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ORIGINAL ARTICLE

Economic evaluation of the proposed alternatives of inter-basin water transfer from the Baro Akobo to Awash basin in Ethiopia

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Abstract Water resources in Ethiopia are relatively skewed towards basins with rivers flowing to the west and southwest. Baro Akobo, which is a part of the eastern Nile River basin, is a west-flowing river with water availability of about 3432 m^3 per person per year. Awash basin in the east is a water-deficit basin with just about 325 m^3 per person. This study identifies and analyses the three possible alternatives of water transfer from Baro Akobo to Awash basin in Ethiopia. The first proposed link is about 685 km long, out of which about 516 km flow is under gravity, while 167 km is proposed to be pumped. The total cost of this link is about 1.793 billion USD. The second proposed link involves 542 km-long water conveyance and its approximate cost will be 1.84 billion USD. The third proposed option suggests a water conveyance of 519 km with an approximate cost of 1.637 billion USD. All the three possible alternatives are critically evaluated and then the most feasible and economical option is recommended for the inter-basin water transfer from Baro Akobo to Awash basin in Ethiopia.

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Introduction

Water is the most essential natural resource to sustain human life on this planet. But, its spatial and temporal variability results in the mismatch of supply and demand. This gap between demand and supply can be minimised by adopting different water management practices. One of such practice is inter-basin water transfer. Davies et al. (1992) defined inter-basin water transfer as the diversion of water from one geographically distinct river catchment or basin to another or from one river reach to another. Inter-basin water transfer currently diverts about 540×10^9 m^3/annum of water, which is $\sim$14 % of all global water withdrawals (Gupta et al. 2010).

Falkenmark et al. (1989) used the annual per capita water availability in a basin as the indicator of water scarcity. They suggested that water scarcities are rare if the water available in a basin is above 1700 m^3 per capita per year, as at this level water shortage (if any) will be only within few localities. If water availability is more than 1000 but less than 1700 m^3 per capita per year, the country will face seasonal or regular water-stressed conditions. If the availability is between 500 and 1000 m^3, it will hamper the public health and well-being of human beings. But if it is less than 500 m^3 per capita per year, shortages are severe constraints to human life. Thus, these conditions are termed as severe, medium to severe, moderate and little or no water scarcity. In Ethiopia, there are 12 river basins. The total runoff from these basins is estimated to be about 122,000 MCM per year (Birhane 2002). The present population of the country is about 100 million (2015). Therefore, annual water availability in the country is about 1220 m^3 per capita, which indicates the water-stressed conditions. Further, it has been noticed that out of the 12 river basins in the country, 2 are water surplus (Abbay and Baro Akobo), 8 (Afar-Denakil, Awash, Genale Dawa, Mereb, Omo Gibe, Rift Valley, Tekeze and Wabi Shebele) are water deficit to different levels and the remaining 2 are dry (Aysha and Ogaden). There are always problems related to water in dry and deficit basins which impact the livelihood of the community and the developmental activities. The total average annual runoff and average annual demand in the Awash basin has been assessed by Adeba et al. (2015) as 4640 MCM and 4670 MCM, respectively, with large intra-annual variability. The per capita average annual water availability in the Awash basin is assessed around 325 m^3. It has been noticed that the population living in this basin suffer water shortage, especially during the dry season (December–April).

Baro Akobo, which is part of the eastern Nile basin, but located in the southwestern part of Ethiopia, is the least developed. Natural resources of the basin have not yet contributed significantly to the economic development of the country. Despite the low level of economic development in the basin, there is a tremendous potential of water and other natural resource development and management. The per capita annual water availability in this basin is found to be of the order of 3400 m^3/year.

Keeping the substantial difference in per capita water availability of the two basins, it is desired that some water can be transferred from Baro Akobo to Awash basin in Ethiopia.

In this study, an attempt has been made to explore the inter-basin water transfer between the two basins. Water availability and the water balance study were carried out using the SWAT model (Arnold and Fohrer 2005) for the Baro Akobo basin. Water balance study for the Awash basin has already been reported by Adeba et al. (2015). To satisfy the water requirements of the Awash basin, three possible water transfer links from Baro Akobo to Awash basin are identified and evaluated economically. On the basis of economic evaluation, the best possible water transfer link from Baro Akobo to Awash basin is advocated.

Suggested methodology

To achieve the above-mentioned objective, the following steps have been followed:

1. Water balance assessment in the Baro Akobo (donor) basin.
2. Assessment of water requirements in the Awash (receiving) basin.
3. Identification of the possible routes of water transfer from donor to receiving basin.
4. Evaluation of the proposed routes of water transfer.
5. Selection of the best possible route of water transfer.

