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An assessment of the surface water resources of the Juba-Shabelle basin in southern Somalia

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Abstract The water resources of the Juba and Shabelle rivers in southern Somalia are important for irrigation and food production, but are influenced by seasonal floods. Prior to the outbreak of civil war in 1991, the Somali Ministry of Agriculture successfully operated a hydrometric network covering the Juba and the Shabelle, data from which provided input to a flow forecasting model. The war resulted in the neglect and abandonment of monitoring stations and an enforced cessation of data collection and management. In 2001 and 2002, part of the pre-war hydrometric network was reinstated and water levels were again recorded at some stations. This paper examines the implications of the 11-year hiatus in data collection, and the now much reduced monitoring network, for assessing and managing the surface water resources. The problems faced have relevance to other basins, within Africa and elsewhere, where there has been a similar decline in data collection.

Key words hydrology; hydrometric network; hydrometry; Juba; Shabelle; Somalia; water resources

Evaluation des ressources en eau de surface des Rivières Juba et Shabelle dans le sud de la Somalie

Résumé Les ressources en eau des Rivières Juba et Shabelle, dans le sud de la Somalie sont importantes pour l'irrigation et la production agro-alimentaire mais sont influencées par des crues saisonnières. Avant la période de guerre civile de 1991, le ministère de l'agriculture somalien a géré avec succès un réseau hydrométrique couvrant la Juba et la Shabelle, dont les données servaient d'entrées à un modèle de prévision des débits. La guerre a conduit à la négligence et l'abandon des stations de jaugeage et un arrêt forcé de la collecte et de la gestion des données. En 2001 et 2002, une partie du réseau hydrométrique d'avant-guerre a été remis en fonctionnement et les enregistrements de hauteurs d'eau ont recommencé en certaines stations. Cet article examine quelles implications les onze ans d'arrêt de la collecte de données, et le réseau de mesure désormais très réduit ont sur l'évaluation et la gestion des ressources en eau de surface. Les problèmes rencontrés sont pertinents pour d'autres bassins versant, en Afrique et ailleurs, où il y a eu un déclin similaire de la collecte de données.

Mots clefs hydrologie; réseau hydrométrique; hydrométrie; Juba; Shabelle; Somalie; ressources en eau

INTRODUCTION

Somalia[1] is on the horn of Africa and is bordered by Kenya to the southwest, Ethiopia to the west and Djibouti to the far northwest in the Gulf of Aden. Northern Somalia is dominated by a mountain plateau, over 2000 m in height. In contrast, the landscape of central and southern Somalia is low-lying and uniformly flat, except for some hilly sand dunes along the Indian Ocean coastal belt. Somalia has only two perennial rivers, the Juba and the Shabelle, both of which flow through the southern part of the country, but originate in neighbouring countries, principally Ethiopia (Fig. 1). Technically,

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[1] Orthography of places in Somalia is based on the English phonetic as per the Gazetteer of the pre-war Somali Democratic Republic (Burgett 1987), or where this has not been available to the authors, on the common spelling currently used within the Somalia Support Secretariat.

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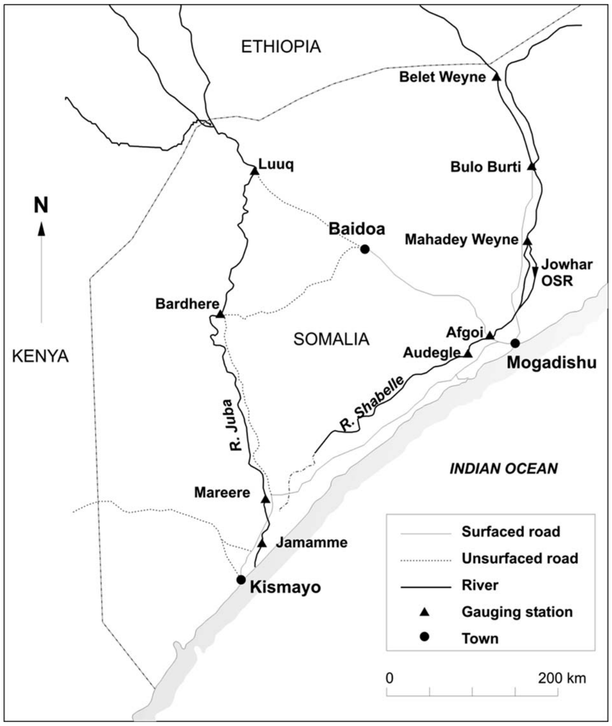

Fig. 1 Map of southern Somalia showing the Juba and Shabelle rivers and locations of past and present river gauging stations (Jowhar OSR is Jowhar Offstream Storarge Reservoir, where the supply channel was also used as a flood relief channel).

the Shabelle is a tributary of the Juba, and as such constitutes a single basin, but since flows from the Shabelle join the Juba only very rarely, and even then result from localized rainfall, the rivers are effectively separate.

Somalia's total land area is 637 540 km^2, of which 30% is classified as desert land unsuitable for agricultural production, 45% is covered by rangelands suitable for livestock grazing, 14% is covered by forest or woodland, and the remaining 11% is classified as arable land (FAO 1995). Livestock production was a major industry until the 1990s, accounting for over 60% of exports. Arable farming was also an important industry, though Ministry of Agriculture (1990) statistics indicate that only 22% of the designated arable land was actually viable for cultivation, and only 12% was actually cultivated, predominantly with maize and sorghum. The under-utilization of potential arable land was due to the predominantly arid climate that limits rain-fed agriculture and causes a heavy reliance on irrigation.

Groundwater is used throughout Somalia, obtained mainly from shallow hand-dug wells, though a few strategic boreholes are used to reach deeper aquifers, which act as an important reserve during the dry season. However, the groundwater quality is generally regarded as poor (Faillace and Faillace 1986). In the downstream reaches of rivers, small freshwater lenses located mainly along the river banks are recharged during periods of high flow, and partially drained during the dry season (Faillace and Faillace 1986).

Therefore, the water resources of the Juba-Shabelle basin are particularly important for irrigation, as well as for Somalia's general development (e.g. domestic and industrial water supply). Ministry of Agriculture (1988) statistics indicate that a maximum of 2230 km^2 of land was irrigated (of a potential 5000 km^2; FAO 1995), 1100 km^2 under flood recession irrigation and the remainder under gravity and pump irrigation. The river flows also provide the safety-net required to sustain livestock herds during periods of serious drought. Several large-scale irrigation schemes used to exist on both rivers, and small-scale irrigation schemes were common on the flood plains throughout the Somali reaches. The rivers are prone to seasonal flooding, with flood recession agriculture being practised in natural depressions (deshek) adjacent to the river banks (Khalif and Ismail 1989).

Somalia has been under civil unrest since the mid-1980s, with the unrest degenerating to civil war in 1991. The conflict has caused destabilization and instability throughout the country, with a series of clashes between the various militant factions and loss of central government control. The destruction of social and economic infrastructure, asset stripping, ethnic cleansing and the disruption of food supplies have, sometimes, been compounded by drought, causing famine and additional deaths. Over the years, many agencies and governments have tried, largely unsuccessfully, to broker deals or undertake peace-keeping missions (World Bank 2005). The latest of these, in January 2009, comprised a reconciliation and power sharing deal between the Transitional Federal Government and the Union of Islamic Courts.

