14 show little evidence of persistence, with the possible exception of Bardheere. For Galcayo, and to some extent Bardheere and Belet Weyne, there are more dry years followed by dry years than wet followed by wet. This is a result of the prolonged dry period in the mid-1980s.

a) year i+1

year i	Dry	Wet
Dry	7	6
Wet	6	4

b) year i+1

year i	Dry	Wet
Dry	8	5
Wet	5	6

c) year i+1

year i	Dry	Wet
Dry	7	6
Wet	6	6

d) year i+1

year i	Dry	Wet
Dry	5	5
Wet	6	5

e) year i+1

year i	Dry	Wet
Dry	8	4
Wet	3	5

f) year i+1

year i	Dry	Wet
Dry	7	8
Wet	7	4

g) year i+1

year i	Dry	Wet
Dry	9	6
Wet	6	3

Figure 3.14. Contingency tables for annual rainfall in Southern Somalia. a) Kismayo b) Mogadishu c)Afgoi d) Baidoa e) Bardheere f) Belet Weyne g) Galcayo

3.8. Summary

A number of different techniques have been used to consider rainfall droughts. These include consideration of minimum annual rainfall, maximum duration of zero-rain spells, and inter-annual runs of below-average rainfall. These could all be considered to be different definitions of "drought". The greatest droughts by each definition, for each rainfall gauging station, are shown in table 3.7. Immediately it becomes clear that the various definitions give conflicting results. Several summarising points can be made about the definitions:

- Long dry spells do not necessarily result in particularly low annual rainfall (this may be partly because the spells generally span two calendar years)
- Droughts of maximum duration and severity often coincide for a given location
- The maximum magnitude drought is almost always a single year, although this does not necessarily correspond to the year of minimum rainfall, which may be part of a longer duration drought

For the period under consideration (1963-1990) a number of conclusions can be made about rainfall droughts across Southern Somalia:

- From consideration of drought severity and duration, the period 1983-87 represents the most extreme drought. This is the case across the whole of Southern Somalia, with the exception of Kismayo
- There is evidence of the severe drought of the early 1970s which affected the West African Sahel.
- Rainfall patterns at Kismayo differ significantly from the rest of Southern Somalia

Gauging station	Minimum annual rainfall	Longest dry spell	Multi-year runs		
			Maximum duration	Maximum severity	Maximum magnitude
Kismayo	1969	1968-69, 1987-88	1976-80	1976-80	1969
Bardheere	1970	1964-65	1983-88	1983-88	1980
Baidoa	1983	1970-71	1985-89	1982-83	1973-74
Mogadishu	1978	1970-71	1973-77, 1983-87	1983-87	1978
Afgoi	1983	1971-72	1973-77, 1983-87	1983-87	1971
Belet Weyne	1974	1979-80, 1985	1983-87	1983-87	1969
Galcayo	1980	1986-87	1983-88	1983-88	1964

Table 3.7. Comparison of most extreme droughts by various drought definitions

- While Galcayo is considerably drier than the southern area, the patterns of inter-annual rainfall are often to similar those at other stations
- Individual rainfall events are localised but the same wide-scale mechanisms (e.g. the ITCZ) seem to dominate at all stations. This means that dry spells can differ greatly between stations while the pattern of annual totals remains similar

Chapter 4: Analysis of low flow and hydrological drought

4.1. Characteristics of the River Shabelle

The River Shabelle has a total catchment area of 307,000 km^2. Approximately one third of the catchment is in Somalia, with the rest in Ethiopia, extending in to the highlands. The total length of the river is approximately 1700 km, with 900 km in Ethiopia and 800 km in Somalia. The Ethiopian part of the catchment reaches elevations of over 3000m ASL and is initially steep, with a dense drainage network. There is one major tributary, the Fanfan, which contributes significantly to Shabelle flow during the rainy seasons (Kammer, 1989). In contrast, the lower part of the catchment is generally flat and gently sloping, and under most circumstances has no major inflows within Somalia. Intense rainfall events within Somalia can contribute significantly to the Shabelle but this is not a regular occurrence. It has been estimated that approximately 95% of the annual flow originates from Ethiopia (Kammer, 1989).

Once the river enters Somalia, it flows in a southward direction until it nears the coast. At Balcad it turns to the southwest to flow along the inside of the sand dunes which parallel the coast, and continues in this direction towards the Juba River.

Flow reduction in the downstream direction occurs throughout the length of the river in Somalia. This is due to a combination of evaporation, infiltration, overbank flow and abstractions, the exact proportions of which are not known. In addition, the average depth of runoff decreases dramatically downstream because the average runoff coefficient is smaller further from the highlands. The reduction in flow between stations is shown in table 4.1 and figure 4.1.

Flooding is rare at Belet Weyne but significant overbank flow occurs between Belet Weyne and Mahaddey Weyn, and in fact the Lower Shabelle is reliant on the occurrence of overbank flow each year for deshek (flood recession) farming.

Gauging station	Catchment area (km^2)	Mean annual discharge (m^3/s)	Mean annual runoff depth (mm)
Belet Weyne	207,000	74.5	11.4
Bulo Burti	231,000	69.7	9.52
Mahaddey Weyn	255,300	65.1	8.04
Balcad*	272,700	49.5	5.73
Afgoi	278,000	47.6	5.40
Audegle	280,000	44.7	5.03

Table 4.1. Gauging stations on the River Shabelle (Averages 1963-89, except * only 1963-1980)

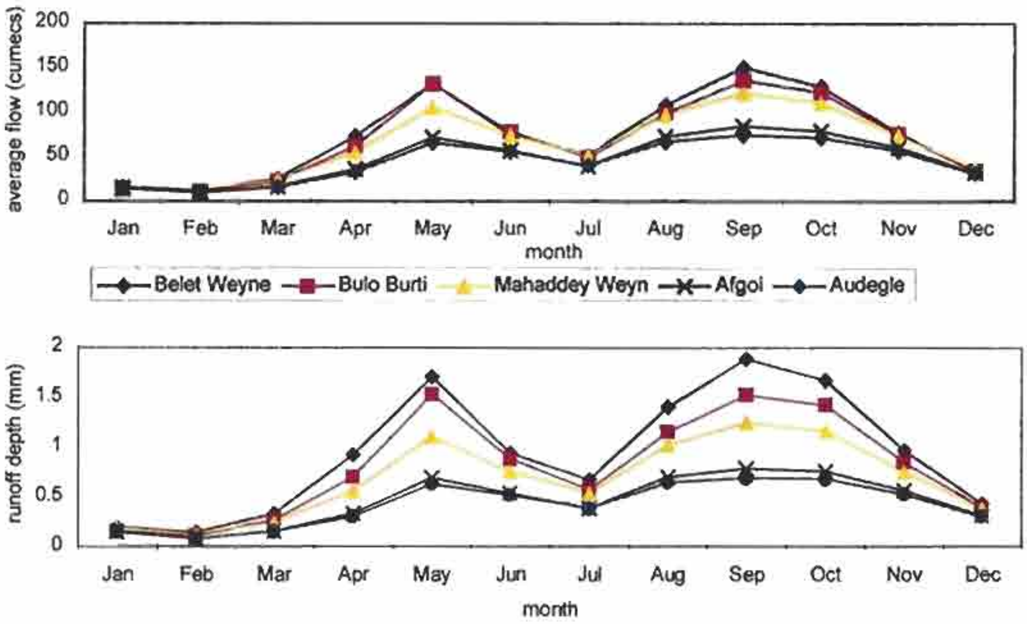


Figure 4.1. Showing the annual distribution of flows on the Shabelle and also the decrease in flow downstream (the key shows the gauging stations from upstream to downstream) (averages 1963-1989)

At Hawaay, the Shabelle loses its well-defined channel and disperses into swamplands covering approximately 850 km^2 (GTZ, 1990). Surprisingly little research seems to have been carried out in to this part of the river. The flow is completely depleted in the swamps, and only under exceptional circumstances does flow from the Shabelle reach the Juba. It is thought that when this does occur it is a result of locally produced runoff as opposed to river flow from the Upper Shabelle. The mechanisms of dispersion have not been studied in detail but evaporation is known to be the major factor. Infiltration to groundwater is thought to be relatively minor due to the clayey soil of the area. This soil is often saline due to the high evaporation (Faillace, 1986a).

Previous studies have shown that there are fine surface deposits along much of the river, so there is often little infiltration to groundwater. Investigations during the Mogadishu groundwater supply project of the early 1980s looked for a hydraulic connection between the river and groundwater around Afgoi but with no success. It was determined that recharge to groundwater in this area was actually occurring predominantly from irrigation rather than from the river itself (Frank Farquharson, personal communication). Faillace (1986a) also found locations of major groundwater recharge to be irrigated agricultural areas. In many stretches however, river water is known to interact with freshwater lenses which alternately recharge and are recharged by the river depending on its level (Faillace, 1987).

4.2. Characteristics of the Juba River

The Juba arises in the Ethiopian highlands, to the southwest of the headwaters of the Shabelle. Its dominant course is south to the coast in Somalia where it discharges to the Indian Ocean. There are three main tributaries of the Juba within Ethiopia, which converge before the border with Somalia. These are the Gestro, the Genale and the Dawa. The longest tributary is the Genale, which flows for approximately 550 km before its confluence with the Gestro and Dawa, and the Juba itself then flows a further 550 km through Somalia. It is estimated that approximately half the flow in the Juba comes from the Genale, with less than 40% from the Dawa and only 7% from the Gestro (Kammer, 1989).

The total catchment area is approximately 233,000 km^2. This is approximately two thirds the size of the Shabelle catchment, yet flow in the Juba is generally about three times greater than that in the Shabelle. Kammer (1989) explained this by the difference in geology between the catchments. The headwaters of both catchments are impermeable volcanic bedrock, while the lower reaches are predominantly limestone. Limestone accounts for a much larger proportion of the Shabelle catchment, with the result that more infiltration occurs there than in the Juba catchment. Baserock continues to be exposed along the Juba riverbed for some considerable distance downstream. Further reasons for the greater runoff in the Juba were proposed by Gemmell (1981), including: lower rainfall in the Shabelle headwaters compared to the Juba; overbank spillage and swamp retention of the Shabelle within Ethiopia; greater extractions for agriculture on the Shabelle; and steeper slopes in the upper Juba catchment.

There is generally an increase in flow between Luuq and Bardheere, but after this, flow starts to decrease, and once the river reaches Jamaame its size is considerably reduced compared to that at Luuq. There is much less reduction in flow than on the Shabelle, but if the runoff depths are considered then it is clear that there are few inflows within Somalia. As on the Shabelle, the average coefficient of runoff decreases significantly once the river leaves the highlands. This is shown in table 4.2 and figure 4.3.

The confluence of the Shabelle with the Juba is between Jilib and Jamaame, although as mentioned previously, inflow occurs only under exceptional circumstances and is thought to be mainly a result of heavy rainfall in the Homboy area.

The Lower Juba Valley contains the most fertile land in Somalia, and prior to the war had a number of large-scale irrigation projects, with more developments being planned. The proposed developments centred around a dam at Bardheere to provide power, flood protection and a water supply for irrigation (GTZ, 1990). However, to date this has not been carried out.

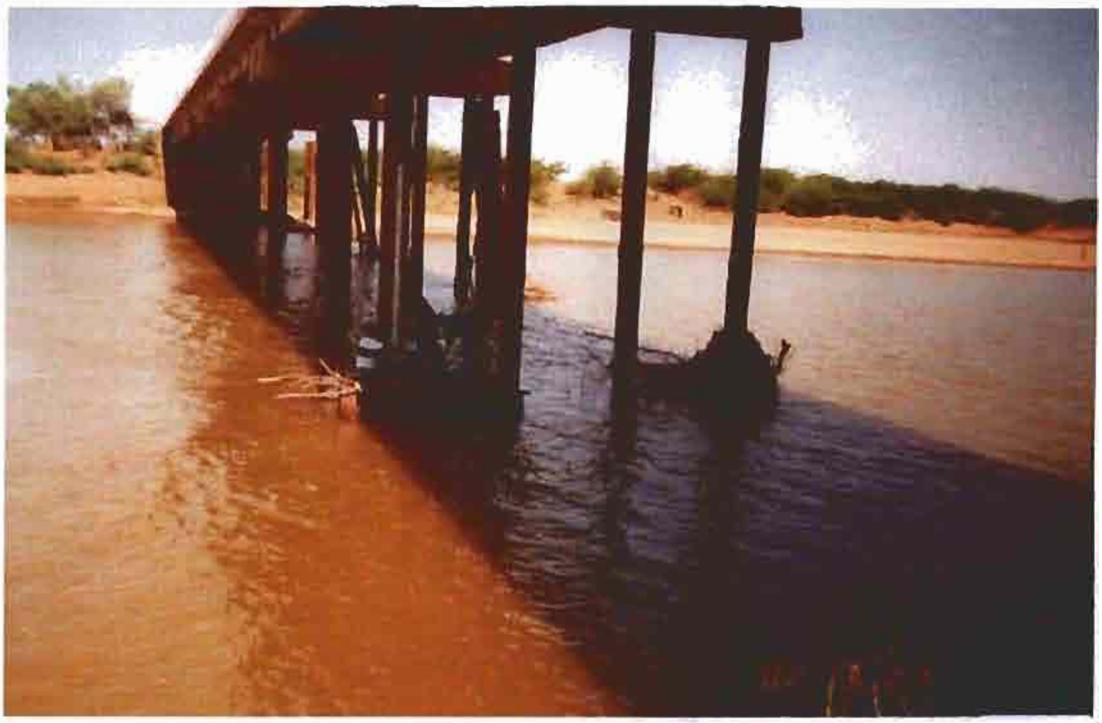


Figure 4.2. Low and high flow periods on the River Juba

Seawater intrusion occurs along the final stretch of the Lower Juba. If the flow falls below 15 m^3/s, the intrusion can extend to Yontoy, approximately 35km upstream, where the intake for Kismayo water supply is located. GTZ (1990) stated that this problem occurs even in 'average' flow years, and is exacerbated by extensive abstractions on the Lower Juba.

Gauging Station	Catchment area (km^2)	Mean annual discharge (m^3/s)	Mean annual runoff depth (mm)
Luuq	166,000	186.4	35.41
Bardheere	216,730	195.2	28.41
Mareere*	240,000	186.0	24.44
Jamaame	268,800	169.5	19.89

Table 4.2. Gauging stations on the River Juba (Averages 1963-1989, excluding 1967-69. Except *, which is only 1977-1989)

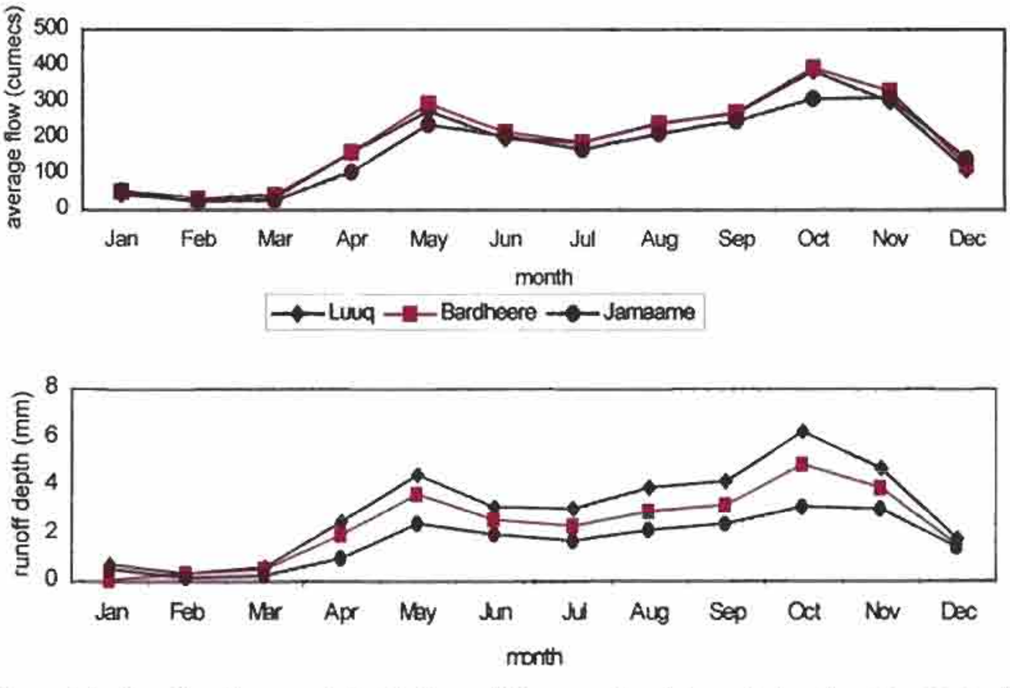


Figure 4.3. Showing the annual distribution of flows on the Juba and also the decrease in flow downstream (the key shows the gauging stations from upstream to downstream) (Averages 1963-1989, excluding 1967-69)

4.3. Data

4.3.1. Data sources

Stage measurements were first carried out in the early 20th century by the Italians, but no records from that time are known to exist today. A number of separate studies through the second half of the century were carried out by consultants for various purposes, with resulting short periods of data collection. Amalgamation of the various sources appears to have been a difficult job even in the 1980s, and has become almost impossible today due to the loss of large amounts of information since the start of the civil war.

The predominant source of information for the river flows is from the project carried out through the 1980s by Sir M MacDonald and Partners in conjunction with the Institute of Hydrology (now CEH Wallingford). This project was resurrected in 2001. Flow archives dating back to 1951 have been held in trust for the Somali Government by CEH since the 1980s, and were released to the FAO in 2001 for use in their proposed "Land and Water Information System for Somalia".

Known data collection activities which have been carried out on the rivers include:

- Fantoli: Pre-1933 monthly and annual stage data
- Selchozpromexport Juba River Scheme. Early 1960s
- Lockwood/FAO. Water Resources Study covering Juba and Shabelle, 1968
- Survey and Mapping Department of the Ministry of Public Works, Somali Government. Data collection until 1967
- Hunting Technical Services and Sir M. MacDonald (1968-9). Project for the Water Control and Management of the Shebelli River
- Fanoole Irrigation Project, Juba River, early 1970s
- Sir M MacDonald, Juba Sugar Project, late 1970s
- B.A.P. Gemmell for FAO and Somali Government, 1980-1
- Sir M MacDonald Ltd and the Institute of Hydrology, 1980s
- FAO 2001-2002

Not all this data is still available or could be located.

4.3.2. Data quality

Data quality in Somalia is often questionable, although the data was extensively examined and infilling carried out by the Institute of Hydrology during the 1980s.

The earliest available recordings are from 1951 for Luuq and Belet Weyne, but the data is intermittent and of questionable quality until 1963. Staff gauges were often placed on bridges where they may have been susceptible to scour and fill processes, and were also often found to be overlapping. Automatic stage recorders were installed at a number of stations in the late 1960s but these were poorly maintained and for most of the 1970s data was again only being recorded from Luuq and Belet Weyne. Data collection was particularly poor in the 1970s (Gemmell, 1982).

The major hydrometric project of the 1980s was initially carried out by the FAO and the Somali Government (Gemmell, 1982), and was continued by Sir M. MacDonald Ltd and the Institute of Hydrology. This work was begun following the recommendations of Henry (1979) to the FAO. The project involved upgrading of the hydrometric network, development of new rating curves, training of field staff and checks on historical data quality. Intermittent records from lower stations on both rivers were filled in using linear correlation from upstream stations (Gemmell, 1982).

Checking of the stage-discharge relationships is infrequent, with the result that the accuracy of discharges determined from the rating curve is uncertain. This could particularly be a problem where the energy gradient is affected by control structures on the rivers (Gemmell, 1982), and where siltation has occurred. Henry (1979) expected sedimentation in the Lower Shabelle to cause the profile of the riverbed to rise over time, resulting in systematic errors in discharge estimations.

River	Gauging station	Latitude	Longitude	Elevation (mASL)	Upstream area (km^2)
Shabelle	Belet Weyne	4:44:00 N	45:12:20 E	176.1	207,000
	Bulo Burti	3:51:20 N	45:34:20 E	133.4	231,000
	Mahaddey Weyn	2:58:20 N	45:12:20 E	104.6	255,300
	Afgoi	2:21:00 N	45:23:30 E	95.0	272,700
	Audegle	1:59:10 N	44:50:00 E	70.1	280,000
Juba	Luuq	3:47:30 N	42:32:30 E	141.4	166,000
	Bardheere	2:20:30 N	42:17:0 E	89.0	216,730
	Jamaame	0:01:10 N	42:41:0 E	0.0	268,800

Table 4.3. Location of gauging stations within Somalia

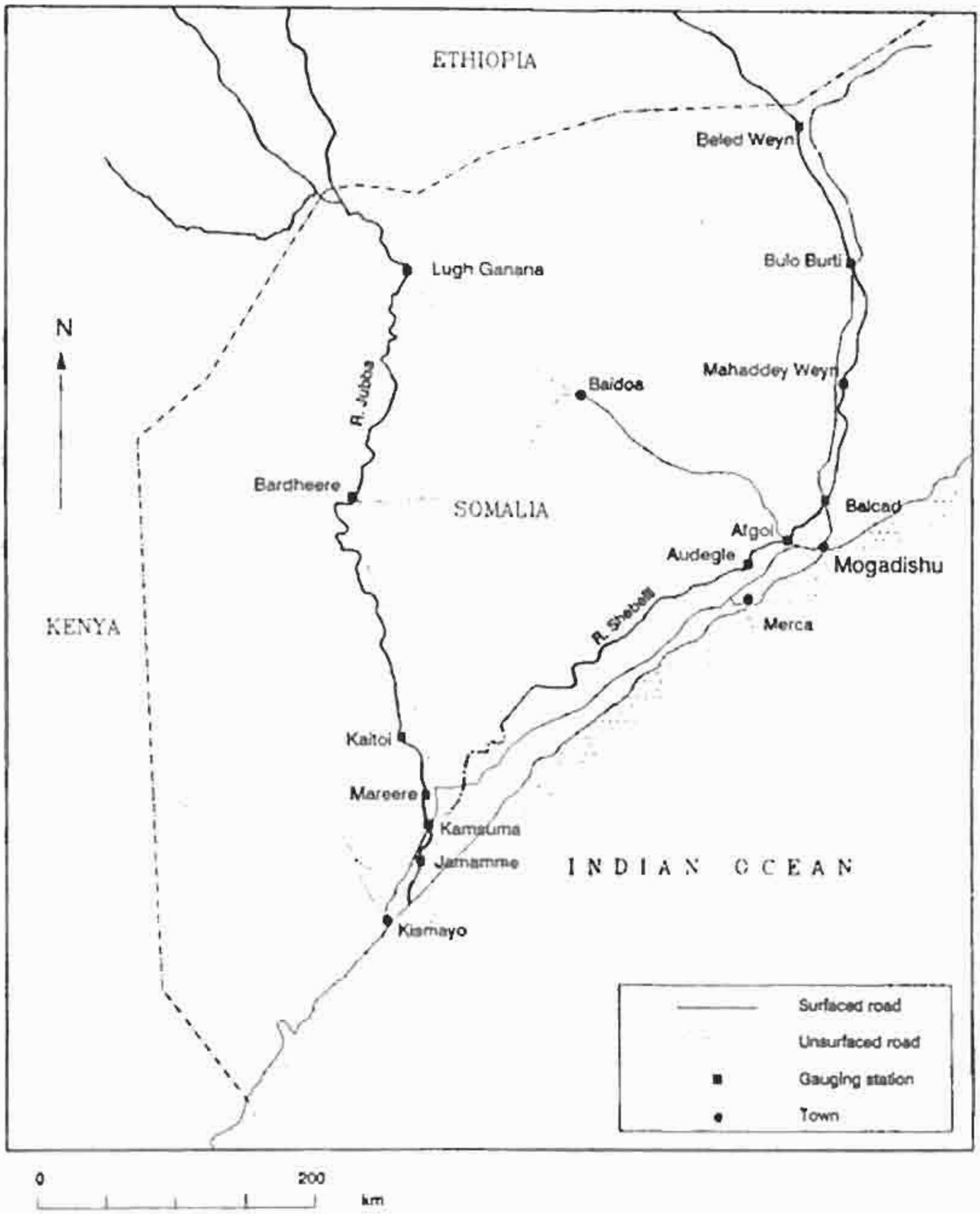


Figure 4.4. Location of gauging stations on the Juba and Shabelle rivers

(Source Institute of Hydrology, 1990)

4.3.3. Gauging stations on the Shabelle

The locations of all gauging stations are shown in figure 4.4, and are described in more detail in table 4.3. Belet Weyne, which is the station closest to the Ethiopian border, has the longest record, with archives extending to 1951. Data collection was carried out from 1963 at Bulo Burti, Mahaddey Weyn, Balcad, Afgoi and Audegle. Stage measurements at Balcad were ceased in 1980 when a barrage a short distance downstream became operational, which had a significant impact on the water level at the gauging site.

4.3.4. Gauging stations on the Juba

The longest running records are found at Luuq Ganane, the furthest station upstream, near the border with Ethiopia. Archives for this station begin in 1951, although with many gaps. The main stations downstream are Bardheere and Jamaame. These are detailed in table 4.3. Infilling of records by CEH has resulted in a full data set for these three stations from 1963 to 1990, although with a gap for approximately two years at the end of the 1960s.