Water balance assessment in a basin is vital to know if it is a water surplus or deficit basin. Water resources availability can be assessed using Soil and Water Assessment Tool (SWAT) model. To use the SWAT model, one has to understand the drainage characteristics and collect spatial, meteorological and hydrological data. Such data are needed to model the physical processes involved in the watershed (Neitsch et al. 2005). Spatial data include digital elevation model (DEM), land use/land cover data and soil data. DEM used for the study is of 90 m resolution and provides the map of the drainage basin that defines drainage area upstream of the gauging stations. Land use information provides a real extent of different land use and land covers such as agriculture fields, commercial and industrial areas, residential centres and the proportion of the basin covered by the forest. The soil physical properties such as soil textural classes, bulk density, hydraulic conductivity and available water content are analysed using soil, plant, air, and water (SPAW) model and incorporated into the SWAT model (Geleta 2011). SWAT also requires meteorological data such as minimum and maximum temperature, solar radiation, precipitation, relative humidity and wind speed on a daily time step. Water withdrawal from a basin is estimated by assessing the various water demands such as irrigation and domestic, industrial, environmental and livestock use. Once the water requirement is assessed, the water balance in a basin can be carried out using the mass balance process. In this study, water demands up to 2050 are considered for estimating the water balance. The methodology followed for the study of water balance is shown in Fig. 1. Once it is decided to transfer the water from a donor to a receiving basin, the topographic map of the two basins is used to identify the possible routes. The basic criterion of such an identification is that as far as terrain topography permits, the shortest route should be followed. Further, depending on the topography of the route, either flow under gravity or pumping is proposed for the water conveyance system. Also, resettlement of the enroute villages is considered as an important issue and is avoided to the extent possible.

Thereafter, the cost of various feasible routes is assessed in different time horizons. All the future costs are transferred as present worth. The various feasible routes are then compared on the basis of the present worth of these possible routes. The feasible route with minimum present worth is recommended as the best possible route.

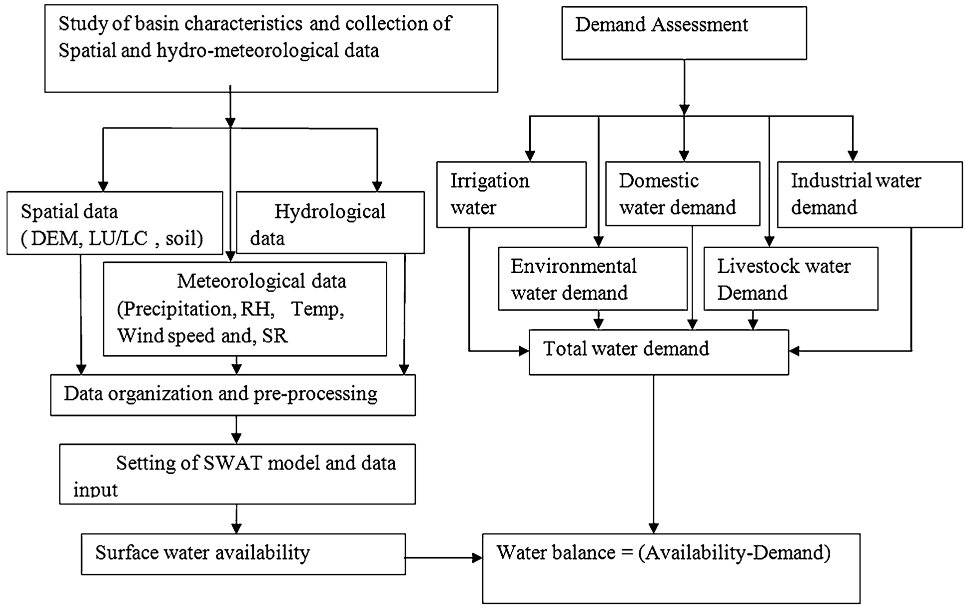

Fig. 1 Flowchart for water balance study in a basin

Water resources of Ethiopia

Ethiopia is divided into 12 major river basins as shown in Fig. 2. The Abay, Baro Akobo, Tekeze and Mereb basins drain the northern and central parts of Ethiopia westward and cover 32 % of the geographical area of the country. The Abay and Baro Akobo are the sub-basins of the Nile which is the longest river in the world with a length of about 6825 km. It has two major tributaries, the White Nile and the Blue Nile. The Blue Nile, known as Abbay in Ethiopia, is the eastern part of the Nile basin. The basin area of Blue Nile (Abay) is about 199,812 km^2. The Abbay basin is located in the north-western part of Ethiopia and drains the northwestern and central highlands to the main Nile River basin. The Abay (Blue Nile) starts at Lake Tana of Ethiopia and joins the White Nile in Khartoum to constitute the Nile River basin. The source of the White Nile is the Great Lake Region of Central Africa in Southern Rwanda and it flows through Tanzania, Lake Victoria, Uganda and South Sudan to join the Blue Nile in Khartoum, the capital of Sudan. The Baro Akobo basin drains the southwestern highlands and joins the White Nile in the republic of South Sudan to become the Nile River in Khartoum. Thereafter, it flows to Egypt before draining into the Mediterranean Sea. It may be observed that the Nile is an important river for Ethiopia, Sudan, and particularly for Egypt as it is the only source of water in Egypt (Abu-Zeid and El-Shibini 1997).

Awash drains the central and eastern highlands in Ethiopia and flows in the eastern direction of the country to end up in lake Abbe, located at the international boundary between Ethiopia and Djibouti.