The ongoing conflict, associated with the absence of dependable land-use management systems and water resource management institutions, has led to reports of severe degradation of land and water resources (Mbara *et al.* 2007, Venema 2007). After the outbreak of war, agricultural production fell by about 50%, largely due to a reduction in cultivated area, and the abandonment of irrigation schemes and collapse of irrigation infrastructure (Mbara *et al.* 2007). Problems were compounded by damage to the remaining schemes caused by severe flooding associated with the 1997/98 El Niño event. With a growing population, demands for water for irrigation and domestic supply are increasing sharply. Effective water and land management are both essential to ongoing relief and rehabilitation efforts, and require good quality information on the country's water and land resources, primarily the Juba and Shabelle rivers (Print 2001a, 2001b).

HYDROLOGY OF THE JUBA AND SHABELLE RIVERS

The Juba and Shabelle rivers originate in the Ethiopian Highlands, where the main streams and their tributaries are deeply incised into the steep slopes of the upper reaches. However, in Somalia, in the middle and lower reaches, there is a virtual absence of tributaries and other drainage channels; there are some spring-fed streams and some local runoff, but these contribute to river flow only in times of heavy rainfall. Over long reaches, particularly on the Shabelle, the riverbanks lie above the level of the surrounding land, so that any spillages are lost permanently from the river and no return flow occurs.

The areas of the Juba and Shabelle basins are 218 114 km^2 (to Jamaame, excluding Shabelle basin) and 296 972 km^2 (to the Juba confluence), respectively (Basnyat and Gadain 2009). The two basins share many common characteristics. Around two-thirds of the area of both basins lies in Ethiopia, and 5% of the Juba basin also lies in Kenya (Kammer 1989). Both basins range in altitude from just above sea level in the south to more than 3000 m in their headwaters in the Ethiopian Highlands.

The Juba River has three main tributaries which all flow southeastwards, joining near the Ethiopia–Somalia border and the Somali town of Luuq. There the Juba turns south to the coast. The total length of the Juba River is about 1100 km (measured on the longest tributary), of which half lies in Ethiopia and half in Somalia.

The Shabelle River flows southeastwards to the Ethiopia–Somalia border. There it turns south towards Mogadishu, but then turns southwest before it reaches the capital city and continues roughly parallel to the coast from which it is separated by a range of sand dunes. Halfway along the coastal stretch, it runs into a series of swamps. Downstream of the swamps the river resumes a defined channel, but flows are very much reduced and the Shabelle discharges into the Juba only in times of exceptional flood. Very little has been written about this area (MacDonald 1983, IUCN 2006). The total length of the Shabelle River is about 1700 km, again approximately half lying in Ethiopia and half in Somalia.

The average annual rainfalls for the Juba and Shabelle basins are 550 and 455 mm, respectively (Kammer 1989). Rainfall in both basins varies considerably. Annual rainfall is lowest on the Ethiopia–Somalia border at around 200 mm, and increases both downstream, to around 500–600 mm at the coast, and upstream, to over 1500 mm in the Juba headwaters and over 1000 mm in the Shabelle headwaters. There are two rainy seasons, related to the northwards and southwards passage of the Inter-Tropical Convergence Zone over the Ethiopian Highlands. The Gu season runs from April to June and contributes around half of the annual rainfall, and the Deyr season runs from October to November and contributes around a third. The highest flows generally occur in the Gu which is the main cropping season.

Potential evapotranspiration is variable in both basins, ranging from 1500 mm per year in the mountains to 1750 mm per year in the south, and being highest at over 2000 mm per year on the border (Hutchinson and Polishchouk 1989).

In the Ethiopian headwaters of the Juba and Shabelle, surface water resources are abundant. In the middle reaches, where runoff is highly localized and seasonal, the rivers themselves still carry considerable volumes of water during most of the year. Downstream of the Ethiopia-Somalia border, discharges reduce progressively with the Shabelle often ceasing to flow in its lower reach in the early part (January–March) of the year. Although the Shabelle has a substantially greater catchment area than the Juba, the flow in the Juba is about three times as large as the Shabelle flow. This is partly due to higher average annual rainfall, but also due to a much better developed drainage network in the upper part of its basin, with three tributaries producing high runoff volumes.

Drought is a recurrent event, with recent droughts in 1973–1976, 1979/80, 1984–1989, 2000/01, 2006 and 2008 (Musgrave 2002, Mutua and Balint 2009) causing major impacts (e.g. www.fsnau.org). At the other hydrological extreme, flooding can have just as devastating an effect, e.g. the severe floods of 1981 (MacDonald/Hunting 1981), the El Niño of 1997/98 (Bradbury and Coultan 1998) when more than one million people were affected, the severe floods of 2006/07, and the recent floods on the Shabelle in 2010 (which washed away the bridge at Belet Weyne).

Furthermore, because most of the water in the rivers originates outside Somalia, the river flows are highly vulnerable to water resource development upstream, in Ethiopia. Anthropogenic factors and predictions of an intensification of the hydrological cycle leading to wider extremes in drought and flood (e.g. Arnell 1999) suggest that trends in Somalia's water resources and, in particular, extreme events (Print 2001c), need careful monitoring. Water resource management in such circumstances requires long, good quality flow records from key locations on the principal rivers.

DEVELOPMENT OF THE HYDROMETRIC NETWORK

Water level readings were reportedly taken from the earliest days of the Italian colonial settlements in Somalia, at various locations including the important upstream stations of Luuq on the Juba and Belet Weyne on the Shabelle (Fig. 1). Studies during the 1960s (Faillace 1964, Selchozpromexport 1965, FAO/Hunting/MacDonald 1969) led to the establishment of a rudimentary hydrometric network. This was strengthened after the 1981 flood as a result of an FAO study (Gemmell 1982), and the input of staff from CEH Wallingford (then the Institute of Hydrology, IH) and Mott MacDonald Ltd (then Sir M. MacDonald and Partners), who provided technical assistance and training to the Hydrology Section of the Department of Irrigation and Land Use in the Somali Ministry of Agriculture. This support was funded by the UK Overseas Development Administration (now the Department for International Development, DFID), as part of the UK government's programme of technical cooperation with developing countries. The hydrometric network was consolidated and a database and flow forecasting model for both the Juba and Shabelle rivers were developed and successfully operated by Ministry of Agriculture staff (MacDonald/IH 1986, 1990b).

Figure 1 shows the locations of the principal river gauging stations, and Table 1 summarizes the characteristics of these stations, as of 1990, ordered from upstream to downstream. The pre-war hydrometric network comprised 23 monitoring stations, including eight river gauging stations on the Juba and seven on the Shabelle. In 1980, a large offstream storage reservoir was constructed at Jowhar in the middle reaches of the Shabelle, south of Mahadey Weyne. The Jowhar Offstream Storage Reservoir (OSR) was commissioned primarily to collect surplus river flow during the wet season, for release for irrigation during the subsequent dry season, though the supply channel was also used as a flood relief channel when required, diverting up to 40 $m^3 s^{-1}$ of flow. Several of the other gauging stations were associated with the Jowhar OSR, and with sediment and water quality monitoring programmes.

The development of the river gauging station network over time is summarized in Fig. 2. Figure 2(a) shows the number of stations operating each year from 1951 to 2010, whilst Fig. 2(b) shows the distribution of pre-war record lengths. There is a steady increase in the number of operating stations from 1963 through to 1990, the most significant sustained periods of growth being in the early 1960s and the 1980s. Many of the principal gauging stations on the Juba and the Shabelle have record lengths in excess of 25 years, whilst the remainder and the stations

Table 1 Characteristics of the main gauging stations in the Juba-Shabelle basin (Basnyat and Gadain 2009, Macdonald/IH 1990a).