Additional stations have also existed at Mareere, Kamsuma and Kaitoi, run by individual irrigation projects. All stations are shown in figure 4.4.

4.4. River modifications and water requirements

Modifications to the river channel have been much more extensive on the Shabelle than the Juba, with a number of barrages having been constructed on the Shabelle. Flood protection bunds along the Juba are extensive. While most of these have now fallen in to disrepair, they will have had a significant impact on the river flows at lower stations before the war. The extent of modification on the rivers within Ethiopia is not known in any detail. It is thought to be minor in comparison to the changes within Somalia, although a dam was constructed in the headwaters of the Shabelle in the early 1980s which could have a significant impact on flows (Sir M.Macdonald Ltd and IH, 1991).

Known flood control structures, large-scale irrigation schemes and barrages within Somalia are outlined below.

Structures on the Shabelle River:

- Jowhar offstream storage reservoir, and associated structures. This became operational in 1980. When operational, the inlet canal was opened at the start of the Gu flood season and closed when the reservoir was full. This process was repeated during the Deyr. During the Hilaal (December to March), the earth dam containing the reservoir was dug out and water was released back in to the Shabelle. There is a 40km stretch between the junctions of the inlet and outlet structures with the Shabelle (Sir M. MacDonald and Partners, 1990).
- Barrages at Balcad, Janaale, Gayweerow, Qoryooley and Falkeerow
- Hawaay weir (Severn and Dennis, 1984)

Structures on the Juba river:

- Fanoole barrage, constructed 1977-1980. Capacity up to 800 m^3/s.
- Flood protection bunds downstream of Fanoole for Juba Sugar Project, Mogambo Irrigation Project, and Fanoole Rice Project (GTZ, 1990)

- Extensive abstractions for Juba Sugar Project, Mogambo Irrigation Project and Fanoole Rice Project (from late-1970s , early 1980s)
- Far Waamo flood relief channel. Diverts flood flows from Fanoole to Deshek Wamo, a large natural depression to the west of the Lower Juba. Constructed to protect banana plantations (GTZ, 1990)

Water requirements on the rivers are primarily for irrigation, but the rivers are also used for domestic supply and livestock watering.

Exact requirements for irrigation are unknown, particularly as the amount of irrigation occurring has reduced significantly since 1990. Prior to 1990 a few studies had been carried out, including the Inter-Riverine Agricultural Study of Hunting Technical Services (1977), and the Masterplan for Juba Valley Development by GTZ (1990). Irrigation efficiencies are extremely low, being estimated at approximately 20% by Henry (1979) and 30% by GTZ (1990), although Hunting Technical (1977) assumed efficiencies of 60% in their calculations.

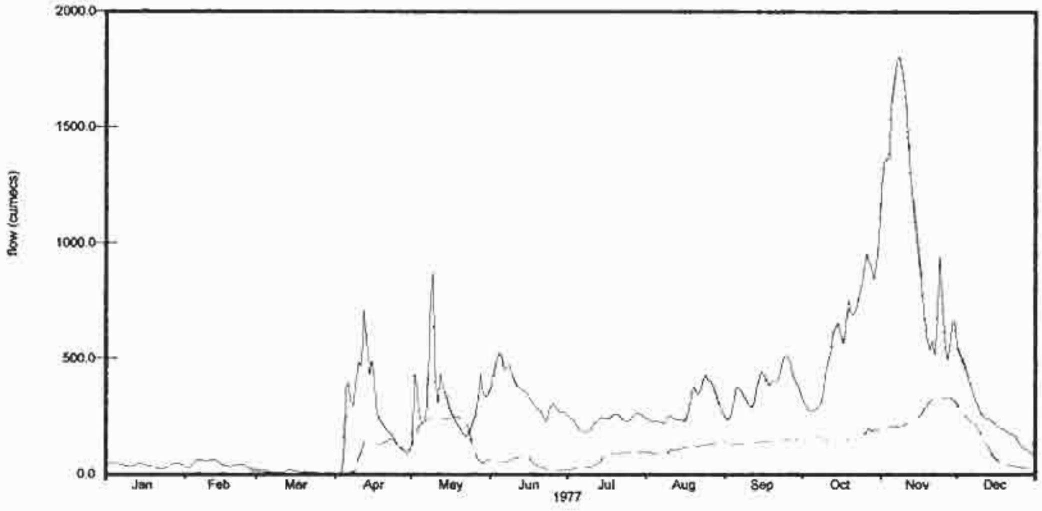
Irrigation requirements on the Juba in 1990 were estimated at approximately 90 m^3/s if all pumps were running at capacity (GTZ, 1990). This was assuming full operation of the major large-scale schemes (Fanoole, Juba Sugar and Mogambo projects), as well as medium-scale banana projects and small-scale pump irrigation further north.

River water requirements for livestock watering are most crucial during the later stages of the Jilaal, since stored rainwater is used through the rest of the year. The maximum requirements are from February to April on the Juba, where 90% water for livestock watering is obtained from the river, in comparison to May-November, when only 10% water comes from the river. The total requirements during the Jilaal were estimated at only $1m^3/s$ by GTZ (1990). Domestic supply for Kismayo, Bardheere and rural areas totals only 0.2 m^3/s, although as mentioned previously, maintenance of adequate quality for the Kismayo supply requires at least 15 m^3/s flow.

4.5. Seasonality

The Juba and the Shabelle have two high flow seasons: the Gu season, extending from approximately April to June, and the Deyr season from approximately August to November (as shown in figures 4.1 and 4.3). This is similar to the rainy seasons in Somalia, although the Deyr season dominates on the rivers. The main dry season (Jilaal) extends from approximately November-March, similarly to the rains but with slightly different timing. The Haggai dry season is less pronounced on the rivers in comparison to the rain, particularly on the Juba, where high flows can be continuous from April to November. Examples of low and high flow periods on the Juba were shown in figure 4.2.

Example of a high-flow year (1977)



Example of a low-flow year (1980)

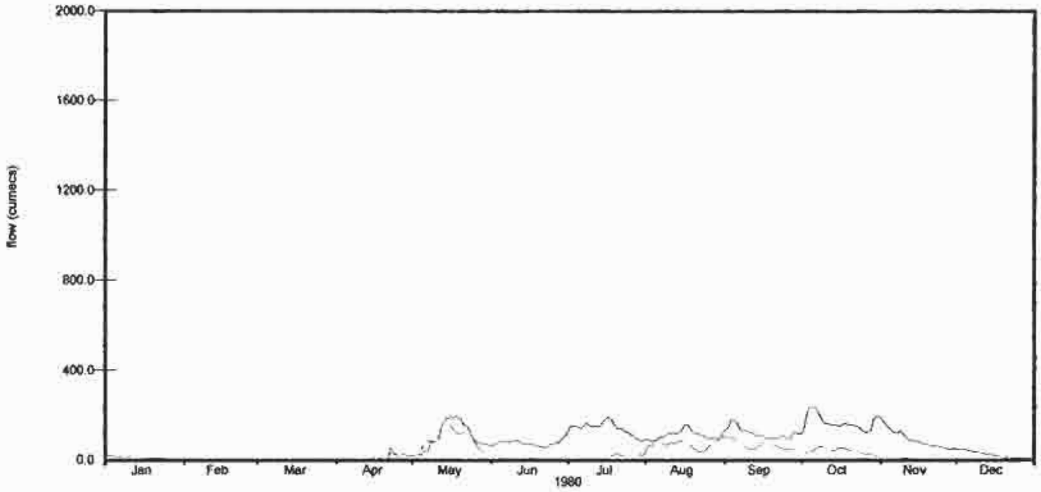


Figure 4.5. Examples of high and low flow years on the Juba and Shabelle (Solid blue line represents the Juba, dotted green line represents the Shabelle)

Variability between years is high. Examples of high and low flow years for the Juba and the Shabelle are shown in figure 4.5. The coefficient of variation of annual flow on both rivers is approximately 0.3, with individual months having much greater variability. The seasons are not always well defined, as is clear from figure 4.5.

4.6. Flow duration curves

Flow duration curves show the percentage of time that particular flows are exceeded. Various percentiles, extracted from such curves, are useful for water resource practices. Commonly used percentiles include the flows exceeded 95 and 80 percent of the time (Q_{95} and Q_{80}) for low flows, and the 20 and five percent exceedances (Q_{20} and Q_5) for high flows.

Flows for various d-day periods can be considered, that is, the distribution of average flows over a period of d-days. The one-day flow duration curve is most often considered, however the 10-day curve may also be of interest for agricultural purposes since this is a commonly used operational time period for irrigation.

Flow duration curves were determined using HYDATA. This is a data management software developed by the Institute of Hydrology, in which the Somalia flow data is stored. It contains tools for basic data analysis, including flow duration curves and low flow analysis.

The 1-day flow duration curve for the Shabelle is shown in figure 4.6.a. The log-normal scale clearly shows the reduction in flow downstream, with the river running dry approximately 1% of the time at Belet Weyne, increasing to 9% at Audegle. It appears from the graph that zero flows occur less often at Mahaddey Weyn than at Belet Weyne and Bulo Burti, despite being further downstream than these two stations. The exact reason for this is not known. However, it is thought that in some cases small flows were considered insignificant and recorded as zero (Gemmell, 1982). This will affect the high percentiles of the flow duration curve and consequently also the low flow frequency analysis. It has been suggested that even when not recorded as zeroes, measurements of very low flows may be inaccurate (Chris Print, personal communication). Siltation at Mahaddey Weyne and lower stations occurs due to artificial flow restrictions (Gemmell, 1981), and measurements of discharge to check the rating curve may not have been carried out frequently enough to establish the effect of this.

If the apparent anomaly in flows between Mahaddey Weyn and the upstream stations is not due to inaccuracies in data collection or gauging, it could be explained by groundwater recharge in the reach between Bulo Burti and Mahaddey Weyn. Faillace (1987) found shallow groundwater adjacent to the river in the long reach between Belet Weyne and Jowhar, which is thought to be hydraulically connected to the river through sand lenses.

It is clear that the use of a log scale greatly emphasises the low-flow portion of the curve, and gauging may not have been accurate enough to justify this. Consequently, a linear scale may be more appropriate, as is shown in figure 4.6.b.

The 10-day flow duration curves are also shown, in figure 4.6.c and d. The differences between this and the 1-day duration curve are minimal. Along with the relatively shallow slope of the curve, this suggests a dampened response, as would be expected from a catchment of this size.

Percentile flows which may be of interest are shown in table 4.4.

Percentile	Flow (cumecs)				
	Belet Weyne	Bulo Burti	Mahaddey Weyne	Afgoi	Audegle
95	3.20	2.19	3.87	0	0
90	5.95	4.97	6.84	0.74	0.44
75	16.72	14.46	18.51	14.11	14.27
50	51.55	50.98	55.21	44.90	46.41
25	113.92	107.51	110.87	83.00	74.02
10	177.14	164.84	150.00	100.94	84.10
5	226.58	209.16	166.09	106.85	97.06

Table 4.4 Percentile flows on the Shabelle

The flow duration curves for the River Juba (figure 4.7. a-d) are similar in shape to those of the Shabelle, although the scale is greater and zero flows are less common. Similarly to the Shabelle, zero flows occur less often at an intermediate station (Bardheere) than at the furthest upstream station (Luuq), although zero flow only occurs less than 1% of the time at Luuq. Proposed reasons for this discrepancy are similar to those given for the Shabelle, including measurement and recording errors, and errors in the stage-discharge relationship. Faillace (1986a) assumed that the river recharges aquifers during high flow periods and vice versa during low flows, although no validation of this hypothesis was carried out.

Again a linear scale can be considered rather than a log-scale, which prevents over-emphasis on low flows. There is more distinction between 1- and 10-day flows in the high flow portion of the curve than on the Shabelle, which indicates a slightly less-damped response on the Juba.

Percentile	Flow (cumecs)		
	Luuq	Bardheere	Jamaame
95	7.04	12.77	3.76
90	12.69	18.87	10.89
75	47.12	53.43	42.15
50	151.63	156.17	144.42
25	270.13	276.94	261.01
20	417.57	428.98	406.03
5	537.33	561.505	474.06

Table 4.5 Percentile flows on the Juba

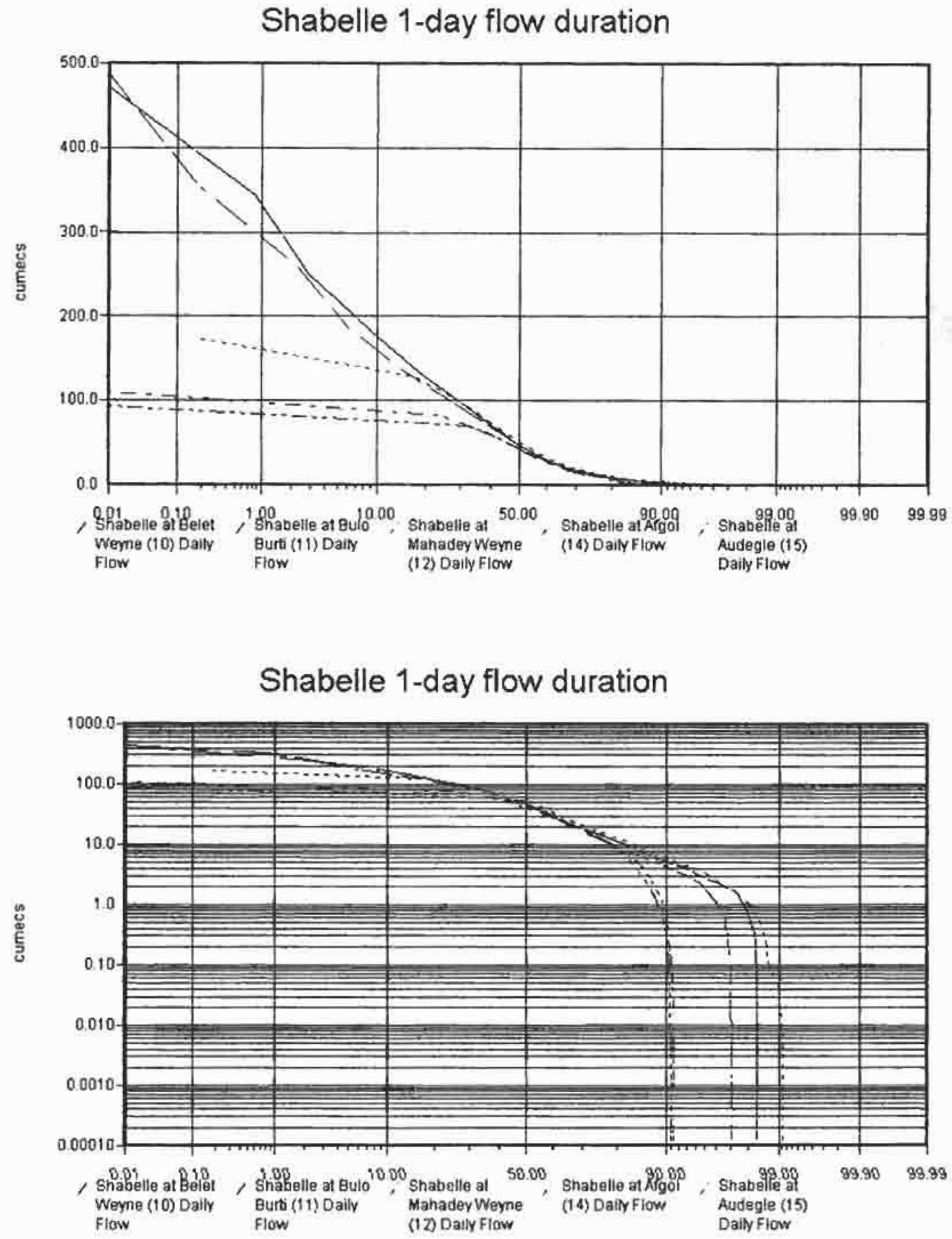


Figure 4.6.a. and b. 1-day flow duration curves for the Shabelle

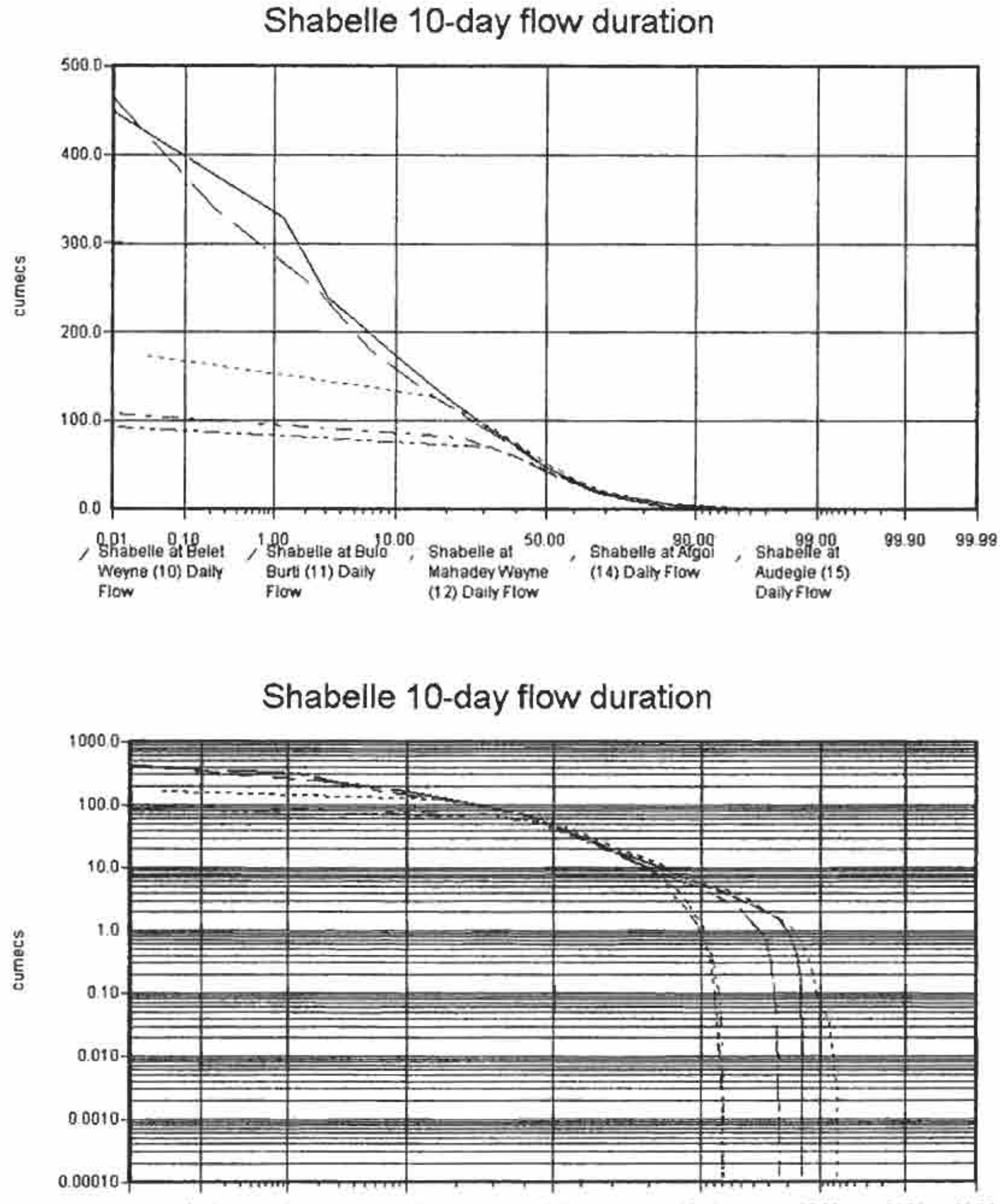


Figure 4.6.c. and d. 10-day flow duration curves for the Shabelle

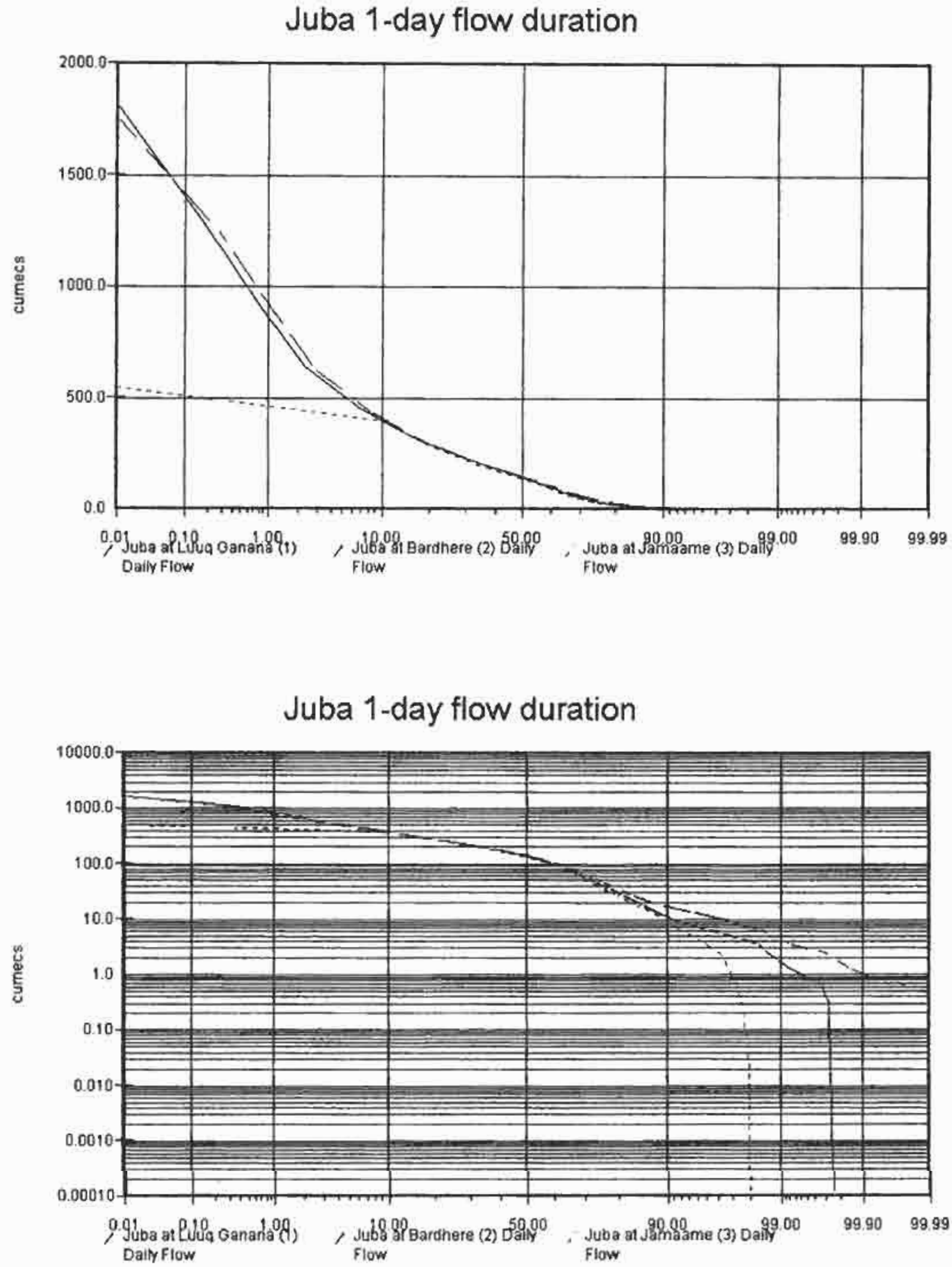
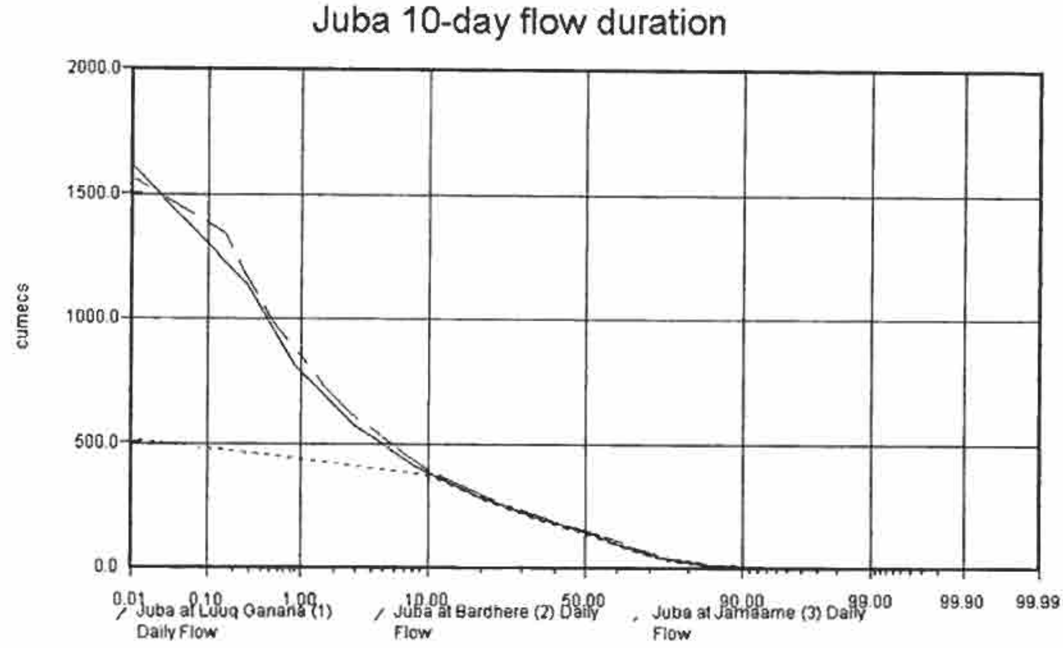


Figure 4.7.a. and b. 1-day flow duration curves for the Juba



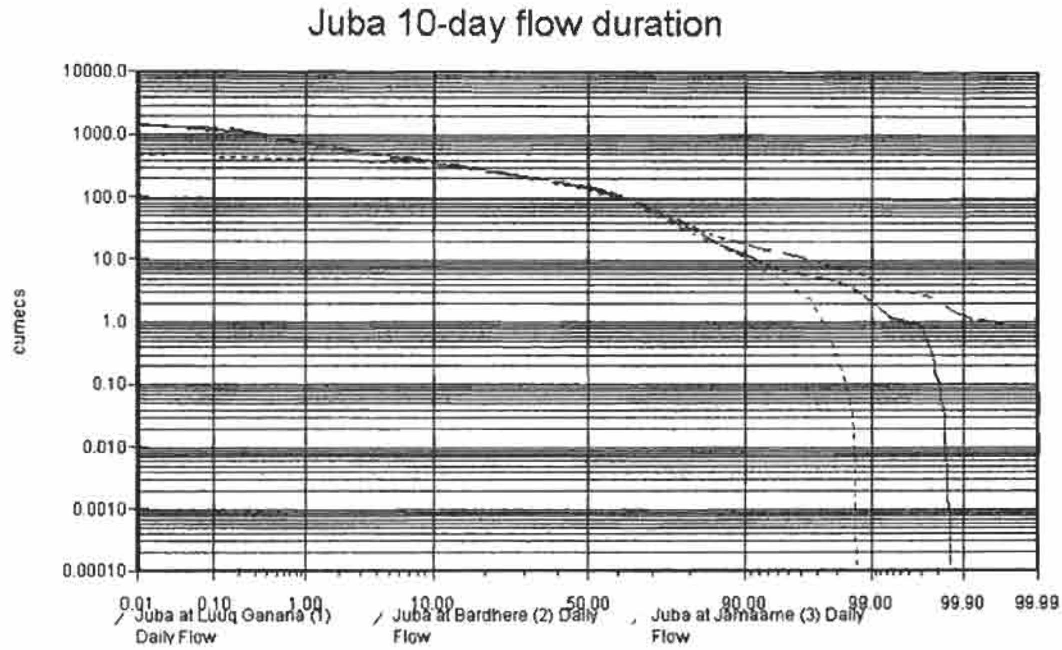


Figure 4.7.c. and d. 10-day flow duration curves for the Juba

4.7. Low flow frequency analysis

Low-flow frequency analysis was carried out on the furthest upstream stations of the Shabelle and the Juba (Belet Weyne and Luuq respectively). Flow data from 1963-1990 was used, with a total of 27 years available for the Shabelle and 24 years for the Juba.