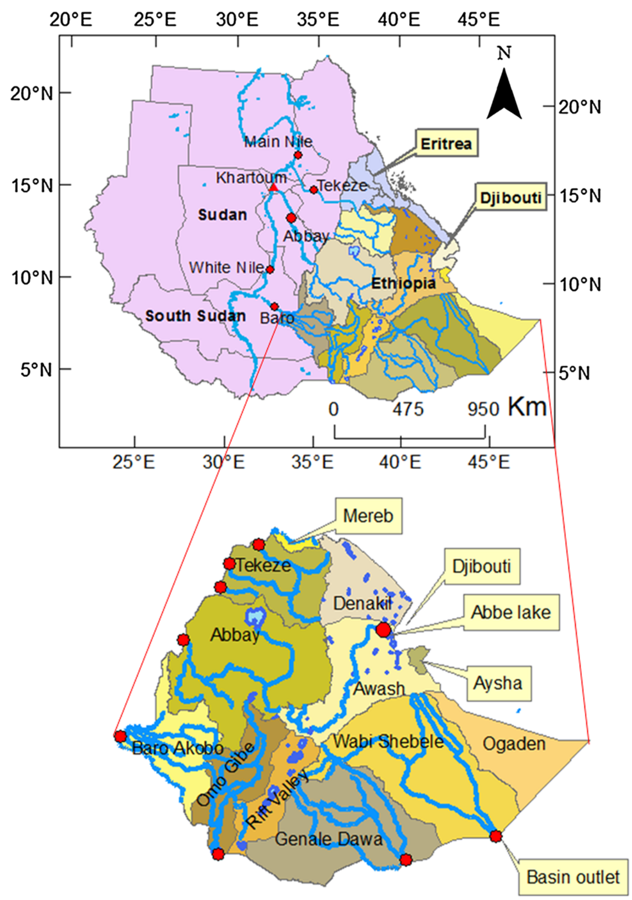

Fig. 2 The Nile River system and river basins of Ethiopia

There are two seasons in the Blue Nile basin, i.e., wet (*Kiremt*) and dry (*Bega*). The wet season in the Ethiopian part of the basin starts in June and ends in September.

The dry period is from October to May. The mean annual flow of the basin at the outlet of the Ethiopian territory is estimated to be 54,400 MCM.

Some of the important tributaries of the Nile River in the Ethiopian part are Jamma, Muger, Fincha, Dhidhessa, Angar, Gilgel Abay, Megech, Ribb, Gumera, Dabus, Beles and Beshlo. The flow in these tributaries varies significantly. However, Degefu (2003) reports that about 86 % of the annual flow in the Nile at the Aswan high dam comes from Blue Nile (Abay). Out of this, about 59 % comes from the Abay sub-basin, 14 % from Baro Akobo–Sobat sub-basin, and 13 % from Tekeze–Atbara–Gash sub-basins (Melesse et al. 2011). The Ethiopian part of the Nile River is relatively wet as compared to the downstream part. The annual rainfall in this part of Ethiopia ranges from 2,200 mm in the southwest to 800 mm in the northwest.

The Tekeze–Atbara River starts in Ethiopia, in the northern portion of the country and joins the Nile River at about 325 km downstream of Khartoum. It is about 880 km long and its area in the Ethiopian portion is about 82,350 km^2, while the total area of the basin is estimated at 202,650 km^2 (Hasan and Elshamy 2011). The specific yield of some of the Ethiopian river basins is very small relative to the area they drain. For example, the Wabi Shebele basin is the largest basin (area-wise), but its specific yield is relatively small.

Administratively, Ethiopia is governed through nine regional states and two city councils as shown in Fig. 3.

From the Ethiopian point of view, the Awash, Denakil, Omo Gibe and Rift valley basins constitute 28 % of the country's area. Shebele and Genale Dawa cover 33 %, while the northeast coast (Ogaden and Aysha basin) accounts for 6 % of the country's area. The annual runoff from these basins is about 122,000 MCM. The details of the river basins in Ethiopia are shown in Table 1. Abay, Baro Akobo and Omo Gibe basins contribute about 76 % of the annual mean runoff from an area of only 31 % of the country. About 70 % of the total runoff is generated during the wet season (June–September).

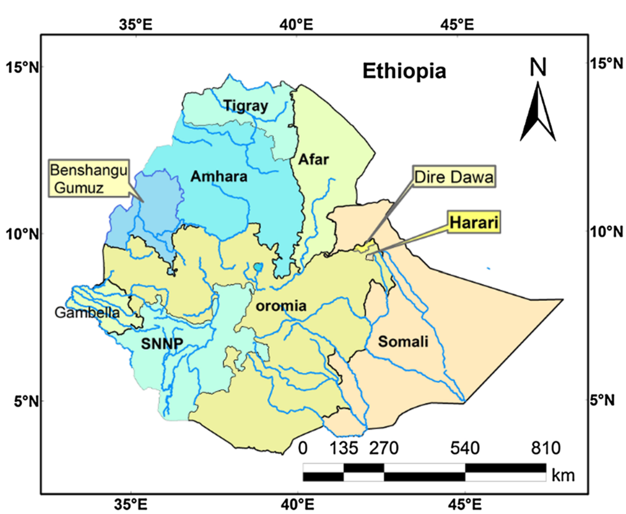

Fig. 3 Administrative boundaries of the various states and main rivers of Ethiopia

The most important issue in Ethiopia regarding the water resources is that the river basins, mainly their lower courses, have maximum potential for development, but are underdeveloped. The development of some of the basins have been neglected and much of the natural resources are untapped. Lowlands/floodplains that surround the Ethiopian highlands have a vast land resource suitable for irrigated agriculture. In some of the basins, irrigation facilities are not adequate. Further, the population density is high in the highland parts which have resulted in the depletion of the per capita water availability. All the basins draining the central and eastern part of the country have water deficit. Therefore, it is important to rationally redistribute the available water resources for the benefit of the nation.

