13 River Hydromorphology and Flood Hazard in Somalia

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Abstract

The Juba and Wabe Shabelle are the largest permanent rivers of Somalia and of the whole Horn of Africa. Though these rivers have neighboring catchments of almost the same size, their hydrology and channel dynamics are rather different. Such differences are investigated in the modern rivers, and a comparison with old (Quaternary?) avulsion channels is made. Basic geomorphic parameters of the old channels are measured from satellite images and bankfull discharge is calculated by simple equations using meander wavelength as the main entry parameter. Geological information and satellite images analysis revealed the occurrence of old, presently inland, deltas. Presently, the Shabelle R. is not entering the ocean north of Mogadisho as it would be expected for the regional gradient, but proceeds southwestward parallel to the coast for a few hundreds of kilometers before to reach the Juba R. A new hypothesis to explain this apparent anomaly is presented. In the last two decades, both the study rivers experienced an increased frequency of high, devastating floods causing several fatalities and affecting thousands of people. The causes of such increase in flood hazard are manifold and include both a climate worsening and human impact.

Keywords

Hydromorphology • Avulsion • Meandering •
Aggradation • Bank breach

13.1 Introduction

In Somalia, there are only two big permanent rivers: the Juba and the Wabe Shabelle (in the local language, "*Wabe*" means river and "*Shabelle*" leopard). There is also another river, the Byoguure (in the local language this name means "running water") in the Daban basin of northern Somalia, but this river has a small catchment and a very limited base flow of a few liters per second (see Chap. 12 of this publication for more details).

Throughout the whole Horn of Africa, the Juba and Shabelle rivers have distinctive geomorphological and hydrological characteristics, and though their catchments are neighboring and with similar size, orientation, source area (the Bale mountains in Ethiopia) and both rivers cross similar terrains, they show different channel morphology dynamics, runoff volumes and flow patterns. Repeated, impressive channel avulsions and evidence of very long paleo/old channels are very common in the Shabelle and provide unique examples to investigate this process.

The Juba and Shabelle rivers play a very important role in Southern Somalia as they are the main source of water for irrigation in a country where the other two-thirds of the territory is dryland unsuitable for agriculture. Though floods supply the surrounding plain with water and nutrients and provide the local farmers with good opportunities for flood recession cultivations, the progressive abandonment of almost all the flow regulation structures and irrigation schemes after the onset of the civil war in 1991 resulted in an increased frequency of devastating floods that affected a large number of people and caused several casualties (Basnyat and Gadain 2009). In the last decade, the frequency of overbank floods significantly increased in response to higher than usual rainfalls in the lower Juba and Shabelle rivers flood plain. However, this already hazardous situation has been exacerbated by uncontrolled river bank breaches by local farmers in an attempt to replace the function of the former irrigation schemes, presently no longer operating.

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The observed increase in precipitation, however, has not decreased the frequency of droughts (SWALIM 2016) that became with floods a major hazard in Somalia (see also Chap. 1 of this book for details).

In this chapter, the hydromorphology characteristics of these two rivers and their recent geomorphological evolution are examined, and the reasons for the increased frequency of devastating floods in their lower reaches are investigated.

13.2 Geographic Setting

The Juba and Shabelle rivers have their source in the Bale and the Chercher and Ahmar mountains in Ethiopia, respectively, (Billi 2015) (Fig. 13.1) at elevations higher than 4000 m asl (Fig. 13.2). In Ethiopia, the Juba is named as Genale river. Both rivers flow from the Ethiopian Plateau-Rift Valley margin and maintain a south-east direction as far as the Ethiopia-Somalia border. Beyond the border, the rivers flow southward but, while the Juba reaches the sea near Kisimayo, the Shabelle turns to south-west around the town of Jowhaar and flows parallel to the coastal dunes running out in the swamps of the Balli plain (i.e., wet plain in the local language) (Vicinanza 1910; Basnyat 2007)) downstream of Afgoye (Fig. 13.1). Beyond these wetlands, the river resumes a poorly defined channel and a very low and intermittent flow. The Shabelle joins the Juba upstream of Jamame only during occasional, extreme floods.

The Juba results from three main rivers (Genale, Dawa and Weyb) joining at Dolo, just before to cross the Somali border, and about 80 km upstream of Luuq, where the most upstream flow gage in Somalia is located. This river has a catchment of about 221,000 km^2 (the catchment portion in Somalia is about 50,000 km^2) and a total length of 2078 km of which 1204 are in Somalia. The catchment area of the Juba almost doubles and becomes about 450,000 km^2 if also the Laag Dheera river, which occasionally joins the Juba a few kilometers upstream the river outlet into the Indian Ocean, near Kisimayo, is included.

The Shabelle has no large tributaries in the Ethiopian headwaters, with the exception of the Fafan river. This river is geomorphologically a tributary of the Shabelle, joining it near Ferfer, at the Somali border (about 30 km upstream of Beled Weyne, where the most upstream flow gage of the Shabelle river in Somalia is located), but actually its flow is very erratic and reaches the Shabelle only very occasionally during extreme floods (Fig. 13.3). The Shabelle has a catchment of about 296,000 km^2 at the confluence with the Juba (about 245,000 km^2 upstream of the Balli swamps) and a length of 2041 km at the confluence with the Juba. In Somalia, its catchment area is about 103,000 km^2 for a length of 803 km Basnyat and Gadain (2009) . The Juba-Shabelle river system is the largest of the Horn of Africa with a total catchment area of about 750,000 km^2.

13.2.1 Climate

The climate of both catchments is very similar and highly variable since it is much more humid and cool in the highlands and rather hot and drier in the lowland (Fig. 13.4). In the Bale and the Ahmar mountains in Ethiopia, annual precipitation is over 1500 and 1000 mm, respectively, whereas in the middle and lower river reaches, it can be as low as 350 (Kebri Dehar) and 250 mm (Beled Weyne), respectively, (Muchiri 2007; Fazzini et al. 2015). The monthly rainfall pattern shows a main wet season (*Gu* in the local language) from April to June and a minor rainy season (*Deyr* in the local language) from October to November (Muchiri 2007: Chap. 2, this volume) (Fig. 13.5). In the catchment portions within Somalia, the highest annual rainfall is recorded at Baidoa (566 mm) and the lowest at Dolo (250 mm). The *Gu* rains account for 43–56% of annual precipitation. In eight out of the 12 meteo-stations considered the month with the highest rainfall is April, with a mean monthly rain of about 93 mm. The onset of the *Gu* rain is rather abrupt since the mean monthly rain of March is about 16 mm, that is, about half of the average monthly precipitation (33.9 mm) which, on its turn, is slightly more than one third of mean April rain (92.8 mm).

Annual precipitation is highly variable in the study area (Table 13.1). On the base of very few representative meteo-stations data, annual rainfall variation coefficient is lower in the headwater of both catchment (e.g., 0.20 in Goba, 0.27 in Negelle and 0.39 in Jijiga) and tends to increase in the downstream portion of the catchments (e.g., 0.49 in Kebri Dehar, 0.54 in Beled Weyne) to decrease again along to the coast (e.g., 0.32 in Afgoye, 0.42 in Kisimayo) (Basnyat 2007; Fazzini et al. 2015).

Rainfall intensity is a very important parameter to predict floods and soil erosion. Unfortunately, hourly data are very scarce, whereas some daily intensity data are available for two meteo-station in the headwaters of both study rivers. In the Juba headwaters, the maximum daily rainfall intensities ever recorded are 112 and 137 mm day^{-1} (mean 43 and 66 mm day^{-1}, respectively) measured by the rain gages of Robe Bale and Negelle, respectively, (Figs. 13.1 and 13.6). In the Shebelle headwaters, the highest daily rainfalls ever recorded are 118 and 128 mm day^{-1} (mean 54 and 59 mm day^{-1}, respectively) at the meteo-stations of Haramaya and Kebri Dehar (about 80 km West of Jijiga), respectively, (Figs. 13.1 and 13.6). It is worth noticing that

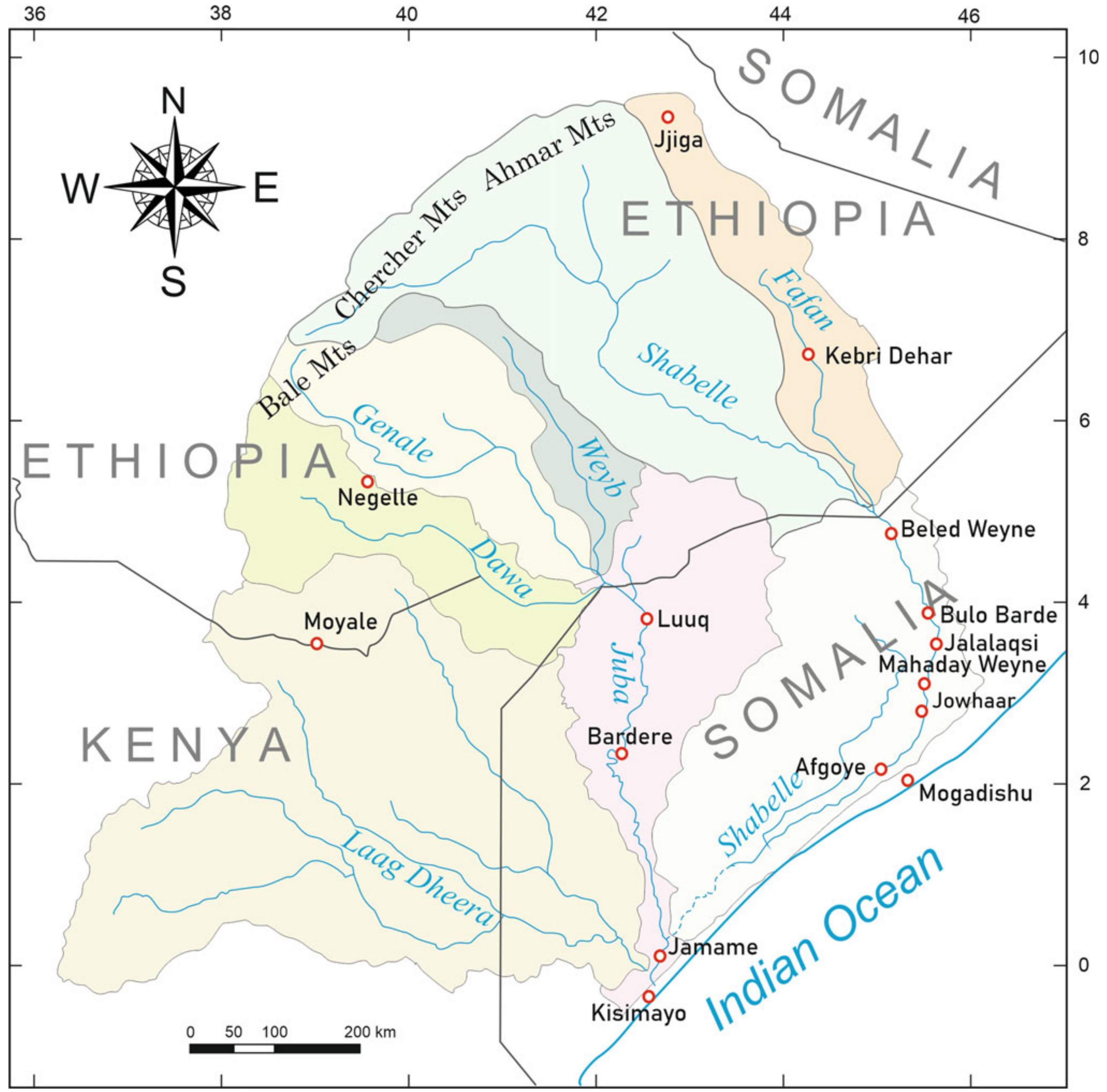


Fig. 13.1 Main catchments and sub-catchments of the Juba and Shabelle rivers. Modified from Balint et al. (2010)

commonly such daily rain amounts are reached in a shorter time (typically two–three hours) rather than in 24 h. Figure 13.6 shows that in these meteo-stations, daily rainfall with 5–10 years return time may range from 50–60 to more than 90–100 mm day^{-1}, i.e., values high enough to produce flooding (Diakakis 2012).

In the 18 meteo-stations considered within Somalia (see Chap. 1 of this volume for more details), mean monthly temperature is rather high in every month ranging from 14.1 to 36.6 °C. The town with the highest mean annual temperature is Luuq (30.7 °C), and the cooler one is Ceerigabo with 17.2 °C. The hottest months typically coincide with the *Gu* rains (the main rainy season from April to June), whereas the relatively cooler ones are from November to February. Mean monthly temperature does not change much through the year. The maximum range, in fact, is recorded at Berbera (11.7 °C) and the minimum at Kismayo (2.9 °C). More detailed information about the climate of Somalia in general and the study area in particular can be found in Muchiri (2007) and in Chap. 1 of this volume.

Fig. 13.2 Hypsometric curves for the Juba and Shabelle rivers. Data from Basnyat and Gadain (2009)

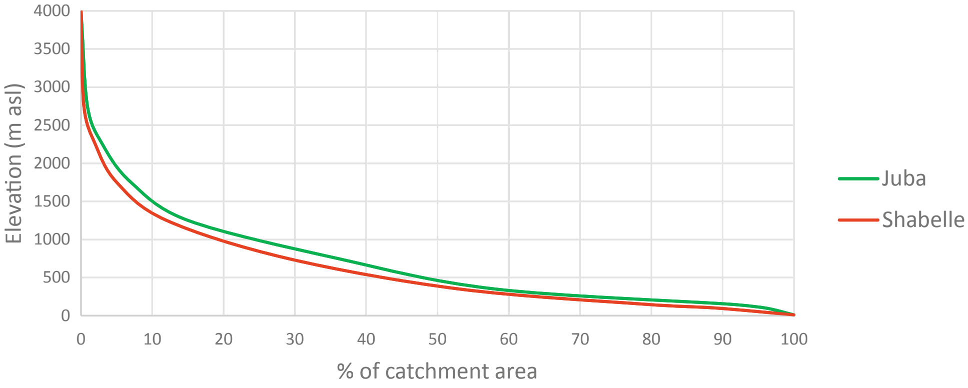


Fig. 13.3 Confluence area between the Shabelle and the Fanfan rivers

13.2.2 River Hydrology

Both the Juba and Shabelle rivers have flow data dating back to the mid-1950s, measured at a few flow gages in Ethiopia and Somalia (the main flaw gages are reported in Fig. 1), but some sparse measurements were undertaken by Italian authorities since 1925 (Italian Government 1925). Though these data sets are affected by several gaps, the situation was much better than in 1990s when almost all the recording stations were not operating because of the civil war. In the early 2000s, the FAO-SWALIM project restored the most important flow gages, flow measurements were resumed, and flow data are available since recent (Muthusi and Gadain 2009). Of course, some differences in the rating curves between pre- and post-war were expected (for many reasons, including streambed deposition and scouring, channel narrowing/widening, etc.). Some calibration to make the two data set comparable was performed by SWALIM (Muthusi