The analysis used a Fortran program designed for annual maxima. Since low flow analysis is involved with minima, the negative values of the annual low flows were taken so that the largest value then became the smallest, and vice versa.

The input to the Fortran program was the annual maxima only, so another method had to be used prior to this to extract the maxima from the time series. This was achieved by exporting the results of HYDATA low-flow analysis: this facility extracts and plots the annual minima but does not fit a distribution. This analysis alone was not sufficient since the distributions were of interest.

Low flows for various d-days were considered- that is, the lowest average flow over a period of d days from each year. Flows from one day up to 180 days were used, which was the longest period that could be considered by HYDATA.

As discussed previously (section 4.6), it is not known how accurate the very low-flow measurements are, and it is possible that some very low flows are simply recorded as zeroes. This creates a large degree of uncertainty in the low flow analysis.

Where zero flows occur (or low flows which are recorded as zeroes), the analysis has to be adapted. Zero flow represents a truncation of the frequency distribution of low flows, since a negative flow cannot occur. If it is the case that low flows have been recorded as zero, then more of the distribution will be truncated than is correct. Data series which include zeroes are referred to as 'censored data', since the end of the distribution is missing (Maidment, 1992).

To analyse censored data, the zeroes are removed and a distribution is fitted to the rest of the data, resulting in conditional probabilities given that the flow is not zero. The theorem of total probabilities can then be used to re-incorporate the zeroes to give the final result:

$$P(X \leq R) = P(X \leq R | X \neq 0)P(X \neq 0) + P(X = 0)$$

Where $P(X=0)$ and $P(X \neq 0)$ must be estimated from the available sample.

The Fortran program fits Extreme Value distributions, the general form of which is:

$$F_Y(y) = \exp\left[-(1-ky)^{1/k}\right]$$

where y is the Gumbel reduced variate, and k determines the type of distribution (Kottegoda and Rosso, 1997). If k=0 then the distribution is Extreme Value Type I (EVI, or Gumbel). If k<0 the distribution is EV2, and when k>0 an EV3 is obtained. The program automatically fits an EV1 distribution to the data, and in addition fits either an EVII or EVIII depending on whether k is positive or negative. Low-flows often fit a Weibull distribution, which is the inverse form of the EVIII.

The program calculates a Shape Factor, CR, which is a function of the sextile means. A distribution can only be fitted if 0.08<CR<3.13. If this is not the case then an error is returned.

A number of problems occurred in the analysis. In some cases, particularly for the Juba, CR was too high so the distributions could not be determined directly. The second problem was that for high return periods, negative flows were often returned which is, clearly, impossible. This was the case even when an EVIII was fitted, which has an upper bound.

In order to overcome both of these problems, Box-Cox transformations of the data were carried out, where:

$$Y_t = \begin{cases} (X_t^{\lambda} - 1)/\lambda & \textit{If } \lambda \neq 0 \\ \ln X_t & \textit{When } \lambda = 0 \end{cases}$$

(Kottegoda and Rosso, 1997). Use of logs ensures that negative flows are not obtained, as does using small values of λ. For simplicity, the log transformation was used wherever possible. However in some cases, when the log transform or a small value of λ was used, a negative value of *k* resulted, which caused the model to fit an EVII distribution to the data. Within the range of observed flows this gave similar results to an EVIII, but at higher return periods there are greater discrepancies since EVII distributions have no upper bound. As a result these transformations were not considered acceptable, and a higher value of λ had to be used. Unfortunately a higher value of λ also resulted in wider confidence intervals at longer return periods, so the lowest value of λ was used which resulted in an EVIII distribution. Apart from the widening confidence limits, the distributions resulting from the use of various transformations were very similar.

It is important to note that a hydrologic year of 1st January-31st December has been used in the analysis. It is common practice to begin the hydrologic year at the start of the wet season, which in this case would be the beginning of the Gu, since this follows the main dry season. This occurs in approximately April, but due to the inter-annual variability an appropriate date is difficult to define. As a result it was thought more sensible to use a calendar year.

Alternatively it might have been preferable for this type of analysis to start the year in the middle of the high flows.

The resulting low-flow curves for longer d-day periods were noticeably different depending on how the hydrologic year was defined. Use of a calendar year results in lower flows over longer d-day periods than an April-March hydrologic year. This is due to the Deyr floods being greater than the Gu. The minimum flow periods are always centred on the Jilaal (approximately January-March). So for long d-day periods, if a calendar year is used then the minimum flow periods start in January and thus incorporate the Gu flood, while periods within an April-March hydrologic year end in March and so include the larger Deyr flood season.

Inter-dependence between years for the long d-day periods was not thought to be a problem as the extracted period of annual minimum always started in January (i.e. there were no annual minimum periods at the end of one year followed by another minimum period at the beginning of the next year).

The Fortran program does not give any measure of goodness-of-fit of the fitted distribution to the sample data. Return periods of the sample data were determined using the Gringorten plotting formula:

$$P(X) = \frac{r - 0.44}{N + 0.12}$$

where r is the rank of a sample value and N is the total sample size (Shaw, 1994). The Gringorten return periods were plotted along with the fitted EVIII distributions, and the shape generally conforms well to the theoretical distribution (these are shown in appendix 1). This is despite the fact that in most cases the data had to be transformed in order for the distribution to be fitted successfully.

The only sample for which a Box-Cox transformation was unnecessary was the 150-day flow frequency on the Juba. In this case, no shape-ratio error or negative flows resulted when using the original data in the analysis. However log-transformed flows were also fitted out of interest, in order to consider the theoretical relationship of the two. Theoretically, if a data set conforms to a Weibull distribution, then the negative logs of that data will have a Gumbel (EV1) distribution (Maidment, 1993). To examine this, an EV3 was fitted to the original data, and an EV1 distribution fitted to the log-transformed data. The result is shown in figure 4.8. The two are very similar although at high return periods, the Gumbel distribution gives slightly lower flows. The similarity between the two provides reassurance that an EVIII is a good fit for the data.

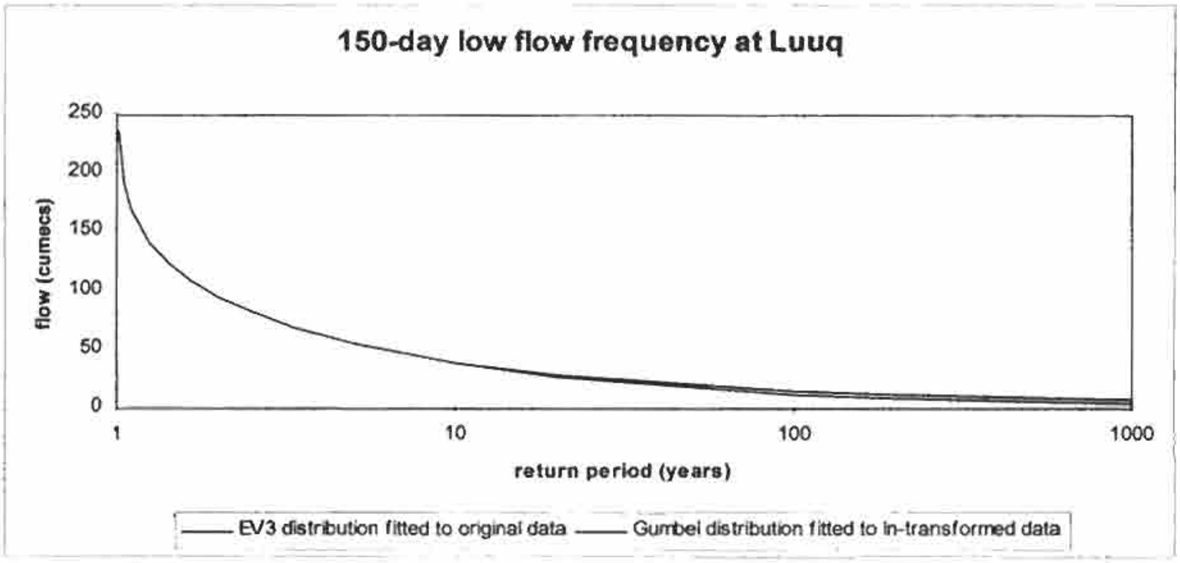


Figure 4.8. Comparison of EVIII distribution fitted to original low flow data and EVI distribution fitted to log-transform data.

The final low-flow curves for various d-days are shown in figures 4.9 and 4.10. The curves allow the probability of failure of a required discharge for management practices to be estimated. This discharge may be variable between water users. Account must be taken of variations in the flows downstream due to both natural and artificial influences.

There is little difference on the Shabelle for the fitted distributions of 1, 10 or 30-day low flows. This is due to the nature of the Jilaal, during which there is little replenishment of flow over approximately a three-month period. The change in the magnitude of the distributions is most prominent after this period has been exceeded, as zero-flows are not obtained over such a long averaging period.

The situation on the Juba is similar, although zero-flows occur less often and did not last for longer than a 30-day period in the sample data.

The 150-day and 180-day distributions on the Juba are unusual as their tails have steeper slopes than those of shorter d-days. From the plots of sample values, it appears visually that these two do not fit as well to the EV3 distribution. This is probably due to the stepped nature of the sample data.

The high return periods where this discrepancy in slope becomes apparent should be used only as a guide due to the small sample size. However the flow is so low at high return periods (e.g. over 100 years) anyway that changes in the flow as return periods increase further are minor, and in this sense such discrepancies may make little difference for planning and management applications.

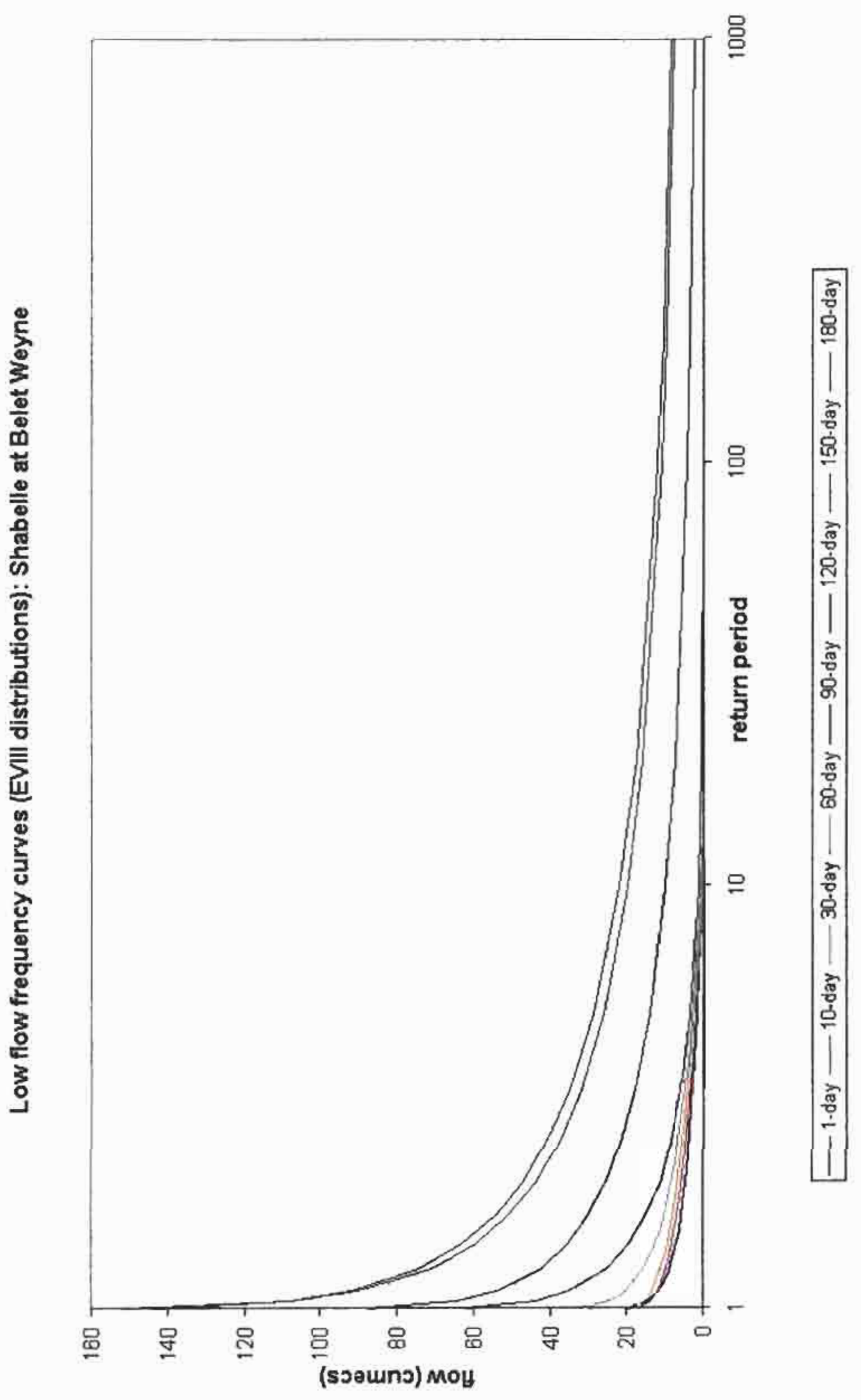


Figure 4.9. Fitted EVIII distributions for low flow frequency curves. River Shabelle at Belet Weyne. Data 1963-1989

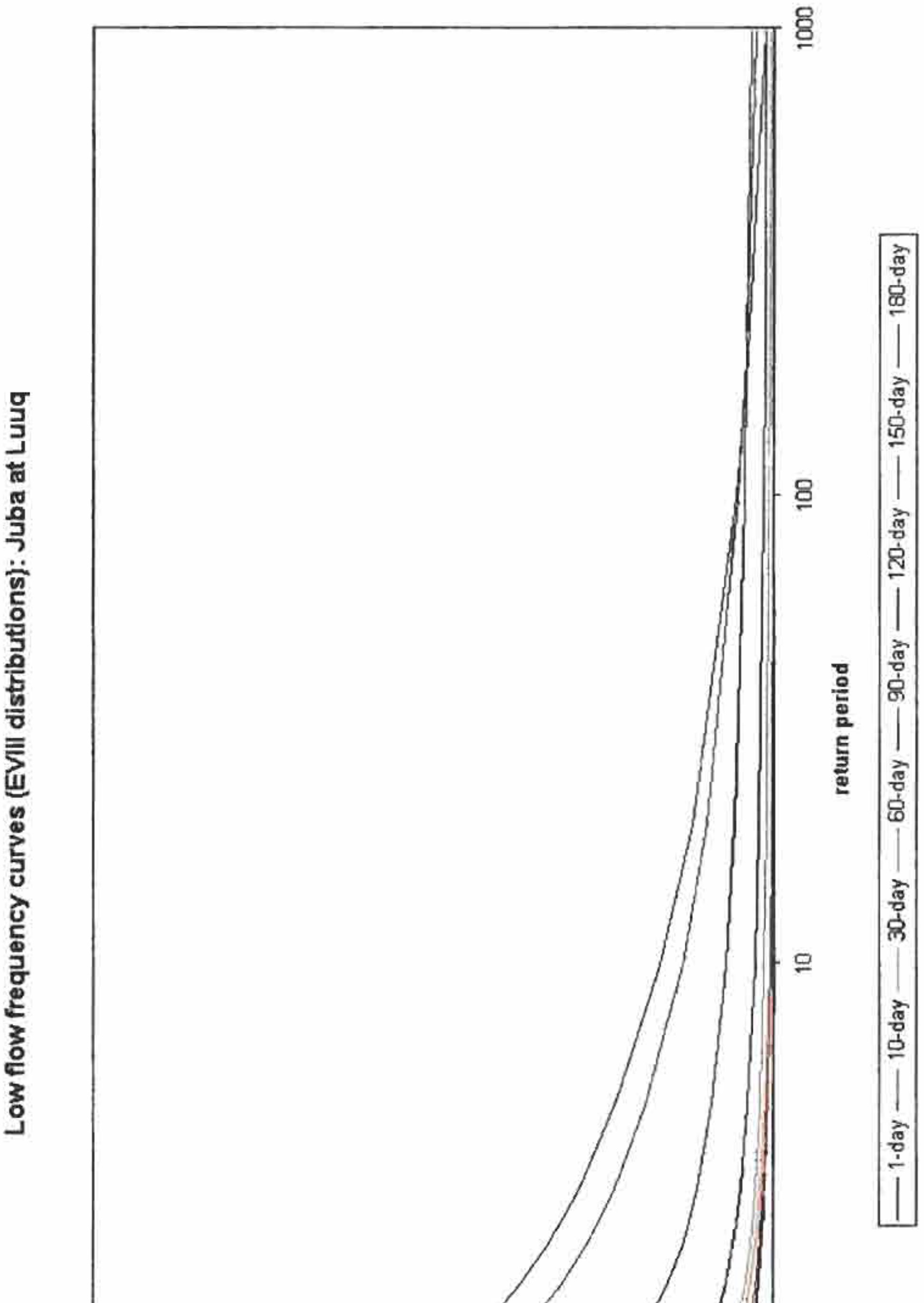


Figure 4.10. Fitted EVIII distributions for low flow frequency curves. River Juba at Luuq. Data 1963-1989

4.8. Investigation of dry-season duration and timing

4.8.1. Dry season duration at Belet Weyne and Luuq

The dry seasons were treated as within-year droughts and analysed as runs. Although the definition of drought is not necessarily correctly applied here, the duration and severity of the dry seasons are nonetheless extremely important. The low flow analysis of the previous section could be considered as a study of within-year drought intensity.

Little irrigation occurs during the dry season as there are few perennial crops. However banana production which occurred on the Lower Juba before the war did require irrigation year round so in this case the dry season conditions are crucial. However the end of the dry season and timing of the start of the flood season is also important for agriculture. In addition, it is during the dry seasons that pastoralists rely on the rivers. Animals are only brought down to the rivers once alternative supplies of water have been depleted, so lack of river water in addition to stored rainwater is particularly problematic.

The duration of within-year droughts was analysed using the model ARIDA (Assessment of Regional Indicators of Drought in Africa). This was developed by CEH for the analysis of historical and current droughts in Southern Africa. It contains facilities for carrying out various low flow and drought analyses, including determining the distribution of short-duration (within-year) droughts as runs below some threshold.

Eighty percentile flow was set as the threshold level for within-year droughts (dry season). This corresponds to approximately 30 m^3/s for the Juba and 12 m^3/s for the Shabelle. The possibility of dependent droughts occurring was considered, and to allow for this, droughts separated by a period of ten days or less were pooled. Probability plots of drought duration were produced by ARIDA, and various distributions could be fitted, including the Pareto, Log-Normal type III, Generalised Extreme Value (GEV) and the exponential distribution. The exponential distribution was unsuitable for both rivers, and the best fits were obtained with the Pareto and the GEV distributions. The best-fit distributions for each river are shown in figure 4.11.

The fit of the distributions to the Juba was much better than to the Shabelle. While the Juba generally has continuously high flow from April-November, there is a much more pronounced reduction in flow between the Gu and Deyr on the Shabelle, during which time the flow can fall below the 80 percentile threshold. The duration of these low flow periods is generally much shorter than those of the main dry season (the Jilaal, from approximately December to March), with the result that a lot more short-duration droughts occur on the Shabelle. This distorts the shape of the frequency distribution. It would certainly be preferable to consider the Jilaal and Haggai low flows separately. This is particularly the case when fitting a GEV distribution, which is correctly applied only to the extreme event from each year. The Pareto distribution, which is often used for peak-over-threshold (or under-threshold) (Mood et al, 1974), is more suitable for the Shabelle.