River/Station	Area (km^2)	Elevation (m a.s.l.)	Approximate bank-full values		
			Max. width (m)	Max. depth (m)	Max. flow ($m^3 s^{-1}$)
Juba					
Luuq	168738	142.6	140	9	1800
Bardhere	200349	89.5	100	8	1800
Mareere	215604	13.0	85	8	590
Jamamme	218114	1.0	65	8	480
Shabelle					
Belet Weyne	193224	176.1	44	7	500
Bulo Burti	207488	134.4	48	6	400
Mahadey Weyne	209865	104.6	46	5	166
Afgoi	244672	77.4	40	5	97
Audegle	245069	70.1	38	5	94

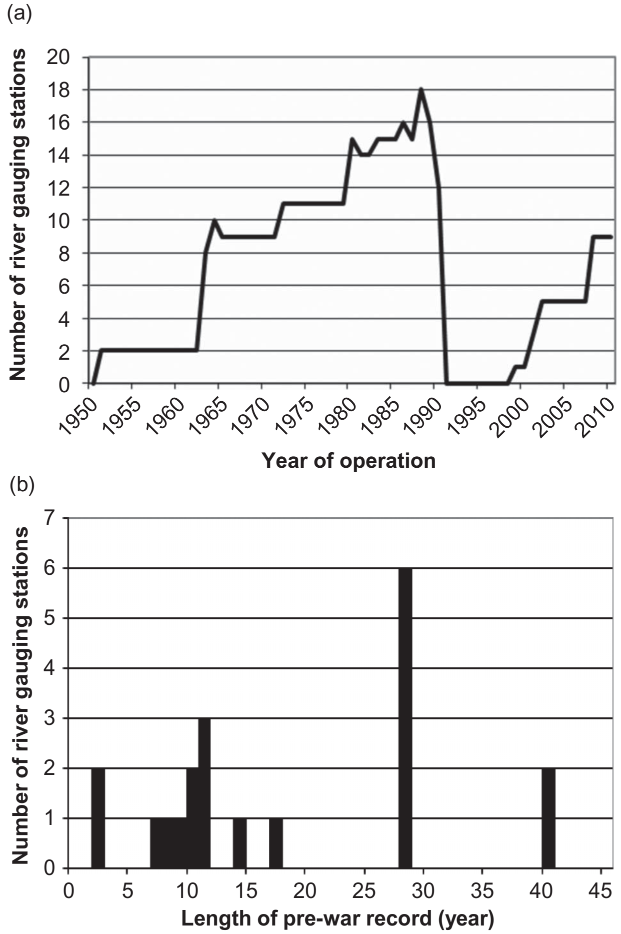

Fig. 2 (a) Development of river gauging station network over time. (b) Distribution of pre-war flow record lengths.

associated with the Jowhar OSR have record lengths ranging up to 20 years, mostly between five and ten years.

SPATIAL VARIATION IN FLOW

Figure 3 shows daily mean flow hydrographs for the principal gauging stations on each river for 1989, the last complete year of data before the war. The general pattern of river flow is similar on the two rivers. Both rivers have two flood seasons, the Gu and the Deyr, reflecting the rainfall patterns. The rivers also show a significant decrease in maximum flow figures between the two most upstream stations and the downstream stations (Table 1). This is because, during the flood seasons, it is normal for the downstream stations to reach a sustained peak and display flat-topped hydrographs because of out-of-bank spillages upstream. The Shabelle hydrographs additionally show some evidence of flow reductions due to irrigation abstractions between the lowermost stations, i.e. weekly abstractions between Mahadey Weyne and Afgoi caused a regular cycle in the 1989 dry season flows.

Figure 4 presents data for the period 1963–1990 from the two most upstream gauging stations on each river: Luuq and Bardhere on the Juba, and Belet Weyne and Bulo Burti on the Shabelle. Figure 4(a) compares average monthly total flows (expressed as a percentage of average annual total flow), whilst Fig. 4(b) shows the 1-day flow duration curves standardized by mean daily flow. The flow duration curve describes the relationship between any given flow and the percentage of time that the flow is equalled or exceeded. The slope of the flow duration curve reflects the relative flow variability and the responsiveness of the catchment to rainfall.

From Fig. 4(a), it is apparent that the flows at the two Juba stations and at the two Shabelle stations closely mirror each other. Whilst the early Gu floods occur simultaneously on both rivers, the Deyr floods peak in September on the Shabelle, a month before those on the Juba. Each of the peak months contributes some 10–20% of the total annual flow, whereas each of the dry season months contributes less than 5%. It can also be seen that on the Shabelle, the Gu and Deyr peak flows are similar in terms of percentage of annual total, though the Deyr floods are sustained for longer. However, on the Juba, the Deyr floods contribute significantly more runoff to the annual total than the Gu floods, though river levels between the two flood seasons are better maintained. The month of lowest flow is February, enabling a calendar year (January–December) to be used as the basis for quantitative analysis.

As Fig. 4(b) demonstrates, the slopes of the flow duration curves between the *Q*5 and *Q*90 (key high flow and low flow statistics, respectively) percentiles are almost identical for the four gauging stations. The curves indicate relatively stable flow regimes, characteristic of slow-responding, more permeable catchments. This reflects the underlying limestones, gypsums (Mustaxiil formations) and sandstones (Jesomma formations) straddling the Somali–Ethiopian border that accommodate moderately productive aquifers with considerable storage which sustain downstream low flows during the dry season. The flow variability on the Juba appears slightly greater than that on the Shabelle. At the high flow end, this is explained by the Juba Deyr floods being larger than the Gu floods, whilst at the low flow end, the dry season flows on the Juba are sustained