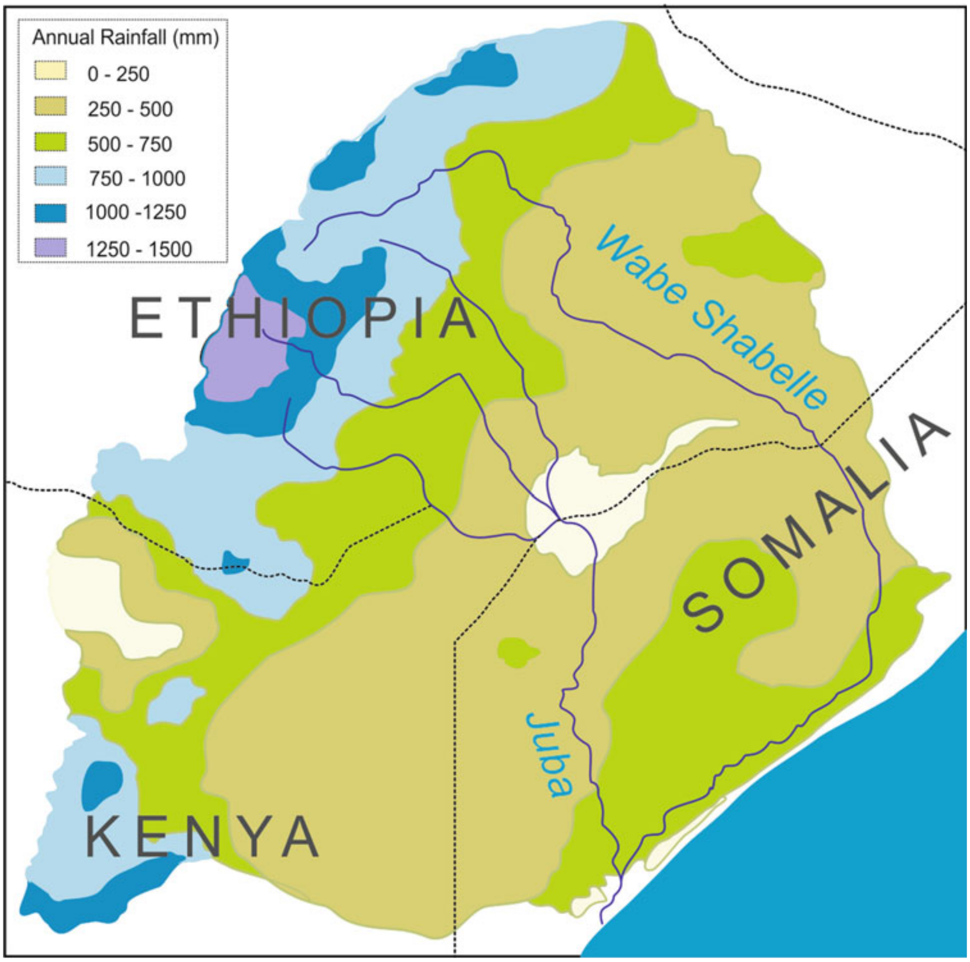


Fig. 13.4 Precipitation distribution across the Juba and Shabelle catchments. Modified from UNEP (2010)

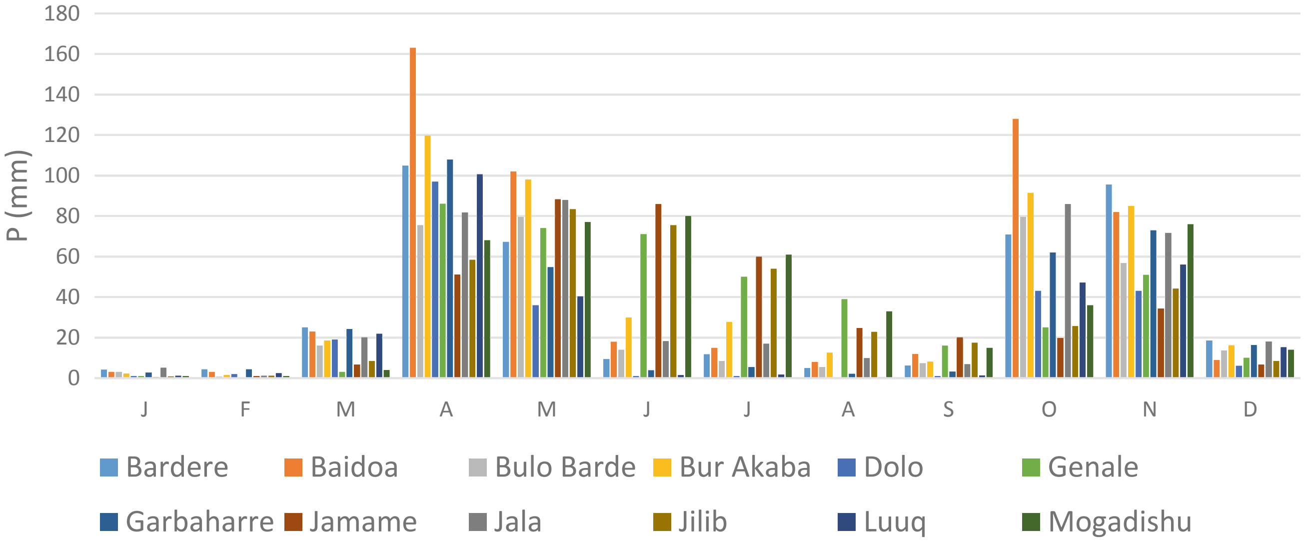


Fig. 13.5 Monthly rainfall variation for a few selected meteo-stations in the study area

Table 13.1 Average annual rainfall (mm) over the study area

Catchment	Average	Maximum	Minimum
Juba (whole basin)	595	1275	239
Juba (within Somalia)	427	704	279
Laag Dheera (whole basin)	534	1355	279
Laag Dheera (within Somalia)	478	571	332
Shabelle (whole basin)	543	1129	266
Shabelle (within Somalia)	460	651	279

Data from Basnyat (2007)

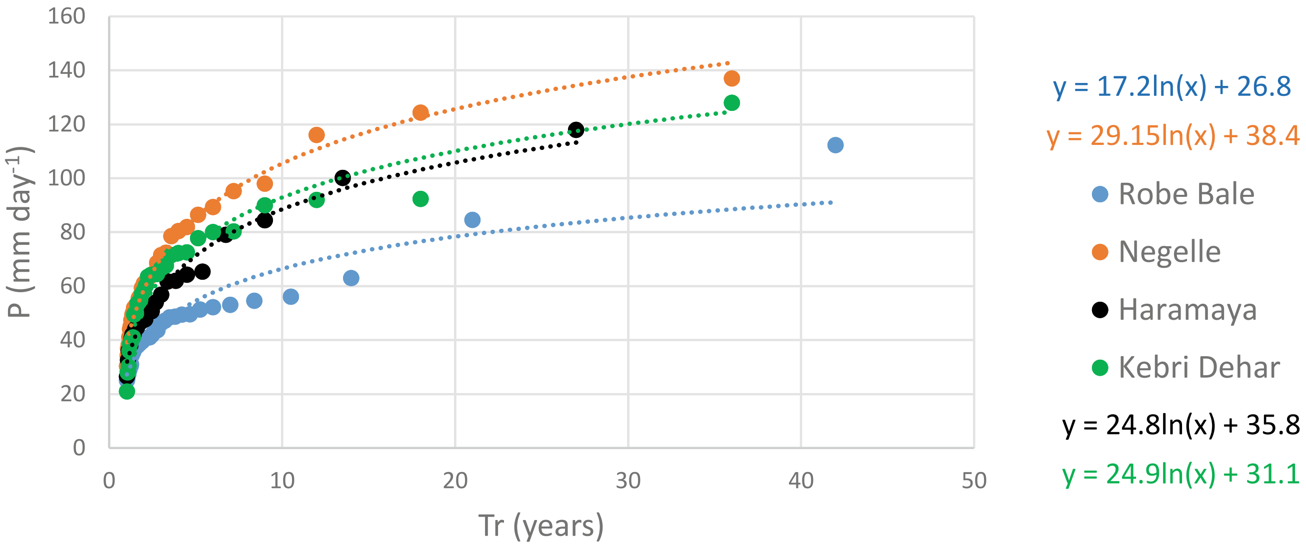


Fig. 13.6 Daily rainfall frequency curves of a few representative meteo-stations in the Juba and Shabelle river headwaters

and Gadain 2009), and new rating curves are still under construction. An important result of the work of Muthusi and Gadain (2009) is that, though the rating curves have changed, the discharge ratio between two adjacent flow gages did not substantially change.

Though the Shabelle has a larger catchment than the Juba (without the Laag Dheera), its average annual runoff volume is less. In both rivers, discharge decreases remarkably from upstream to downstream reaches. At Luuq (most upstream Juba flow gage in Somalia—Fig. 13.1), for instance, annual runoff is 6128 × 10^6 m^3 $year^{-1}$, whereas at Jamame, it is 5145 × 10^6 m^3 $year^{-1}$, that is, a water loss of about 15%. In the Shabelle, at Beled Weyne (most upstream Shabelle flow gage in Somalia—Fig. 13.1), annual runoff is 2580 × 10^6 m^3 $year^{-1}$, but it becomes as low as 126 × 10^6 m^3 $year^{-1}$ at Afgoye, which corresponds to a reduction of about 95%. The reasons for such a different hydrological behavior of this river are manifold, the most important of which include:

(a) the lack of tributaries of the Shabelle in its lower course. The Fafan river is the most downstream tributary joining the Shabelle at the Ethiopia-Somalia border. But, this river has a very low discharge and only occasionally; during very large flood discharges, its water reaches the Shabelle (Fig. 13.3);
(b) water diversion for irrigation purposes;
(c) streambed infiltration and ground water recharge;
(d) the great thickness of the alluvial deposits. A borehole dug in 1923, 13 km east of Jowhaar, reached a depth of 107 m from the surface, i.e., 3 m below sea level, without encountering the bedrock. The stratigraphy recorded by Gigliale (in Crema 1923) consists of a basal alternation of sand and fine and coarser gravel for a thickness of about 40 m, overlain by alternations of sand, sometimes with fine gravel and dark red clays. Groundwater was found at a depth of 68 m in the basal gravels, but discharge was rather modest: 2.5 m^3 per hour;
(e) bedrock characteristics. The middle to lower reaches of the Shabelle are underlain by limestone and gypsum formations within which karst cavities may be present at depth (Fig. 13.7).

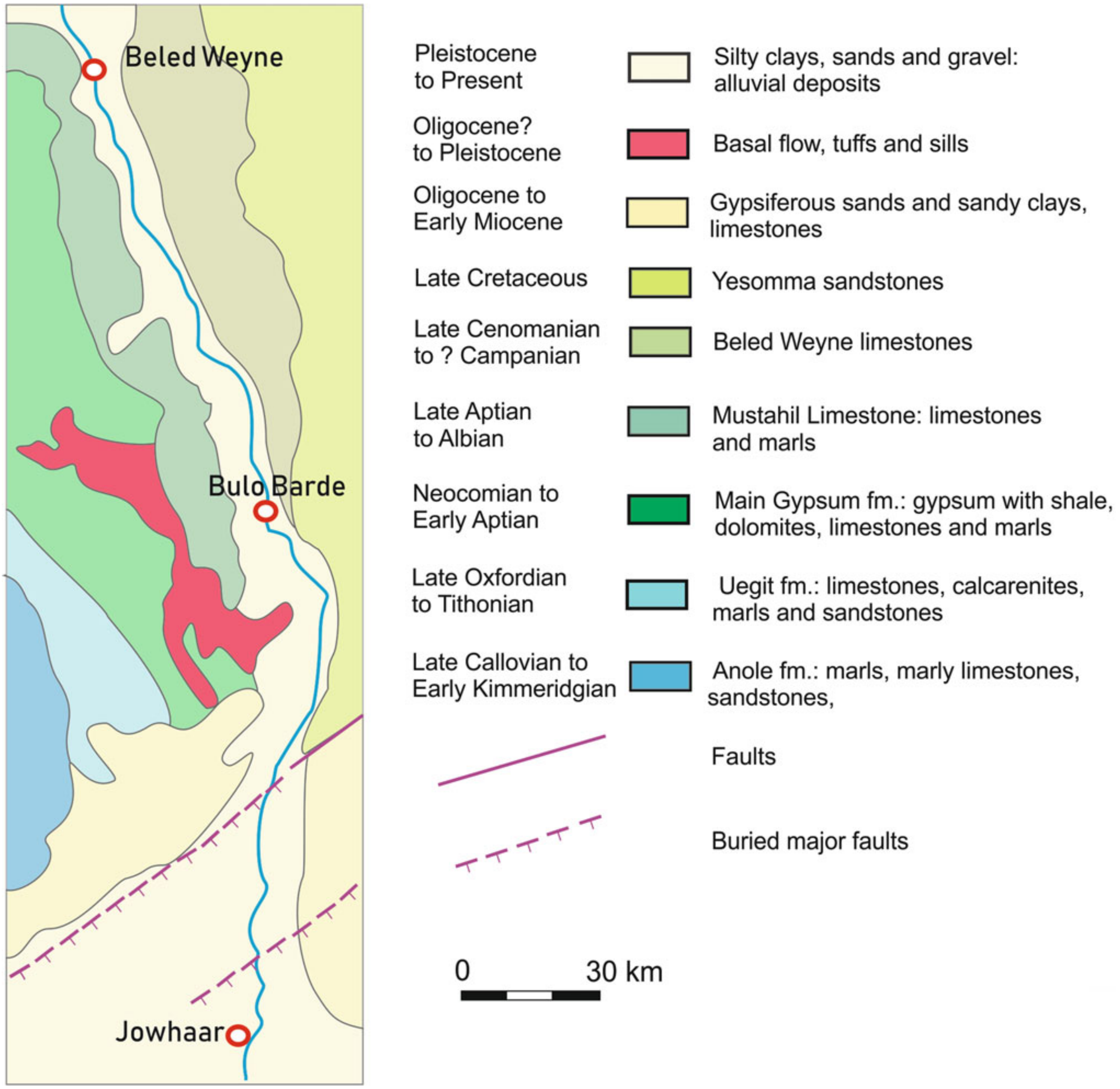


Fig. 13.7 Geological map of the area around the Shabelle river from Beled Wayne to Jowhaar. Modified from Abbate et al. (1994)

The monthly flow pattern follows that of monthly precipitation (Figs. 13.8 and 13.9). The largest mean runoff volumes and discharges are recorded in October–November and May at Bardere for the Juba and at Beled Weyne for the Shabelle (Figs. 13.8 and 13.9). The flow peaks in May follow the *Gu* rains, whereas those of October and November coincide with the *deyr* rains. The latter are propelled by the monsoon type rains that have their maximum from July to September in the Ethiopian headwaters (Fazzini et al. 2015).

Only the flow time series recorded at Luuq on the Juba and at Beled Weyne on the Shabelle are long enough to try some considerations on flow variability. Not only the annual runoff of the Juba is much larger (about 58%) than in the Shabelle, but this latter river is subjected also to a wider runoff variability with a variation coefficient of 0.48, whereas it is only 0.28 in the Juba (Fig. 13.10). The highest flow variability is recorded in March (1.73) in the Juba as runoff volume is substantially influenced by sporadic early beginning of the *Gu* rains in this month. The lowest flow discharges are recorded from January to March in both rivers with values ranging from 1 to 6 m^3s^{-1} in the Juba and from 0.76 to 2.00 m^3s^{-1} in the Shabelle. In this latter river,

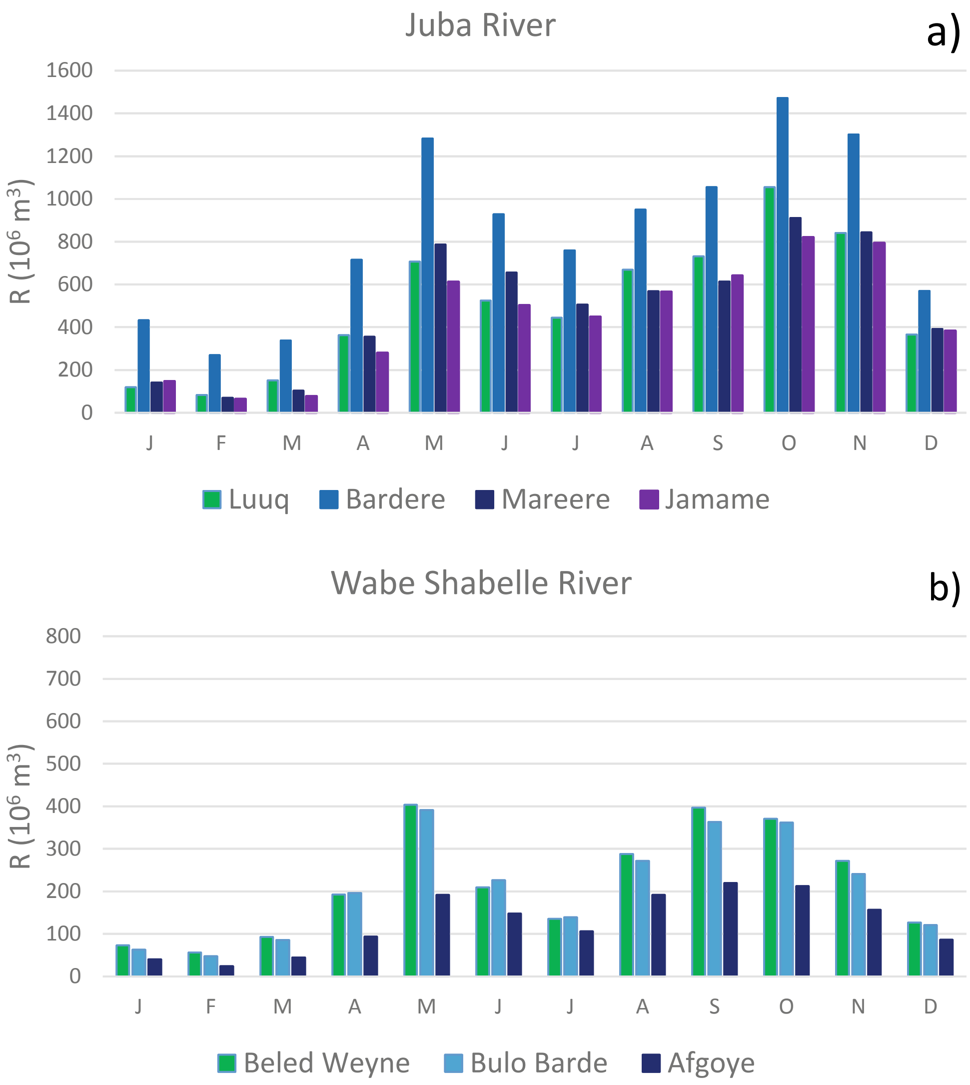


Fig. 13.8 Runoff monthly distribution of Juba **a** and Wabe Shabelle **b** rivers. Notice, the runoff volume of the former is about three times larger than the latter