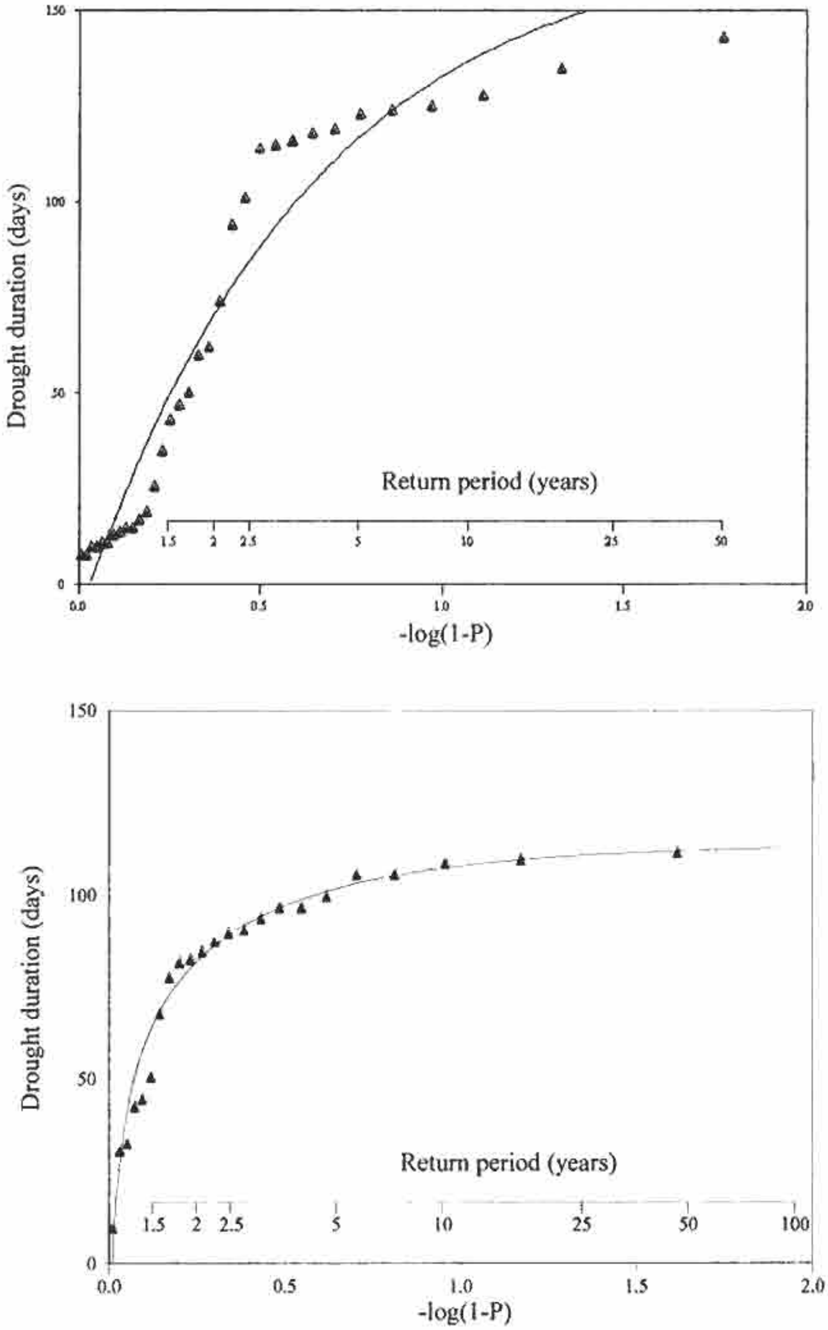


Figure 4.11. Cumulative distributions of within-year drought duration, where P is the probability of non-exceedence. a) Pareto distribution fitted to Shabelle at Belet Weyne, correlation 0.940 b) GEV distribution fitted to Juba at Luuq, correlation 0.941

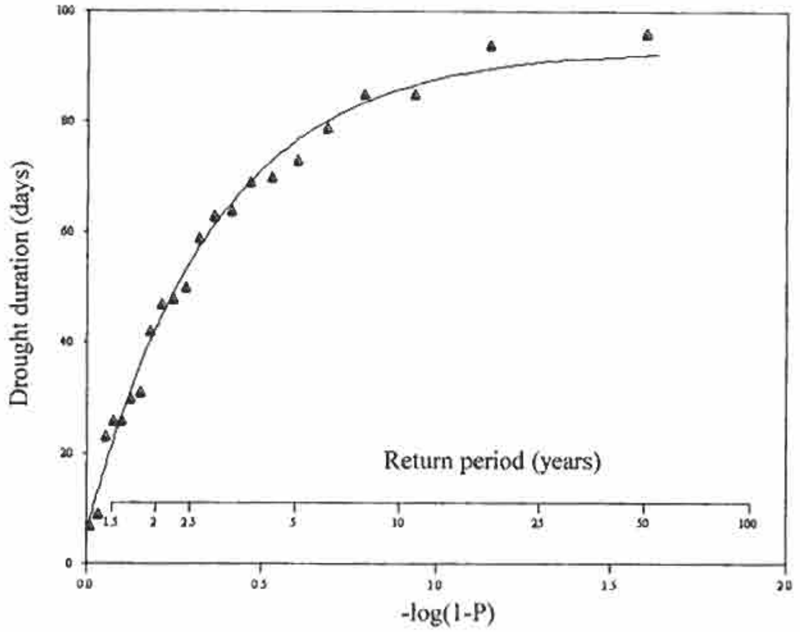


Figure 4.12. Cumulative Pareto distribution fitted to dry-season duration (flows below 88 percentile) at Jamaame. Correlation 0.949

4.8.2. Low flow durations at Jamaame

Due to the problem of seawater intrusion in the Lower Juba, the periods at Jamaame (the furthest downstream station) during which flow falls below 15 m^3/s were also considered using ARIDA. From the flow duration curve, 15 m^3/s was approximated as 88 percentile flow at Jamaame, and this was used as the threshold in the short-duration drought analysis. Flow falls below the 88 percentile level in most years, with the potential to cause problems for Kismayo water supply. There is little evidence of this situation worsening over the time period of analysis. The distribution of durations below the 88 %ile threshold is shown in figure 4.12, fitted to a Pareto distribution.

4.8.3. Timing

For the Juba, the start of the Gu flood season was defined as the end of the final drought period of the year (where a drought is defined as a period of time below 80 percentile flow, as in section 4.8.1.). In some years, the flow exceeds the 80 percentile for a short time and then falls below again, but this was not considered to be a true start. The same principle was also used for the Shabelle, but the date used was not always the last in the year due to the occurrence of low flows during the Haggai.

The timing of the start of the Gu season was classified by decade (ten-day period), and the distribution of start time between decades is shown for the two rivers in figure 4.13.

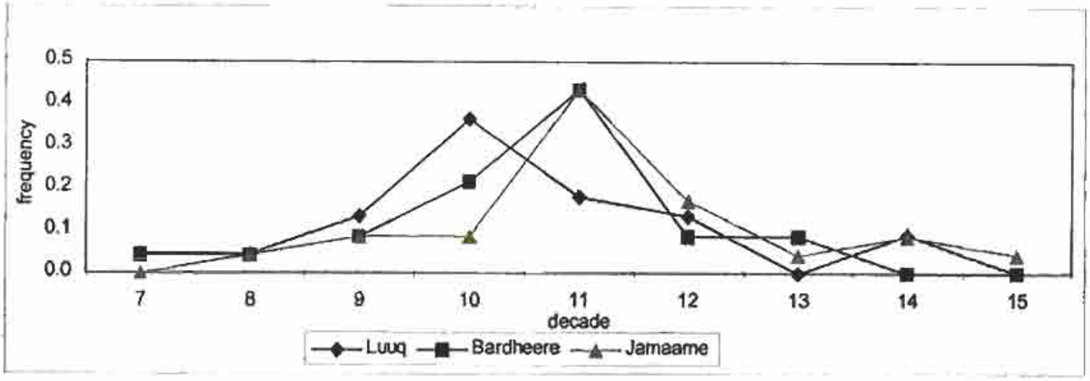


Figure 4.13.a Timing of start of Gu season on the Juba river.

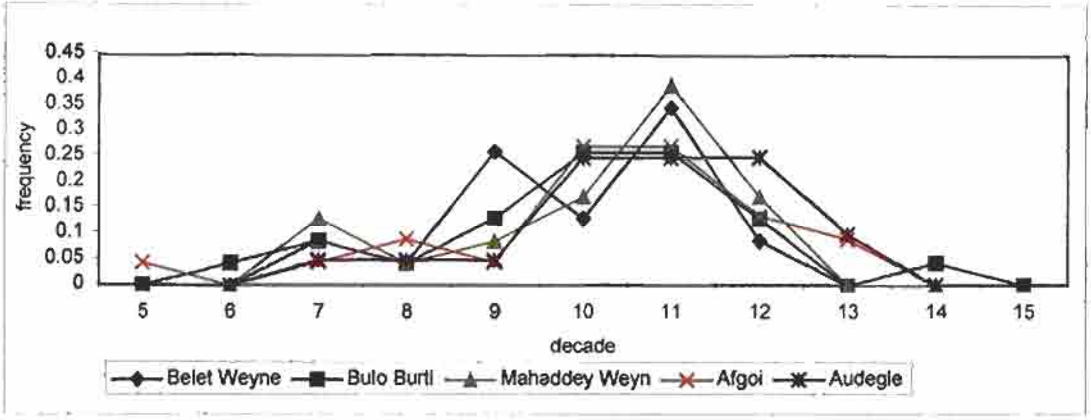


Figure 4.13.b. Timing of start of Gu season on the Shabelle.

On the Juba, the most probable start of the Gu season at Luuq is the first decade of April. This is one decade earlier than the season is likely to start downstream. For the Shabelle the situation is somewhat more complex, with 80 percentile flow sometimes being exceeded at a downstream station before Belet Weyne. This is due to the change in the shape of the flow duration curve along the Shabelle, since considerable overbank flow occurs downstream, which restricts the high flows. For the Shabelle, at every station the most probable start time for the Gu season is the second decade of April, with in some cases the first or third decades of April being equally likely.

The timing of the Deyr is important since it is a larger season than the Gu. This cannot be defined using the same threshold as the Gu since it follows the Haggai flows, which are generally much higher than the Jilaal flows that precede the Gu. From the average flow distributions shown in figures 4.1 and 4.3, it seems that an appropriate threshold for distinguishing the Haggai from the Deyr would be the 50 percentile flow. Attempts to define the start of the Deyr in this way were not, however, entirely successful, particularly on the Juba. As there is often little decrease in flow during the Haggai season on the Juba, in over one third of years the flow does not fall below the 50 percentile. This occurs in approximately 10% of years on the Shabelle. However, when flow does fall below the 50 percentile mark during the Haggai, it is most likely to increase above this threshold again during the second half of July (decades 20 and 21), as shown in figure 4.14.

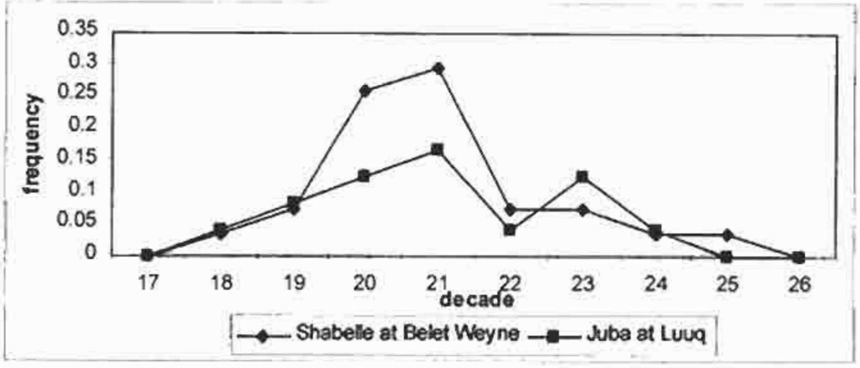


Figure 4.14. Timing of the Deyr season on the Juba and the Shabelle

4.9. Multi-year run analysis

Annual time series of flow in comparison to the mean, for Luuq on the Juba and Belet Weyne on the Shabelle, are shown in figure 4.15. The downstream stations show the same patterns, although the proportions are not always the same as a result of abstractions downstream.

The inter-annual patterns of runoff are similar for the two rivers, suggesting a relative uniformity in rainfall patterns across the upper parts of the two catchments (this is investigated further in chapter 5).

4.9.1. Drought periods from 1963-1989

Drought periods were defined as years where rainfall was below average, on the assumption that water-use activities are conditioned towards average flow situations. There was little difference between the mean and the median for either river, so use of the mean was considered acceptable.

The drought periods were characterised by duration, severity and magnitude (as defined in chapter 2), and the results of this are shown in tables 4.6 and 4.7. Difficulties were encountered at the beginning and end of the data sets, and where there was missing data (as on the Juba from 1967-69), because the start and end dates of runs could not strictly be defined.

The most extreme drought of the period (1963-1989) can be classified either by duration, severity or magnitude, but this results in differing rankings of the droughts in each case.
For the Shabelle, the most extreme drought by:

- Duration is 1984-1989
- Severity is 1973-1975
- Magnitude is 1979-1980

For the Juba, the most extreme drought by:

- Duration is 1973-1976
- Severity is 1979-1980
- Magnitude is 1979-1980

There are advantages and disadvantages to the use of each of these characteristics. Multiple years of below-average water supply can have a devastating cumulative effect, so in this sense consideration of duration is crucial. However if a long-duration negative run is only just below average for most of the time, crop growth may still be successful and the depletion of water supplies minor. A drought of great severity is most likely to also be one of long duration, although this is not necessarily the case, as in the drought period of 1979-1980. For the Juba, the drought of greatest severity lasted only two years, resulting in a very high magnitude for this drought. The drought of greatest magnitude on the Shabelle occurred at the same time as the Juba. The second ranked drought by magnitude (which commenced in 1973) also coincides for the two rivers.

Standardised magnitudes are also shown in table 4.6 and 4.7 (i.e. the actual magnitude divided by the standard deviation of annual flow), so that droughts on the Juba and Shabelle can be more easily compared. However, comparison is still difficult because the durations of most droughts differ between rivers.

Start year	Duration (years)	Severity (total deficit, mm)	Magnitude (mm/ year)	Normalised magnitude
1964	3	10.4	3.4	-0.96
1971	1	1.4	1.4	-0.39
1973	3	10.4	3.5	-0.97
1979	2	8.2	4.1	-1.13
1984	6 (followed by end of data)	8.5	1.4	-0.39

Table 4.6. Drought periods at Belet Weyne

Start year	Duration (years)	Severity (total deficit, mm)	Magnitude (mm/year)	Normalised magnitude
1964	3 (followed by gap in data)	14.4	4.8	-0.44
1973	4	22.9	5.7	-0.52
1979	2	29.0	14.5	-1.32
1984	3	27.4	9.2	-0.84
1988	1	5.3	5.3	-0.48

Table 4.7. Drought periods at Luuq

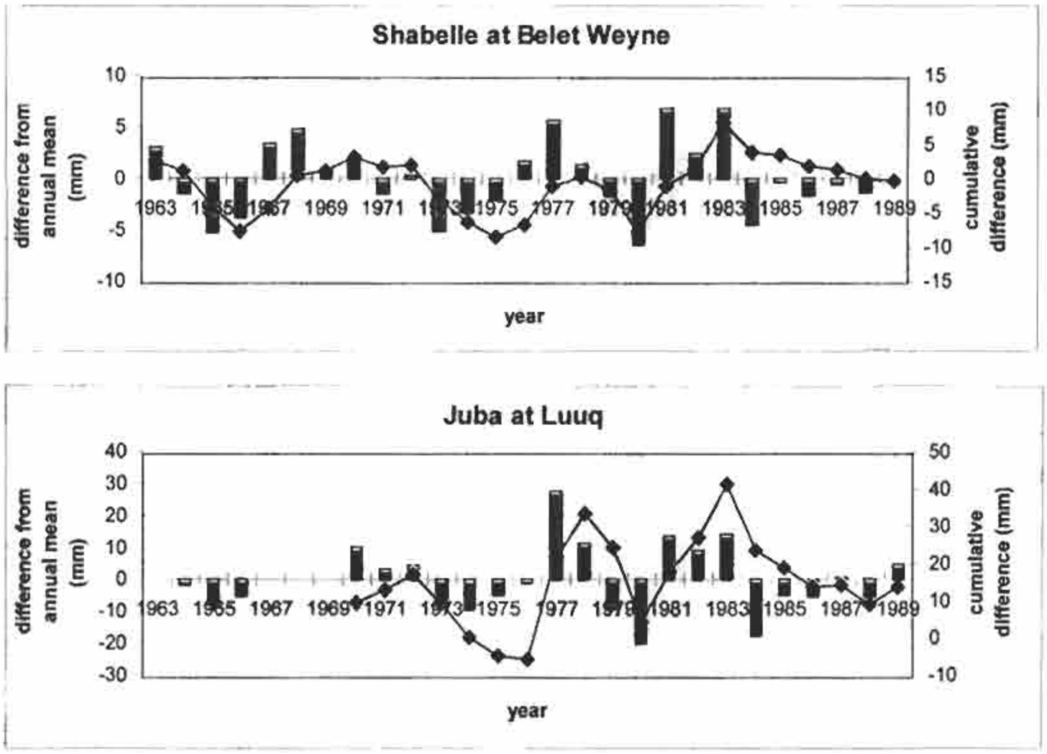


Figure 4.15. Annual runoff from the Juba and Shabelle (data missing for Juba, 1963 and 1967-69)

The mid to late 1980s represented a lengthy period of below-average conditions. This had not ceased on the Shabelle when flow measurements were interrupted by the civil war, so the total duration of this drought is not known. In most years of this drought, the flow was only just below the mean, so it is possible that the impacts of the drought were minor. This will be discussed further in chapter 6.

4.9.2. Appropriateness of use of annual flows

Annual flow is not necessarily representative of the distribution of flows in the river through the year. For example, one large flood event could results in a high annual flow, when flows through the rest of the year had actually been below average. To investigate this, the time-series of total annual flows and annual minima for the Shabelle and for the Juba are plotted for comparison in figure 4.16.

The general inter-annual pattern is the same for annual minima as for annual totals, but the minima lag one year behind the totals. The similarity is greater for the Shabelle than the Juba. Cross-correlations between the annual totals and the annual minima were highest at lag-1. These were approximately 0.65 for the Shabelle and 0.55 for the Juba.

This lag resulted in some years having very low flows but above-average annual totals. On the Shabelle, 1967, 1976 and 1981 are notable in this respect. The 1981 event was particularly significant, as two months of zero-flow had occurred at Belet Weyne (being at the end of the severe drought of 1979-1980) but this was followed by an early and extended Gu flood with return period estimated by Gemmell (1982) at 10,000 years. The situation in 1981 was similar for the Juba.

A significant discrepancy occurs on the Juba in 1970, which is the only year that zero flow has been recorded at Luuq. The annual flow for 1969 is missing so it cannot be compared. The pattern of low flows is generally similar on the Juba and the Shabelle, but this is not the case in 1970. The reason for the extreme low flows on the Juba in this year is unknown.

The lag occurs because the lowest flows are at the beginning of the calendar year, and are responding to total flows in the previous year. This is related to groundwater recharge mechanisms. After one or more years of below-average total flow, the sand lenses in hydraulic connection become depleted so low flows in subsequent years cannot be sustained by groundwater recharge.

4.9.3 Run durations

The runoff plots in figure 4.12 show that runs above and below the mean are commonly of duration longer than one year. If the durations of both positive and negative runs are considered, it becomes clear that there is a predominance of three-year runs, as shown in table 4.8. This is discussed further in chapter 5.

It is interesting to note that the predominance of three-year runs is less evident at sites further downstream, particularly at Afgoi and Audegle. This is most likely to be due to variations in abstractions, which make comparison between years for these stations problematic. The focus has been on Luuq and Belet Weyne since they most closely represent the natural states of the Juba and Shabelle (although modifications and extractions do exist within Ethiopia).

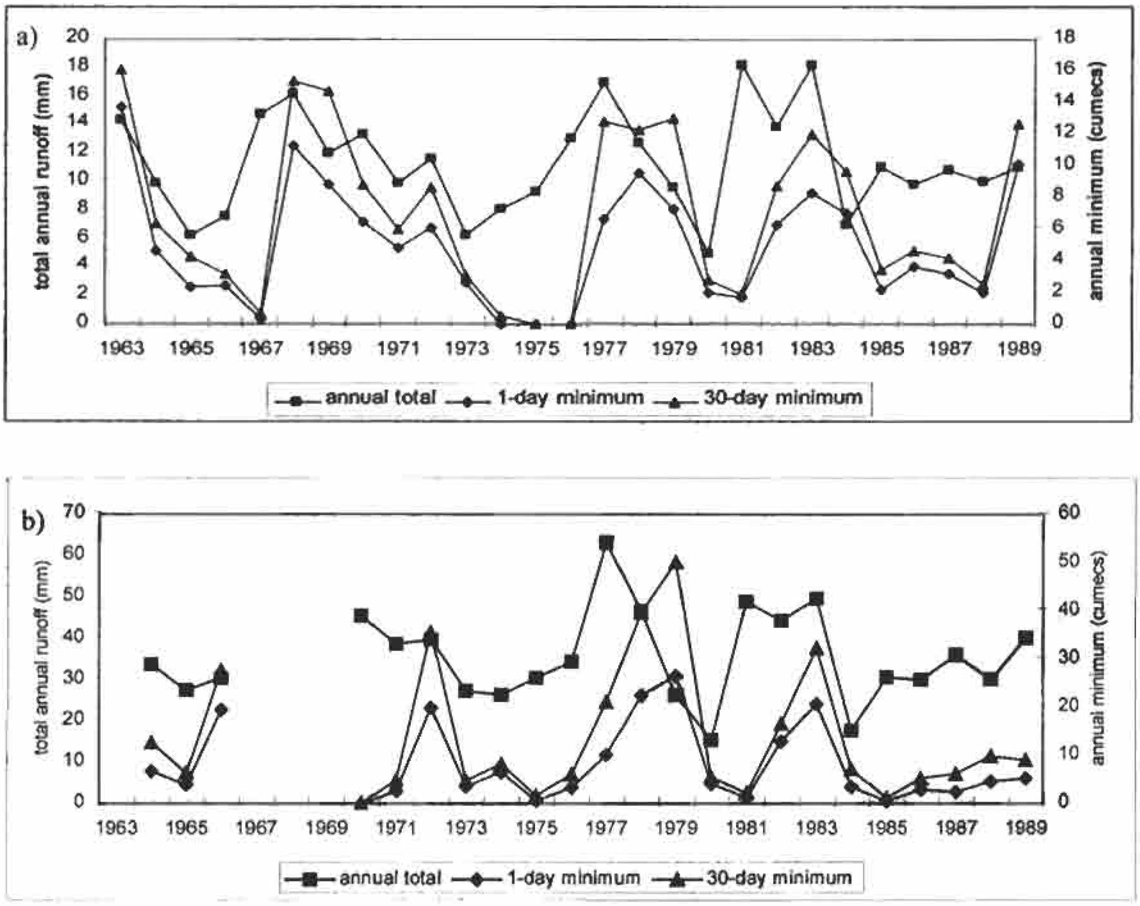


Figure 4.16. Comparison of annual minimum flows to annual totals a) Shabelle at Belet Weyne b) Juba at Luuq

Duration (years)	Number of occurrences	
	Luuq	Belet Weyne
1	3	3
2	2	1
3	4	5
4	1	0
5	0	0
6	0	1

Table 4.8. Frequency of occurrence of runs of various durations

4.9.4. Distributions of multi-year run characteristics

It would be desirable to know the frequency distribution of multi-year run characteristics, as for within-year runs in section 4.8. Either the distribution of all runs, or of the largest drought in a pre-defined period (e.g. the maximum drought in 25 years) may be of interest. However this is not possible using the 27 available years of record alone, since only about five multi-year droughts occur within this time. Yevjevich *et al.* (1983) considered the maximum duration of drought in 25 year and 100 year periods, and suggested that a distribution could be developed by the generation of many 25-year periods of synthetic data, followed by extraction of the maximum drought duration from each period. While simple in concept, the generation of new data can be problematical and has not been carried out in this study. The properties of the annual time series, particularly the autocorrelations, were nevertheless examined. This was for the preliminary stages of fitting an ARMA model to the data, which could then be used for data generation. The autocorrelations will be discussed in chapter 5.

4.10. Tests for persistence

A simple test for persistence, used by Gommes and Petrassi (1994), was carried out on the annual flow data for the two rivers. This involved classification of each year as a "wet" or a "dry" year, dependent on the occurrence of above- or below-average runoff. The class of the following year was then considered, and recorded in a simple contingency table.

		year i+1	
		Dry	Wet
year i	Dry	10	4
	Wet	5	7

a) Belet Weyne

		year i+1	
		Dry	Wet
year i	Dry	8	4
	Wet	4	5

b) Luuq

Table 4.9. Contingency tables showing relationship of runoff in year i to runoff in year i+1

From the limited period of data available, it appears that there is some tendency for dry years to be followed by dry years on both rivers, but there is less evidence of this for wet years. This is due to the sustained period of below-average runoff through the second half of the 1980s. These relationships are inconsistent at downstream stations due to abstractions and other river modifications.

River and gauging station	Minimum annual runoff	Years recording zero flow	Longest dry season duration	Multi-year drought characteristics		
				Maximum duration	Maximum severity	Maximum magnitude
Shabelle at Belet Weyne	1980	1974, 1975, 1976	1974-75	1984-89	1973-75	1979-80
Juba at Luuq	1980	1970	1979-80	1973-76	1979-80	1979-80

Table 4.10. Comparison of most extreme droughts by various drought definitions

4.11. Summary

Various different analyses of drought characteristics have been carried out. These include low flow analysis, analysis of dry season duration, and consideration of multi-year drought periods. A "most extreme drought" can be determined from each of these analyses, and the results of this are shown in table 4.10. There is more consistency in this than the equivalent comparison which was carried out for rainfall (section 3.9). The exception to this is the one year that zero-flow was recorded on the Juba, which was 1970.

Three periods of drought can be distinguished, which are similar on both rivers. These are 1973-76, 1979-80, and 1984-89. The below-average period of the 1980s was the most sustained, although for much of the time this was only just below average. It is clear that in most cases, the rivers react similarly. This suggests some uniformity of rainfall across the eastern Ethiopian highlands, which will be discussed further in chapter 5.

Chapter 5: Ethiopian rainfall, and other influences on runoff

5.1. Purpose of study

In section 4.9, it was mentioned that autocorrelations of annual runoff data had been calculated. These calculations will be discussed in section 5.3. It is the results of this exercise that led to the development of this chapter, in order to increase the understanding of the influences on runoff in the Juba and Shabelle rivers.

5.2. Southeast Ethiopian rainfall

5.2.1. Data sources and quality

Monthly data for Ethiopian rainfall were available from two sources: the Climate Research Unit (CRU) at the University of East Anglia, and from a report of a development project in the Arsi and Bale regions of Ethiopia (Ethio-Italian Cooperation, 1997).

Problems were encountered in determining the geographic locations of some of the stations in the CRU archive, as the supplied grid coordinates did not appear to correspond to settlement locations on any maps. If a settlement of the same name was found within the region, the data were assumed to correspond to this station.