Characteristics of the Baro Akobo basin

The Baro Akobo basin is located between latitudes 5°31′ and 10°54′N and longitude 33° and 36°17′E and covers an area of 75,906 km^2 (Fig. 2). The rivers originate in the eastern highland parts of the basin and flow westward to the Gambella plain. About 31 % of this area falls in Oromia; 9.8 % in Benshangul Gumuz; 24.6 % in Southern Nations Nationalities and People's state (SNNPRS); and 34.3 % in the Gambela state. The population in the basin is estimated at 6.77 million (2015). About 60 % of the basin population lives in Oromia; 11 % in Benshangul Gumuz; 21 % in SNNPRS; and about 8 % in Gambela State. The elevation in the basin ranges between 300 and 3000 m. Almost 50 % of the basin area falls below 1000 m, and 42 % in between 1000 and 2000 m. The remaining 8 % falls above 2000 m. The mean temperature of the lowland part of the basin (below 1000 m) is 29.3 °C, while it is 18.6 °C for highlands. The maximum temperature for the basin ranges from 17.7 to 40.5 °C, while the minimum temperature range is from 6.4 to 26.1 °C. The temperature is relatively high in the floodplains (lowlands). Precipitation in the basin varies with altitude. The annual rainfall ranges between 782.30 and 1082.8 mm in areas with an altitude range between 500 and 1000 m, and it ranges between 1740 and 2500 mm in areas with an altitude of 1000 m and above. The distribution of weather stations considered in this study is shown in Fig. 4. The soil map of the basin and its physical properties are shown in Fig. 5 and Table 2. The mean monthly rainfall and mean monthly minimum and maximum temperatures at various weather stations are shown in Fig. 6.

Table 1 River basin information of Ethiopia

No.	Basin Name	Area (km^2)	Population ($10^{6)}$)	Precipitation (mm)			Runoff (BCM)	Per capita water availability	Temperature (°C)		Evaporation (mm)	Potential irrigable land (10^3 Ha)	Per capita irrigable area (Ha)	Hydro-power potential (GW/year)	States/regions/main cities covered
				Max.	Min.	Aver.			Min.	Max.					
1	Wabi Shebelle	202,697	9.58	1563	223	425	3.16	330	6	27	1500	238.9	0.02	5440	O, SNNP, H, S
2	Abay	199,812	22.32	2220	800	1420	54.4	2552	11.4	25.5	1300	815.6	0.04	78,822	O, A, BG
3	GenaleDawa	171,042	6.45	1200	200	528	5.28	910	15	25	1450	1074.5	0.17	9270	O, SNNP, S
4	Awash	110,000	14.27	1600	160	557	4.64	325	20.8	29	1800	134.1	0.01	4470	O, SNNP, A, Af, S, DD, AA
5	Tekeze	82,350	8.73	1200	600	1300	8.2	939	10	22	1400	83.36	0.01	5980	T, A
6	Denakil	74,002	2.04	1500	100	120	0.86	422	5.7	57.3	2450	158.8	0.08	No potential	A, Af, T
7	Ogaden	77,121	3.44	800	200	400	Negligible	Negligible	25	39	2400	Negligible	Negligible	No potential	S
8	Omo Gibe	79,000	12.04	1900	400	1140	16.2	1378	17	29	1600	67.928	0.01	36,560	O, SNNP
9	Baro Akobo	76,000	6.77	3000	600	1419	23.24	3432	17	28	1800	1019.50	0.15	13,765	O, BG, SNNP, Gm
10	Rift Valley	52,739	10.08	1800	300	600	5.4	555	10	27	1607	139.3	0.01	800	O, SNNP
11	Mereb	6900	2.73	2000	680	1200	0.65	336	18	27	1500	67.569	0.04	No potential	T
12	Aysha	2223	1.65	500	120	100	Negligible	Negligible	26	40	2350	Negligible	Negligible	No potential	S
Total		1133,886	100.1				122.03					3799.56		155,107	

Source MoWIE (2015), Awulachew et al. (2007)

AA Addis Ababa, *Af* Afar, *A* Amhara, *DD* Dire Dawa, *Gm* Gambella, *H* Harari, *O* Oromia, *S* Somali *SNNPS* Southern Nations, Nationalities and Peoples state, *T* Tigray