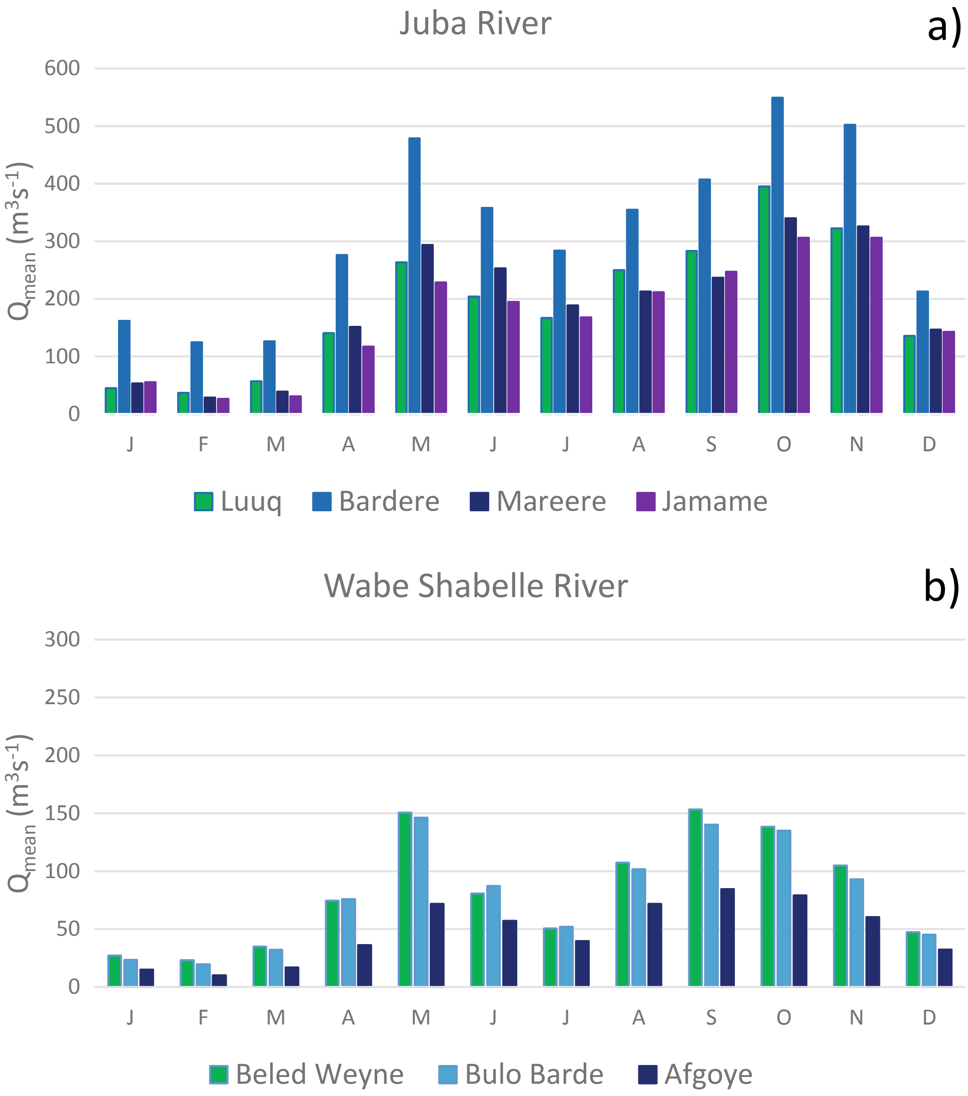
however, during particularly long periods of low or no rain, the streambed may become partially or even completely dry (Fig. 13.11), especially in the middle-lower reaches, from Mahaday Weyne to Balcad, as it happened twice in one year in March 2016 and in December 2016-March 2017 (World Bank-FAO 2018).

13.3 River Morphology

All the geomorphic parameters used in this study were obtained from measurement on Google Earth Pro® satellite images. In order to increase the accuracy of meander wavelength (*Lw*) data, measurements were repeated two times on both side of the river reach. Elevation data for gradient calculation were obtained from averaging 4–5 values measure in the vicinity of the reach extremities. Average channel width was calculated by measuring the width at not less than 20, equally spaced, cross-sections. Channel and valley length were measured using the "Ruler" function available in Google Earth Pro®.

Within the Somalia territory, both the Juba and Shabelle river courses can be divided in two main portions with different geomorphological characteristics. In the upstream part, both rivers are entrenched and flow within a very narrow alluvial plain incised into a generally flat landscape 10–60 m higher. In the Juba, entrenched reaches (Fig. 13.12) alternate with bedrock reaches in which there is no flood plain and the river is bound by the valley slopes (Fig. 13.13). In the Shabelle, the flood plain of the entrenched part is wider (Fig. 13.14) and the river maintains such a morphology as far as Jalalaqsi. In these upstream reaches, both rivers show a moderate sinuosity. In the Juba, channel sinuosity is mainly controlled by bedrock structure as a fault system is present (Abbate et al. 1994), especially in the bedrock reaches between Luuq and Bardere. The Shabelle,

Fig. 13.9 Mean monthly discharge of Juba **a** and Wabe Shabelle **b** rivers. Notice, the discharge of the former is about three times larger than the latter



instead, flows across a wider alluvial plain, and the river is not laterally constrained. Though its sinuosity is low (1.60), examples of channel dynamics such as meander neck cut offs, abandoned channels, ox-bow lakes, point bar scrolls and lateral meander migrations can be observed (Fig. 13.15).

In the downstream reaches, both rivers enter a wide flood plain (from a few kilometers upstream of Dujuma in the Juba and from about 20 km downstream of Jalalaqsi in the Shabelle), without any lateral confinement (Fig. 13.16). In these downstream reaches, channel sinuosity increases to 1.80 in the Shabelle and 1.90 in the Juba and both rivers show all the typical morphological elements of meandering rivers (Figs. 13.17 and 13.18).

The Juba river shows an increase in channel dynamics in the downstream reaches, whereas the Shabelle is more dynamic than Juba between Jalalaqsi and Jowhaar. In its most downstream reaches, this river seems to be rather stable with very few cases of lateral migration or meander cutoff (Table 13.1).

A characteristic that the two study rivers have in common is a tendency to anastomosing (Fig. 13.19) and channel avulsion. In the Shabelle, this latter process is more pronounced and extensive (Fig. 13.20). Some basic geomorphic parameters of the modern Shabelle river and of the old avulsion channels between Mahaday Weyne and Afgoye (as indicated in Fig. 13.20) were measured and reported in Table 13.2. These data show clearly that the old channels were larger than that of the modern Shabelle. However, such a difference is even more striking if we consider bankfull discharge.

The discharge of a river may be highly variable, from drought to devastating floods, depending on local climate and catchment physical characteristics. Among the very many flow conditions experienced by a river, geomorphologists and hydrologists (e.g., Wolman and Leopold 1957; Leopold et al. 1964; Ackers and Charlton 1970) have identified bankfull flow as the most appropriate discharge to

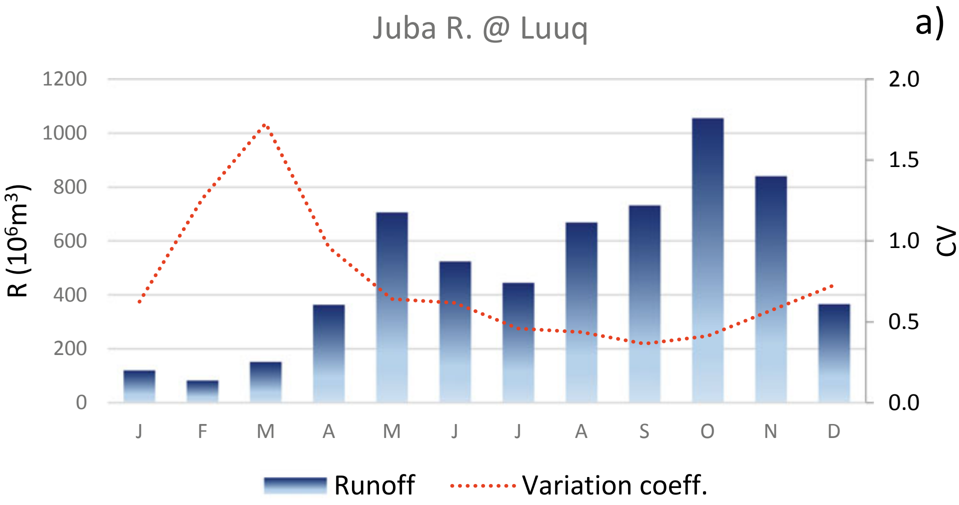


Fig. 13.10 Mean monthly distribution of runoff and of variation coefficient observed at Luuq on the Juba (**a**) and at Beled Weyne on the Shabelle (**b**)

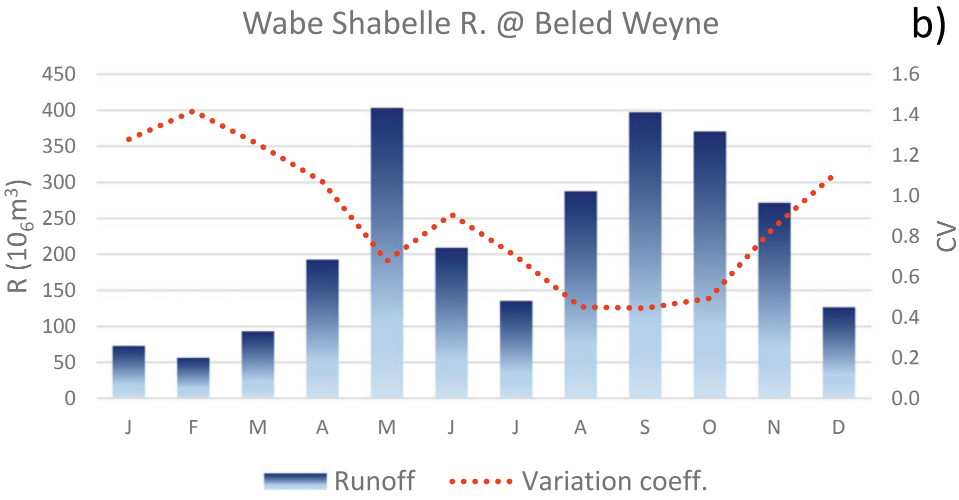


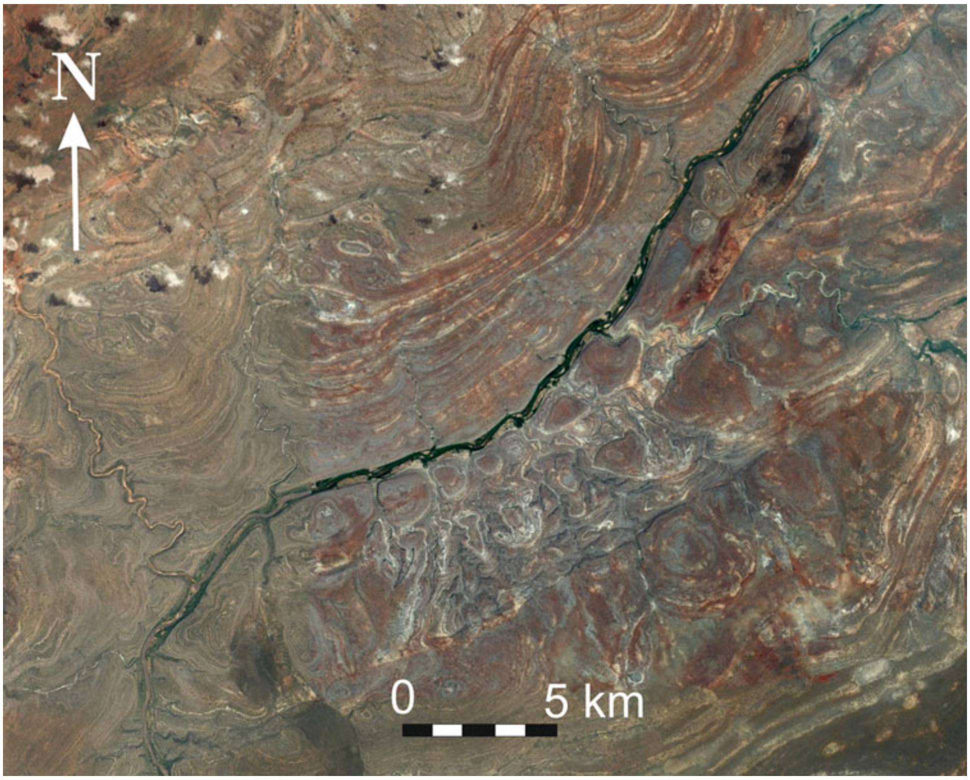
Fig. 13.11 Very low discharge (26/02/2018) and dry bed in the Shabelle river between Jowhaar and Balcad

Fig. 13.12 Entrenched reach of the Juba river at Luuq

compare different river systems in terms of channel pattern and morphology, flow hydrology and sediment yield. In fact, bankfull discharge is associated with the "dominant discharge", i.e., the flow which, in the long term, performs most of the work in terms of sediment transport and yields the largest part of the sediment load (Wolman and Miller 1960). For these reasons, bankfull flow has a relevant geomorphologic significance, since some channel parameters, such as channel hydraulic geometry or meander wavelength, are adjusted to it. In other words, the morphology of a river channel is largely determined by bankfull flow. Hence, in paleohydrologic analysis, this is the best, unambiguous parameter to connote a river flow since it can be inferred from the paleochannel geometry and sediment characteristics and can be used for comparison with modern fluvial systems. Though there is some uncertainty about which discharge best approximates bankfull flow, especially for rivers under different climate and flow regime conditions, many authors (e.g., Leopold et al. 1964; Andrews 1980; Torizzo and Pitlick 2004) restrict bankfull flow to a discharge with a return time ranging from 1.58 to 2.33 years.