The Ethio-Italian (1997) report contained monthly rainfall data from 14 stations in the Arsi and Bale regions. The longest records used in the report were for Assela from 1966-1996, Dodola from 1954-1996 (with some gaps in the record) and Goba from 1962-1984.

As with the Somali rainfall (chapter 3), some problems were encountered with data discrepancies between sources. Data for Ginir and Goba appeared in both sources. For Goba, the data were available in both cases for the same time-period, although a few extra months had been infilled (by unknown means) in the Ethio-Italian project. However the data for Ginir were completely different between the two sources. It seems probable that the CRU data is incorrect as it gives a calculated average annual rainfall of 1309mm, which is considerably higher than any other station in the area. The average calculated from the Ethio-Italian source is 854 mm/year, which is more similar to that of surrounding stations. Given the inaccuracies in the coordinates of the CRU stations, it is also possible that the 'Ginner' of the CRU data is not actually the same as the 'Ginir' found on maps and used in the Ethio-Italian project.

The annual rainfall total for Deder is also unexpectedly high, considering the lower averages of nearby Dire Dawa and Harar. Unfortunately there was no other data source against which to check the quality of this data.

Figure 5.1. Map of southeast Ethiopia, including locations of rainfall gauging stations
Source: University of Texas, http://www.lib.utexas.edu/maps/africa/ethiopia_pol99.jpg

5.2.2. Rainfall characteristics

The eastern part of Southern Ethiopia has seasons similar to Somalia, while in the west there is a tendency towards a single rainy season. Where there are two seasons, the timing of the rains is slightly different from Somalia due to the difference in arrival time of the ITCZ, and the influence of topography. The first rains are known as the *Belg*, and the second, main rainy season is called the *Kiremt*. The annual rainfall distributions for various stations in southeast Ethiopia are shown in figure 5.2 (determined using CRU data).

The total annual rainfall is predominantly dependent on altitude, and reaches well over 1000 mm in the upper highlands (Kammer, 1989). This decreases at lower altitudes, and near the border with Somalia reaches low levels of 2-300 mm/ year, similar to those experienced at

Luuq and Belet Weyne. At a few locations, notably Assela and Goba, rainfall is influenced significantly by orographic effects in addition to elevation (Ethio-Italian Cooperation, 1997).

5.3. Comparison of Ethiopian rainfall to Juba and Shabelle runoff

On both the Juba and the Shabelle, the Deyr season is larger than the Gu, in contrast to the rains within Somalia. This is due to the Ethiopian rainfall patterns, where the main rains (the *Kiremt*) correspond to Somalia's Deyr season. The *Belg* season, which is the equivalent of the Gu in Somalia, is relatively minor, although its importance varies across the country and is more significant in the southeast than elsewhere.

There is less distinction between seasons on the Juba compared to the Shabelle, because the Juba arises further west in the Ethiopian highlands where the rainfall is more continuous from April through to October. In the east there is more distinction between the Belg and the Kiremt rains and as a result the seasons on the Shabelle are better defined.

5.3.1. Rainfall in the Upper Juba catchment

The three main tributaries of the Juba are the Gestro, the Genale and the Dawa. These are located almost entirely in southeast Ethiopia, with part of the Dawa catchment extending into Kenya. The contribution (estimated by Kammer, 1989) of each of the tributaries to flow in the Juba is shown in table 5.1. These estimates suggest that the highest losses occur on the Genale, which can be explained by a higher proportion of outcropping basement rock in that sub-catchment, particularly along the riverbed, resulting in relatively more runoff (Kammer, 1989).

Unfortunately rainfall data was only available for stations in the Gestro sub-catchment. Since this makes the smallest contribution to Juba runoff, correlations between the available rainfall and Juba runoff may be lower than it would be for other parts of the catchment. In addition, the high spatial variability in rainfall means that attempts to correlate runoff to point rainfall will not necessarily be successful.

Juba sub-catchment	Area (km^2)	Proportion of rainfall	Proportion of runoff at Luuq
Gestro	27,000	14%	50%
Genale	57,000	42%	40%
Dawa	60,000	37%	7%

Table 5.1. Contribution of sub-catchments to Juba flow. (From Kammer, 1989)

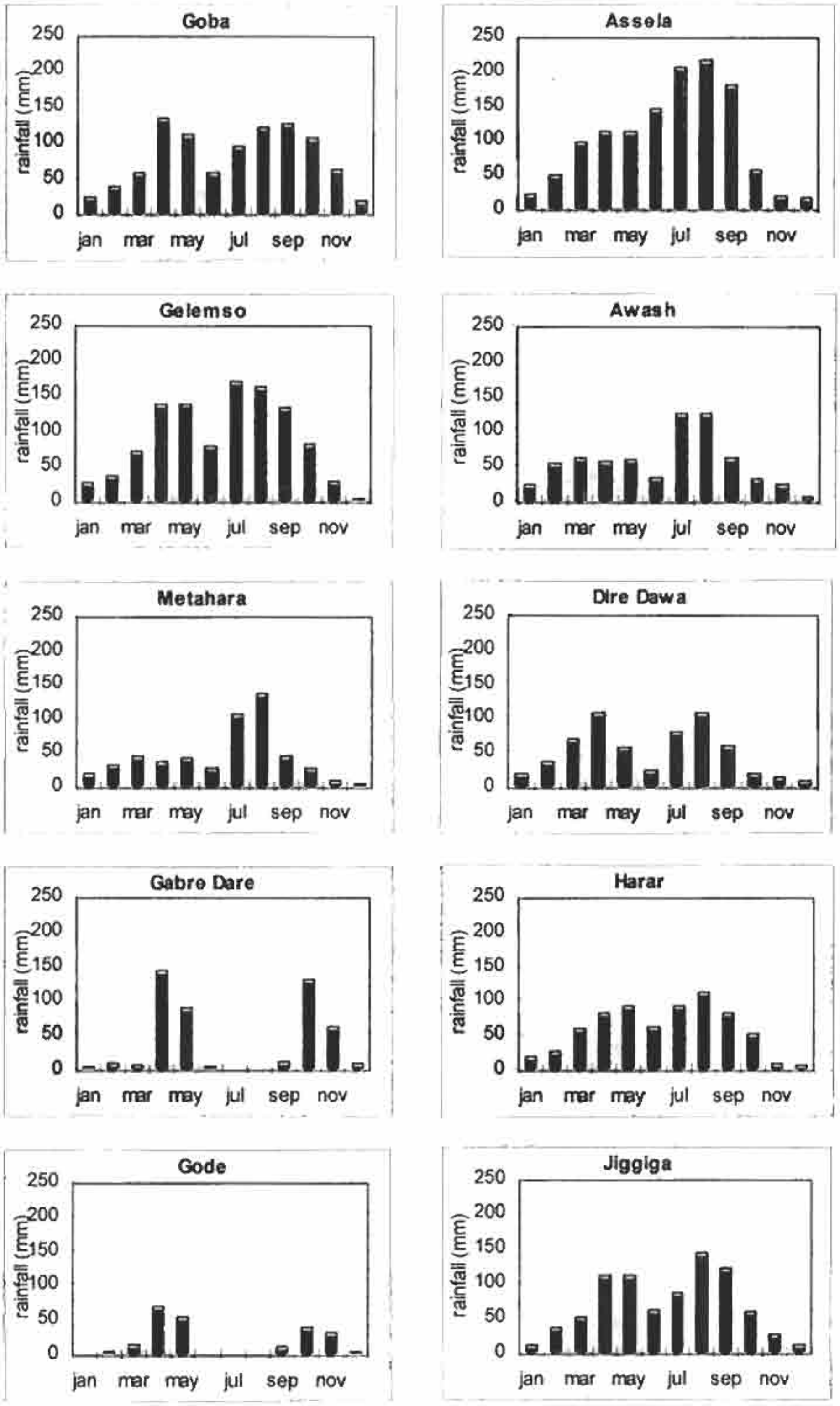


Figure 5.2. Distribution of rainfall at various stations in southeast Ethiopia

Comparison between rainfall stations is difficult because most of the records are of different lengths and do not always cover the same years, although they are all between 1963-1990. Stations were only used for correlations if more than ten years of data was available.

Table 5.2 shows that the runoff in the Juba at Luuq is most closely correlated at the annual level to the rainfall at Goba (this is also shown in figure 5.3). This is to be expected, as it is the only station within the Juba catchment. Significant correlations to annual rainfall at Assela and Metahara also exist, which does not immediately seem surprising since they are relatively close to the Juba catchment and situated at equally high altitudes. However Metahara is on the northern side of the Rift Valley and thus a particular connection to the Juba catchment would not really be expected, and also, correlations to rainfall at Awash and Gelemso, which are close to Metahara, were not significant.

Ethiopian rainfall station	Correlation to runoff	
	Juba at Luuq	Shabelle at Belet Weyne
Assela	0.522	0.607
Goba	0.813	0.720
Metahara	0.786	0.726
Gelemso	0.103	0.033
Jiggiga	0.189	0.249
Dire Dawa	0.488	0.647
Deder	0.515	0.386
Harar	0.222	0.091
Gode	0.701	0.496

Table 5.2. Correlations of Ethiopian annual rainfall with runoff on the Juba and Shabelle (for stations with more than 10 years data).

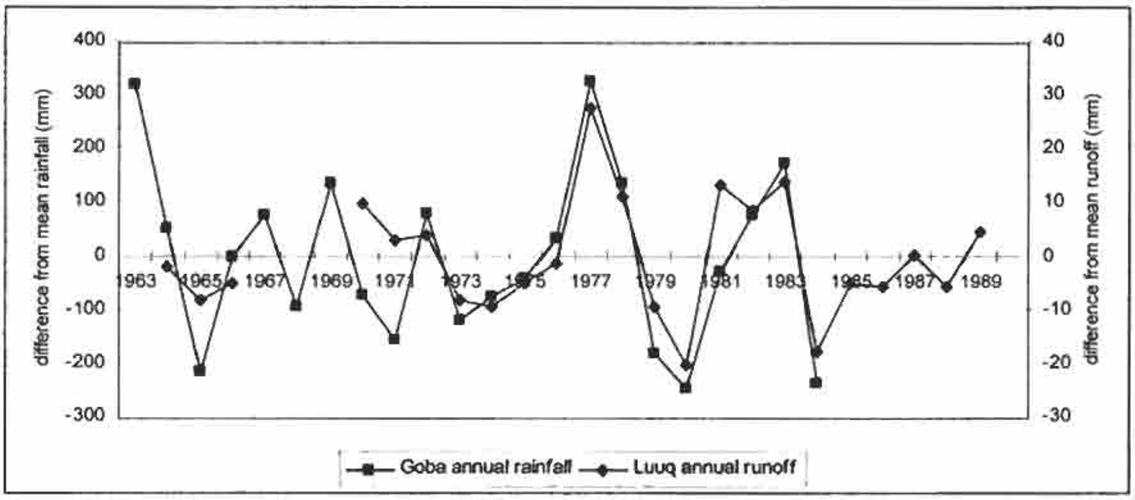


Figure 5.3. Annual time-series comparing rainfall at Goba and runoff at Luuq

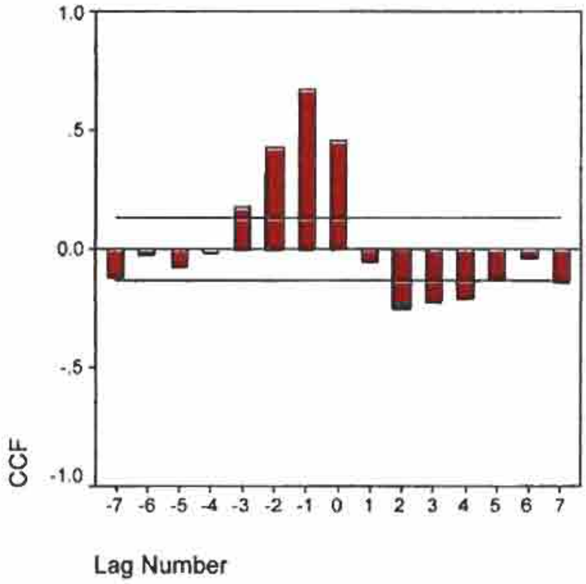


Figure 5.4. Cross-correlogram for monthly runoff at Luuq against monthly rainfall at Goba

Monthly correlations are considerably lower than annual, if only the zero-lag correlations are considered. This is a result of the time-delay involved in the rainfall-runoff routing. A much greater correlation for monthly data is achieved at lag-minus one (shown in figure 5.4). Significant positive correlations are obtained for lag-zero to lag-minus three, and significant negative correlations from lag-two to lag-four, reflecting the seasonality of the rainfall and runoff.

Scatter-plots of Luuq runoff against Goba rainfall indicated that the correlation is much stronger in some months than others. Significant correlations (at 5% level) of runoff to the previous month's rainfall were obtained for runoff in January, May, August, November and

December. The variability between months is shown in table 5.3. Suggested reasons for the differences include:

- Effective rainfall is expected to be highest around November. This is the end of the second rainy season, when the catchment will be at its wettest and the runoff coefficients will be greatest, and correlations between rainfall and runoff may be higher. (Runoff coefficients are also shown for comparison in table 5.3)
- The time-delay between the occurrence of rainfall at Goba and resulting runoff at Luuq is probably between zero and one month, in which case the use of monthly data is inadequate. However, travel-times are increased during flooding due to the higher roughness of overbank flow. Thus the months of highest flow may be expected to have greater lag-1 correlations.
- The timing of the rainy seasons varies across the catchment (although details are not known for the western-most areas) and the relative contributions from each of the sub-catchments may vary accordingly.
- Given the assumption of Faillace (1986a) that the river is recharged by shallow groundwater lenses during low flows, groundwater would be expected to make a proportionately greater contribution during low-flow periods, with rainfall contributing less.
- Abstractions from the river within Ethiopia will be greater during the crop-growing seasons, which will distort the rainfall-runoff relationship at these times.

5.3.2. Rainfall in the Upper Shabelle catchment

Shabelle runoff is best correlated at the annual level to rainfall at Goba and Metahara (as shown in table 5.2 and figure 5.5). Goba is actually situated in the headwaters Juba, but due to its high altitude and proximity to the Shabelle catchment, the correlation is not that surprising. The apparent importance of rainfall at Goba to both the Juba and Shabelle rivers explains the similarity in inter-annual variability between the two rivers.

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
R^2 fit of linear trend line	0.32	0.29	0.20	0.18	0.70	0.06	0.08	0.40	0.02	0.00	0.63	0.61
Cross-correlation	0.680	0.534	0.443	0.429	0.837	0.251	0.278	0.629	0.134	-0.091	0.791	0.780
Runoff coefficient (%)	4.0	4.2	2.5	3.0	2.9	4.9	5.8	3.6	2.9	4.6	6.7	15.7

Table 5.3. Relationship of runoff at Luuq in month *x* to rainfall at Goba in month *x-1*

As with the Juba, the correlation of Shabelle runoff to rainfall in Metahara is somewhat surprising since the two are separated by the Rift Valley, with mountains of great elevation. Correlations to the easterly stations were not significant, even though these are within the Shabelle catchment. However, those stations are at the head of the Fanfan tributary, which flows only intermittently in its lower reaches and so does not always contribute to flow in the Shabelle (Kammer, 1989).

There is a surprisingly close relationship of annual runoff on both the Juba and the Shabelle to rainfall at Goba through most of the time series. The exception to this is from 1967-1971, when the correlation seems to completely break down. The difference is most prominent in 1968. The reason for this cannot be known for certain, however, the rainfall for some months in 1968 (January-April) and 1969 (December) had been infilled in the Ethio-Italian project from which the data was taken. The means by which this was carried out was unknown, so the reliability of these years of data is questionable.

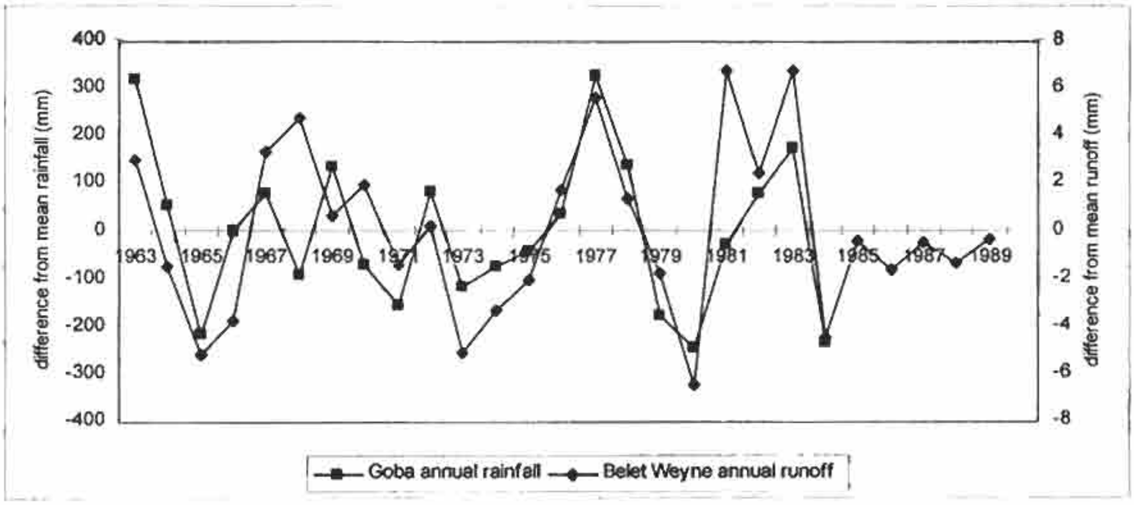


Figure 5.5. Annual time-series comparing rainfall at Goba and runoff at Belet Weyne

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
R^2 fit of linear trend line	0.09	0.02	0.19	0.25	0.58	0.16	0.18	0.10	0.29	0.02	0.47	0.70
Cross-correlation	0.594	0.689	0.431	0.498	0.762	0.404	0.424	0.322	0.510	0.104	0.686	0.834
Runoff coefficient (%)	1.09	0.65	0.87	1.54	1.30	0.86	1.20	1.53	1.53	1.30	0.85	0.66

Table 5.4. Relationship between runoff at Belet Weyne in month *x* and rainfall at Goba in month *x-1*

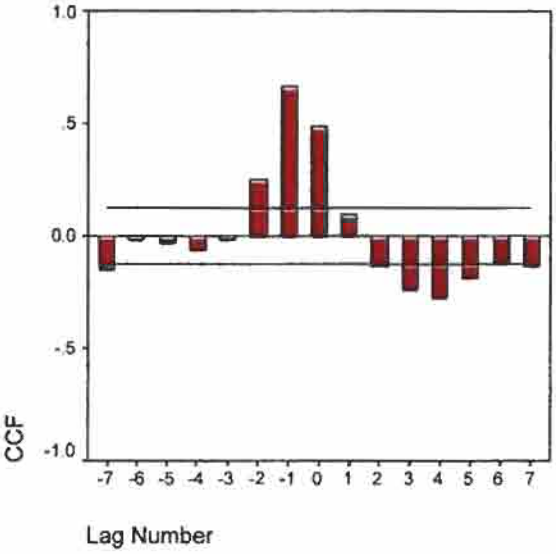


Figure 5.6. Cross-correlogram for monthly runoff at Belet Weyne against monthly rainfall at Goba

Monthly runoff at Belet Weyne was compared to rainfall at Goba for the previous month, and as for the Juba, the relationship was found to vary through the year. The correlations show similar patterns through the year to the Juba, with significant lag-one cross-correlations occurring for runoff in January, February, May, November and December, although there is no evidence of the February correlation in the rainfall-runoff scatterplots.

Possible reasons for the differing relationships through the year are similar to those given for the Juba. However, runoff coefficients are much lower for the Shabelle than for the Juba (reasons for this were discussed in chapter 4), and they are highest at the peak of the Gu and Deyr seasons, so are low again by November-December. Thus high runoff coefficients may not be an adequate explanation for the good correlation of Goba rainfall to runoff in these months. An additional factor is the seasonal importance of the Fanfan tributary, which affects the relative contribution from the various sub-catchments. On this assumption, correlations to Goba rainfall would be expected to be greater during the dry seasons (e.g. January and February), when the Fanfan does not reach the Shabelle.

It is most likely that there is no single explanation for the months of high correlation, as they occur during completely different phases of the hydrological year, but various mechanisms have been suggested which could contribute.

5.4. Evidence of cycles

5.4.1. Evidence of cycles in Somali runoff records

As mentioned in chapter 4, annual autocorrelations of Juba and Shabelle runoff were calculated, which was intended as the preliminary stage of data generation in order to investigate the distribution of multi-year drought durations. The latter part of this process was not carried out, but the autocorrelations themselves proved to be of considerable interest.

Figure 5.7 shows the correlograms for annual time-series of runoff on the Juba and Shabelle. Time-series of annual runoff often exhibit a significant positive correlation at lag-1, but at higher lags the correlation would be expected to decrease exponentially (as in an autoregressive lag-1, or Markov process). As a result it was surprising to find a significant negative correlation at lag-3 years for both rivers. This provides some explanation for the predominance of 3-year runs, which was discussed in section 4.8. The lag-3 correlation was also observed at downstream stations, although it was less pronounced.

These autocorrelations suggest that there is a cyclical process in rainfall and/or runoff generation. However, an unusual aspect is that if a cyclical process is occurring, a positive correlation would then be expected at lag-6, and this was not observed at all on the Shabelle and only slightly on the Juba. The lack of this effect could be due to differences in the amplitude of the cycle, reducing the correlation at longer lags.

The autocorrelations of annual rainfall within Ethiopia were also determined, in order to compare them to those of the Juba and Shabelle runoff. There appeared to be little similarity in correlations across the region, although comparison was hampered by gaps in the data, resulting in inconsistent time-periods between stations.

The only rainfall station at which there was any significant evidence of inter-annual autocorrelations was Goba, which has a significant correlation at lag-2, and some correlation at lag-3. Figure 5.7 shows this in comparison to the autocorrelations of runoff on the Juba and Shabelle. The pattern at Goba appears similar to the Juba, and is not dissimilar to the Shabelle, although the rivers show stronger correlations at lag-3 than Goba rainfall. This suggests that the primary influence on inter-annual variability of runoff is rainfall in the Ethiopian Highlands, with the region around Goba apparently playing a particularly dominant role.

5.4.2. Previous studies finding evidence of cycles

A number of previous studies across Africa have also found evidence of cycles, in both rainfall and runoff records. Gommes and Petrassi (1994) carried out a study of rainfall variability and drought in sub-Saharan Africa, which included some discussion of trends and cycles, largely to note that "extreme caution is required in the interpretation of cycles..." particularly when only short data sets are available. This is an important point as, in example, Sahelian rainfall in the first half of the twentieth century was apparently clearly cyclical, but since the 1960s there has been little evidence of the cycle, with prolonged below-average rainfall occurring (Beran and Rodier, 1985). Despite the warning about cycles, Gommes and Petrassi (1994) went on to find evidence of cycles in rainfall for all parts of Africa, although but none of the amplitudes were significant. For the Horn of Africa and Kenya, there was some evidence of a 4-5 year cycle in the rainfall.

Tardy and Probst (1992) found evidence of cycles in major rivers in Africa including the Nile, Niger, Congo and Zambezi. All exhibited approximately a three-year cycle, while some also had a significant 5-6 year cycle and two southern African rivers had evidence of an 11-year cycle. Cycles were also found for other rivers worldwide. The timing of the cycles across the world did not coincide but appeared to be propagated around the globe, from west to east in Europe and Asia, and from south to north in the Americas.

Evidence of cycles of varying lengths was also found by Nicholson (2000) using spectral densities. There were peaks in densities for East African rainfall of 5 years (significant in Somalia and southeast Ethiopia), 3 years (significant in southern Somalia) and 2.3 years (significant across the whole of Somalia and Ethiopia). This was similar for much of eastern and southern Africa, but in contrast, the Sahel was found to be dominated by cycles of greater than 7 years (Nicholson, 2000).