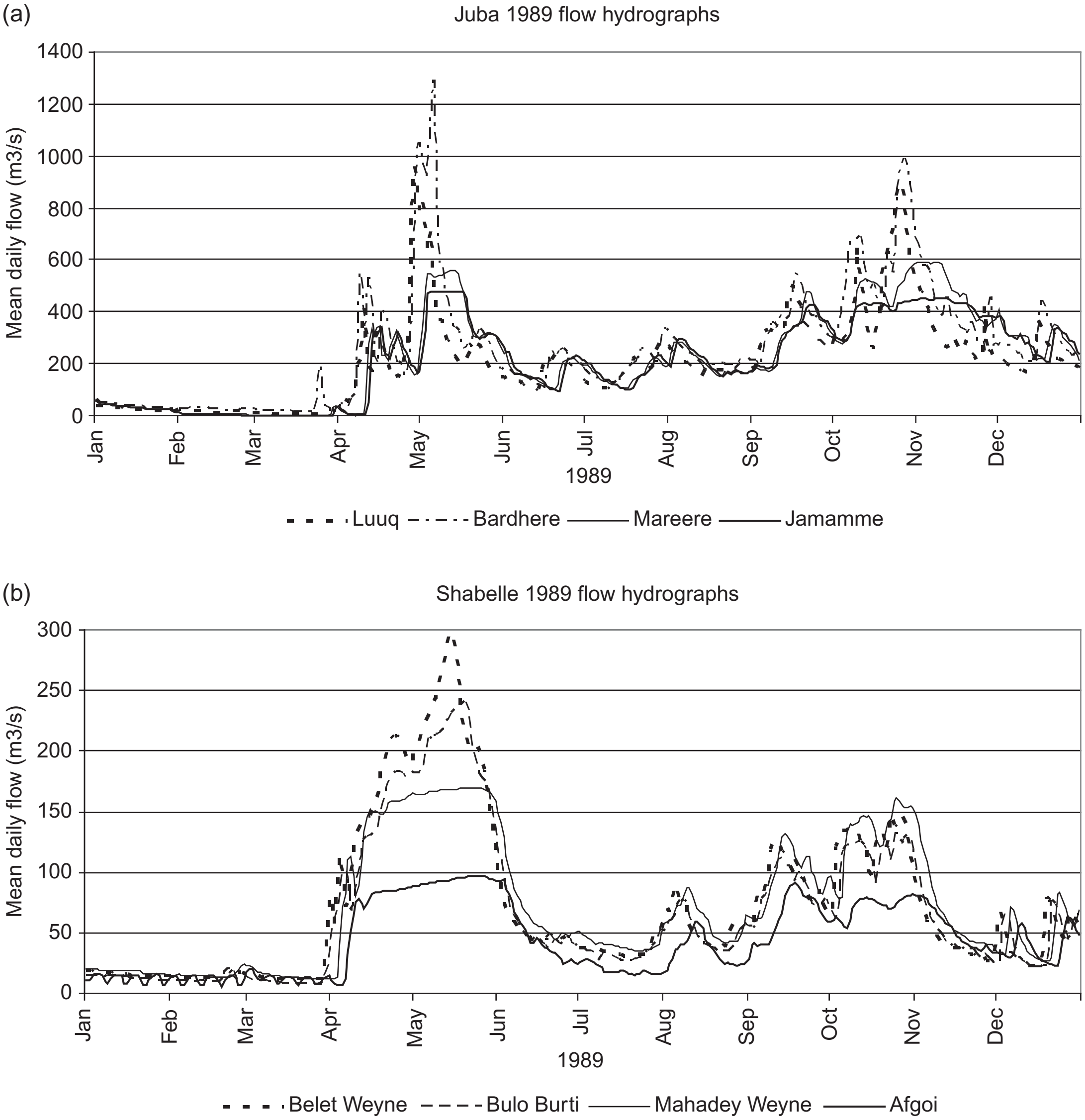

Fig. 3 Hydrographs from (a) Juba and (b) Shabelle river gauging stations for 1989.

for longer because the flow in the Juba is about three times as large as that in the Shabelle.

REHABILITATION OF THE HYDROMETRIC NETWORK

During the civil war, the hydrometric network fell into complete disrepair with no monitoring and collection of water level data. The Jowhar OSR became non-operational due to silting up of the supply and outlet channels. In 1999, a staff gauge was installed on the Shabelle at Jowhar, a new station south of Mahadey Weyne, by CEFA (European Committee for Agriculture and Training), to measure water levels only. Rehabilitation of the pre-war hydrometric network by the FAO Somalia Water and Land Information Management (SWALIM) project (Print 2001b) started in 2001 when the four upstream stations were reinstated (Okoth 2002):

- On the Juba at Luuq, the new staff gauge was fixed to the pre-war datum, and water level data are available from October 2001.
- At Bardhere on the Juba, the old staff gauge still existed though some parts of it had been vandalised. From September 2001 until 25 February 2008, the water level was measured from a bridge using a graduated drop rope, and an adjustment to the measured water levels of −1.16 m. A new staff gauge came into operation on 26 February 2008, the corresponding adjustment for which is −2.62 m.

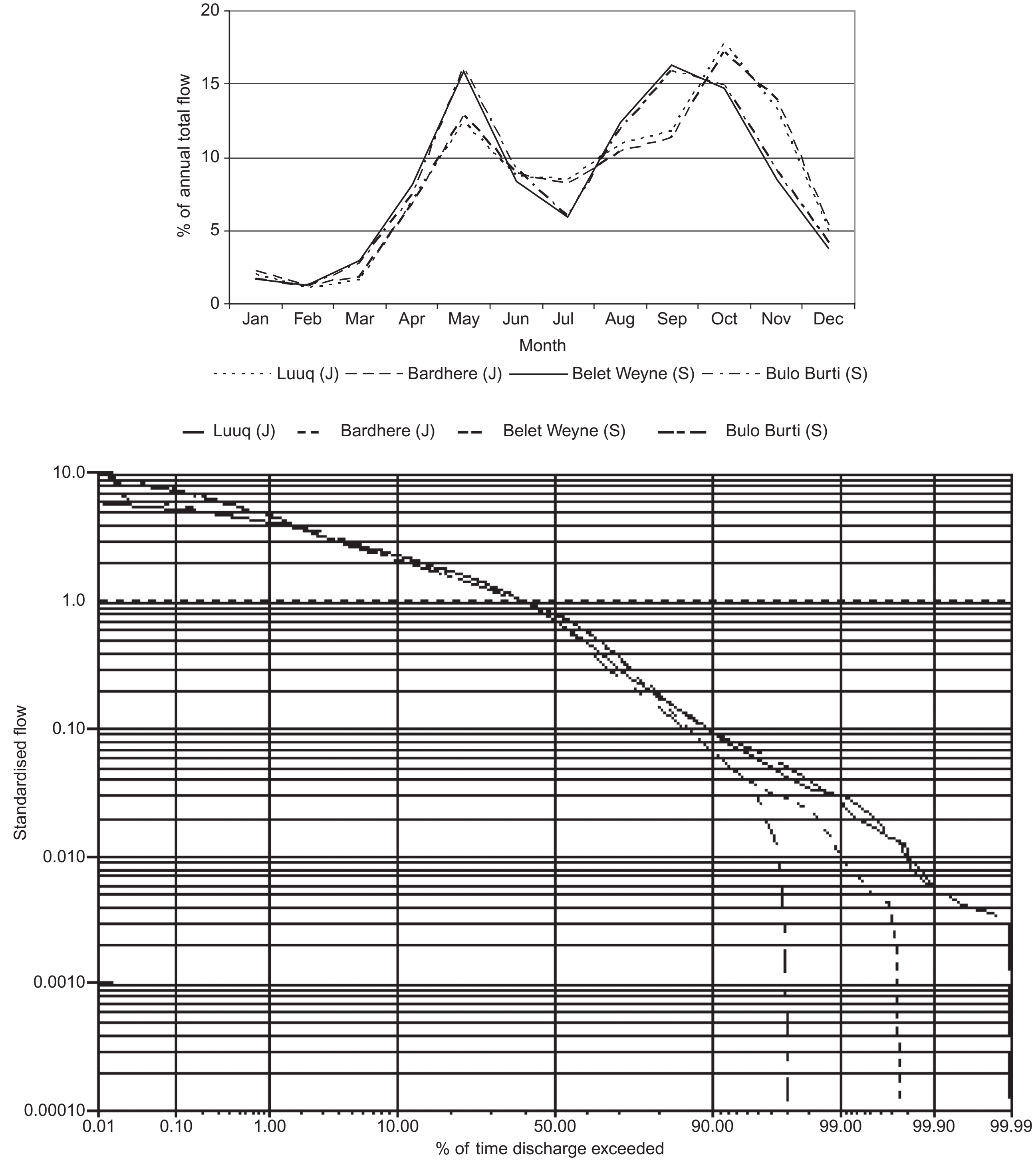

Fig. 4 (a) Distribution of 1963–1990 average monthly total flows; (b) 1963–1990 1-day flow duration curves (J: Juba gauging stations, S: Shabelle gauging stations).

- On the Shabelle at Belet Weyne, water level data are available from April 2002. The new staff gauge was adjusted to the pre-war datum after a site survey in 2004, using an adjustment of −1.738 m (Cody 2005).
- At Bulo Burti on the Shabelle, the bridge that held the old staff gauge was destroyed, and there have been delays in fixing the new staff gauge to the pre-war level. Water level data are available from April 2002, and a visual examination

suggests a provisional datum adjustment of the order of +1 m, until the true adjustment figure can be confirmed.

In 2008, further new staff gauges were reinstalled on the Juba at Bualle, a new station between Bardhere and Mareere, and on the Shabelle at Mahadey Weyne, Jowhar, Afgoi and Audegle.