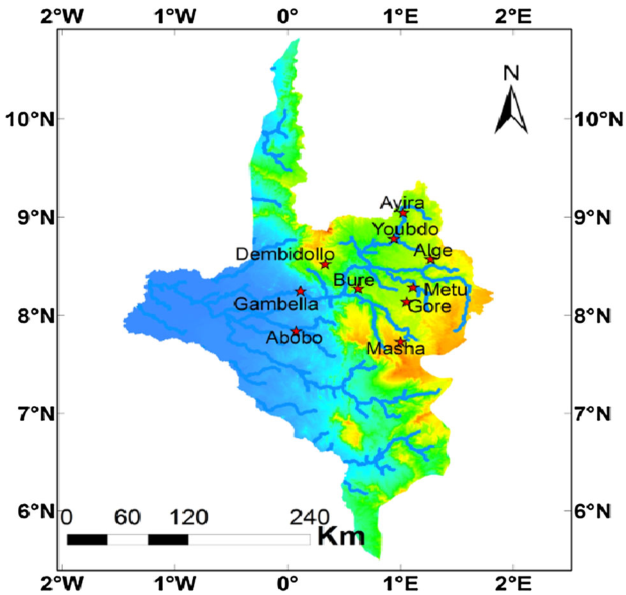

Fig. 4 Location of weather stations in the Baro Akobo basin

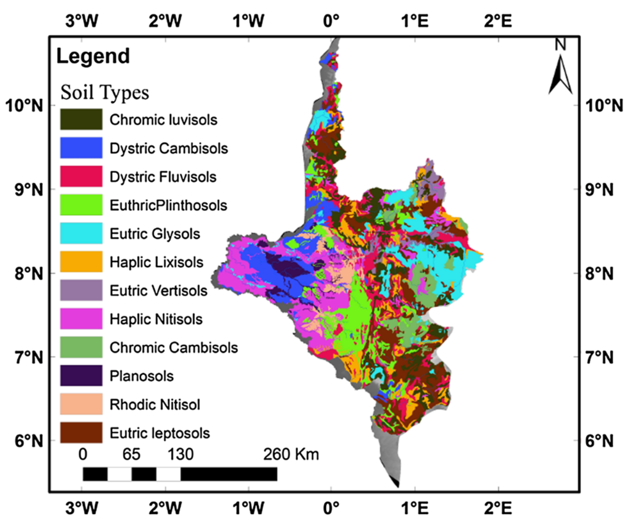

Fig. 5 Soil map of the Baro Akobo basin

The basin is characterised by 17.81 % agricultural land, 56.78 % forest cover of different types (deciduous mixed and evergreen), 22.20 % grassland, 3.06 % water body and 0.02 % low-density urban setting. The land use map of the basin is given in Fig. 7 and Table 3. Slope classes and the respective watershed areas are shown in Table 4.

Large-, medium- and small-scale potential irrigation sites in the basin are identified with an irrigable area of 1.02 million hectares (Awulachew et al. 2007).The major crops grown in the different agro-ecological zones of the basin include maize, coffee, tea, sorghum and cotton. Coffee is the most important cash crop in the area and the country as a whole.

Estimation of water yield of the Baro Akobo basin

The sum of the surface runoff, lateral flow and base flow is considered as the total yield of the basin. It can either be measured directly at the outlet of the basin or calculated through empirical relationships. Water balance models such as SWAT can be used to assess the availability of water resources and the influences of water management on the resources. The water yield of the basin when modelled by SWAT includes the total amount of runoff generated by the sub-basin and entering the main channel system. The water balance can be estimated by the simple continuity equation of inflow = outflow + change in storage. The contribution of each sub-basin during the simulation period is summed up to arrive at the total yield of the basin. The catchment area and the mean annual runoff of the major tributaries of the Baro Akobo River basin are shown in Table 5. A total of mean annual flow of 2,3240 MCM of water is estimated for the basin by the SWAT model. Baro Akobo basin is a transboundary river basin. The proposed transfer of volume is 116 MCM/year. This amount is very small compared to the runoff generation of about 23,240 MCM (Table 1). Moreover, the origin of the river lies in the country, and it can always be negotiated with the downstream riparian countries to use this fair share according to international water laws. Further, the storage is done during the wet season for transfer and use during the lean season. The existing flow will not get affected at the downstream.

Water demand assessment in the Baro Akobo basin

The major contributors towards water demand in this basin are: irrigation, environmental flows, domestic water requirements, industrial uses and the water requirements for livestock, etc. The present and future water requirements for various purposes are estimated as follows.

Irrigation water demand

The major irrigated crops in the basin are: cotton; oil crops like soybean; sunflower; rice; and sugarcane. The present irrigated land in the basin is estimated at 140,000–172,000 ha which is just about 1.84 % of the total area of the basin. The government envisages that the irrigated land will increase at about 6 % annually (Demese et al. 2010). This means that by 2050, the total potential of irrigable land (1.02 million ha) in the basin will be covered by irrigation. This will be about 13.45 % of the basin area. The crop water need (mm) per total growing period for different crops is given by Brouwer and Heibloem (1986) and Critchley and Siegert (1991). Based on their estimate,