5.5. Possible causes of inter-annual variability and cycles

There are various factors which could potentially influence the inter-annual variability of rainfall and/or runoff. These include:

- Variations in sea surface temperature (SST), including the effects of El Niño-Southern Oscillation (ENSO)
- Intensity and frequency of tropical cyclones in the Indian Ocean
- Anomalous movement or strengthening/weakening of the ITCZ
- Varying intensity of tropical jets
- Biogeophysical feedback mechanisms
- Sunspot cycles
- Vegetation cycles

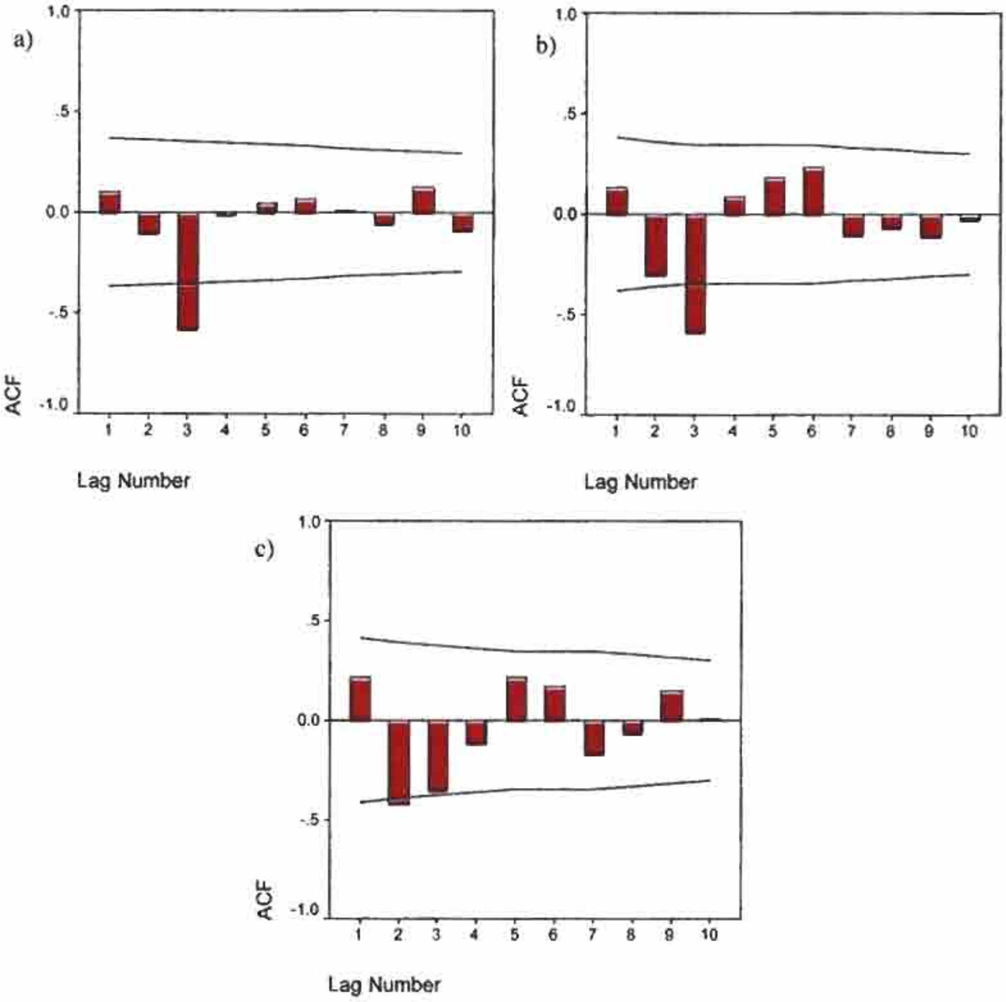


Figure 5.7. Annual autocorrelations. a) Runoff at Belet Weyne b) Runoff at Luuq c) Rainfall at Goba

5.5.1. The influence of SSTs and the SOI on African rainfall

The influence of the Southern Oscillation Index (SOI), and particularly of El Niño (the negative extreme of the SOI) on global precipitation patterns is of increasing interest and has been widely studied.

The SOI itself is a measure of the difference in sea-level pressure between Tahiti and Darwin (on opposite sides of the equatorial Pacific). It reflects changes in Pacific Ocean circulation, and the atmospheric conditions associated with that circulation. Under normal circumstances, upwelling along the coast of Peru causes low sea surface temperatures (SST) in the Eastern Pacific, which results in atmospheric subsidence in this area and drives the easterly trade winds. However under El Niño conditions, upwelling fails to occur, causing an increase in SST. This reduces the strength of the trade winds and decreases the pressure contrast between Tahiti and Darwin, resulting in a negative SOI and disrupting atmospheric circulation (NOAA, 2002). Changes in SST and atmospheric circulation patterns during El Niño can sometimes be observed worldwide. When exceptionally strong upwelling occurs, 'La Niña' conditions result, which represent a positive SOI anomaly, and can also have a global influence.

Global anomalies in precipitation patterns associated with the SOI were investigated by Ropelewski and Halpert (1989). They considered various regions where significant correlations could be found between the SOI and precipitation, which included tropical and southern Africa. High- or low-index events often last for a year or more, but anomalous precipitation patterns may only be observed during part of the time. For example, Ropelewski and Halpert (1989) found that high SOI often resulted in dry conditions in equatorial East Africa from November-March. They also found that during El Niño, the ITCZ tends to shift northward, resulting in increased equatorial rainfall, coincident with decreased rainfall in southeast Africa.

Opposing conditions are often found between equatorial and subtropical latitudes in Africa (Nicholson, 1993), so wet conditions in equatorial East Africa might be expected to coincide with dry conditions in the Sahel. However in an earlier paper, Ropelewski and Halpert (1987) had found little evidence of Sahelian precipitation patterns being related to El Niño. Some Sahelian studies have shown that the ITCZ in itself may not be a defining factor in rainfall fluctuations (Grist and Nicholson, 2001), and it is likely that in this region, other factors dominate over the effects of the SOI. Most studies suggest that the effect of ENSO is more strongly felt in Southern Africa (e.g. Botswana, as discussed in section 2.5) than in the rest of the continent.

Typical anomalies in global SST during an El Niño event are shown in figure 5.8. Warming across the Indian Ocean is evident, although to a lesser extent in the Gulf of Aden (off the north coast of Somalia). This warming coincides with anomalously low pressure over equatorial east Africa during ENSO events, which may cause enhanced rainfall (Latif *et al.*, 1999). It was shown by Latif *et al.* (1999) that the pressure anomalies are forced directly by SSTs in the Indian Ocean rather than indirectly by Pacific SST anomalies, suggesting that weak ENSO events may not have an impact on East African precipitation. This is similar to Botswana, where drought is well correlated to SST increases in the Pacific Ocean but does not always occur during minor ENSO events, when the SOI is weaker and more short-lived (Nicholson *et al.*, 2001).

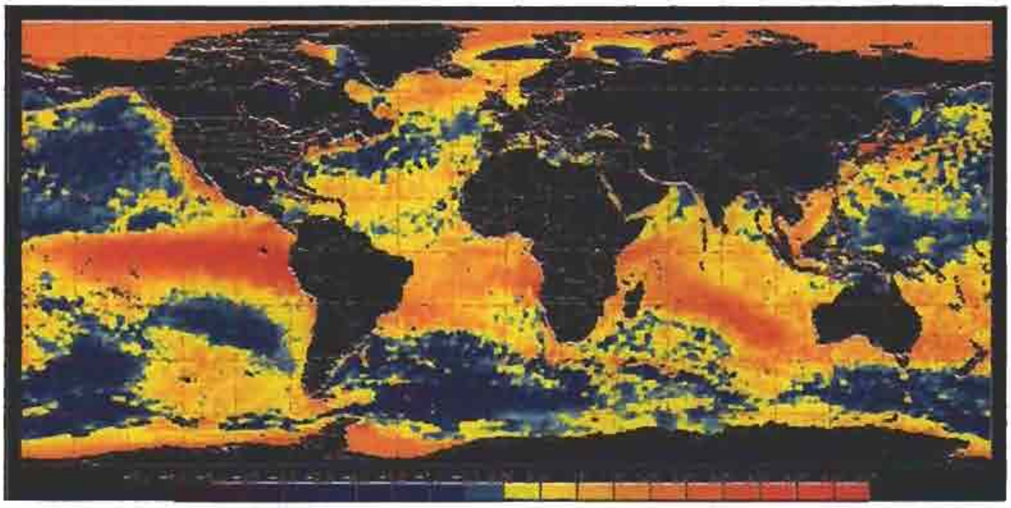


Figure 5.8. Sea surface temperature anomalies during the El Niño event of 1997-98 (negative anomalies in blue, positive anomalies in red)
Source: http://www.osdpd.noaa.gov/PSB/EPS/SST/climo_archive/anomnight.1.5.1998.gif

The SOI has similar cyclical frequencies to the rainfall and runoff cycles determined by Nicholson (2000) and Tardy and Probst (1992). Tardy and Probst stated that the SOI has significant periodicities of 3.6 years and 6 years, and Nicholson (2000) found the predominant variability in SSTs to be on a scale of 5-6 years. This is coincident with the main cycle in East African rainfall.

Most studies into the influences of SST on African rainfall anomalies seem to have concluded that while the SSTs may have some influence, there are also other factors which may be equally or more important (e.g. Nicholson 2000, Ropelewski and Halpert 1989, and Bekele 1997). These could include the formation of tropical cyclones in the Indian Ocean and the monsoon flow from the Atlantic, although these are also indirectly affected by SST.

5.5.2. Previous studies considering the influence of SSTs on Somali and Ethiopian rainfall

A few studies have involved an investigation in to the influence of the SOI and SSTs on Somali rainfall. Effects on Ethiopian rainfall have been more widely considered, and use of ENSO for long-range forecasting in Ethiopia has been proposed (Bekele, 1997).

Effects of ENSO on Ethiopian rain appear to oppose those in Somalia, with El Niño years often corresponding to the occurrence of drought in North and Central Ethiopia. Bekele (1997) found the Belg rains in particular to be deficient during ENSO events, while Kiremt rains were only affected if a SST anomaly was highest between January-June. Beltrando and Camberlin (1993) found there was also a strong positive correlation between September rainfall in Addis Ababa and the average SOI for June-November, although correlations for the rest of the Kiremt season were weak.

5.5.3. Relationships of runoff in Somali rivers to the SOI and Indian Ocean SSTs

Various time-series of the SOI are available on the Internet. A monthly time-series from 1951-2002 was obtained from the University Corporation for Atmospheric Research (UCAR) at http://www.cgd.ucar.edu/cas/catalog/climind/soi.html. A time-series of spatially averaged Indian Ocean SST anomalies was obtained from the University of Washington at http://tao.atmos.washington.edu/data_sets/indianSST.

The SOI and Indian Ocean SST anomalies (IOA) were first compared to each other, and as shown in figure 5.9, a strong negative correlation exists between the two. This is also clear from figure 5.8, since positive SST anomalies occur in the Indian Ocean during El Niño (negative SOI) events.

Following this, the SOI and IOA time series were compared to monthly runoff from the Juba and Shabelle. Seasonality was removed from the runoff time-series by normalising (subtracting the mean and dividing by the standard deviation for each month individually).

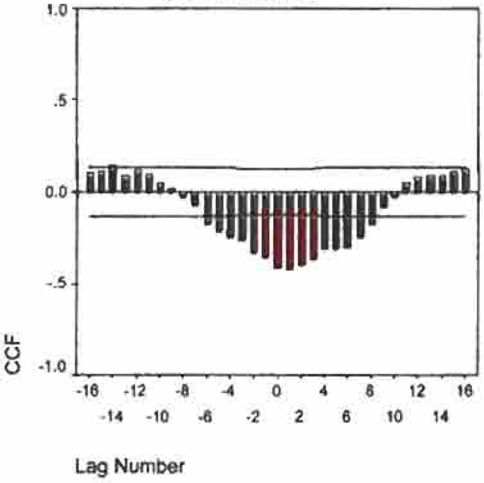
Some correlation of both the SOI and IOA to runoff on both rivers was discovered, with this being more evident for the IOA. This supports the findings of Latif *et al.* (1999) that rainfall over the Horn of Africa is influenced only indirectly by the SOI, through SST anomalies. Runoff was negatively correlated to the SOI and positively correlated to IOA.

Correlations to normalised monthly rainfall at Goba, Assela, Dire Dawa and Gode were also considered. They were not significant, but the tendency was towards negative correlations of rainfall to SOI, with positive correlations to IOA.

These results suggest that while the influence of the SOI and SSTs on rainfall in southeast Ethiopia (and consequently on Juba and Shabelle flows) may sometimes be minor, the reaction tends to be the same as that in Somalia. That is, there is a tendency towards high rainfall during El Niño events. In contrast, North and Central Ethiopia are more likely to display the opposite reaction to El Niño.

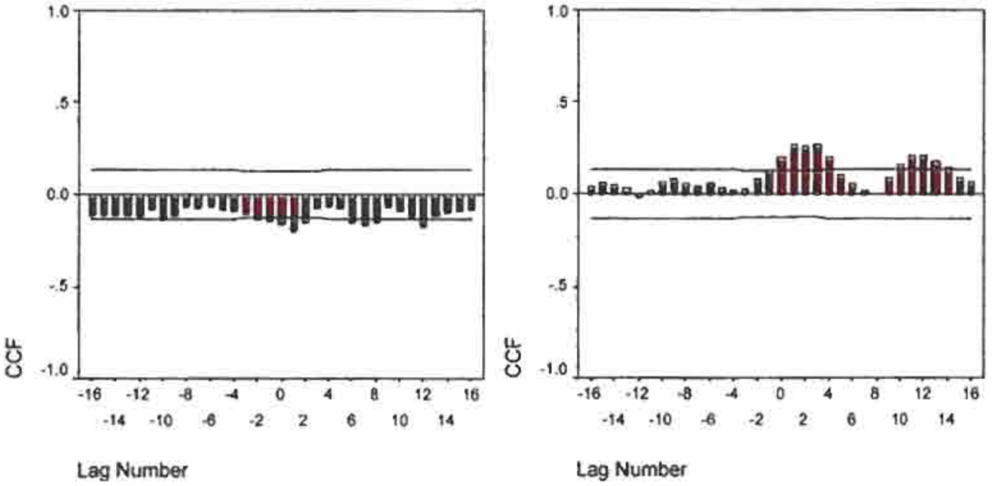
This can be explained by the latitudinal difference between southeast Ethiopia and Somalia in 10comparison to North and Central Ethiopia. Nicholson (e.g. 2000) found that equatorial and subtropical regions of Africa often exhibit opposing rainfall anomalies, and this seems to be supported in the Horn of Africa.

a) SOI and IOA



b) SOI and Shabelle runoff (at Belet Weyne)

c) IOA and Shabelle runoff (at Belet Weyne)



d) SOI and Juba runoff (at Luuq)

e) IOA and Juba runoff (at Luuq)

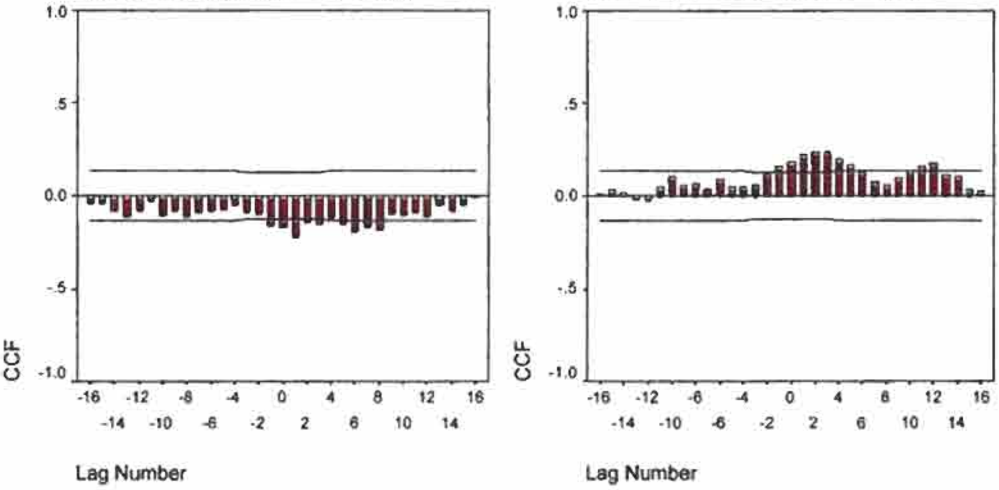


Figure 5.9. Monthly correlations of the SOI and Indian Ocean temperature anomalies to runoff on the Shabelle (at Belet Weyne) and the Juba (at Luuq).

5.5.4. Influences of the ITCZ, tropical cyclone activity, and other aspects of atmospheric circulation

The basic annual pattern of rainfall over Ethiopia and Somalia is determined by the movements of the ITCZ. However Nicholson (2000) suggests that the ITCZ is not the only controlling factor of African rainfall, and also that even if this does control the mean rainfall conditions, inter-annual variability is not necessarily controlled by the same processes. Nicholson (2000) found that while there is high spatial variability in mean climate conditions across Africa, temporal variations tend to be similar over the continental scale. She thus presumed that temporal variability is influenced more by wide-scale atmospheric or oceanic circulation. Also since drought conditions often occur in northern and southern Africa simultaneously, this could not be explained easily by movements of the ITCZ (Nicholson, 1986).

Nevertheless, Ropelewski and Halpert (187) found that the tendency of the ITCZ to shift northward during El Niño events altered rainfall patterns across Africa. In addition, studies by Beltrando (1990) suggest that weakening of the ITCZ over East Africa tends to coincide with below normal rainfall during the short rainy season of the region (this would not necessarily require a shift in the position of the ITCZ).

Beltrando and Camberlin (1993) suggested (on the basis of previous studies) that the main rains in the Ethiopian Highlands may be affected by the Atlantic-Congolese monsoon flow, although the extent of this influence was not known. They also note a significant change in atmospheric circulations over the Horn of Africa between September and October, which could be related to the Tropical Easterly Jet (TEJ) and may influence rainfall variability. Nicholson (1986) found the TEJ to be weaker during dry years in the Sahel.

Rainfall deficiencies in Ethiopia are associated with a greater intensity of tropical cyclones in the southern Indian Ocean (Bekele, 1997). The effect is more significant for the Belg rains, since the Kiremt rains occur at the time when there are fewest cyclones in the southwest Indian Ocean (Shanko and Camberlin, 1998).

Changes in the intensity of Hadley cell circulation have also been suggested as an influencing factor, with stronger circulation causing drought in the subtropics and higher rainfall near the equator. Kanamitsu and Krisnamurti (1978) found this to have been the case in 1972, during the major Sahelian drought.

The quasi-biennial oscillation is a phenomenon of the stratosphere in equatorial regions, which is already used widely in forecasting (Zachary Atheru, personal communication). This oscillation consists of a reversal in the direction of stratospheric winds over the equator (alternating between east and west winds) on average once every 28 months, although this varies between 20-36 months. This is known to affect hurricane activity and monsoons, and is also likely to have some influence of rainfall in Somalia and Ethiopia (Heaps *et al.*, 2002).

5.5.5. Other influences on rainfall and runoff variability

The 11-year sunspot cycle has been a popular explanation for cyclicity in drought occurrence. However, Tardy and Probst (1992) concluded since that cycles of drought are not synchronised across the globe, the sunspot cycle could not be exclusively a drought-causing phenomenon since even if some parts of the world are suffering from drought at the time of sunspot maxima, other areas will be experiencing at- or above-normal rainfall.

Biogeophysical feedback mechanisms (such as those discussed in chapter 2) are known to be significant in causing drought to persist in West Africa, but less evidence of this phenomenon has been found elsewhere. This is possibly due to the lesser importance of boundary layer processes in rainfall generation away from the Sahel.

The evidence of cycles is stronger in river flows than in rainfall. While there is some evidence of cyclical processes in rainfall, the effect appears to be amplified in runoff. This could be related to the inertia of groundwater processes, to vegetation cycles, to temperature variations, or to anthropogenic causes.

Vegetation cycles in some regions are known to affect the inter-annual variability of streamflows. For example, in Botswana, high runoff in one year promotes vegetation growth, which results in lower runoff in subsequent years due to higher roughness and greater evapotranspiration (Howard Wheater, personal communication).

Temperature variability has not been considered in this study due to the lack of data. However, it is of great significance as it affects the potential evaporation, thus influencing runoff generation.

Runoff variability will also be influenced by variations in abstractions, and by river modifications (e.g. flood protection bunds and irrigation canals falling in to disrepair). It is possible that more abstractions occur during dry years to compensate for the lack of stored rainfall. This would amplify the difference in flow between wet and dry years.

5.6. Conclusions concerning influences on runoff

Inter-annual variability of runoff on the Juba and Shabelle rivers is clearly influenced by rainfall in the Ethiopian highlands. The rainfall gauging station with the closest correlation to runoff on both rivers is Goba, which is in the headwaters of the Juba, but is not far from the Shabelle. The high rainfall and low permeability of the bedrock allow significant runoff generation from this area, although the relative contribution to flow varies through the year.

The cycle of approximately six years which is evident in runoff (and to some extent in rainfall at Goba) is thought to be related mostly to variations in SST in the Indian Ocean, which in turn is dependent on the SOI. There is a negative correlation of rainfall and runoff to the SOI, such that El Niño events tend to coincide with high rainfall and runoff in Somalia. The SOI appears to affect rainfall in southeast Ethiopia in the same way as it does rainfall in Somalia. In contrast, north and central Ethiopia often experience drought during El Niño events. This latitudinal opposition in rainfall anomalies between equatorial and subtropical regions is common in Africa (Nicholson, 2000).

The cycles appear to be amplified in runoff in comparison to rainfall at Goba, which suggests that rainfall-runoff processes also play a role. This may be related to vegetation cycles and temperature variations, with variable abstractions for irrigation also having an effect.

Chapter 6: Discussion of the spatial extent and impacts of drought

6.1. Water requirements

The technical difficulties involved in finding a definition of drought were discussed in section 2.1. This section is more concerned with the geographical and social factors that contribute to the problem of defining drought in Somalia. The complications involved in this are immediately clear when the water requirements of the Somali population are considered. Their needs are extremely variable depending on their geographical location and their lifestyle. Somalia has been broken down by the Food Security Assessment Unit (FSAU) in to "food economy zones", based on the primary source of food and income to an area. These zones are not restricted by regional boundaries, and are used to help assess the variability in food security across the country. A map of the food economy zones is shown in figure 6.1. The variation in lifestyle is particularly noticeable when considering the country as a whole, since agriculture is concentrated around the rivers in the south, while the north and central parts of the country are predominantly pastoral. However even within Southern Somalia, which has been the focus of this study, there is considerable local variability. The areas immediately around the rivers (including the river banks and desheks) have irrigated or flood-recession agriculture. Away from the rivers, pastoralism or agro-pastoralism is common, with rainfed agriculture being concentrated in the relatively fertile and high-rainfall area around Baidoa. Much of Southern Somalia is classified as agro-pastoralist, where people keep livestock but also plant crops. The livestock effectively provide insurance against crop failure, and additional resistance to drought it provided by the use of diverse cropping patterns, to allow for the unpredictability of the rains.

Maize is grown in riverine areas but away from the rivers, sorghum, more resistant to water shortages, is common. Cowpeas and sesame are also grown (Hundertmark, 2001). Commercial farming of tobacco, onions, maize and tree crops is carried out on the Juba, and before the war, banana plantations existed on the Lower Juba. Sorghum is rain-fed while maize and other crops are usually irrigated. As a result, poor sorghum production will not necessarily coincide with low maize yields, if rainfall has been poor but river levels high.

The main growing season for most of the country is the Gu, although the Deyr season dominates in the rivers. Approximately 75% crop production is during the Gu season (FSAU, 2000). Water requirements for agriculture vary through the season. Needs are highest for seed germination but water availability must continue throughout the season. Sowing of seeds for Gu crops generally occurs in April, with harvesting taking place in August. Deyr season crops are sown in October-November and harvested in February-March (USDA, 2002).