Initially, the in-country NGO staff were trained to read staff gauges daily, accurately record measurements and reliably transmit data by radio, telephone or email in a systematic and consistent manner, but these activities are now carried out by SWALIM staff. During the Gu and Deyr seasons, the water levels are sent on a weekly basis or more frequently; in the dry seasons, the data are sent on a monthly basis. It is hoped, eventually, to telemeter some of the gauges.

Daily mean flow data are needed as input to the Somalia flow forecasting model, in addition to day-to-day requirements for water resources management. Like the original river gauging stations, indeed like most flow measurement stations in Africa (Sene and Farquharson 1998), the reinstalled stations are all natural, rated sections. It is essential that discharge measurements (gaugings) are taken regularly to calibrate the stations and derive rating relationships between water level and river flow. The average number of discharge measurements made per year at a station provides a good indication of whether the station is being visited and calibrated on a regular basis.

Figure 5 shows the annual variation in the number of pre-war discharge measurement at Luuq (average 4.28 per year) and Bardhere (2.82) on the Juba, and Belet Weyne (3.11) and Bulo Burti (2.36) on the Shabelle. It is clear that, even before the war, discharge measurements were not made on a regular basis. This is surprising given that the staff gauge positions on or near bridges make them susceptible to scour and fill processes, and frequent shifts in the ratings might be anticipated. However, at all four stations, there is reasonable consistency in the gauged flows between 1963 and 1990, with only a little scatter at the low flow ends of the ratings. The derived ratings were used for considerable periods, in some cases the entire period of pre-war record. MacDonald/IH (1991) note that this apparent consistency may mask seasonal variations, but with the irregular and generally infrequent discharge measurements this cannot be covered by adjustments to the rating equations, which are generally fairly stable at high flows.

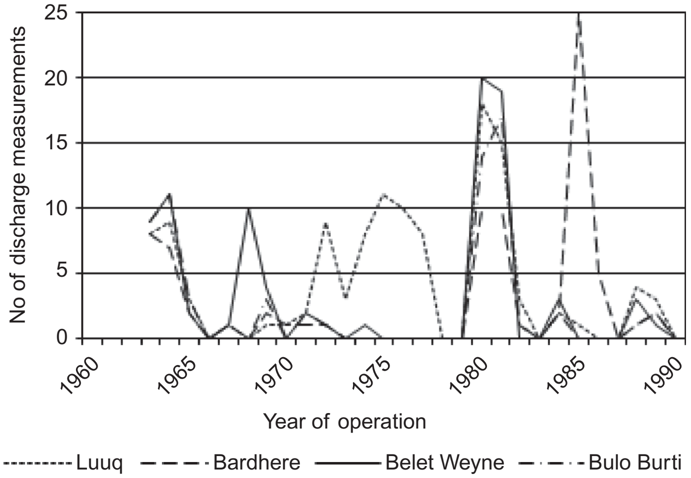

Fig. 5 Frequency of pre-war discharge measurements.

As part of the rehabilitation of the hydrometric network, discharge measurements at Luuq and Bardhere on the Juba and Belet Weyne on the Shabelle recommenced in September 2009. However, the measurement programme is restricted by the ongoing security situation and very few gaugings have been made, particularly at Bardhere and Belet Weyne. Given both the inaccessibility of stations and the continued insecurity impact on fieldwork at the rehabilitated gauging stations, the pre-war ratings provide the best, indeed the only, estimates of the current rating relationships.

TEMPORAL VARIATION IN FLOW

The key issue to be addressed is whether the historical and recent flow data are comparable. That is, how representative are the pre-1990 flows of present conditions and of the long-term flow regime, and how representative are the post-2001 flows at the four upstream stations (Luuq, Bardhere, Belet Weyne and Bulo Burti), in terms of both the historical context and the long-term flow regime? With no better information, comparison of the pre- and post-2001 flow data must assume that the relatively stable pre-war ratings at the four rehabilitated gauging stations are still valid 11–20 years later.

On both the Juba and the Shabelle, the pre- and post-2001 mean flow data (to end of July 2010) were visually compared, using time series with monthly data (Fig. 6) and double mass plots of the upstream and downstream runoff on each river with daily data (Fig. 7), the latter recommended by Sutcliffe (2004) as a technique for assessing rating curves.

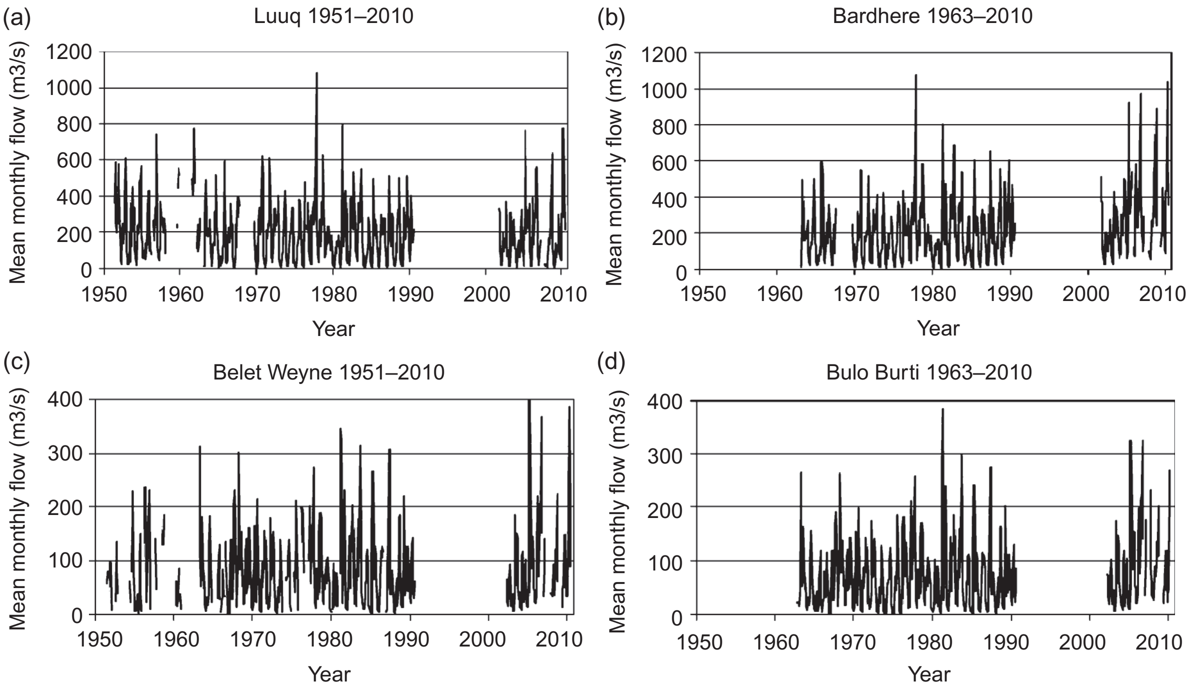

Fig. 6 Mean monthly flow time series: (a) Juba at Luuq 1951–2010; (b) Juba at Bardhere 1963–2010; (c) Shabelle at Belet Weyne 1951–2010; and (d) Shabelle at Bulo Burti 1963–2010.

Table 2 Long-term flow statistics of stations used in analysis: (a) 1963–1990; (b) 2001–2010 Juba or 2002–2010 Shabelle.