Table 2 Physical properties of soil in the Baro Akobo basin

No.	Soil name	Max. depth (mm)	Hydraulic conductivity (mm/hr)	Textural composition			Soil BD (g/cc)	Soil AWC (cm/cm)	Area (Km^2)	Watershed area (%)
				Clay	Silt	Sand				
1	Chromic luvisol	1830	1.7	38	6	56	1.5	0.11	3531	5
2	Dystriccambisol	700	14.88	21	35	44	1.44	0.13	8164	11
3	Dystricfluvisol	1400	15.49	20	40	40	1.43	0.14	10,086	13
4	Eutricplinthosol	2000	29	17	70	70	1.5	0.08	2237	3
5	Eutricglysol	600	2.16	40	37	37	1.41	0.13	6857	9
6	Hapliclixisol	1829	15	9	21	21	1.39	0.2	7141	9
7	Eutricvertisol	1400	0.45	61	25	25	1.31	0.11	2195	3
8	Haplicnitisol	8000	6.9	29	58	58	1.5	0.1	10,710	14
9	Chromic cambisol	1320	1.56	38	40	40	1.52	0.1	8455	11
10	Planosols	1800	15.76	17	61	61	1.49	0.1	2045	3
11	Rhodicnitisols	2460	72	8	78	78	1.45	0.07	6083	8
12	Eutricleptosols	2500	0.01	50	40	40	1.34	0.12	6935	9

the irrigation water requirement for different crops has been estimated and reported in Table 6.

Environmental flow

Environmental water requirement is the amount of water required in a river course to sustain a healthy ecosystem. The specification of an environmental water requirement varies depending on the objective of environmental water management. It can be complex and its estimation should be viewed in the context of natural variability of flow regimes (Poff et al. 1997). The total environmental water requirement consists of ecologically relevant low-flow and high-flow components (Smakhtin et al. 2004). It has been estimated that ~20–50 % of the mean annual river flow in different basins needs to be allocated to freshwater-dependent ecosystems to maintain a fair condition (Smakhtin et al. 2004). Baro Akobo is an international river basin which includes part of the eastern Nile basin. It has important wetlands and a variety of instream flora and fauna. So, the environmental flow requirement of the basin is estimated to be about 25 % of the mean annual river flow of 23,240 MCM/year and is estimated to be 5810 MCM/year.

Domestic water demand

Domestic water demand depends on the population in the basin. The domestic water requirements depend on the size of the settlement, climatic conditions and commercial activities. Here, domestic per capita water requirement is for various purposes such as drinking, bathing and food preparation. It is estimated on the basis of water withdrawn for the use of the local population. In other words, it is a long-term household need for decent life quality. For an average condition in the basin, the per capita water demand for domestic purposes is considered as 245 lpcd which may go up to 380 lpcd by 2050. On this basis, the present domestic water requirement in the basin is estimated to be about 500 MCM/year, which may go to about 2000 MCM/year in 2050.

Industrial water demand

Every manufactured product uses water at different stages of the production process. This includes processes like fabrication, washing, cooling or transporting a product and for sanitation needs within the manufacturing facility. The most water-intensive industries such as beverages, textiles, chemicals and forest products are not present in the basin. Data on industrial water use is difficult to get because most of the available small industries use their own water sources. In this study, an estimate of water use for industries is taken as 14 % of the total domestic water supply. Thus, the current water demand is estimated at 70 MCM/year and the projected demand is 280 MCM/year.

Livestock water demand

Livestock husbandry requires a provision of enough quantity and quality of water. Some of the factors influencing the intake of water by the animals include the size and growth stage of the animal, environmental and management factors, production level and the quality of water (its temperature, salinity and odour). The daily water needs of livestock vary among animal species (King 1983). Table 7 shows the different species of livestock existing in the basin and their water requirement.