For the Shabelle at Beled Weyne, the time series of discharge is not very long (only 47 years), but it can be considered sufficient to construct a reliable flood frequency diagram (Fig. 13.21). The discharges with a return time

Fig. 13.13 Bedrock reach of the Juba river about 100 km downstream of Luuq



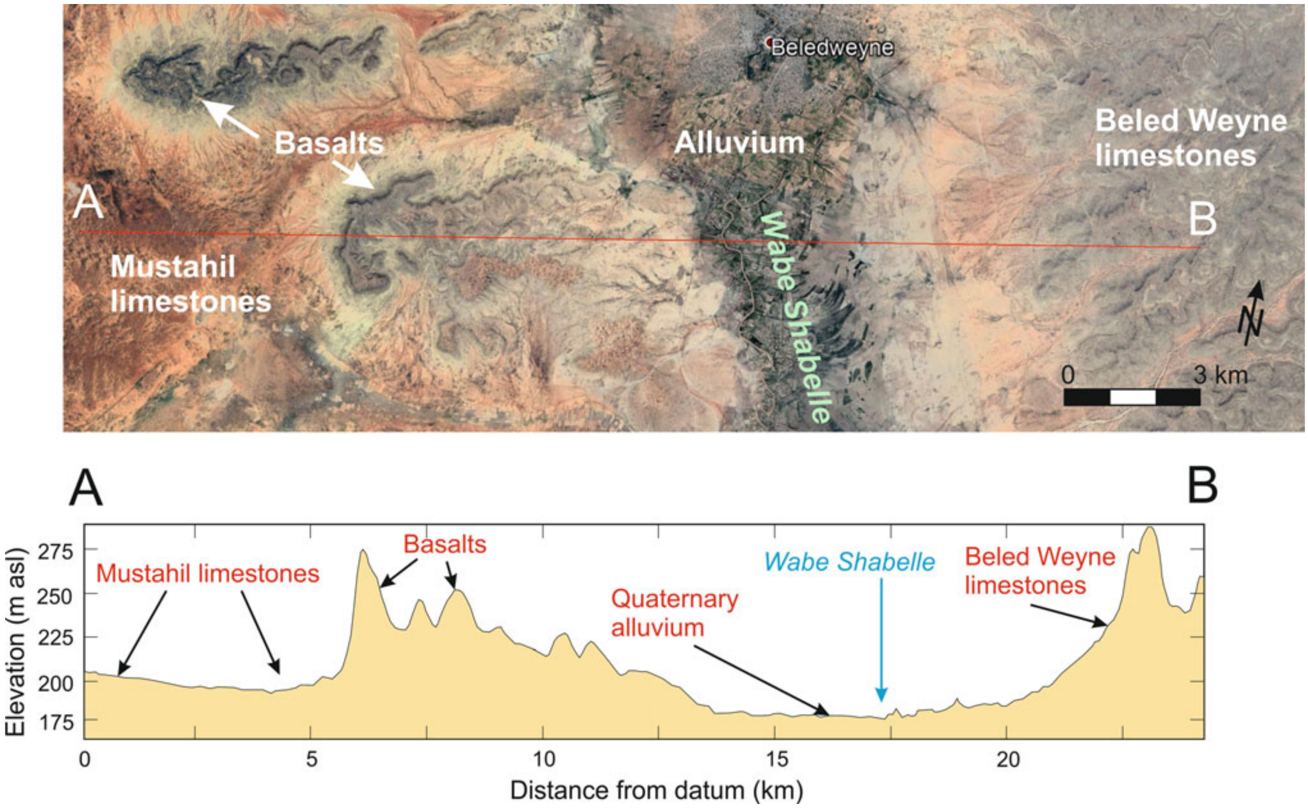
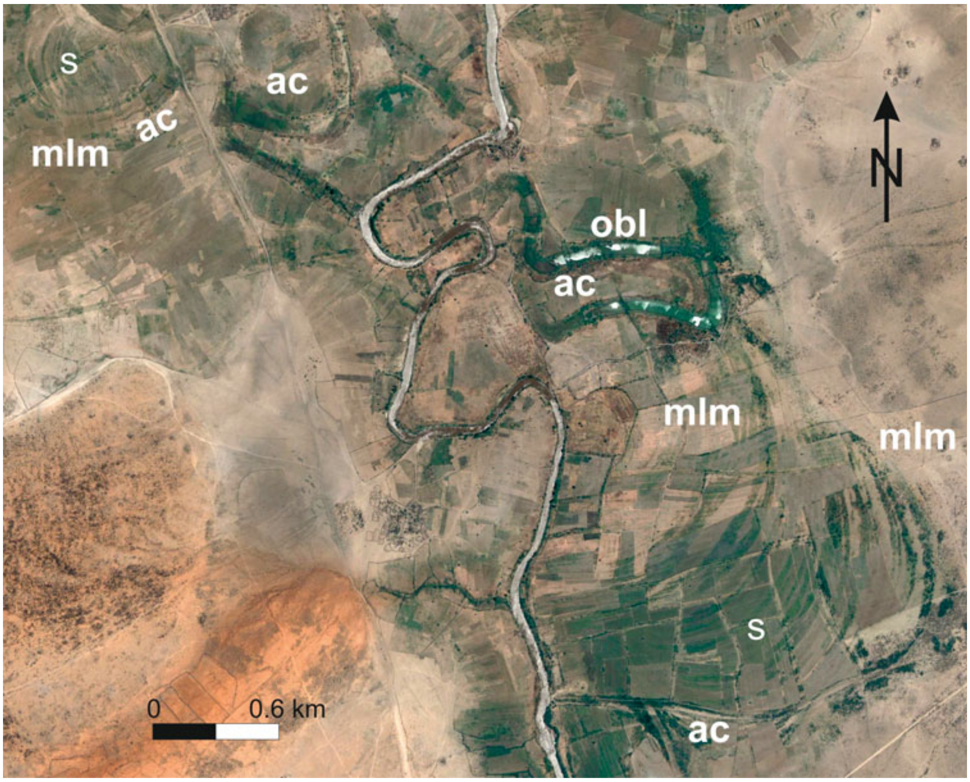


Fig. 13.14 Cross-valley profile of the Shabelle river near Beled Weyne. The alluvial plain is narrow and confined

Fig. 13.15 Channel dynamics evidence in the Shabelle river about 12 km downstream of Beled Weyne: mlm = meander lateral migration; *s* = point bar scroll; ac = abandoned channel; obl = ox-bow lake



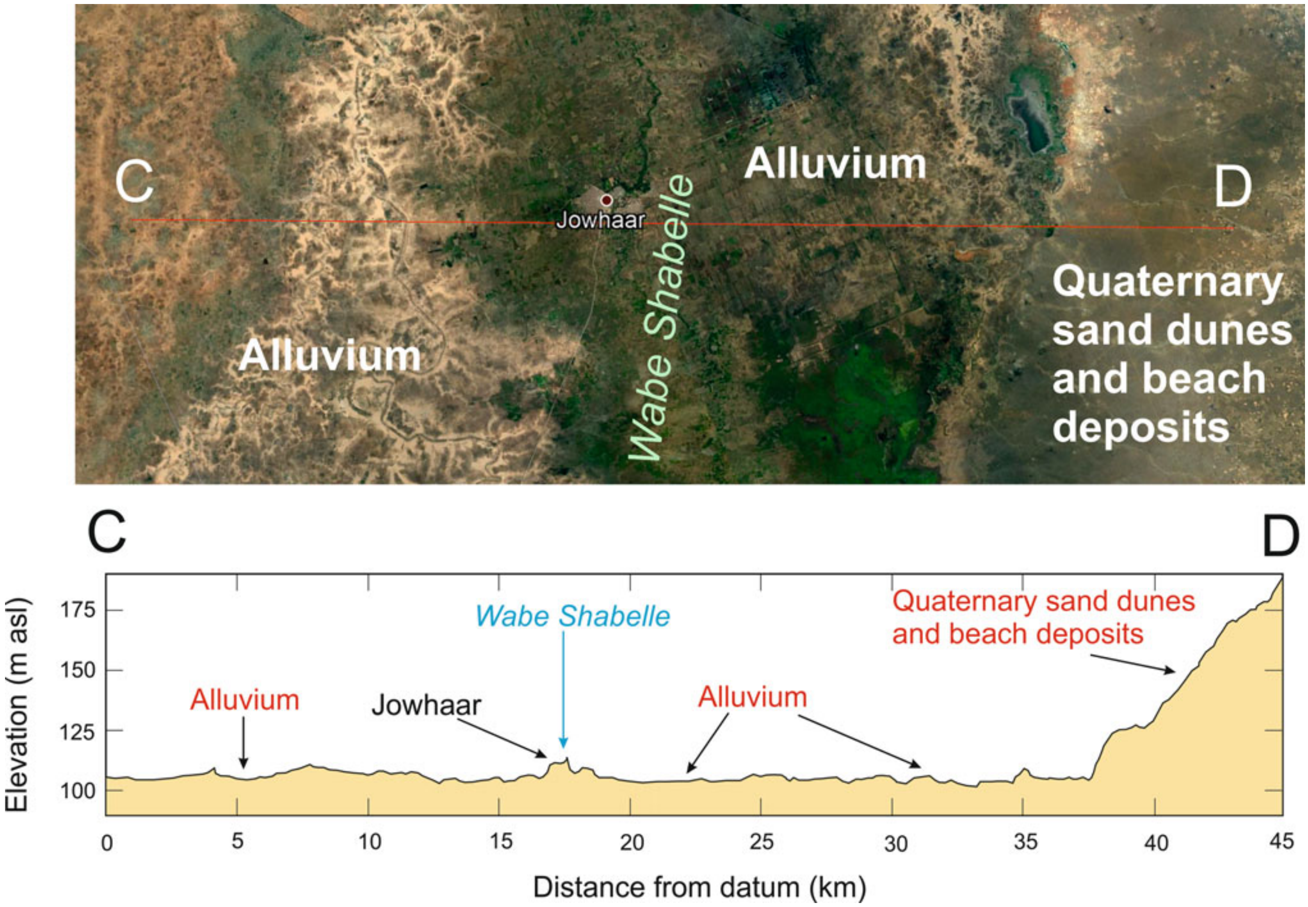


Fig. 13.16 Cross-valley profile of the Shabelle river at Jowhaar. Notice the wide alluvial plain (more than 35 km), the lack of lateral constraints and the perched position of the river, which is more elevated than the surrounding flood plain

interval of 1.58 and 2.33 years calculated with the semi-log diagram of Fig. 13.21 and with the Gumbel extreme values method range from 209 to 269 m^3s^{-1}. For the downstream reach, the only data available are those measured at Mahaday Weyne (Basnyat 2007). Here, the time series is much shorter (only 26 years), but though its limitation is recognized, for completeness of approach, the same calculations were adopted and bankfull discharge resulted to range from 143 to 150 m^3s^{-1}. Notwithstanding the limited data, the lower values obtained at Mahday Weyne are not surprising since both mean monthly discharge and maximum discharge at this measuring station are about 45% smaller than at Beled Weyne.

In order to infer bankfull discharge of the old channels, the empirical relationship of Dury (1976) (in Knighton 1998), which is based on meander wavelength, was used:

$$Q_b = (L_w/32.86)^{1.81} \qquad (13.1)$$

in which L_w is the average meander wavelength (Table 13.2). Equation (13.1) was first calibrated on the data of the modern Shabelle. For the reach downstream of Mahaday Weyne, Eq. (13.1) returns a bankfull discharge of 184 m^3s^{-1}. This value is slightly higher than the calculated ones, but the small number of data and the very small standard deviation may lead to consider the values of 143–150 m^3s^{-1} probably a little lower than the actual ones. To further analyze this assumption, the equation of Williams (1978),

$$Q_b = 4.0A_b^{1.21}J^{0.28} \qquad (13.2)$$

in which A_b is the cross-sectional area at bankfull flow and J is gradient which was also used. To calculate the cross-section area, information was derived from the cross-sections and the bankfull depth data reported by Basnyat (2007). Equation (13.2) returned a bankfull discharge of about 168 m^3s^{-1}. This value falls in between the bankfull discharge obtained by the flood frequency distribution and the empirical Eq. (13.1) of Dury (1976). The difference between the result of Eqs. (13.1) and (13.2) is small, and since bankfull discharge of the modern river at Mahaday Weyne was calculated from a short time series with values of maximum annual discharge very similar (Fig. 13.21), it can be supposed that such a short time series is not able to

Fig. 13.17 Meander neck cutoffs on the Juba river near Jamame

capture the natural variability of high flow and likely the actual bankfull discharge is a little larger than the calculated values of 143–150 m^3s^{-1}. Moreover, given that the result of Eq. (13.2) is very close to that of Eq. (13.1) and considering that for the old channels, the parameter that can be measured with the best accuracy is meander wavelength, bankfull discharge of these avulsion channels was calculated by means of Eq. (13.1), and the results are reported in Table 13.3. The old channel OC R1.3 is straight and only a couple of meanders are present. Its sinuosity, in fact, is 1.26, which is typical of straight channels, so, for this river, another equation derived by Dury (1976) on the base of theoretical considerations and field data, which is more suitable for non-meandering rivers, was used:

$$Q_b = (0.0396/J)^{1.35} \tag{13.3}$$

in which J is gradient.

The results of Table 13.3, which were obtained from meander wavelength (and gradient as in the case of channel OC R1.3), confirm the difference already observed considering the geomorphic parameter but also point out that old channel OC R1 was formed by a river much larger than the modern one. With the exception of the straight channel OC R1.3, which is an avulsion of channel OC R1 (Fig. 13.20) and does not show evidence of channel lateral dynamics, thus likely indicating a short occupancy of this channel; in all the other old channels, examples of the typical dynamics of a meandering river (cutoffs, point bar lateral migrations, ox-bow lakes, etc.) are present (Fig. 13.22) and suggest that in the old channels bankfull discharges much larger than present were maintained for a time long enough to develop these characteristic meandering river morphologic units.

Unlike the Shabelle, in the Juba, old avulsion channels are not so common and restricted to the lowermost reach

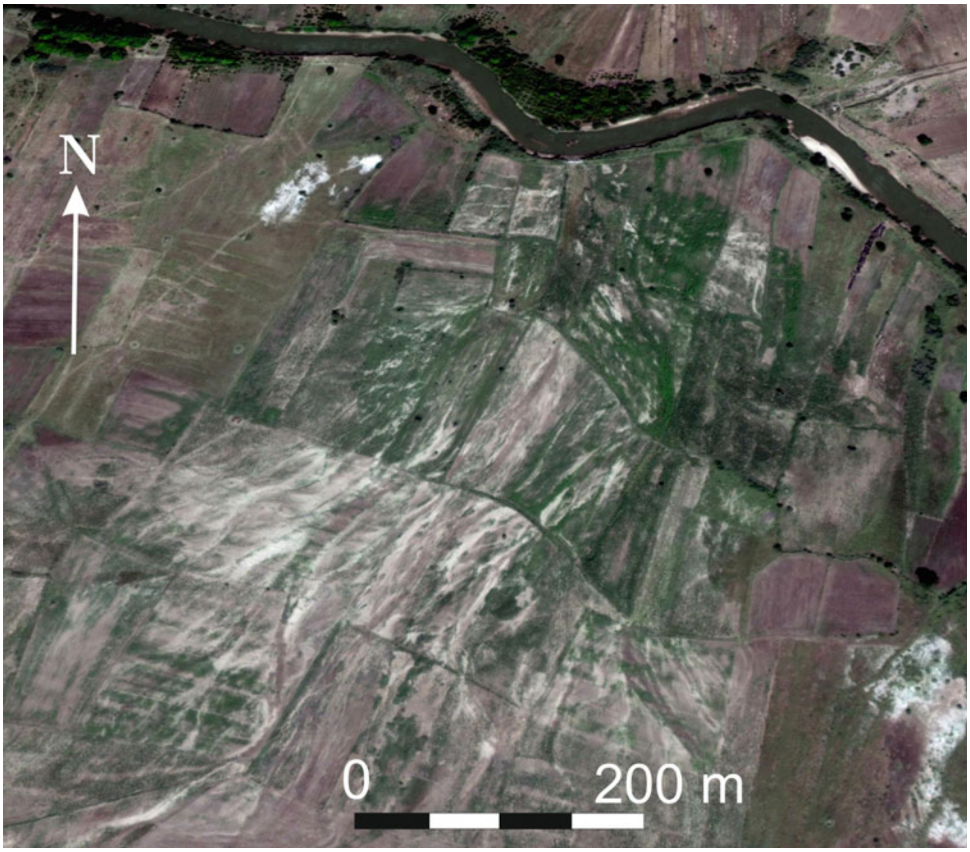


Fig. 13.18 Crevasse splay on the Shabelle river (Google Earth coordinates: 3°09″53″ N 45°32″ 30″ E)

between 20 km upstream of Jilib to Jamame. In this reach, the modern river has an average bankfull width of 80 m, a sinuosity of 1.97, mean meander wavelength of 1102 m, mean radius of curvature of 263 m, and the gradient is about 0.000012. All these geomorphic data indicate that the Juba is a larger river with a larger runoff (Figs. 13.9 and 13.10), larger mean meander wavelength and curvature radius than the Shabelle in its middle to lower reach between Mahady Weyne and Jowhaar (Table 13.2). In the Juba, avulsion channels are much less in number, length and continuity. For these reasons, it was not possible to measure meander wavelength and curvature radius for a sufficient number of bends. The average channel width of avulsion channels (about 60 m) was measured on different short reaches that, however, cannot be assumed as part of the same avulsion channel given the fragmentation of their pattern. This is also confirmed by the standard deviation which is 8.9 m in the modern river and 31 m in the old channels which, in any case, are smaller than the modern Juba.