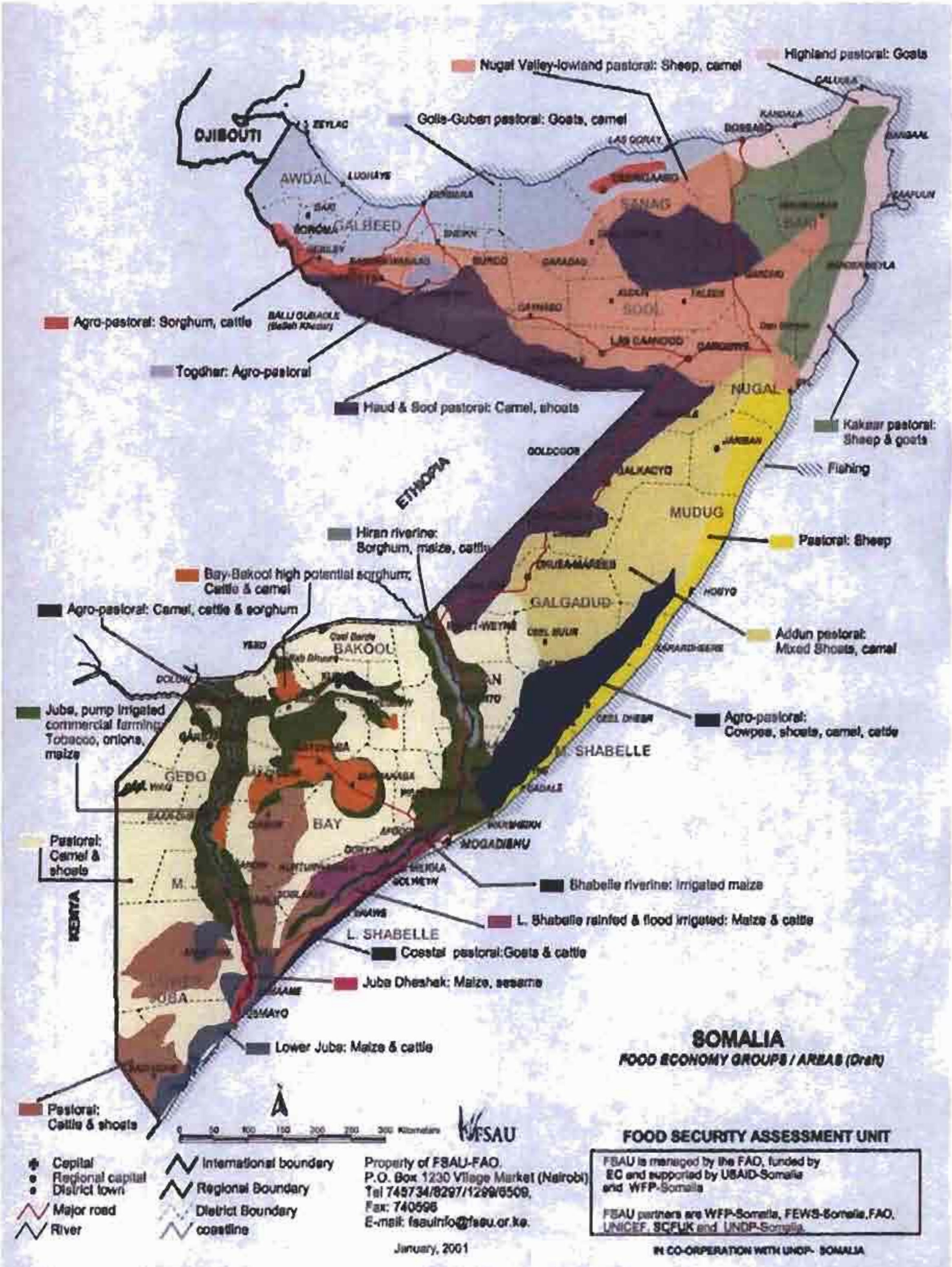


Figure 6.1. Food economy zones of Somalia. Source: UNDP-Somalia and FSAU

Water requirements of pastoralists can be high, as livestock need to be fed and watered. Stored water is required to sustain communities and livestock through the dry season, and adequeate rainfall is also necessary to allow growth of rangeland for grazing. The pastoralist lifestyle is finely tuned to the environment. Being nomadic, they move where the water is available, prioritise water supplies so as to maximise availability, and aim to reduce overgrazing through their constant movement. However this does not mean that the pastoralists are not still susceptible to drought. Stored rainwater is used for as long as possible. Once these supplies have been depleted, livestock must then be moved to a borehole supply or to the rivers. Use of borehole water can result in over-grazing of the surrounding area, and places extra strain on the supply, which is probably used during the rest of the year only for domestic use (USAID, 1979). Migration to the rivers can result in competition with settled farmers for riverbank space and water during times of low-flow. In a FEWS monthly report from 1999, it was pointed out that "Since pastoralists normally have bigger guns, riverine crops are likely to suffer from livestock grazing"!

Migration to rivers occurs only once rainwater supplies have been depleted, suggesting the occurrence of a rainfall drought. This movement increases the usage of river water and, if river levels are already low, the compounding effect of livestock watering can be particularly serious. Thus the coincidence of a rainfall and streamflow drought would be expected to have the most severe consequences.

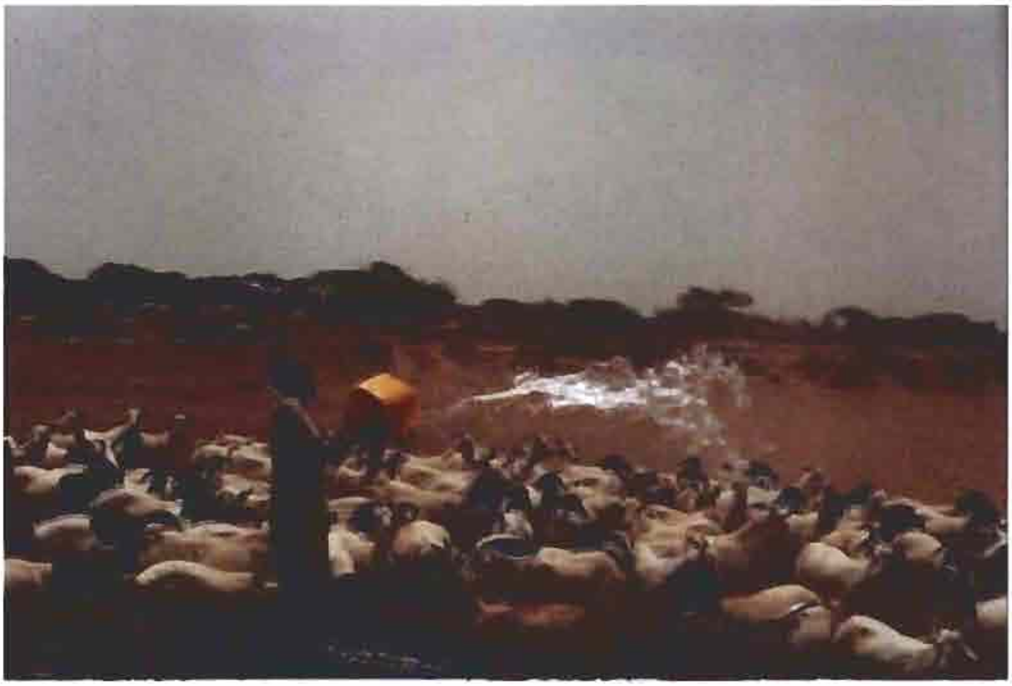


Figure 6.2. Pastoralist watering his livestock

Inadequate water supply for a single season or year can have a devastating effect on agriculture, causing complete crop failure. Short-term failure of rains may have less effect on rangelands, and the timing of the rains is less crucial for pastoralists than farmers. This is part of the reason why pastoralism is more resilient to droughts (at least those of short duration), and it is as a result of this resiliency that livestock are kept for insurance against crop failure by agro-pastoralists. Failure of rains for a year would ultimately be expected to have little effect on livestock herds, with serious effects generally being expected only after three years of inadequate rains (Graham Farmer, personal communication). The effects of prolonged drought on pastoralism may precipitate rapidly, as the remaining water sources and grazing land become over-used (Hussein, 1976). The seriousness of a drought can be assessed by livestock condition and numbers. When water shortages are severe, more livestock have to be sold or slaughtered. Sheep and goats are the first to be slaughtered during periods of drought, followed by cattle, with camels, the prized possessions, being retained until last (Lewis, 1975).

It is important to note that low rainfall is not automatically a problem, and high rainfall is not necessarily beneficial. Drought periods can actually be important for reducing livestock numbers, which increase during years of plentiful rainfall, helping to maintain the ecological balance (Lewis, 1975). Exceptionally high rainfall or river flows, on the other hand, can cause extensive damage through flooding.

6.2. Perceptions of drought in Somalia

Drought is commonly perceived in Somalia to be a periodic phenomenon. Inevitably, the periodicities cited vary greatly between sources. A number of examples are shown below:

- Hutchinson, 1992 estimated that Deyr crops will fail one year in three
- Williams (1979): In the Gedo region, pastoralists believe severe droughts have a cycle of about 10 years
- Sidow Adou (FEWS NET, personal communication) estimates that severe drought occurs once every four years, with localised deficits occurring frequently
- Brunken and Haupt (1987) state that minimum irrigation requirements cannot be met during the Hilaal in one out of two years
- Hunting Technical Services (1977) state that Gu rains are sufficient for cropping only in 60-70% years
- USAID (1979): "in this arid country where rainfall is erratic, and droughts constitute an eminent threat every four or five years, the availability of a steady water supply is one of the most critical perceived needs of a majority of the population"

- Anon (1987) estimated crop failure in the Bay region once every 3-4 years, with reduced grain production once in two years

Drought appears to be accepted as a fact of life in Somalia. However, the issue of food security is much wider than having adequate rainfall. This is particularly the case in a country suffering constant factional fighting, but factors such as market prices, fuel costs, food aid distribution, livestock bans and pests are also crucial. Other meteorological factors besides rainfall, such a strong, hot winds can affect crop yields, and irrigation and flood protection practices along the rivers also have a significant impact (FSAU and FEWS-NET, 2000).

6.3. Memorable droughts in Somalia

The Somalis have named the most severe droughts, making them more memorable. In the twentieth century, notable droughts included *Xaaraamacune* ("the eater of forbidden food") in 1911-12, *Siigacase* ("the blower of red dust") in 1950-51 and *Dabadheer* ("the long-tailed one") from 1971-75 (Bradbury *et al*, 2001). It is not known if the significant period of drought which occurred in the mid-1980s has a name. A famine in the early 1990s has become known as *dad cunkii* ("the time of cannibalism"), but this was more a result of the war rather than meteorological or hydrological causes (Bradbury *et al*, 2001).

The drought of the 1970s was particularly severe in northern Somalia, including the Nugal, Sanag, Toghder and Bari regions (Lewis, 1975). Southern Somalia was also affected at this time through reduced flow in the Shabelle, and records of drought in the Gedo region in 1975 have been found (Williams, 1987). This coincided with the widespread drought of the West African Sahel, and was also felt in Ethiopia. A major famine in Ethiopia from 1972-73, and continued below-average rainfall in Ethiopia was indicated by low flows in the Nile since 1965 (Demissie, 1989).

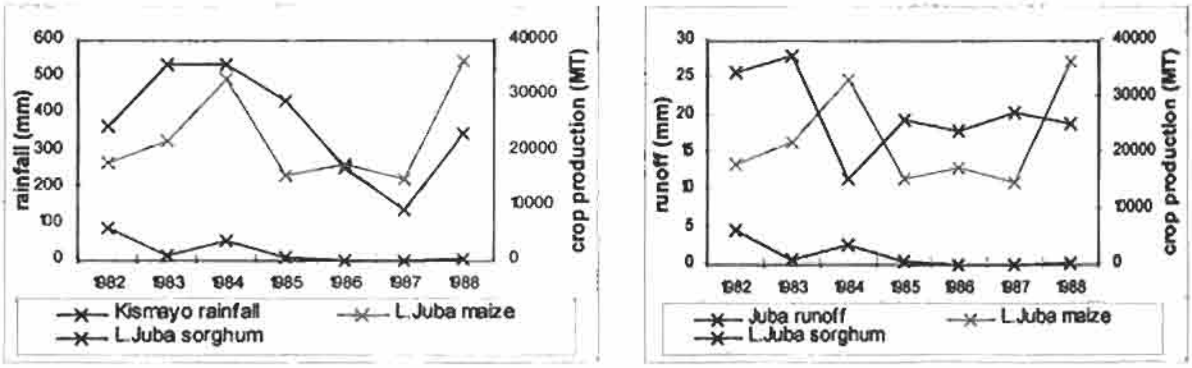
During the 1980s Ethiopia suffered widely-publicised famines (including 1982-3 and 1987-8 (Demissie, 1989)), and this extended to Somalia. Major droughts occurred in 1983-4, including the Bay region in 1983 (Anon, 1987) and the Gedo region in 1984 (Williams, 1996).

6.4. Influence of rainfall and streamflow on crop production

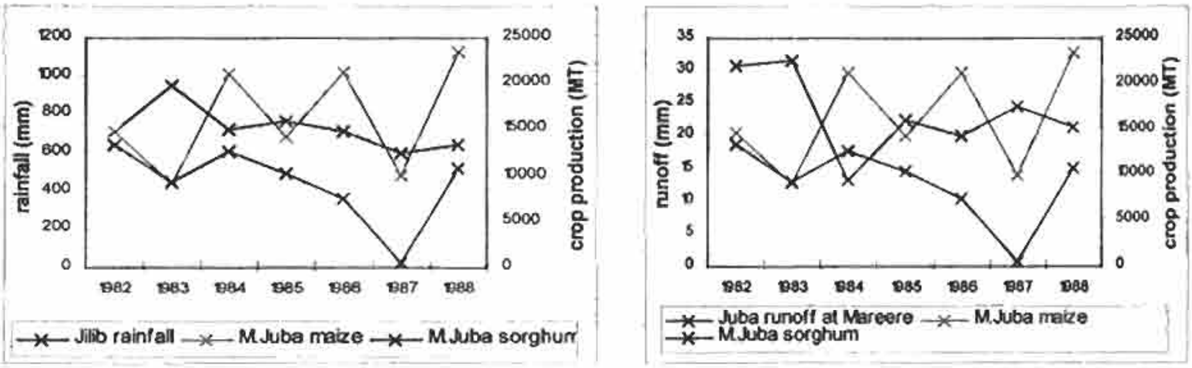
The FSAU hold records of crop production and cropped areas for both pre- and post-war, which are available at the district and the regional level. The post-war records begin in 1996, while pre-war data is from 1982-88. Pre-war data was collected by the Ministry of Agriculture of the Somali Government, and little is known about the collection methods or quality of these data. The data are nevertheless relied upon for comparison of current crop production to long-term averages.

The pre-war crop production and area statistics, for the Gu and Deyr seasons for each year, were available for all the regions of Southern Somalia. This includes the Gedo (Upper Juba), Middle Juba and Lower Juba, the inter-riverine regions of Bay and Bakool, and the Hiraan (Upper Shabelle), Middle Shabelle and Lower Shabelle. These seven years of data were compared to the rainfall and runoff records in order to consider the impact of rainfall and runoff variations on crop production.

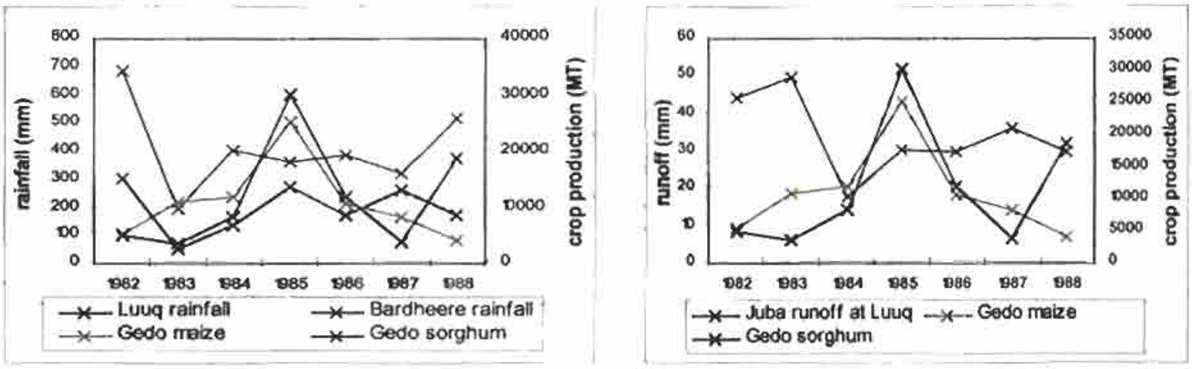
a) Lower Juba



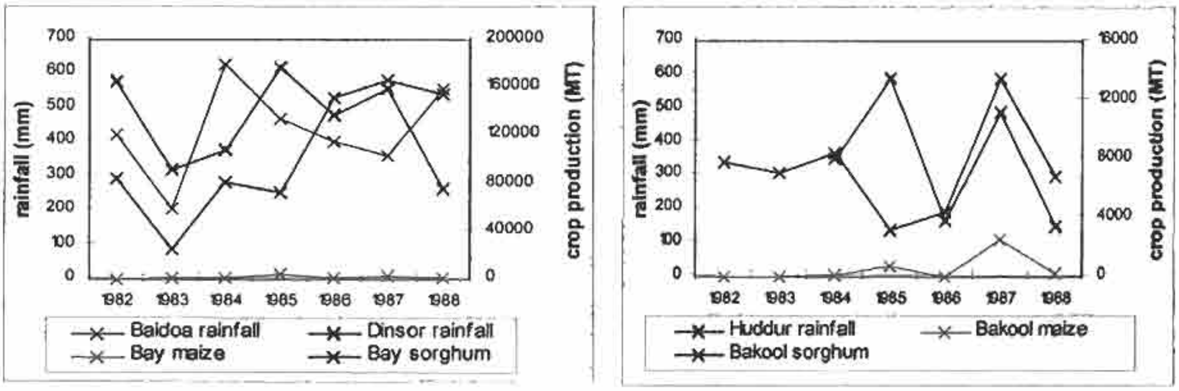
b) Middle Juba



c) Gedo

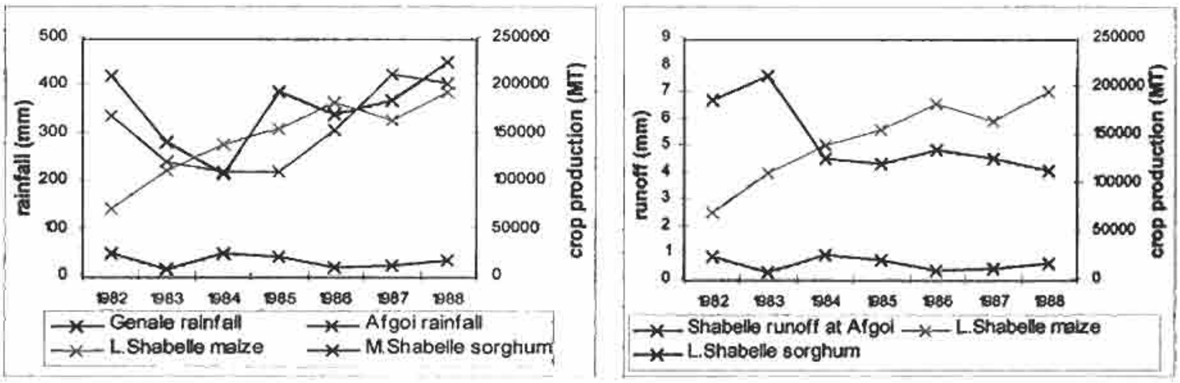


(figure 6.3)

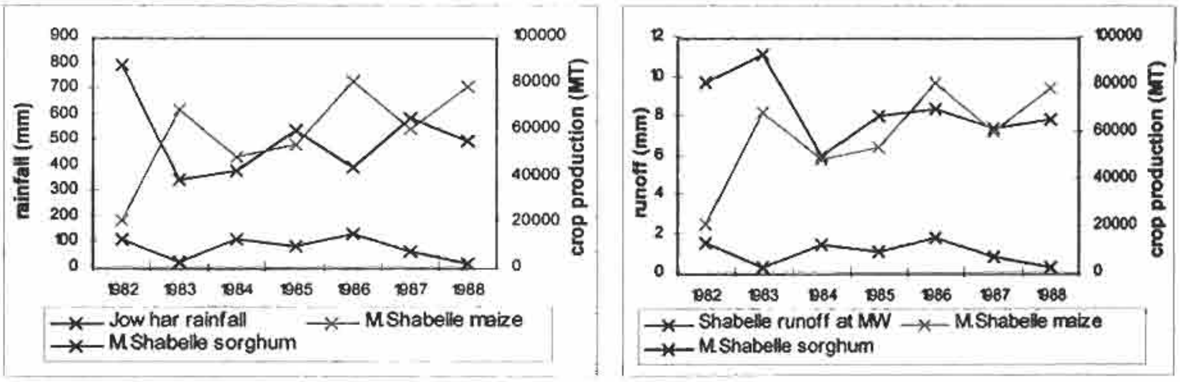

d) Bay

e) Bakool

f) Lower Shabelle



g) Middle Shabelle



h) Hiraan

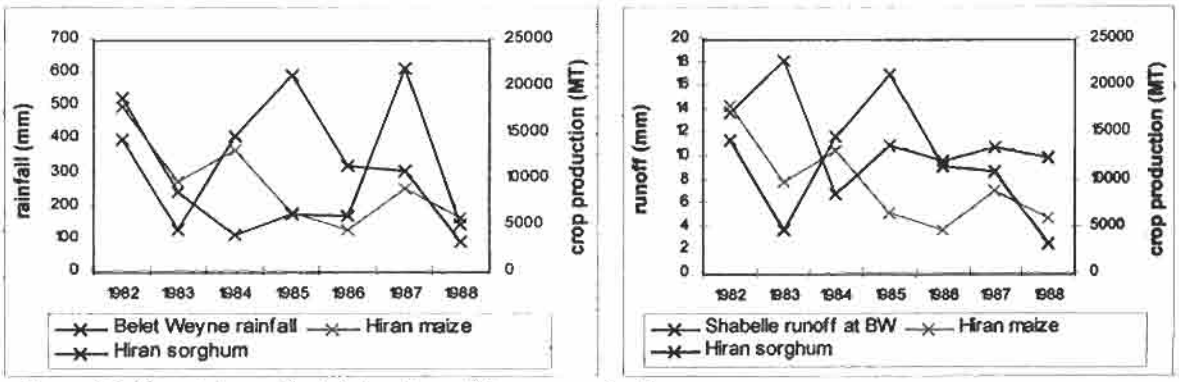


Figure 6.3. Correlations of rainfall and runoff to crop production

Plots of annual maize production against rainfall and runoff are shown in figure 6.3. Regional crop data is used, and rainfall is represented by point measurements within those regions. Where there were records for more than one station in a region, they are both plotted. River runoff is also considered, for regions which the Juba and Shabelle pass through.

Correlations between gross rainfall or runoff and crop production are surprisingly poor. For some regions, there is little observable connection between rainfall or runoff and crop production, while for others there appears to be a good relationship in some years but not in others.

The lack of relationship to runoff was particularly noticeable, with the exception of the Middle Shabelle region, where fluctuations between years in runoff and maize production were similar. Similarities between runoff and sorghum would not be expected since it is a rain-fed crop, but maize is usually irrigated except in the Bay region (FSAU, 2001), and thus would be expected to be better correlated to runoff. In some cases, for example the Middle Shabelle, an inverse relationship between runoff and crop production appears to exist. This suggests that crop growth is more likely to be inhibited by excess flooding than it is by low flows, as pump irrigation aids in the maintenance of water supply to the crops even during low flow periods. Thus it is possible that low river levels have only minor effects on agriculture. Pastoralism is more likely to be significantly affected by very low flows during the dry season, but unfortunately no records of livestock numbers were available to test this hypothesis.

Relationships of crop production to runoff are not necessarily expected to be high, since the crop production figures are a lumped estimate for a whole region, while the rainfall figures are only point measurements. However, since in chapter 3 it was determined that rainfall patterns, at least on the annual scale, are often similar between locations, point rainfall may give a reasonable approximation of the condition of a whole region. Indeed, for the Lower Juba there is a definite correlation between rainfall at Kismayo and maize production, while sorghum production in the Bay region shows some connection to rainfall at Dinsor. An extremely good correlation between sorghum production in the Bakool region and rainfall at Huddur appears to exist from 1986-88, but the years before this show considerable discrepancy.

There are a number of possible reasons for the lack of correlation between rainfall and crop production levels. First of these is the questionable data quality, particularly, in this case, of the crop yields. Secondly, in the riverine regions the combined importance of rain and irrigation could complicate the relationships. Thirdly, excessively high rainfall or runoff can damage crops as much as a lack of rainfall or runoff. The characteristics of the rainfall, including its duration and timing, are crucial in determining crop success. Finally, although agriculture is ultimately dependent on rainfall for its success, there are a number of other factors which contribute, including pests and strong winds (as discussed in section 6.2).

6.5. Comparison of rainfall and streamflow drought

It is of particular interest to compare historical periods of rainfall and streamflow drought. The primary reasons for this are:

i. To see if rainfall and streamflow droughts tend to coincide, which has important implications for food security in Somalia, and also indicates the spatial extent of climatic influences

ii. To establish whether a single definition for drought in Somalia exists

The comparison is mainly concerned with the inter-annual variability of rainfall and runoff. Comparison of within-year droughts is more complex, since differences are known to exist between the timing and duration of rainfall and runoff, and since zero-flows rarely occur while zero-rain is the norm.

The spatial extent of rainfall drought is of interest, although it is not always easy to determine given the sparse raingauge network and questionable data quality. Spatial extent of hydrological drought is a lesser issue since the Juba and Shabelle are the only perennial rivers- although the similarities between these two rivers should also be addressed. If information about groundwater and seasonal flows in togga were available, the spatial extent of hydrological drought could be investigated in much more detail.

The coincidence of drought conditions at various locations in Southern Somalia is shown in figure 6.4. This shows nine horizontal time-lines, with one for each river, and the seven rainfall gauging stations (from Chapter 3). Years with below average rainfall or runoff are marked in red, while above average conditions are marked in blue. On the assumption that a "drought" can be adequately described as a year of below-average rainfall, figure 6.2 can then be interpreted as demonstrating the spatial extent of drought in Southern Somalia.