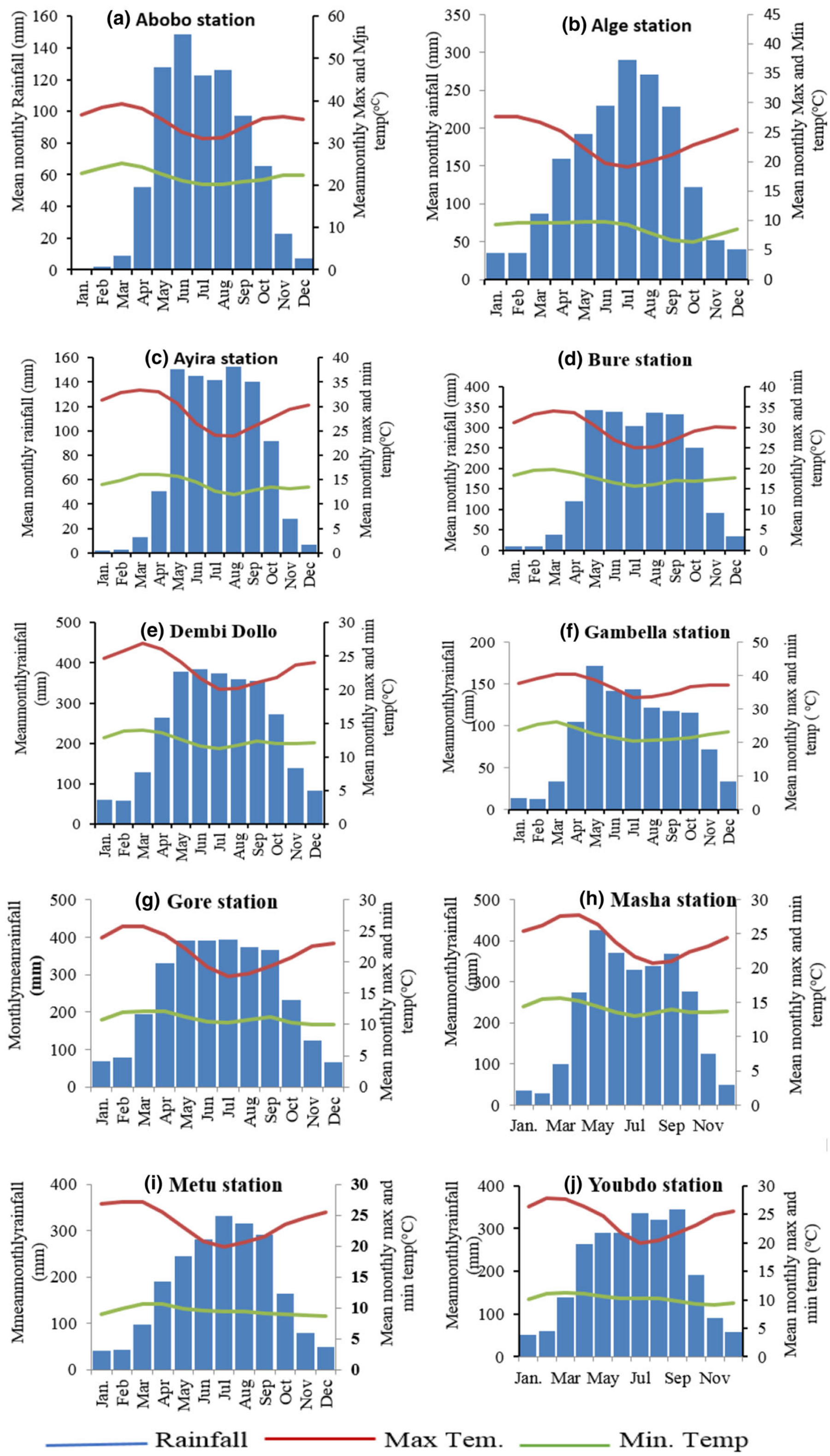

Fig. 6 Long-term weather data of the Baro Akobo basin at different stations

The total water requirement of livestock in the basin is determined based on the population of different animal species in the basin and this demand is also projected to 2050. The growth and development plan of the government is to improve the breeds and productivity of the livestock in the basin, so as to keep the number of the livestock as low as possible in the coming 20–30 years. So, assuming the number of livestock to decrease or at least be the same as

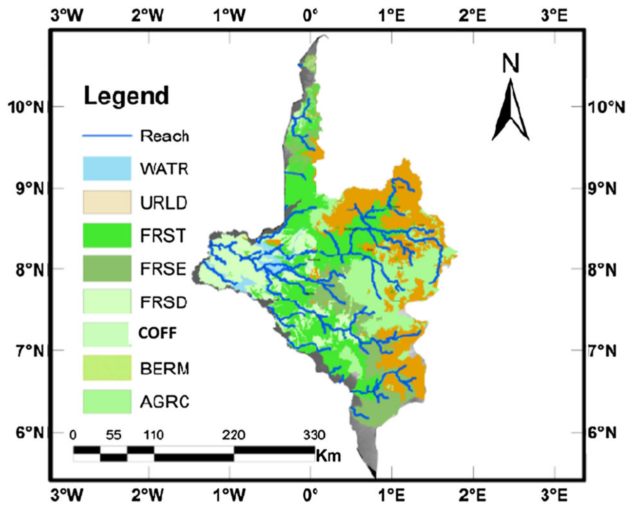

Fig. 7 Land use map of the basin

that at present, the projected water demand will be the same as that in the present, i.e., 89.4 MCM.

Summary of water demands

The largest portion of water in the basin is used for irrigation and the next important water use is allocated to environment. The projected total water demand of the basin will be the sum of all the above requirements and is equivalent to 18,639.4 MCM. The basin actually yields about 23,240 MCM of water. This shows that about 4600.6 MCM/year of surplus water is available in the basin. So it is possible to transfer 116 MCM of water from this surplus. This is 0.5 % of the mean annual flow of the basin and 2.5 % of the surplus water available in the basin. Table 8 gives the summary of water demand in the basin.

Characteristics of the Awash (receiving) basin

The Awash River rises at an altitude of about 3000 m amsl to the west of Addis Ababa. It is divided into the Upper Awash (elevation above 1500 m amsl), middle Awash (elevation between 1500 and 1000 m amsl) and lower Awash (elevation between 1000 and 500 m amsl). The total geographical area of the Awash basin is estimated to be around 110,000 km^2, out of which 64,000 km^2 is termed as the western catchment and the remaining 46,000 km^2 is classified as the eastern catchment (Berhe et al. 2013). The Awash River flows northeastward along the rift valley into the Afar triangle and terminates in Lake Abbe at an elevation of about 250 m amsl. The current (2015) population in the basin is about 14.27 million. This population is spread among different states in the basin in the proportion of about 37.5 % in Oromia, 22.7 % in Addis Ababa, 18.7 % in Amhara, 9.9 % in Afar, 7.5 % in Somali State and 2.7 % in Dire Dawa administrative council.