River/Station	Mean (m^3 s^{-1})	Daily mean flows		BFI	Annual total flows	
		*Q*95 (m^3 s^{-1})	*Q*5 (m^3 s^{-1})		Mean (mm^3 $year^{-1}$)	CV
(a)						
Juba						
Luuq	187.61	7.04	537.34	0.75	5913	0.29
Bardhere	195.48	12.87	561.38	0.76	6166	0.30
Shabelle						
Belet Weyne	79.93	4.67	234.65	0.82	2357	0.32
Bulo Burti	69.73	1.96	209.68	0.84	2203	0.33
(b)						
Juba						
Luuq	182.03	10.60	553.55	0.71	5753	0.29
Bardhere	278.08	46.50	732.35	0.79	8760	0.30
Shabelle						
Belet Weyne	92.22	11.94	288.37	0.80	2889	0.35
Bulo Burti	91.10	11.91	283.27	0.82	2781	0.35

Note: *Q*95 is 95% flow from flow duration curve, *Q*5 is 5% flow from flow duration curve, BFI is baseflow index, CV is coefficient of variation.

Figure 6 indicates that the recent flow data appear to be reasonably consistent with the historical data, though the extremes may have increased. However, over the periods 2001–2010 and 1963–1990, there are no significant trends at the 95% confidence level. This is perhaps not unexpected given the high inter-annual variability of flows in the two rivers, shown in Table 2 to be between 0.29 and 0.33. These figures reflect the great spatial and temporal variability in the climate, predominantly in the Ethiopian highlands where most of the flow originates. The higher the inter-annual variability in rainfall and river flow, the more important long record lengths become (Sene and Farquharson 1998). Long flow record lengths are necessary to obtain reasonable estimates of the mean and variability of river flows. Short periods of

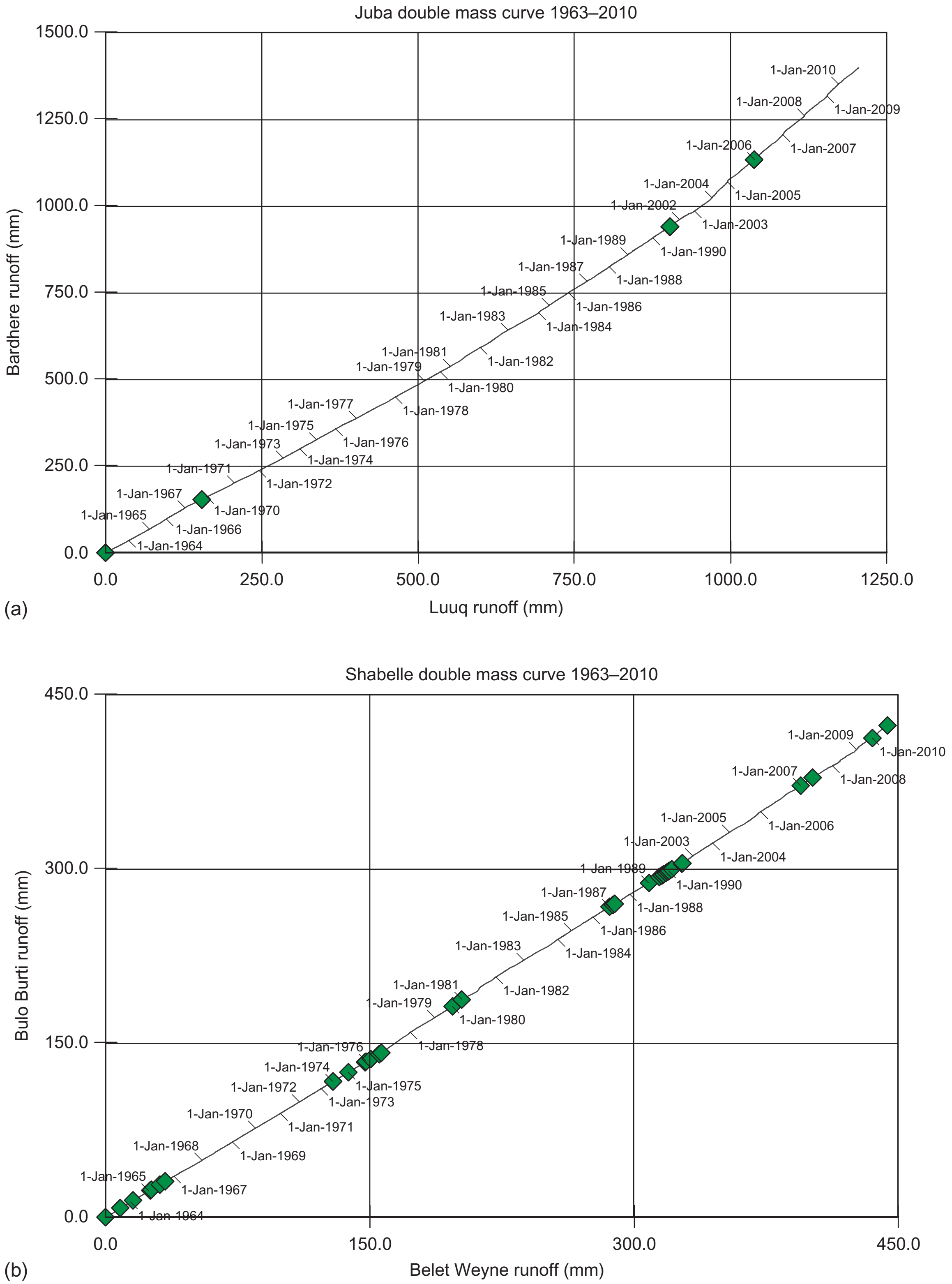

Fig. 7 Double mass plots based on mean daily flow: (a) Juba at Luuq and Bardhere (1963–2010); and (b) Shabelle at Belet Weyne and Bulo Burti (1963–2010). In both figures: diamond symbols indicate missing data at one of both stations.

observation of water levels and flows provide only a glimpse of the true, long-term behaviour of a river and, at worst, can be misleading.

The double mass plot in Fig. 7(a) shows the relationship between the pre-war flows at Luuq and Bardhere on the Juba to have been relatively constant since 1963, apart from a slight break of slope in 1981 when there was a minor change in the rating at Luuq following some exceptional flows (>1400 m^3 s^{-1}). However, the post-2001 slope is significantly steeper, indicating a relative increase in the flows at Bardhere. Figure 7(b) shows a stable relationship between the flows at Belet Weyne and Bulo Burti on the Shabelle, again apart from a slight break in slope in 1978 when there was a minor change in the rating at Bulo Burti. This suggests that any change on the Shabelle appears to be consistent between the two stations.

Table 2 summarizes the long-term flow statistics of the four stations. Table 2(a) presents statistics for the common period 1963–1990, chosen to exclude the widespread periods of missing data in the records between 1951 and 1963 at Luuq and Belet Weyne. Table 2(b) shows the equivalent statistics for data since 2001 on the Juba and 2002 on the Shabelle. For daily mean flows at each station, the mean flow, the *Q*5 and *Q*95 percentiles derived from the flow duration curve in Fig. 4(b), and the baseflow index (BFI; see below) computed using a hydrograph separation technique (Gustard *et al.* 1992), are presented. For annual total flows at each station, the mean flow is presented, in addition to the coefficient of variation.

The mean flows give an indication of flow availability, *Q*5 an indication of flood flows, *Q*95 an indication of low flows, and BFI the proportion of the long-term river flow that derives from stored sources. BFI typically ranges from 0.1 for relatively impermeable catchments, which have little if any storage and where the flow is dominated by response runoff from rainfall events, to 0.99 for highly permeable catchments where flow is dominated by groundwater storage. However, there can be large spatial variability in BFI values in parts of the world with highly seasonal flow regimes, including sub-Saharan Africa (UNESCO 1997). The pre-war BFI values for the Juba and Shabelle show good spatial coherence and, together with the flow duration curves (Fig. 4(b)) indicate slow-responding, baseflow-dominated catchments, reflecting the underlying geology (described earlier).