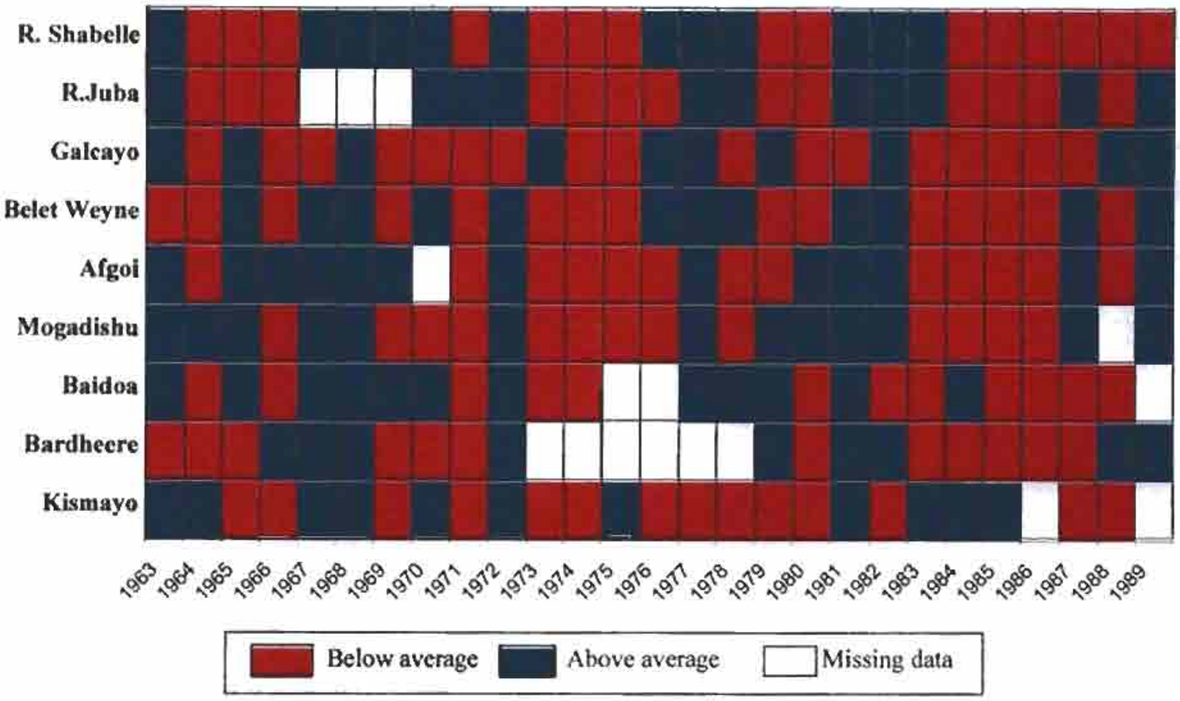


Figure 6.4. Spatial and temporal variability of rainfall and runoff. This shows seven horizontal timelines from 1963-1989, the top two for runoff and the lower seven various rainfall gauging stations.

While there is variability between locations, and differences exist between rainfall and runoff, there are a few quite well defined periods of above- or below-average conditions in both rainfall and runoff together. Above-average years include 1967-78, 1972 and 1981-82. Periods of drought particularly notable for their spatial extent include 1971, 1973-75 and 1984-86. These are evident in both rainfall and runoff (although the magnitude of the 1980s drought was small on the rivers). The droughts of 1973-75 and 1984-86 are those mentioned in the previous section, which were experienced across much of Sub-Saharan Africa. These seem to have been the most extensive periods of drought in terms of both time and space. From these similarities, it appears that widespread rainfall deficits across Southern Somalia must coincide with deficits in rainfall in southeastern Ethiopia, since this is where river runoff originates.

This has serious implications for food security. Rain-fed crops near the rivers may be sustained by pump irrigation from the river if rainfall is insufficient, but the coincidence of low river levels can make even irrigation problematical. The previously mentioned problem of livestock grazing along the rivers is especially severe if rainfall and runoff deficits occur simultaneously.

The time-period available for analysis is not long enough to determine the frequency of occurrence of these widespread droughts. The fact that this occurred twice (early 1970s and mid-1980s) within a 27-year period indicates that it may be an unfortunately common phenomenon. However, these droughts coincide with the below-average conditions of the Sahel and the Nile during this time-period, which are known (as longer records exist) to have been exceptional. If droughts of such great extent are unusual for the Sahel and the Nile, it is likely that the droughts which occurred simultaneously in Somalia were also unusually severe.

6.6. Consideration of drought definitions

There are two distinct types of "drought" which need to be considered in Somalia. First is the Jilaal, the main dry season. While this is expected to be dry and thus may not necessarily conform to a usual definition of drought, its duration and severity are still of great importance. The second type is the failure of rainy seasons, which applies more accurately to a description of drought since it involves a change from the norm. This second type may involve failure of only a single season's rain, or could be concerned with an extensive period of below-average rainfall or runoff over a number of years. The variability of both rainfall and runoff has to be accounted for.

Thus it is clear that it will not be possible to obtain one single definition of drought that could be applied to any situation in Somalia. There are additional problems with definition, concerning the choice of an appropriate threshold level and useful time-scale, and the regional extent of the drought.

Drought is a demand-driven concept, with its perception being dependent on the impacts on society. Making the correct choice of threshold level (below which drought can be said to be occurring) requires a thorough analysis of impacts, and of water requirements of the various users. Since different users, for example farmers and pastoralists, have different water requirements, the use of more than one threshold will probably be necessary. Knowledge of impacts is also necessary for the determination of an appropriate timescale. A short timescale (e.g. weeks) will be important to agriculturalists, while pastoralists would be expected to look over a longer timescale, possibly months or years. In this study, detailed consideration of impacts and water requirements has not been possible, and as a result it has been necessary to assume appropriate timescales and thresholds.

Considering the regional extent of drought also complicates its definition. This involves not only the area over which a drought is actually occurring, but also the minimum areal extent at which drought would be considered significant. Spatial variability of rainfall is extremely important, and the pastoralist lifestyle is designed to make the best of the situation. From an individual point of view, small-scale deficits are probably the most significant, and these are unlikely to ever be described quantitatively in detail due to the immense gauge network that would be necessary. However from a climatological point of view, wider scale variability is of interest, and more progress has been made in this respect in this study.

It seems clear that while having a single definition of drought would make the life of meteorologists and hydrologists much simpler, it is not really necessary from an operational point of view. The food economy zones shown in figure 6.1 have been defined precisely for that reason, to take in to account the differing requirements across the country. Nevertheless, an understanding of impacts is still necessary in order to allow thresholds to be determined on a more local scale or for different user groups. Characterisation of rainfall and runoff, including their spatial and temporal variability, is still of the utmost importance to ascertain the likelihood of those water requirements being met.

Chapter 7: Conclusions and recommendations

7.1. Conclusions

An attempt has been made in this study to gain a comprehensive understanding of the surface water resources of Southern Somalia. It would be preferable, in any detailed study of water resources, to also consider groundwater, but due to the absence of relevant data this has not been possible. In addition, only permanent watercourses have been considered, since few studies have been carried out on the seasonal flows in togga and there are little or no data available. The problems of data availability and data quality have been constant throughout the project. Nevertheless, the basic characteristics of rainfall and runoff have been defined. This has included consideration of seasonality, spatial variability, and rainfall and runoff frequencies.

The focus of the study has been on droughts and low flows and to that end, analyses have been carried out to consider both long duration (multi-year) and short duration droughts, with the latter being focussed on the characteristics of the dry seasons. A definition of "drought" has been difficult to obtain. The technical problems with defining drought were outlined in chapter 2, but the problem with definition in this particular circumstance has stemmed more from a lack of detailed knowledge of the impacts of low rainfall and runoff in Somalia. This made the choice of a suitable threshold difficult. When considering the dry season, 80 percentile flow was used as a threshold, and for multi-year droughts, rainfall and runoff were compared to the average. It is recognised that a single definition of drought in Somalia is not actually necessary, as the spatial variability in water needs and availability are widely recognised and are already accounted for in drought monitoring.

The spatial variability of water availability has been of great interest. Investigation of the inter-annual variability of runoff on the Juba and Shabelle showed evidence of a six-year cycle in the runoff of both rivers. This is thought to be connected to the Southern Oscillation Index, but a number of other factors influencing the runoff were also considered. Periods of low rainfall often coincide with those of low runoff. Since most of the runoff in the rivers is generated in the eastern Ethiopian highlands, this suggests that the controls on long-scale (multi-year) variability of rainfall act similarly over southeastern Ethiopia and southern Somalia. This could have significant consequences. For example, pastoralists only move to the rivers once stored rainwater is depleted. If the river levels are already low when they get there, the effects are much more severe. Such periods of coinciding low rainfall and runoff occurred, for example, in the early 1970s and the mid 1980s.

7.2. Recommendations

There are three basic areas in which all recommendations can be placed. These concern: data quality and quantity; further analysis of available data; quantification of water requirements and impacts.

Recommendations concerning data:

- Data quality and availability are a constant problem in Somalia. Discrepancies in the historical rainfall records need to be resolved.
- Time-series of groundwater levels and records of spate flows in togga would be extremely useful, particularly as such a large percentage of the population is reliant on groundwater for their water supply.
- If possible, more information and data concerning rainfall and runoff in southeast Ethiopia should be obtained, although it is recognised that the sharing of information between countries is not always an option.

Further analysis of available data:

- Further analysis of the available rainfall data is possible, and would be desirable. For most analysis in this study, only data from 1963-1990 has been utilised, but data is actually available for some stations for almost 100 years. In particular, use of this data would allow distributions to be determined for multi-year drought durations. The length of data available for runoff is unfortunately too short for this to be carried out.
- Seasonal rainfall and runoff should be analysed in addition to annual. Since the two seasons are important independently, much useful information may have been lost by lumping them together.

The definition of drought is demand-driven, and is not a purely hydrological or meteorological phenomenon. More detailed knowledge of water requirements of the various users in Southern Somalia would be desirable.

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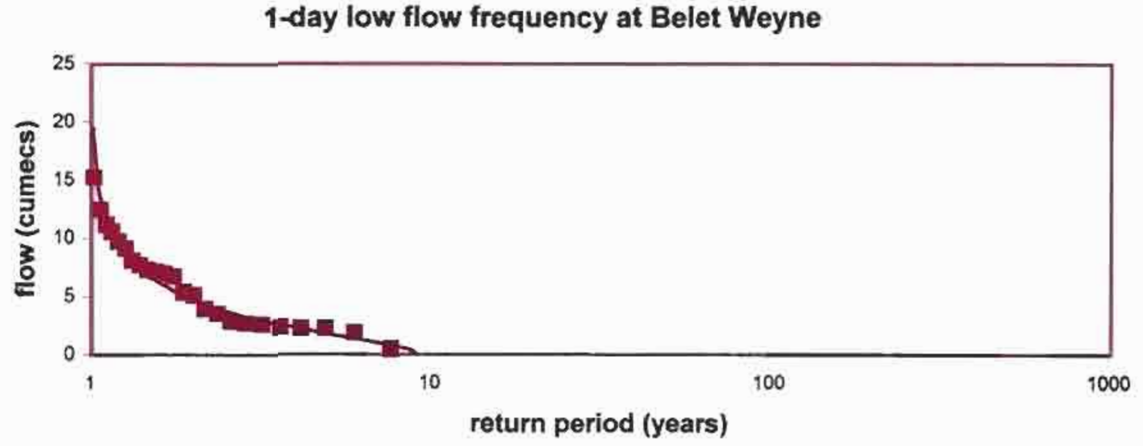
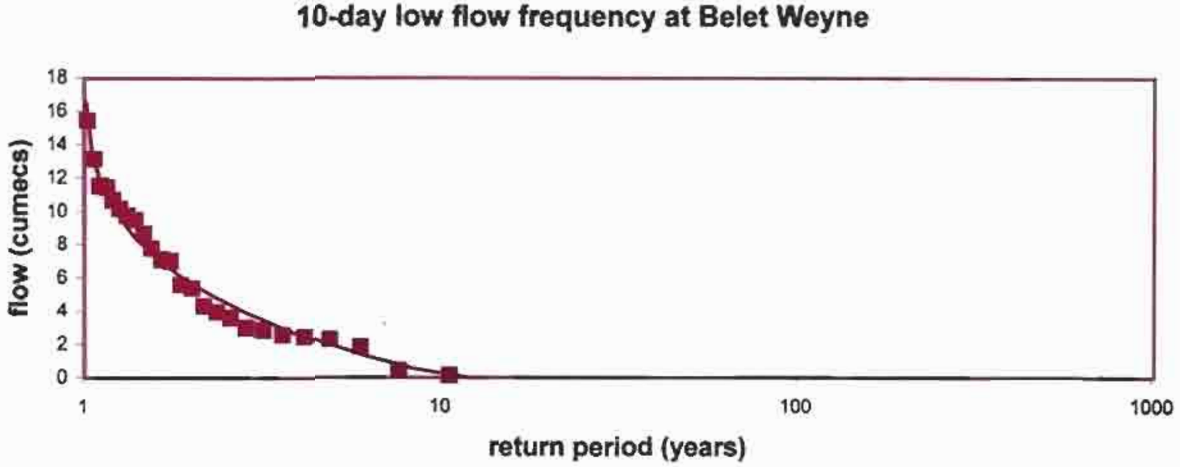
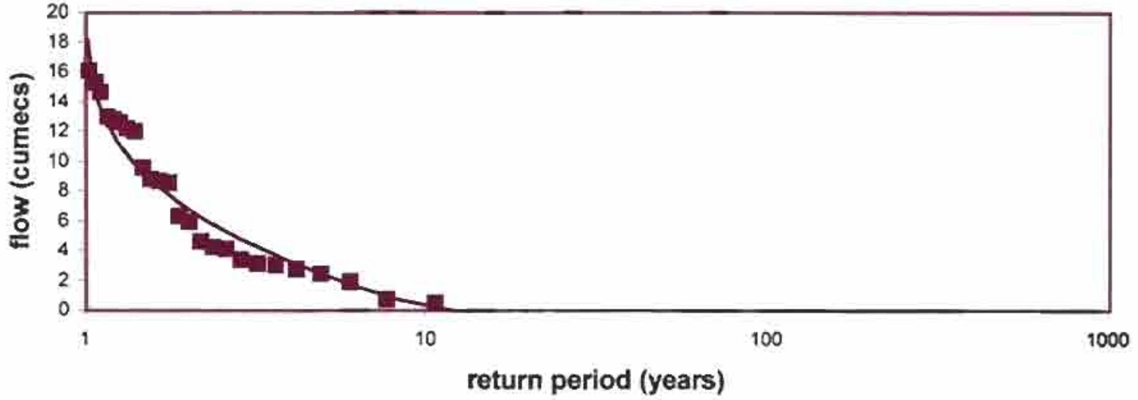
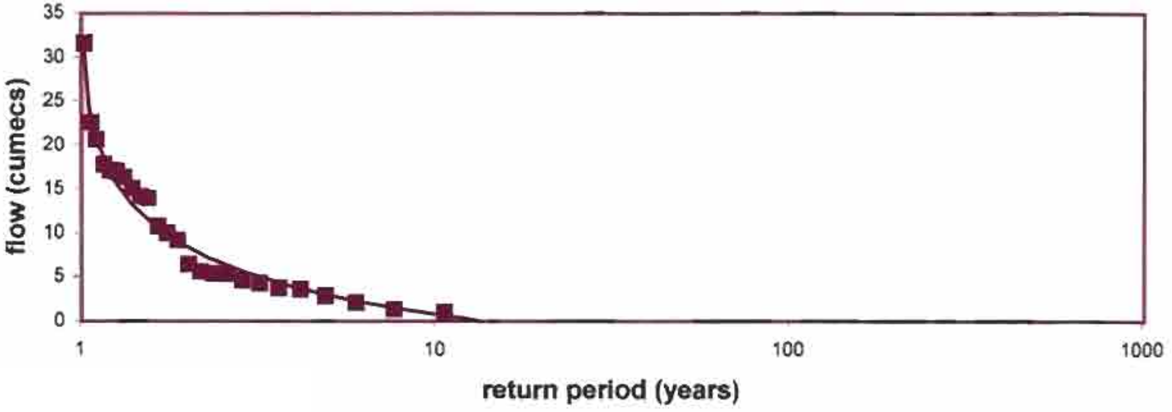

1-day low flow frequency at Belet Weyne

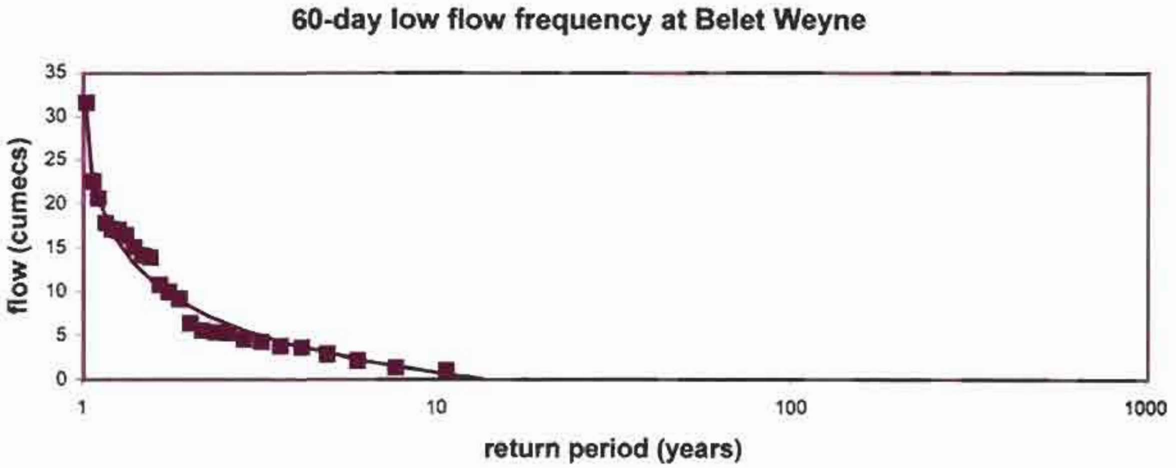

10-day low flow frequency at Belet Weyne

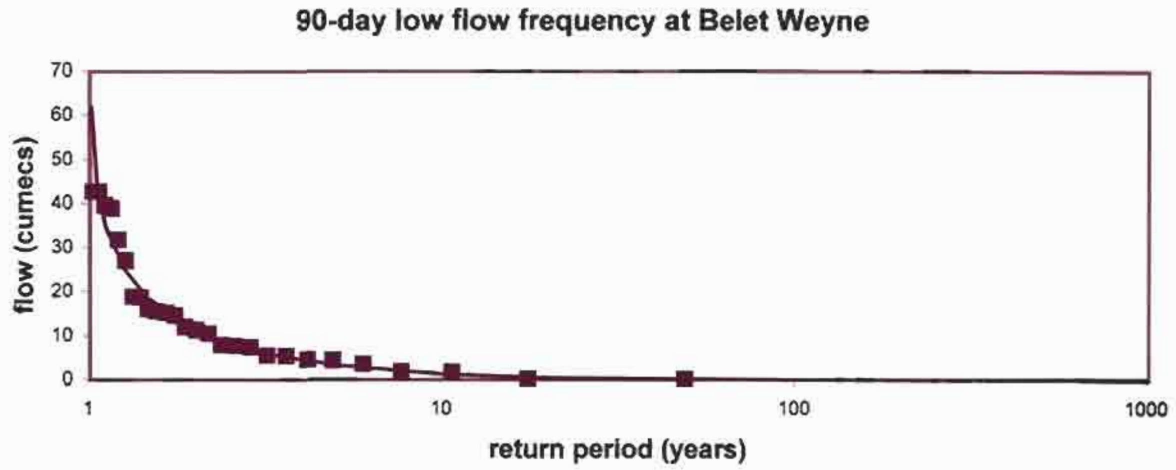
30-day flow frequency at Belet Weyne

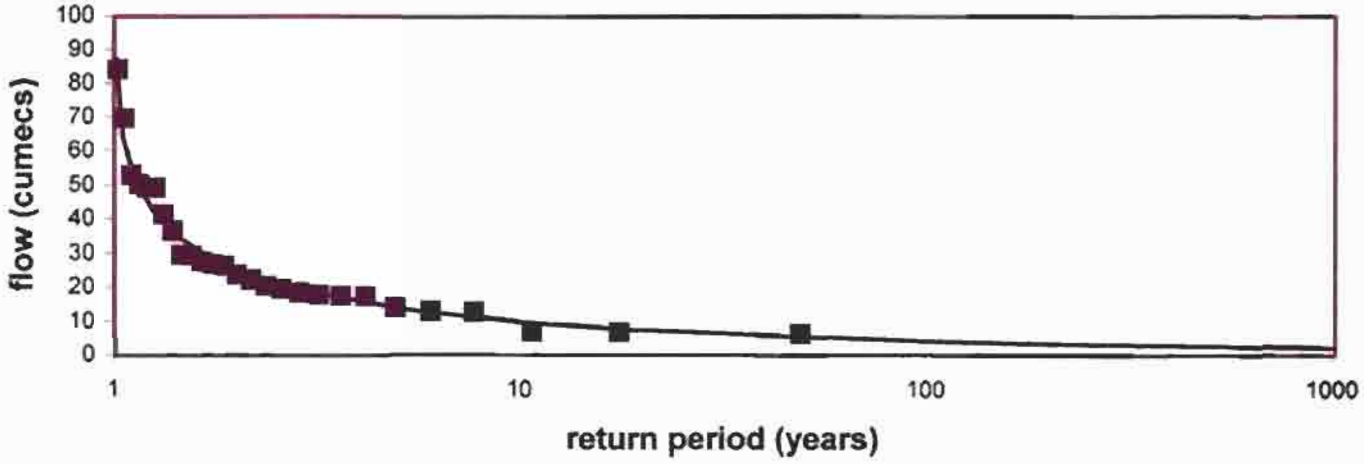


60-day low flow frequency at Belet Weyne

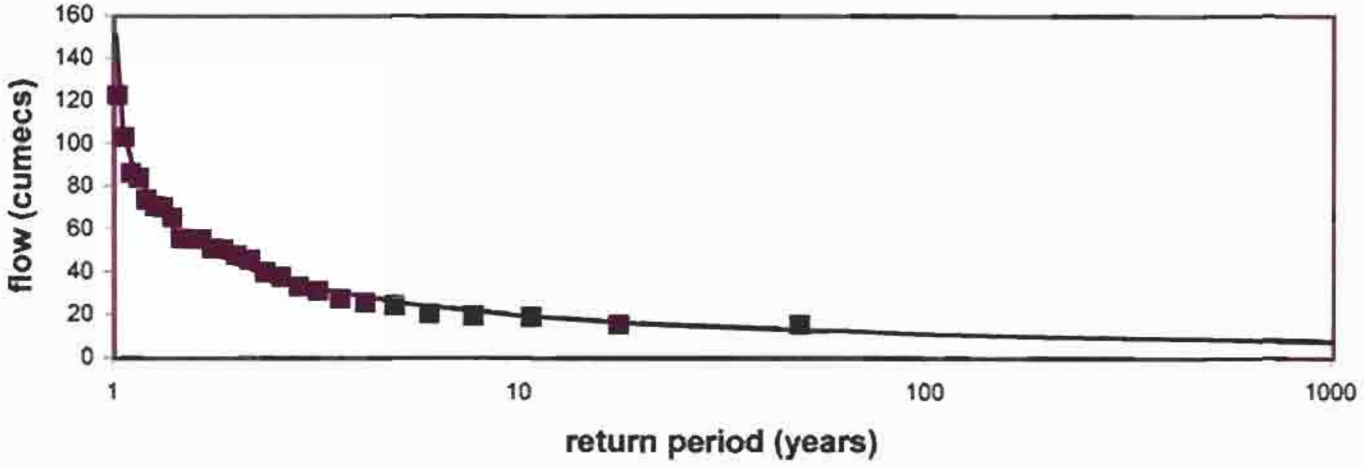



60-day low flow frequency at Belet Weyne
flow (cumecs)
35
30
25
20
15
10
5
0
1
10
100
1000
return period (years)

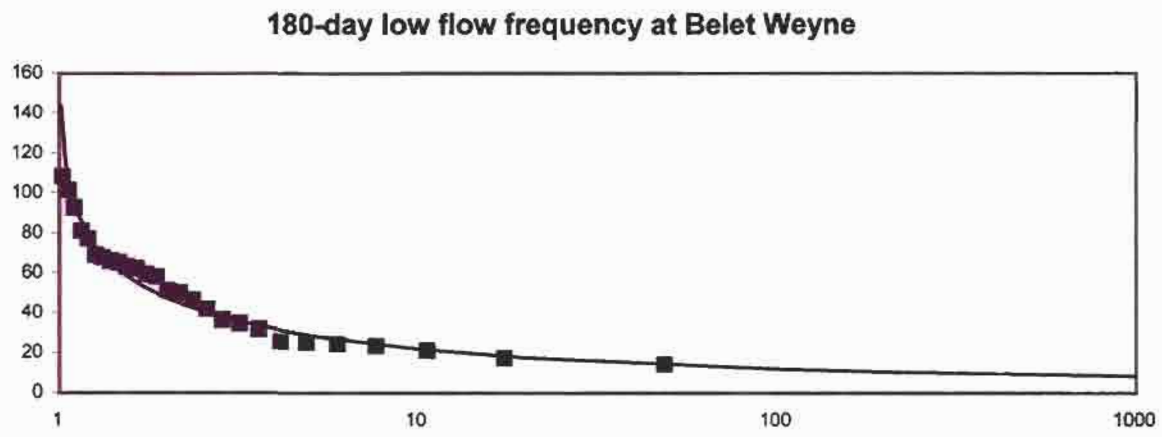

90-day low flow frequency at Belet Weyne
flow (cumecs)
70
60
50
40
30
20
10
0
1
10
100
1000
return period (years)



120-day low flow frequency at Belet Weyne



150-day low flow frequency at Belet Weyne



Fitted EVIII distributions with Gringorten plotting positions