The assessment of bankfull discharge with Eq. (13.1) returned a value of 577 m^3s^{-1}, whereas bankfull discharge calculated by measured data is in the range of 424–449 m^3s^{-1}. Apparently the difference with the result of Eq. (13.1) seems large, but at the closest gaging station in Jamame, only 16 years of reliable data measured before 1990 are available, and the variation coefficient of the yearly maxima is only 14% in spite of the high annual variability of rainfall (SWALIM 2016). In the work of Basnyat and Gadain (2009), a longer list of yearly maxima is reported, but the value of 477 m^3s^{-1} recorded in 12 years out of 26, with also this same discharge recorded in five years in a row, opens serious question of uncertainty about the bankfull discharge obtained from these field data. These authors report that for both the Juba and the Shabelle rivers, flood peaks are flattened because of bank breaching for irrigation purposes and indicate discharges of 500 and 160 m^3s^{-1} as the bankfull discharges of the Juba at Jamame and of the Shabelle at Mahaday Weyne, respectively, i.e., values not too far from those obtained by Eq. (13.1) (577 and 187 m^3s^{-1} for the Juba and Shabelle, respectively).

13.4 Flooding

In the last two decades, an increased frequency of high floods has been recorded in Somalia (Fig. 13.23) the large majority of which occurred in the middle to lower Juba and Shabelle rivers reaches (SWALIM 2016). In this region, according to SWALIM (2016), the number of people affected by the five- and ten-year flood is about 382,000 and

Fig. 13.19 Anastomosing reach of the Juba river (Google Earth coordinates: 0°12′14″ N 42°46′ 04″ E)

808,000, respectively. Most devastating floods were recorded at the end of the 1990s and in 2006–2007, but recurrent inundations are a serious threat with fatalities and property damage. SWALIM (2016) associates the high floods of 1991/1992, 1994/1995, 1997/1998, 2002/2003, 2006/2007 and 2009/2010 to el Niño episodes, that were particularly marked also in 2014/2015 and 2015/2016.

The maps of the rainfall anomalies over Somalia (FSNAU-FAO 2018) for the 2000–2017 interval (Fig. 13.24) clearly show an increase in the frequency of higher than average rains during the minor rainy season (*Deyr*, i.e., October and November), paralleled by a similar pattern of the wetter *Gu* rainy season (April-June), though with lower positive anomalies and the increased frequency recorded predominantly in April. In most of the cases, the highest rainfalls are concentrated in the southern portion of Somalia, that is, in the middle to lower reaches of the Juba and Shabelle rivers. Very long time series of *Deyr* and *Gu* rains are not available for the study rivers headwaters. Those with the longest record and as least as possible data gaps are Gode and Jijiga for the Shabelle and Moyale and Goba for the Juba. Unfortunately, these time series have different lengths and cover different time intervals. Nevertheless, though with caution, they can be used to investigate if in the river headwaters, there is some evidence of increasing trends. Figure 13.25 shows that with the exception of the *Gu* rain at Jijiga which is characterized by an increasing trend, all the other trends are negative or there is no trend at all.

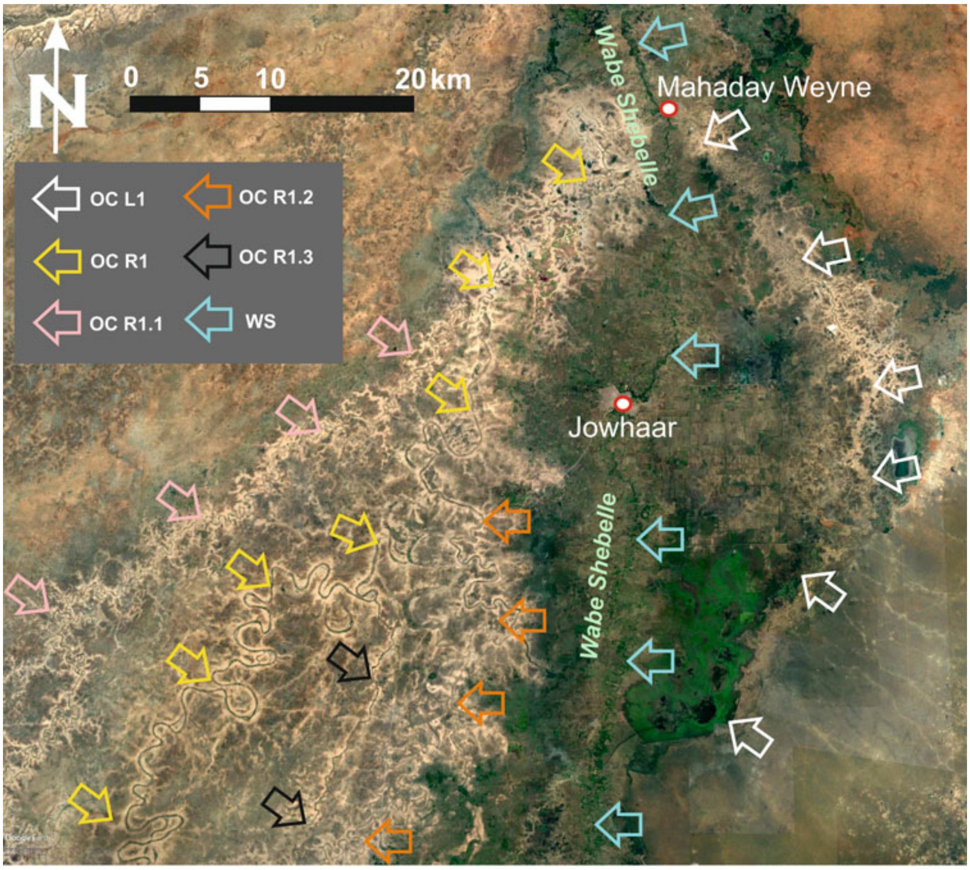


Fig. 13.20 Avulsions and old channels of the Wabe Shabelle downstream of Mahaday Weyne. OC = old channel; *R* = right; *L* = left; 1 = main avulsion; 1.2 = secondary avulsion of main avulsion; 1.3 = secondary avulsion downstream of 1.2; ws = Wabe Shabelle

Table 13.2 Main geomorphic parameters of the Shabelle and the avulsion channels between Mahaday Weyne and Jowhaar (Fig. 17.20)

	S	J (m/m)	W (m)	R_c (m)	R_c max (m)	R_c min (m)	R_c/W	L_w (m)	L_w max (m)	L_w min (m)	L_w/W	L_w/R_c
W S	1.93	0.000246	25.1	84.7	184	41	3.37	587	1018	326	23.4	6.93
OC R1	2.64	0.00013	122.8	434.2	905	198	3.54	2108	3956	1041	17.2	4.85
OC R1.1	2.36	0.00020	67.8	133.3	234	81	1.97	656	1192	235	9.7	4.92
OC R1.2	3.19	9.68E-05	78.6	274.6	507	123	3.49	1118	1987	643	14.2	4.07
OC R1.3[a]	1.26	0.00033	89.4		358	164						
OC L1	1.74	0.00017	44.4	117.8	207	47	2.65	548	958	181	12.4	4.66

[a] This channel is straight (S = 1.26), and no meander parameter was measured. WS—modern Wabe Shabelle river, OC R1, OC R1.1, OC R1.2, OC R1.3—avulsion old channels on the right of the present river (see Fig. 17.21); OC L1—avulsion old channels on the left of the present river (see Fig. 17.21), S—channel sinuosity, J—channel gradient; W—width; R_c—meander curvature radius, L_w—meander wavelength

Long-term daily discharge data are available only for the flow gages of Luuq and Beled Weyne on the Juba and Shabelle, respectively. The time series of the Shabelle is rather continuous, whereas that of the Juba is interrupted by two wide gaps (Fig. 13.26). In spite of a general decreasing trend of precipitation in the headwaters, the Shabelle daily discharges show an increasing trend, especially after 2002, whereas in the Juba, there is no evidence of significant change throughout the last six decades.

In their middle to lower reaches, the river pattern and the flood plain of the Shabelle and, to a much lesser extent, of the Juba are characterized by several avulsion episodes and channels (Figs. 13.19 and 13.20). According to Aslan et al. (2005), avulsion is favored when: (a) The river is rapidly aggrading, thus resulting in a channel perched over the flood plain (Fig. 13.16) and creating a cross-valley gradient. The aggradation process is typically driven by high sediment transport and deposition rates which, in rivers with cohesive

Fig. 13.21 Flood frequency curves for the Shabelle river (WS) at Beled Weyne and Mahaday Weyne

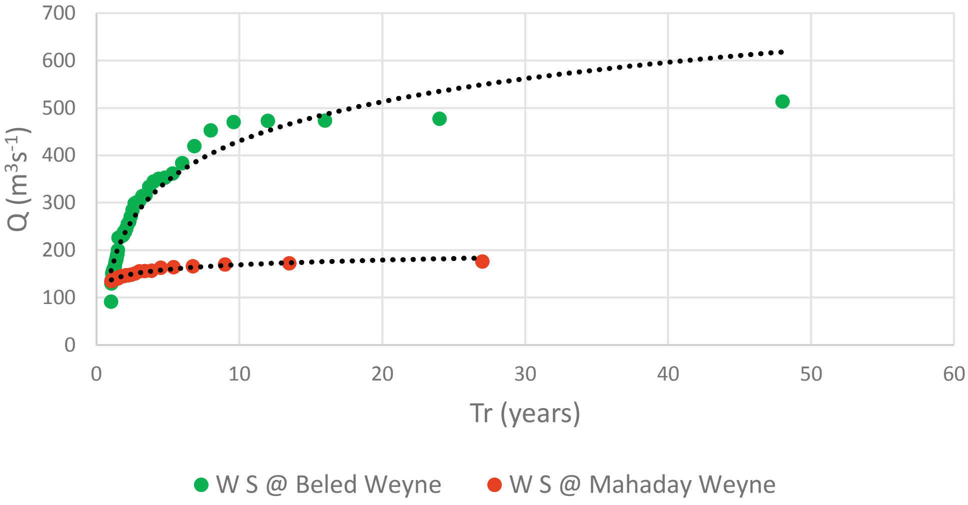


Table 13.3 Bankfull discharge calculated by different methods for the modern Shabelle between Mahaday Weyne and Jowhaar and the avulsion, old channel in the same area

	Actual	Dury (1976)	Williams (1978)
	Q_b (m^3s^{-1})	Q_b (m^3s^{-1})	Q_b (m^3s^{-1})
W S	143–150	184	167.8
O C R1		1867	
OC R1.1		226	
OC R1.2		592	
OC R1.3[a]		654	
OC L1		163	

[a] This channel is straight (S = 1.26), so no meander wavelength was measured; discharge was measured with Eq. (13.3) (see text). *WS*—modern Wabe Shabelle river; OC R1, OC R1.1, OC R1.2—avulsion old channels on the right of the present river (see Fig. 17.21), OC L1—avulsion old channels on the left of the present river (see Fig. 17.21). OC r1.3 was not included because it is a straight channel and no meander parameter was measured

Fig. 13.22 Neck and chute meander cutoffs in the old avulsion channel OC R1 (Google Earth coordinates: 20°21′32″ N 45°06′40″ E)

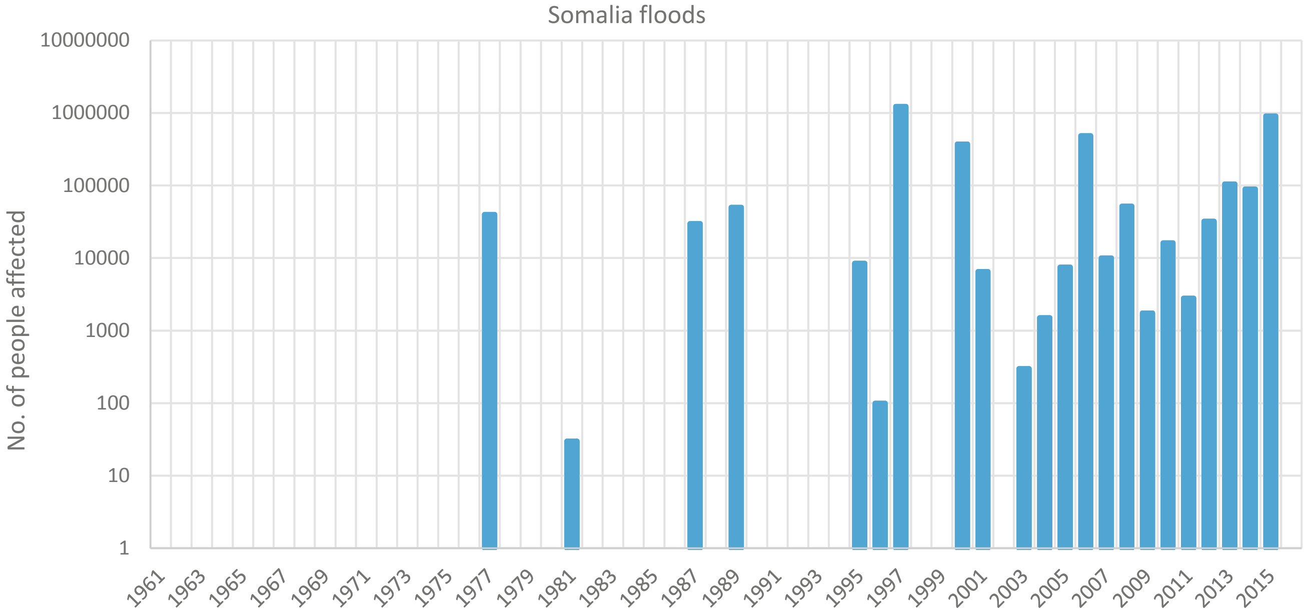


Fig. 13.23 Number of people affected by the increased frequency of floods in Somalia

banks, may result in a marked reduction of channel conveyance capacity; (b) substantial discharge variations; (c) subsidence; (d) in-channel human impact. Both the Juba and Shabelle transport high concentrations of suspended sediment; however, the only suspended sediment concentration data available were obtained by Omuto et al. (2009) by a two-year (2007–2008) field measuring campaign. Though their data are temporally limited, they cover a wide range of rates (from 2 to almost 3000 kg s^{-1}) and these authors were able to construct a suspended sediment rating curve, which is valid for both rivers:

$$Q_{ss} = 0.087Q^{1.9645} \qquad (13.4)$$

in which Q_{ss} is the suspended sediment transport rate in kg s^{-1} and Q is discharge in m^3 s^{-1}.

The rating curve of Omuto et al. (2009) shows that an appreciable amount of suspended sediment is transported even with very low discharges, as low as 4 m^3 s^{-1}. Such a result was anticipated by Crema (1923) in one of his very first reports about the Southern Shabelle, described as transporting fine sediment in suspension all year round.

A remarkable reduction in flow discharge is observed in the Shabelle, whose annual runoff decreases from 2580 × 10^6 m^3 $year^{-1}$ at Beled Weyne to 1507 × 10^6 m^3 $year^{-1}$ at Afgoye, corresponding to a water loss of about 42% throughout a river length of about 422 km. Water loss affects also the Juba, but at a much lesser extent. In fact, runoff is 6097 × 10^6 m^3 $year^{-1}$ at Luuq; it increases to 8787 × 10^6 m^3 $year^{-1}$ at Bardere to decrease again at Jamame, where it is 5145 × 10^6 m^3 $year^{-1}$ and records a water loss of 16% in the 1204 km long reach between Luuq and Jamame.

For Beled Weyne, a rather long series of flow data is available to construct an average flow duration curve, whereas for the same river at Afgoye, unfortunately, the data are not enough. The flow duration data for this flow gage were therefore obtained from the Beled Weyne data by simply reducing them by 42%. Two suspended sediment transport duration curves were then obtained by applying Eq. (13.4) to both station flow duration data (Fig. 13.27). The result is that at Beled Weyne the annual suspended sediment yield is 28 × 10^6 t $year^{-1}$ (equivalent to 147 t km^{-2} $year^{-1}$) and at Afgoye is 9.7 × 10^6 t $year^{-1}$ (equivalent to 50 t km^{-2} $year^{-1}$).