The comparison of historical and recent daily and annual flow statistics in Table 2 reveals that the post-2001 mean flows (both daily and annual) compare reasonably well at Luuq, but are overestimated at Bardhere and on the Shabelle. At low flows, post-2001 *Q*95s are higher at all four stations, the largest relative differences being at Bardhere and Bulo Burti. At flood flows, post-2001 *Q*5s are again comparable at Luuq, but are overestimated at the other three stations, particularly Bardhere. The post-2001 BFIs continue to show good agreement. The coefficients of inter-annual variation of the post-2001 flows range between 0.29 and 0.35, comparable with the pre-war equivalents indicating a high inter-annual variability of flows at all four stations.

Figure 8 shows average monthly flow hydrographs for the post-2001 period. The general pattern of the monthly hydrographs is similar to Fig. 4(a); however, there are some notable differences:

– There is less consistency between the flows at the upstream and downstream station on each river. On the Juba, this is most noticeable through the Deyr floods where the Bardhere flows are lower

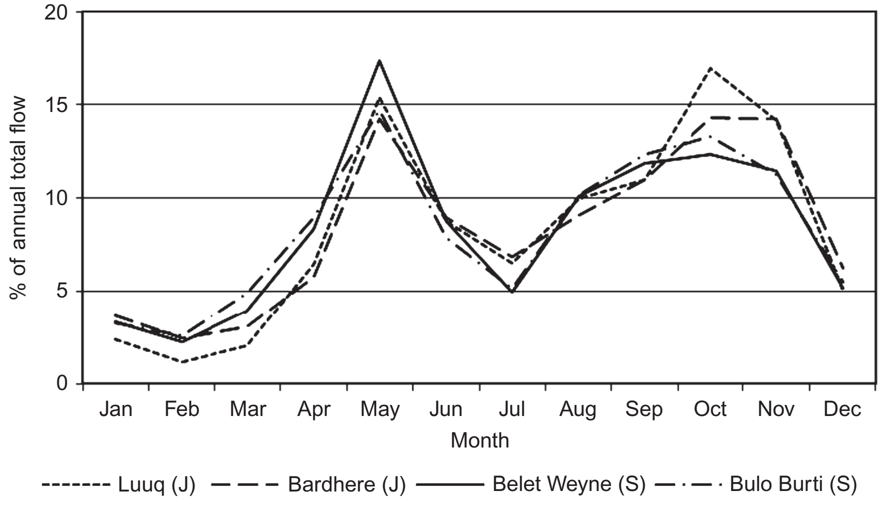

Fig. 8 Distribution of 2001–2010 average monthly total flows (J: Juba gauging station, S: Shabelle gauging station).

and more flat-topped; on the Shabelle, the greatest difference is through the Gu floods.

- The low flows between January and March are higher than for the pre-war data for all stations except Luuq; this is not unexpected given the overestimation of low flows represented by *Q*95.
- The river levels on both rivers are not as well maintained between the Gu and Deyr floods.
- On the Shabelle, the Deyr flood flows are lower and more flat-topped, and peak in the same month as the Juba Deyr floods, i.e. one month later than previously.

Table 3 compares mean annual flows for three periods: 1963–1990, 1980–1990 and either 2001–2010 on the Juba or 2002–2010 on the Shabelle. The means for the latter two periods are also expressed as ratios of the mean for the baseline period 1963–1990. The period 1980–1990 was chosen because many new river gauging stations were opened in 1980, and the hydrometric network was operating at its optimum in the subsequent decade. The 2001–2010 period was chosen in order to assess the short periods of new data in a historical context. For the period 1980–1990, flows were almost the same as the long-term values for all stations except Bardhere where they were 7% higher. These results do not suggest that flows during the 1980–1990 period, when most of the hydrometric network was in operation, were notably different to the longer-term flows. For the period 2001–2010, flows were 3% lower than the long-term values at Luuq, but some 42%, 23% and 26% higher at Bardhere, Belet Weyne and Bulo Burti, respectively.

DISCUSSION

The differences between the post-2001 data and the pre-war data apparent from Fig. 8 and Table 3 are partly explained by the relatively short recent record length of 8–9 years and the influence of the extreme floods in 2006 which are included in that record. The lower flows between the Gu and Deyr flood seasons and the lower Shabelle Deyr flows may also be due to a change in rainfall distribution in the headwaters. East Africa is a region where an apparent shift in climate, and hence flow regime, has been identified in recent years, with mean rainfall increasing slightly since the 1960s (Nicholson 1989, Gommes and Petrassi 1994). This change suggests that mean flow in Somali rivers may have increased slightly since the 1960s. However, the droughts within the middle and latter parts of the 1963–1990 period suggest that the latter part was possibly drier than normal (Musgrave 2002). Given the limited availability of recent flow data, it would be useful to make comparisons with regional rainfall records, but there are also few good/known quality rainfall data for Somalia, or for the relevant region of Ethiopia where most of the river flow originates. Furthermore, easily accessible data do not extend to the period of recent data collection or lack agreement (Ethio-Italian Cooperation 1997, Musgrave 2002, Thiemig *et al.* 2010).

Looking to the future, studies that project changes in average surface runoff conditions from climate and hydrological models often disagree on the direction and magnitude of change, with East Africa expected to experience either a small decrease or a large increase (Arnell 2004, Tate *et al*. 2004, Goulden *et al.* 2009), in line with predicted changes in runoff in the Juba-Shabelle basin of between −10% and +45% by 2030 (Arnell 1999). The current consensus is that annual runoff in East Africa is likely to increase (Conway *et al*. 2009). Like the Juba-Shabelle basin, many large river basins in the region remain sparsely instrumented and under-studied (Conway *et al*. 2009). The uncertainty of these future predictions increases the need to continue long-term monitoring at benchmark stations on the Juba and Shabelle.

Table 3 Means of annual total flows for selected periods (1963–1990, 1980–1990 and 2001–2010 Juba or 2002–2010 Shabelle) and ratios to 1963–1990 means.

River/Station	1963–1990 (mm^3 year^{-1})	1980–1990 (mm^3 year^{-1})	1980–1990 as ratio of 1963–1990	2001–2010 (mm^3 year^{-1})	2001–2010 as ratio of 1963–1990
Juba					
Luuq	5913	5791	0.98	5753	0.97
Bardhere	6166	6601	1.07	8760	1.42
Shabelle					
Belet Weyne	2357	2371	1.01	2889	1.23
Bulo Burti	2203	2262	1.03	2781	1.26

Abstractions may also affect river flows. There are also a number of irrigation schemes within Somalia which are likely to have affected river flow in the past (e.g. see low flows at Afgoi in Fig. 3, resulting from 1135 km^2 under irrigation in 1989; Mbara *et al.* 2007) and may continue to do so, although no formal records are currently kept. It is believed that very little of the water abstracted for irrigation returns to the river directly, instead infiltrating the ground as local recharge and/or evaporating. Therefore, the development of the pre-war irrigation schemes over time should have corresponded to an increase in abstractions over time. During the war, as the larger schemes were abandoned and the smaller canals and channels fell into disrepair, the quantity of water abstracted should have decreased. These abstractions, and any return flows, will be implicitly included in the gauged river flows. Unfortunately, it is not yet possible to gauge the change in abstractions accurately, since the rehabilitated stations are in the upper reaches in Somalia, whereas the majority of agricultural abstrations are from the middle and lower reaches.

Until recently, the development of water resources on the two rivers in Ethiopia was thought to be minor (Musgrave 2002). However, the potential for small, medium and large-scale irrigation schemes within the Shabelle basin in Ethiopia totals some 2380 km^2 (Awulachew *et al.* 2007), and it is anticipated that this potential will be further utilized in future. Water resource developments (e.g. dams, irrigation schemes, etc.) within Ethiopia are likely to cause downstream flows on the Shabelle in Somalia to decrease over time, particularly during the two dry seasons, although the recent data do not yet reveal any such trends.

On both the Juba and the Shabelle, the post-2001 flows at the upstream and downstream rehabilitated stations do not match as well as the historical flows. The recent data at Luuq compare reasonably well with the pre-war data, in contrast to Bardhere where there are some notable differences. These results indicate a suspected problem with the post-2001 data at Bardhere. The flows at Bardhere, particularly the low flows, are too high, and it is unlikely that this is caused wholly by local storm runoff. It is possible that the Bardhere rating has shifted; also, the datum adjustment applied to the water level measurements should be checked. On the Shabelle, any change appears to be consistent between Belet Weyne and Bulo Burti. The BFIs provide no definitive indication of lower baseflow in the river due to upstream development; indeed, the flows at both stations, particularly the low flows, are relatively higher. Again, it is possible that the ratings at both stations have shifted, and again the datum adjustments at both stations need checking.

Results suggest that the post-2001 data at Luuq on the Juba are most reliable, whilst at the other stations there are some issues with the data that need to be addressed before these data can be fully utilized. Questions surrounding the datum adjustments and ratings must be resolved urgently as the post-2001 data are essential for regularly published flow bulletins, and for a flow forecasting model. There is no definitive indication that the pre-1990s flow data are not representative of present conditions and, because of their quality and length of record, these currently provide the best dataset for assessing and managing water resources at these three stations.

The post-2001 data at Luuq were examined in more detail to assess the number of years of new data necessary in order to estimate flow statistics within 10% of the long-term values. Figure 9 shows the variation of the percentage error in key flow statistics at Luuq, as additional complete years of flow data are collected. For each statistic, the series of values from the nine years of new flow data were compared to the long-term value from the historical data. After increasing from 15% to 21% in the first three years, the underestimation in mean daily flow steadily decreased to around 3% after five years and has remained in that range. Similarly, the underestimation in $Q5$ increased from 20% to 25%, before decreasing to around $\pm 5\%$. The underestimation in mean annual flow steadily decreased from 28% to 5% over five years. For mean daily flow, $Q5$ and mean annual flow, estimates are within 10% of the long-term values after four years.

In contrast, BFI is always within -7% and does not improve significantly through time. This is in line with the findings of Gustard *et al.* (1992) that annual values of BFI are relatively stable and can be estimated with confidence from short records, provided extreme (very wet or very dry) years are avoided. Over the period of recent record, the error in $Q95$ reduced from 124% to around 40–50%, which is an improvement but implies that low flows are being disproportionately overestimated compared to other aspects of the flow regime.

For the design of major water resources schemes, it is usually desirable to collect a minimum of 15–20 years of reliable data from which to estimate mean flow, whilst much longer sequences are required to be able to estimate flood and drought events with high return periods, and also to assess variability and

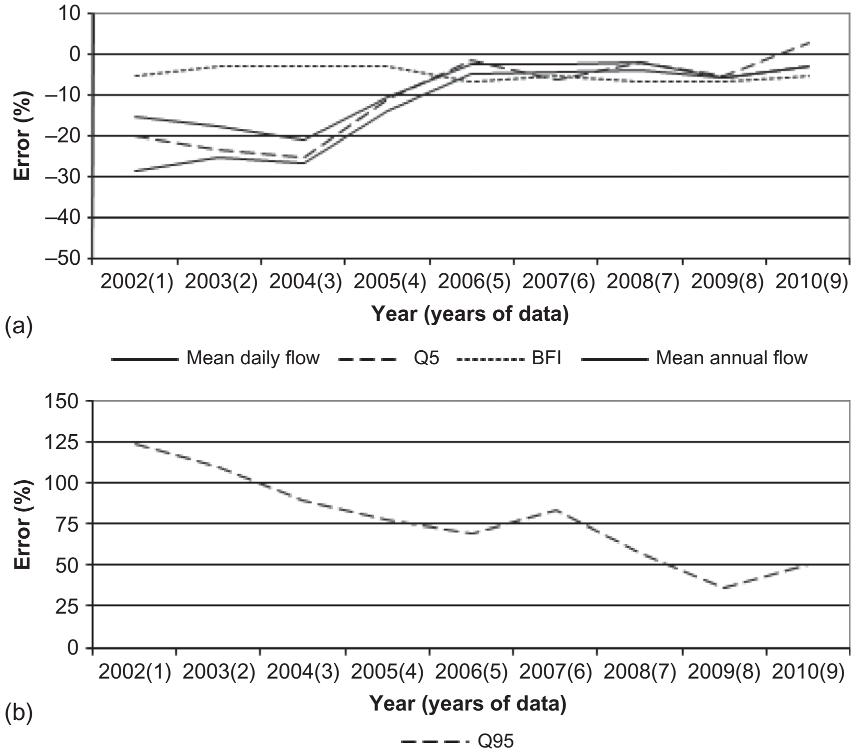

Fig. 9 Variation of percentage error in key flow statistics for Juba at Luuq: (a) mean daily flow, *Q*5, BFI and mean annual flow; and (b) *Q*95.

possible trends in river flows (Sene and Farquharson 1998). If the post-2001 flow data on the Juba and Shabelle can be amalgamated with the pre-war data, this will provide some extremely valuable long-term data series. Subject to the security situation, it is planned to extend the discharge measurement programme to other stations on the Juba and Shabelle (including Bulo Burti) so that, ultimately, new ratings can be developed to enable a more comprehensive comparison of these periods.

CONCLUDING REMARKS

In southern Somalia, water resources planning and management in an integrated and sustainable manner has been obstructed by the lack, until recently, of an effective system for monitoring and assessing resources. There had been no new quantitative hydrological data for the Juba and Shabelle rivers from 1990 until 2001 or 2002, respectively, when four of the principal gauging stations were rehabilitated. Following reinstatement of the hydrometric database, the initial focus was on developing systems and standards for collating, inputting, validating and archiving the newly collected water level data. More recent work has been directed towards prudent analysis and comparison of the pre-war and post-2001 data, with recognition of the possible errors.

The availability of post-2001 data and related discharge measurements is expected to improve over the next few years, assuming that the hydrometric network continues to be rehabilitated, subject to sufficient resources being available and a stable security situation. In such circumstances, a priority must be placed on confirming datum adjustments and gauging discharge to develop the existing ratings. The lack of data since 1990 is unusual, but not unique. Lebanon experienced a similar situation as a result of the civil war from the mid-1970s to 1990 (Sene *et al.* 1999, 2001). However, in many countries in sub-Saharan Africa, there has been a marked decline in hydrometeorological data collection and management in recent years (Sene and Farquharson 1998). Many countries are faced with the challenge of managing their water resources using data of less than satisfactory spatial extent and temporal quantity and quality.

The particular problems of data collection, and investment in data collection, in developing countries are being addressed, to some extent, through regional initiatives such as the UNESCO FRIEND programme (UNESCO 1997, Gustard and Cole 2002) and the WMO WHYCOS project (Rodda *et al.* 1993, Houghton-Carr *et al.* 2000). Such initiatives are particularly important for transboundary river basins, such as the Juba-Shabelle basin. In this instance, access to data from upstream Ethiopian gauging stations would be helpful and in spirit of the cooperative approach necessary for successful and sustainable management of water and other natural resources in international basins.

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