For lowland, low-gradient rivers bedload is commonly in the range of 1–10% of suspended load with the most common range between 2 and 5% (e.g., Schumm 1977; Babinski 2005; Cantalice et al. 2013; Joshi and Xu 2017). Using these latter, precautionary values, the difference between the bedload yield in Beled Weyne and Afgoye is 651,651 and 23,266 m^3 $year^{-1}$ considering a bedload proportion of 5 and 2%, respectively. Assuming that these volumes are trapped as bedload sediment (Joshi and Xu 2017), an average aggradation rate of about 0.05 and 0.002 m $year^{-1}$, results, respectively, for the reach between Beled Weyne and Afgoye. Repeating the same procedure for the Juba between Bardere and Jamame, similar values of aggradation rates of 0.09 and 0.003 m $year^{-1-}$ are obtained and a sediment yield of 543 and 158 t km^{-2} $year^{-1}$ at Bardere and Jamame, respectively. At Bardere, the bedload yield calculated in this study as 5% of suspended sediment is about 13 × 10^6 t $year^{-1}$. This value is not too far from that of 20 × 10^6 t $year^{-1}$ reported by Pozzi (1982), which corresponds to a

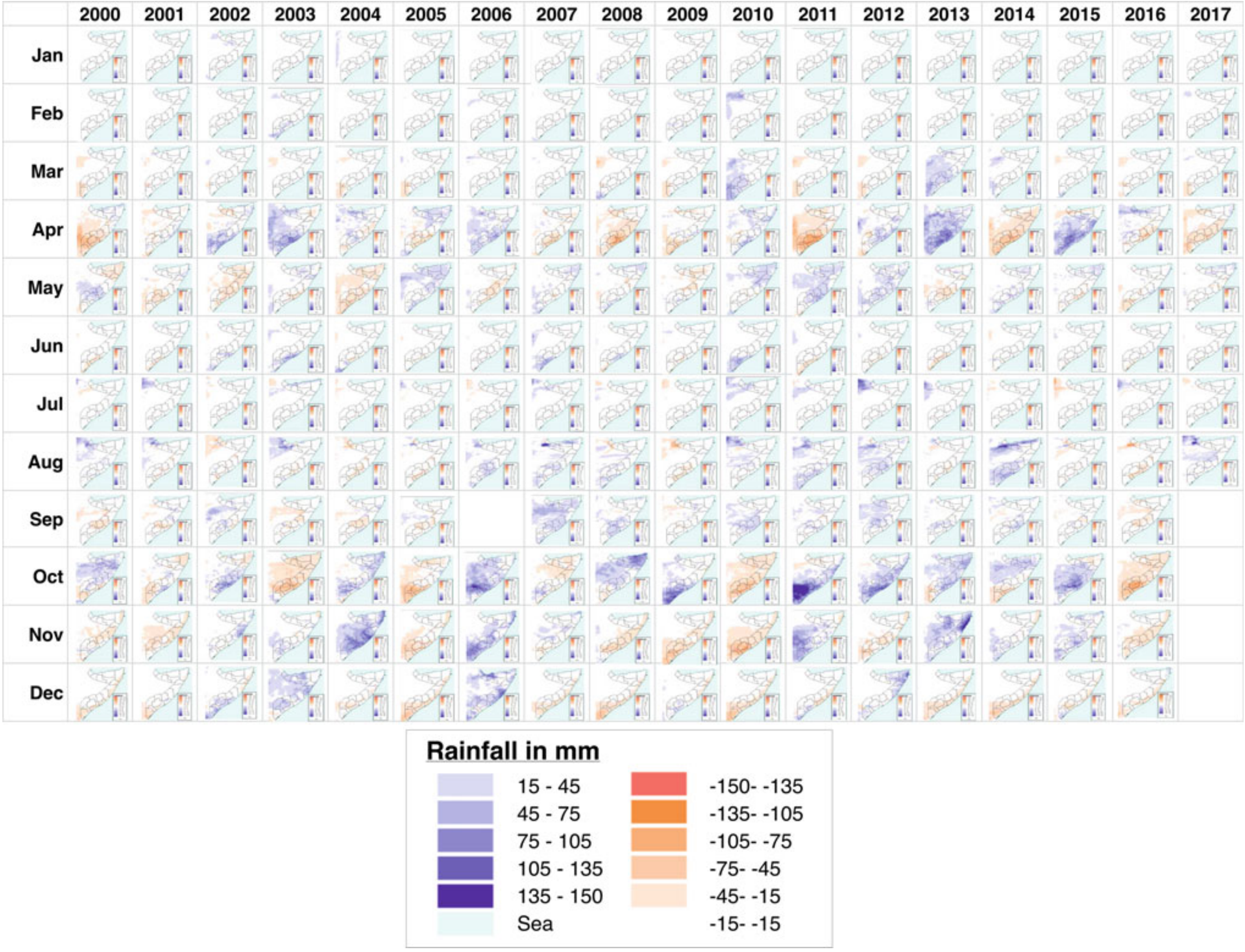


Fig. 13.24 Monthly rainfall distribution across the last two decades in Somalia (FSNAU-FAO 2018)

proportion of 8%. This author affirms that his results were presented in an unpublished technical note (by Technital) and were obtained on the base of FAO data, but no citation is reported nor any information is given about the method used to calculate the bedload yield. Pozzi reports also that at Soblale (150 km SW of Afgoye), the Shabelle has no sediment transport, its water is permanently clear, that there is no evidence of in-channel sedimentation and the channel width measured in 1960 was exactly the same measured about 70 years before by captain Vittorio Bottego (1895).

13.4.1 Human Impact on Flooding

According to Mbara et al (2007), before the onset of the civil war in 1991, irrigation schemes were rather efficient in Somalia. They relied on the Juba and Wabe Shabelle river water and largely contributed to the development of agriculture. Irrigation water was diverted from the rivers by weirs (Fig. 13.28) and conveyed to primary supply canals (see Mbara et al. 2007 and Basnyat and Gadain 2009 for a detailed description of all the irrigation schemes of southern Somalia). Irrigation schemes are more numerous in the Shabelle with 135,000 ha of potentially served land, against the 25,000 of the Juba (Basnyat and Gadain 2009). The long-lasting state of civil war resulted in the abandonment of many of these irrigation schemes that forced the farmers to breach the river banks, thus weakening them and causing uncontrolled flooding and water loss (Fig. 13.29). Due to lack of maintenance, deposition occurred at the gates and in the canals reducing substantially their water conveyance efficiency.

From satellite images (Google Earth 2018), 88 points with bank breach/overtop were identified in the Wabe Shabelle between Beled Weyne and Afgoye, though the most of them is concentrated in the reach between Bulo Barde and Mahaday Weyne. Out of these 88 bank breach/overtop points, 15 are clearly unofficial man made, whereas the other

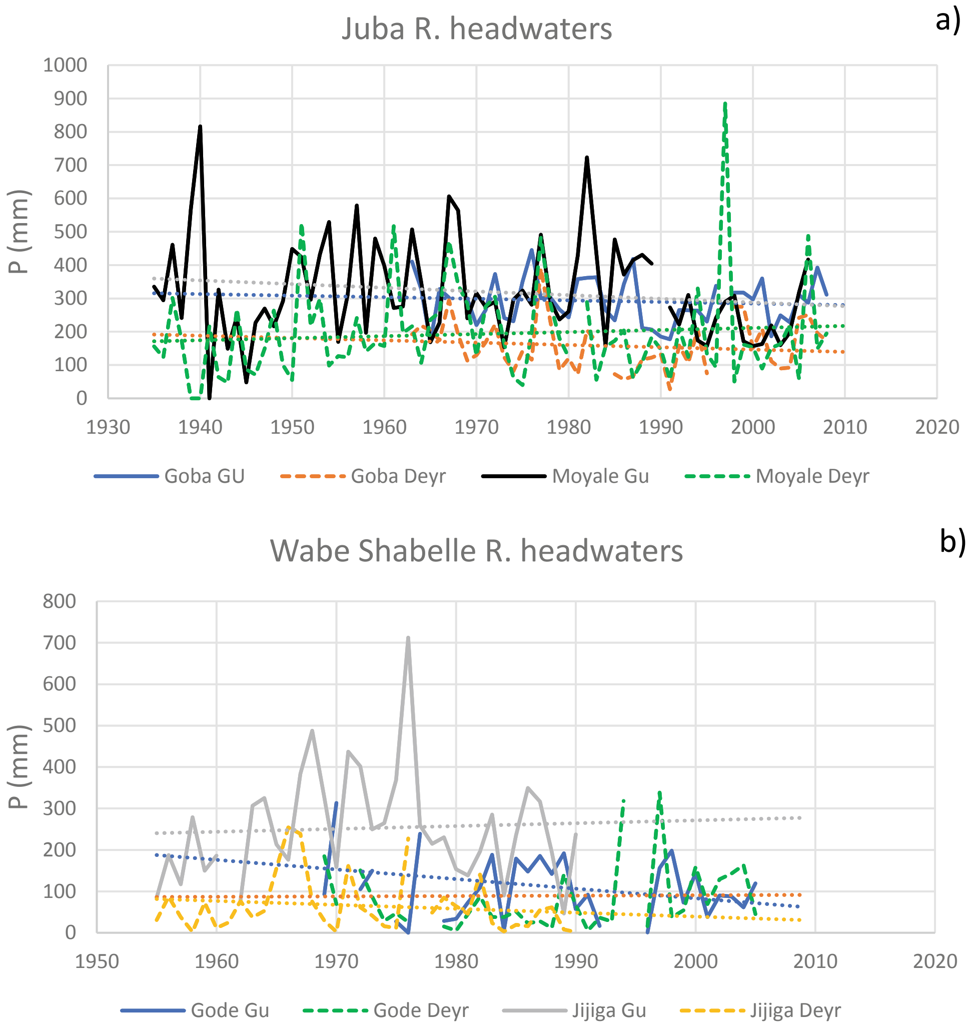


Fig. 13.25 Precipitation time series in the Juba **a** and Shabelle **b** headwaters

73 consist of natural bank breaches/overtop with which evidence of recent or repeated sedimentation is associated. Some of the bank breaches are used by villagers simply to access the river, but can work also as conveying waterway to irrigate the cropland near the village. This situation is particularly common on the Shabelle, whereas on the Juba breaching by farmers is rare.

Basnyat and Gadain (2009) already warned that "unregulated practices of river bank breaching have increased the vulnerability of the riverine communities to progressively smaller peak flows". In some of its lower reaches, the Shabelle is perched (Fig. 13.16) thus exacerbating the risk and the consequences of flooding. The vertical accretion of a lowland, low-gradient flood plain river is commonly associated with high rates of fine sediment transport. The finer component (silt and clay and, subordinately, sand) is deposited close to the bank by overbank flows, whereas the coarser fraction (typically sand and small proportions of fine gravel and grains) is deposited on the streambed because the transport capacity decreases as the river flow spills over the banks, thus resulting in the streambed aggradation (Brierley and Fryirs 2005). The greater the height of the streambed and the natural levees above the flood plain and the higher is the probability of crevasse splays and flood channel formation. Sediment has often been neglected in flood risk analyses, but changes in sediment dynamics and supply may result in channel instability and may have important negative repercussions affecting people and properties.

Both the Juba and the Shabelle transport a lot of sediment. Omuto et al. (2009) have measured concentrations ranging from 1 to 40 gl^{-1} in both rivers. In both the study rivers, the remarkable downstream water loss, the large volumes of water diversion for irrigation (about 12,000 $\mathrm{m}^3\ \mathrm{ha}^{-1}\ \mathrm{year}^{-1}$, which mostly affects the downstream flow decrease of the Shabelle given its lower runoff) (Yibeltal 2015) and the additional water loss by unregulated withdrawal (especially in the Shabelle) are all conditions leading to a marked increase of the already observed high potential for streambed aggradation as showed in the previous section. Hailemariam et al. (2016) studied the land

Fig. 13.26 Daily discharge time series for the Juba at Luuq **a** and the Shabelle at Beled Weyne **b** in the last six decades

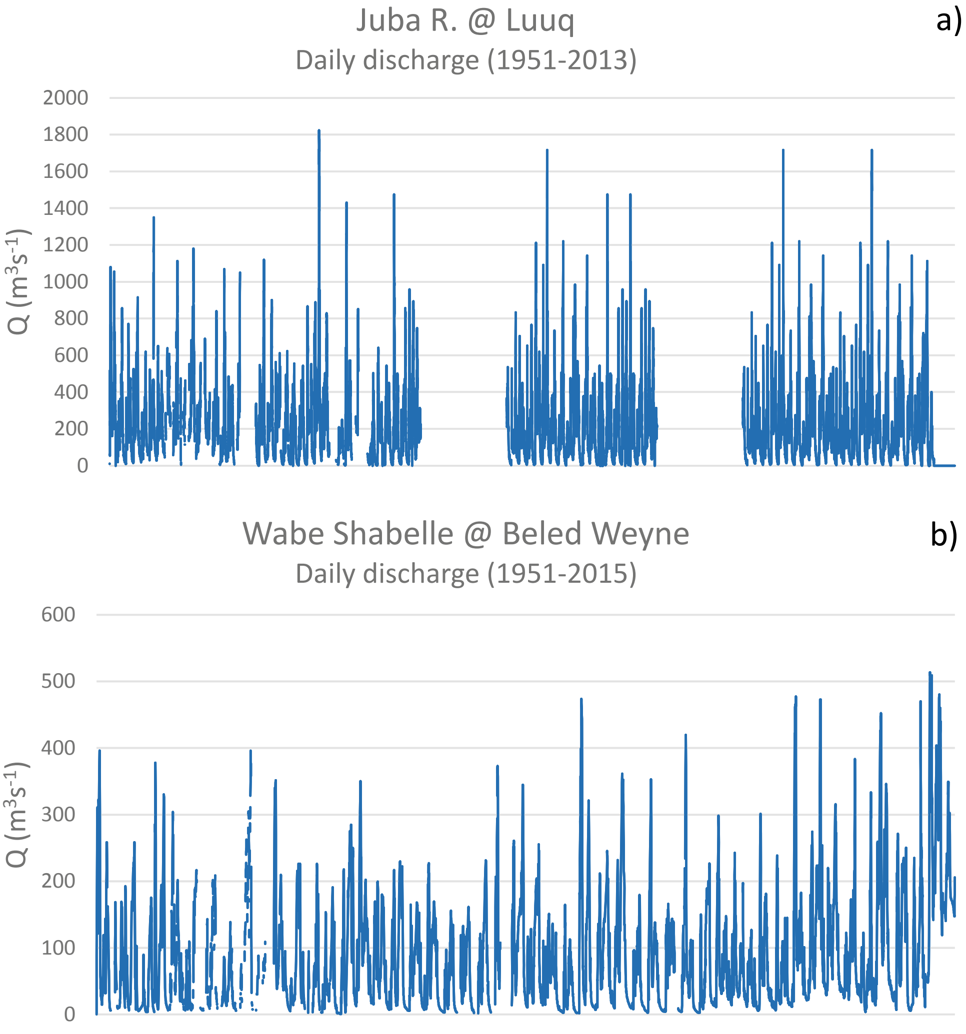
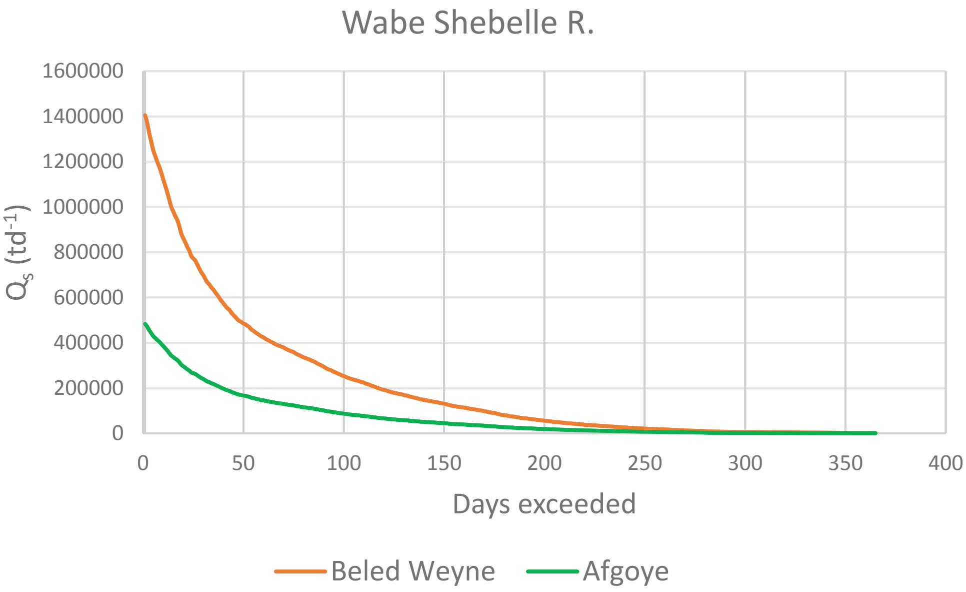


Fig. 13.27 Suspended load duration curve of the Shabelle at Beled Weyne and Afgoye



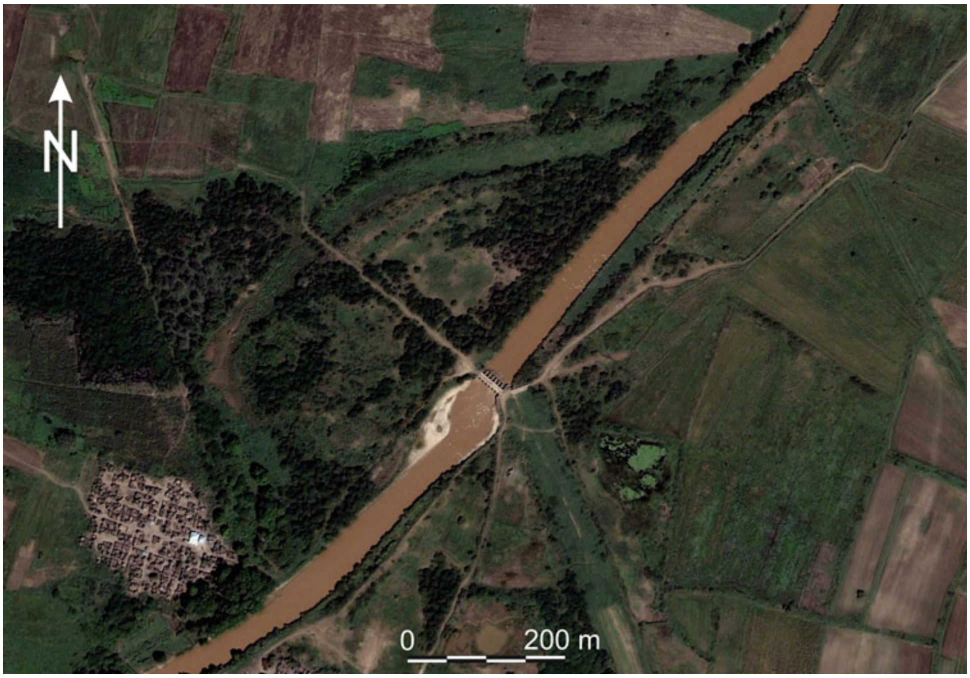


Fig. 13.28 Weir and irrigation scheme on the Shabelle (Google Earth coordinates: 2°53′14″ N 45° 32′37″ E)

Fig. 13.29 Manmade bank breaching on the Shabelle

Table 13.4 Land use/cover distribution (%) and change in the Bale mountains (Hailemariam et al. 2016)

Land use/cover	1985	1995	2005	2015	2015–1985
Afroalpine	0.9	0.9	0.9	0.8	−0.1
Grassland	21.5	21.0	20.7	19.2	−2.3
Woodland	43.7	43.5	41.6	40.3	−3.4
Shrubland	18.2	17.6	16.0	15.8	−2.4
Farmland	15.4	16.8	20.5	23.2	7.8
Urbanized	0.02	0.1	0.1	0.7	0.68
Total	100	100	100	100	

use/land cover change in the Bale mountains, which are the source of both the study rivers, through the 1985–2015 interval. Their results are summarized in Table 13.4 and clearly indicate that farmland is the only land use constantly increasing during the study interval. Woodland, grassland and shrubland altogether decreased with the same proportion of farmland increase. This is an additional human activity factor leading to an increase in sediment supply, and presumably, it is contributing to the streambed aggradation of the study rivers and to the reduction of their flow conveying capacity.

13.5 Discussion

13.5.1 Channel Changes

A primeval fluvial system of the Shabelle flowing along the same regional slope as today was probably active since long time ago as witnessed by some meandering flood basalt flows (Oligocene? to Pliocene—Abbate et al. 1994) that filled the valley bottom and that today offer typical examples of relief inversion (Sembroni and Molin 2018) (Fig. 13.30).

High sediment transport rates and/or a marked change in discharge and the creation of a transverse valley gradient are among the main causes of river avulsion (Aslan et al. 2005). All these factors are present in the modern Shabelle river. The many avulsion channels that are present in the flood plain downstream of Jalalaqsi are very evident in satellite images. Unfortunately, there is no information about their age, but the very good preservation of their geomorphological characteristics and of the channel dynamics processes traces and the fact that old avulsion channels are present also in the Balli plain as far south as Baraawe suggests a much.

Younger age (probably Holocene) than the meandering flood basalts of Fig. 13.30. The data of Table 13.2 and the bankfull discharges obtained from Eq. (13.1), which are based on the average meander wavelength (i.e., a parameter that can be measured with greater accuracy for both old and modern channels), demonstrate that the old avulsion channels were larger and were formed by a dominant discharge larger than that of the modern Shabelle. Moreover, the variety of well-preserved evidences of channel processes suggests that higher than today forming discharge conditions were maintained for a relatively long time.

Pollen analysis data (Jolly et al. 1998), the existence of lakes now disappeared in East Sahara, and lakes with higher water levels than experienced at present (Hoelzmann et al. 1998) in Eastern Sahel and in Eastern Ethiopia (Lake Abhe) (Mayewski et al. 2004) indicate that between approximately 9.000 and 6.000 years ago, rainfall was much higher than present in Eastern Sahara (100–200 mm year^{-1}—Haynes and Haas 1980; Kropelin 1987) and in Eastern sub-Saharan Africa, probably in response to a strong enhancement of the African monsoon (Street-Perrott et al. 1990). Two–three thousand years of higher precipitation and discharges (as much as ten times larger) are enough to provide the old avulsion channels with a larger size than the modern Shabelle and to propel their channel dynamics.

The occurrence of a transverse valley gradient is another important factor favoring channel avulsion (Aslan et al. 2005). By means of the “Elevation Profile” function of Google Earth Pro®, a west–east cross-section was traced a few km north of Mahaday Weyne (Fig. 13.31). Notwithstanding some inaccuracy of the profile due to excess exaggeration of the elevation scale, a general convex upward shape of the surface can be easily identified. The modern Shabelle is located in the most elevated point, and very old avulsion channels are located at a slightly lower elevation, but also the latter are on top of a secondary convex upward surface. This morphology and the lateral spreading of the old avulsion channels recall a delta or a fan delta. The stratigraphic data of the exploration well drilled near Jowhaar, presented by Crema (1923), are not very detailed since only the grain size and color of the different layers are reported. The boring is 107 m deep, and the stratigraphy shows three upward coarsening depositional cycles starting with reddish clays and followed by sand and fine gravel. In the uppermost cycle, the dark red clays include intercalations of gypsum, sand and fine gravel, and occasionally, the clay is mixed up with pebbles. The author affirms that the bore was entirely within alluvial deposits and no bedrock was encountered.

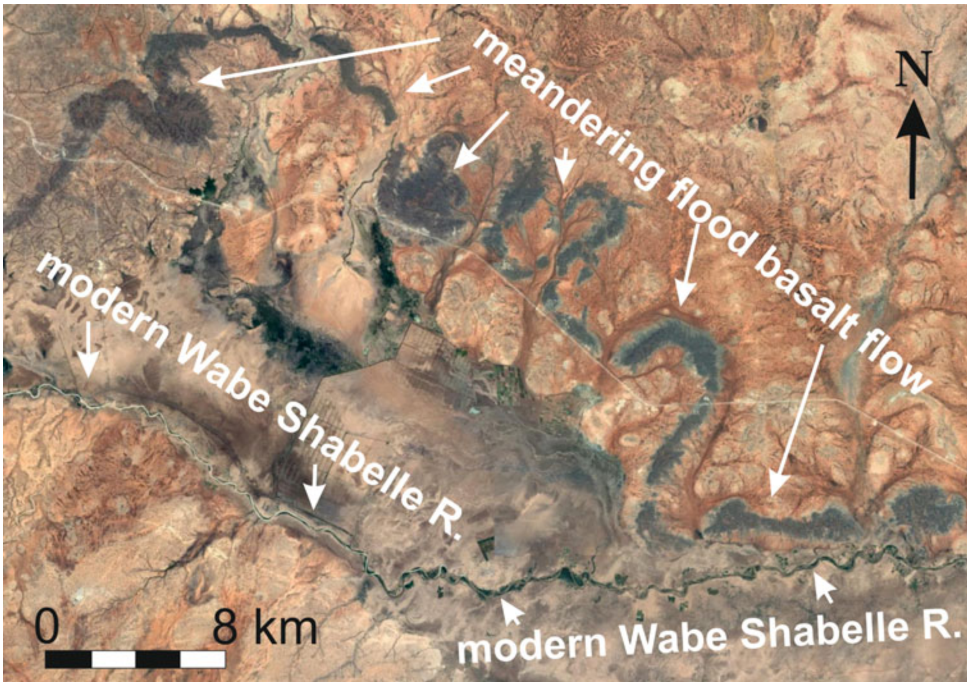


Fig. 13.30 Ancient channels of the Wabe Shabelle filled with basalts. Erosion resulted in a relief inversion with the meandering basalts higher than the surrounding terrains

This information, though poorly detailed, is very important because lets us to suppose the occurrence, downstream of Mahady Weyne, of Quaternary(?) shallowing upward cycles, commonly associated with a coarse grained delta or a fan delta (sensu Nichols 2009). The bore upper part is about 4 m below the present ground surface, whereas the lowermost level (reddish-greenish clays) reached by the boring is 4 m below the current sea level.

Old deltas are still evident in the Juba around Dujuma (Fig. 13.32) and in the Laag Dheera river about 85 km NW of its confluence with the Juba. Abbate et al. (1994) assign a Neogene to Pleistocene age to these deltaic deposits, whereas in the Shabelle, more modern (Pleistocene to present) sediments probably cover the older deltaic deposits. Figure 13.32, and the studies of Mège et al. (2015) and of Sembroni and Molin (2018) indicate that a fluvial system almost coinciding with the modern Shabelle existed (Figs. 13.30 and 13.33) when the old delta of the Juba (Fig. 13.32) was formed.

The occurrence of a narrow graben almost parallel to the modern coast and the continental slope (Abbate et al. 1994) explains why the older delta of the Shabelle is not visible and may also account for the deviation to the SW of the river. Dainelli (1943) assumes that the Shabelle was prevented from entering the Indian Ocean north of Mogadishu due to the presence of the coastal dunes, which forced the river to the SW. Today, the coastal dunes elevation is around 200 m asl, nevertheless, during wetter intervals of the past the combination of hydrometeoric erosion processes and higher flood discharges should have been able to breach the coastal dunes and to outflow into the Indian Ocean forming a delta. Bathymetric maps of the Somalia coast do not show any evidence of a submerged delta. Though south of Merca the 70 km long coastal dunes belt becomes very narrow (less than 4 km) and it is about 70 m higher than the inland flood plain, the Shabelle was never able to cut through it to reach the ocean. This suggests that the recent structural arrangement of the Somalia coastal belt with the formation of the longitudinal depression slightly inclined to the SW may have forced the Shabelle to follow the local slope preventing it to proceed straight into the Indian Ocean (Fig. 13.33). That is confirmed also by the ephemeral streams originating in the Bur region which are perpendicular to the depression axis in their upstream reaches and turn slightly to the south as they enter the depression.

13.5.2 Increased Risk of Flooding

Southern Somalia has seen an increase of flood frequency throughout the last two decades. As reported in the previous sections, it seems there is a decreasing rather than an increasing trend for precipitation in the Juba and Shabelle headwaters. In spite of that, the Shabelle shows an increasing trend in annual runoff for both the rainy seasons, whereas in the Juba, the main rainy season (*Gu*) shows an increasing trend and the small rainy season (*Deyr*) shows a moderate decreasing trend (Fig. 13.34). In the Shabelle annual, seasonal and monthly maximum runoff data indicate a marked increase in the last three decades, with the *Gu* season

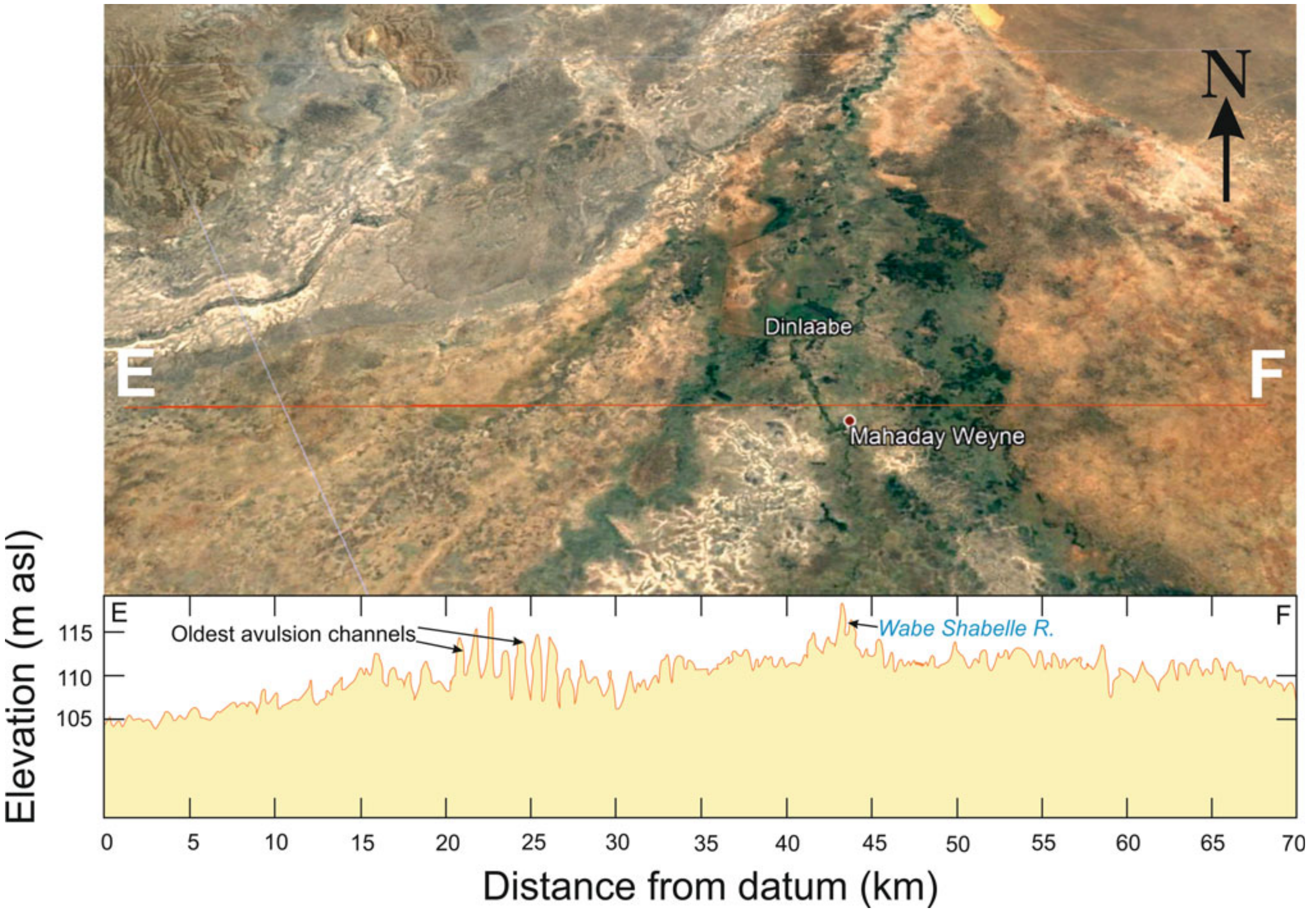
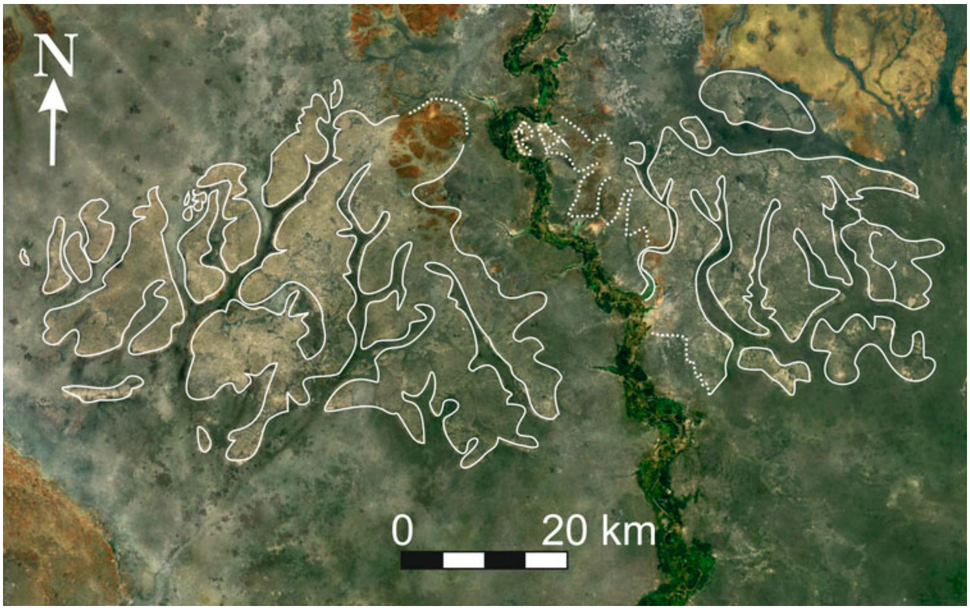


Fig. 13.31 Terrain profile traced across the Wabe Shabelle flood plain a few km north of Mahaday Weyne. Notice, the convex upward shape of the ground surface and the modern Shabelle on its highest point

Fig. 13.32 Neogene to Pleistocene (Abbate et al. 1994) delta of the Juba river



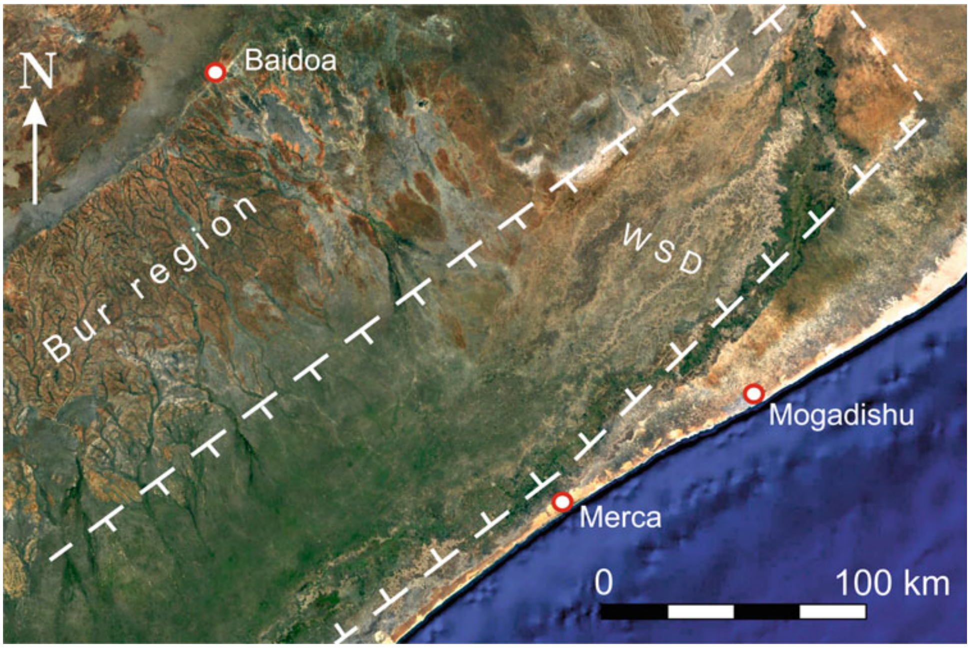


Fig. 13.33 Simplified structural setting of the lower Wabe Shabelle. WSD = Wabe Shabelle Delta

characterized by an increase of 47%. In the Juba, the increase of runoff in the *Gu* season is paired by the decrease in the *Deyr*. These data show a contrasting situation between the two rivers and clearly explain the increased frequency of flooding of the Shabelle, but not that of the Juba. Also, the annual maximum discharge shows a marked increase for the Shabelle at Beled Weyne and a moderate increase for the Juba at Luuq (Fig. 13.35).

Figure 13.24 depicts how torrential rains became more common throughout the last two decades in the lower reaches of both rivers. Under such circumstances, flooding may occur also without a substantial contribution from the monsoon rains on the Ethiopian highlands. Moreover, the perched position of both rivers on the flood plain extended the flooding duration before the inundation waters take their way back into the rivers.

The change in land use/land cover, characterized by a substantial increase in farmland, in the headwaters of both rivers likely resulted in an increase of the sediment supply which, given the downstream decrease in discharge by water loss, resulted in higher sedimentation rates and streambed aggradation. Omuto et al. (2009) report a mean suspended sediment concentration of 11.8 and 0.93 gl^{-1} measured for the Juba at Bardere and Buale, respectively, during a 2007–2008 field campaign. For a location no longer identifiable (Kaitoi, according to the Italian spelling) in between these two localities, Pozzi (1982) reported a maximum suspended sediment concentration of 11.3 gl^{-1} on the base of some FAO data (source not cited in the reference list). These data, though limited in number and in time coverage, suggest that the suspended sediment concentration of the Juba has increased, at least in the last four decades. The same author reports also a few bankfull width data measured in 1960 at Beled Weyne (65 m), Mahaday Weyne (38 m) and Afgooye (47 m) on the Shabelle. Unfortunately, no information is provided about the exact positions of the cross-sections. Nevertheless, repeating some bankfull width measurement from Google Earth on a long reach of a few kilometers upstream and downstream these locations, the average bankfull width of today is substantially smaller: 43 m at Beled Weyne, 28 m at Mahaday Weyne and 22 m at Afgooye. The bankfull widths measured on today's river have a variation coefficient ranging between 12 and 23%, and none of the values is larger than those of 1960. These results confirm that the Shabelle decreased in width in its lower reaches, i.e., those more often affected by devastating floods. This conclusion seems to be confirmed also by the comparison of a postcard pictures of the Shabelle at Jowhaar and Afgoye taken in the early 1920s with pictures of today (Fig. 13.36).

The demand for more water for irrigation, that can be fulfilled only by the rehabilitation of abandoned irrigation schemes and the construction of new ones (Yibeltal 2015), may reduce drastically the practice of uncontrolled river bank breaching by farmers. However, only after an accurate study on the effects of water diversion on sedimentation and streambed aggradation and an accurate plan for water management, the worsening of the situation in terms of the flood hazard can be kept under control and possibly reduced.

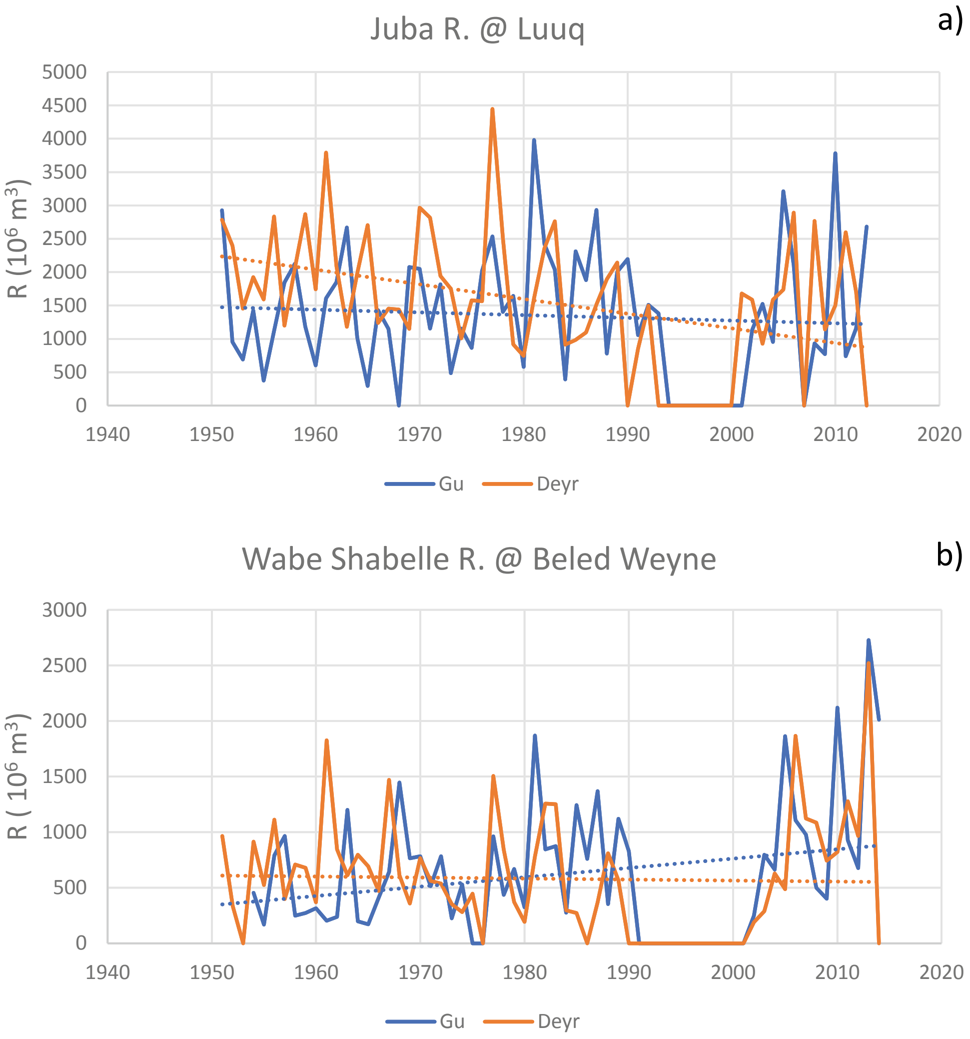


Fig. 13.34 Runoff time series for the Juba @ Luuq (**a**) and the Shabelle @ Beled Weyne (**b**)

13.6 Conclusions

The Juba and Wabe Shabelle rivers are the only permanent rivers of Somalia and the largest of the Horn of Africa. Both rivers are characterized by active channel dynamics that is witnessed also by old, avulsion channels still clearly visible in the lower alluvial plains. Shabelle geomorphic and hydrologic parameters, such as channel width, meander wavelength, sinuosity and bankfull discharge demonstrate that the old avulsion channels were larger and were formed by a dominant discharge larger than today. In the old channels of both Shabelle and Jubabankfull, discharge was maintained for a time long enough to develop the typical geomorphological units of high sinuosity meandering rivers. Between approximately 9.000 and 6.000 years ago, rainfall was more abundant (100–200 mm year^{-1}) than today in Eastern Sahara and in Eastern sub-Saharan Africa. Two–three thousand years of higher precipitation may have resulted in larger discharges (as much as ten times larger in the Wabe Shabelle) capable to form much larger rivers than present and to propel their channel dynamics. The old (Quaternary) rivers formed also large deltas or fan deltas that are still evident from satellite images though in the Shabelle, modern sediment is partly hiding the older deltaic deposits. The recent structural arrangement of Southern Somalia coastal belt with the formation of the longitudinal depression slightly inclined to the SW may have forced the Shabelle to follow the local slope and prevented it from proceeding straight into the Indian Ocean as supposed by a few authors (e.g., Mohr 1962; Sembroni and Molin 2018). This hypothesis is also supported by the lack of any evidence of submerged deltas in bathymetric maps of the Somalia coast.

Both the Juba and Wabe Shabelle are a very important resource for agriculture, but many of the irrigation infrastructures are degraded after several years of civil war. In the last decade, such difficult situation has been exacerbated by a marked increase in the frequency of devastating floods whose driving factors are to be found in climate worsening and several human impacts including an increase of farming

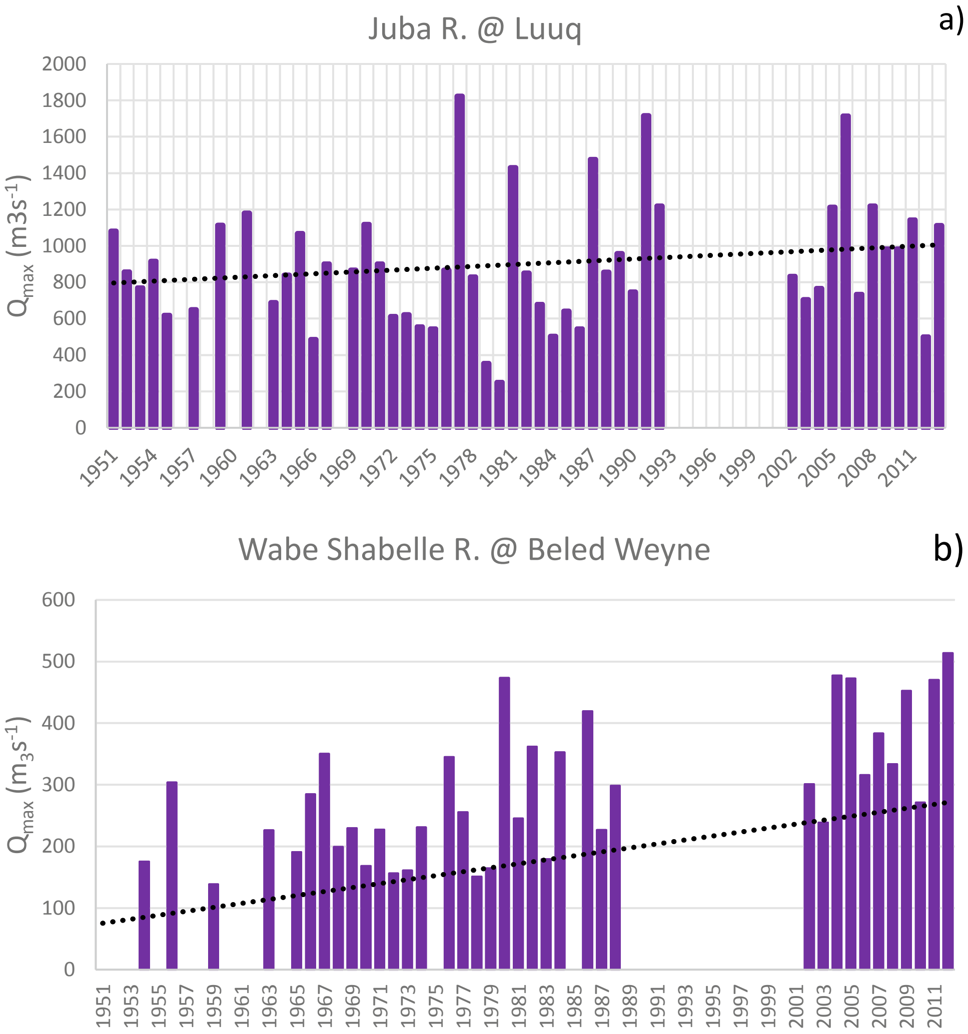


Fig. 13.35 Annual maximum discharge time series for the Juba @ Luuq (**a**) and the Shabelle @ Beled Weyne (**b**)

in the rivers headwaters, manmade bank breaches for irrigation that, associated with high rates of sediment transport and deposition, have negatively affected the conveyance capacity of the rivers. In the Shabelle between Beled Weyne and Afgoye, 88 bank breach/overtop points were found, of which 15 are clearly unofficial manmade, whereas the other 73 consist of natural bank breaches/overtop.

The change of the land use/cover in the headwaters of both rivers, characterized by a substantial increase in farmland, resulted in an increase of sediment supply, higher sedimentation rates and streambed aggradation. An average aggradation rate of about 0.05 and 0.002 m year^{-1} for the Shabelle at Beled Weyne and Afgoye, respectively, was calculated. Moreover, from the comparison of some channel width measurements of the Shabelle made by Pozzi (1982) in 1960 with modern river data, a channel narrowing of about 40% is evident.

All these factors, combined with an increased frequency of heavy rains during the small rainy season (especially in the lower Juba and Wabe Shabelle) resulted in several, devastating floods causing fatalities and affecting several thousands of people. In the Shabelle, in fact, annual, seasonal and monthly maximum runoff data indicate a marked increase in the last three decades with the *Gu* season characterized by an increase of 47%. In the Juba, the increase of runoff in the *Gu* season is paired by the decrease in the *Deyr*. These data show a contrasting situation between the two rivers and clearly explain the increased frequency of flooding of the Shabelle, but not that of the Juba. Yet, the annual maximum discharge time series shows a marked increase for the Shabelle at Beled Weyne and a moderate increase for the Juba at Luuq. Under such circumstances of channel narrowing, aggradation and bank breaches, flooding may occur also without a substantial contribution from the monsoon rains on the Ethiopian highlands.

Sediment has often been neglected in flood risk analyses, but changes in sediment dynamics and supply may result in channel instability (mainly aggradation, degradation and bank breaches) that, combined with substantial change in the rainfall regime, may have negative effects on people and properties.

Fig. 13.36 Channel of the Wabe Shabelle in 1920 and today at Jowhaar and Afgoye. Both the old reaches look wider than today

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