The total annual surface water resource potential of the Awash basin according to previous study by Adeba et al. (2015) is estimated to be about 4640 MCM. Awash is fed by several major tributaries at the upper, middle and lower parts of the basin (Berhe et al. 2013). Ginchi, Berga, Holleta, Bantu, Leman, Akaki, Mojo and Hombole are the major tributaries of the upper Awash and contribute an annual flow of about 1600 MCM. Arba I, Arba II, Keleta, Kesem, Najeso and various other small perennial tributaries contribute an annual flow of about 2960 MCM to the middle Awash. Logia is another tributary of Awash which adds an annual flow of about 80 MCM to the lower Awash.

The average water demand is estimated to be about 4670 MCM, meaning thereby an average deficit of about 30 MCM. This deficit is expected to increase to 116 MCM in the coming 35 years (2050). The availability of water fluctuates from year to year and within a year. The seasonal (intra-annual) shortage of water is more serious than the inter-annual deficit in the basin, as precipitation in the basin is highly variable in space and time.

Table 4 Slope classes of the basin

No.	Slope classes	Watershed area (Km^2)	Watershed area (%)
1	0–15	59,464.76	78.34
2	15–35	13,913.57	18.33
3	>35	2527.67	3.33
Total		75,906	100

Table 3 Land use category of the basin

No.	Land use category	Class	Watershed area (Km^2)	Watershed area (%)
1	Agricultural land close grown	AGRC	13,357.05	17.64
2	Bromegrass	BERM	16,949.81	22.43
3	Forest deciduous	FRSD	11,841.34	15.58
4	Forest mixed	FRST	21,230.91	27.97
5	Forest evergreen	FRSE	10,027.18	13.19
6	Water body	WATR	2322.72	3.16
7	Residential low density	URLD	176.99	0.03
	Total		75,906	100

Table 5 Catchment area and mean annual runoff of the Baro River and its tributaries

S no.	Tributary name	Catchment area (km^2)	Mean annual runoff (Mm^3/year)
1	Baro	30,006	12.786
2	Akobo	13,245	3.895
3	Gilo	12,815	3.225
4	Alwero	8015	1.374
5	Serkole	7705	1.322
6	Triatid	2690	0.415
7	Pibor	1430	0.221
	Total	75,906	23,240

Table 6 The estimated present and future irrigation potential of the Baro Akobo basin

No.	Crop	Estimated present irrigated area (ha)	Total crop water requirements (mm)	Present water requirements (BCM)	Projected area ($\times 10^3$ ha)	Projected water requirements (BCM)
1	Cotton	47,950	1000	0.48	306	3.06
2	Oil crop	29,400	575	0.16	306	1.76
3	Rice	42,100	1010	0.42	255	2.58
4	Sugarcane	20,550	2000	0.41	153	3.06
Total		140,000		1.06	1020	10.46

Table 7 Livestock population and their water requirements

Livestock type	Livestock population (million)	Average water requirement (l/head/day)	Total water requirement (MCM/year)
Cattle	3.5	54	68.99
Sheep	1.3	7.14	3.4
Goats	0.8	5	1.46
Equines	0.34	55	6.8
Beehives	3.8	450 l/1000 birds/day	0.62
Total			81.27
Add 10 % of the above for wildlife			8.13
Grand Total			89.4

June to September is the main rainy season in the basin during which the availability of water exceeds demand. The basin is arid in its northern part where the average annual rainfall does not exceed 160 mm. Further, in the Awash basin, fast urbanisation has resulted in an increased demand for water in general. Its western portion is densely populated and urbanised. There are a number of important cities in the basin such as Addis Ababa and Adama, which require more water to satisfy its requirements.

The basin supplies water to meet domestic, industrial and agricultural water demands for the cities and surrounding rural settings. About 80 % of Addis Ababa's domestic water supply is from surface water resources of the basin, while 20 % comes from groundwater (Rooijen et al. 2009). The competing and conflicting interests of various regions and sectors have aggravated the scarcity of water resources. Overall, the basin is water stressed and unable to meet its present and future water requirements. This calls for a sustainable and effective measure to meet the water demands in the basin.

Conventionally, water resources development for irrigation and hydropower in Ethiopia was first started in the Awash basin itself in the 1950s. However, it is still not been able to meet its requirements. It is felt that in such basins, one of the sustaining and effective measures is to get the water through inter-basin transfer from a water surplus basin. The other option is to provide storage in the basin so as to capture excess water during the wet season. Depending on the feasibility of the options, both can help in reducing the gap between the water supply and demand to a large extent. Keeping this in mind, this study explores the different options of inter-basin water transfer from Baro Akobo to the Awash basin.

Table 8 Summary of water demand in the basin

No.	Type of demand	Present demand (2015) (MCM)	Future demand (2050) (MCM)	Percentage of total demand
1	Irrigation	1060	10,460	56.12
2	Environmental	5810	5810	31.17
3	Domestic	500	2000	10.73
4	Industrial	70	280	1.50
5	Livestock	89.4	89.4	0.48
	Total	7529.4	18,639.4	100

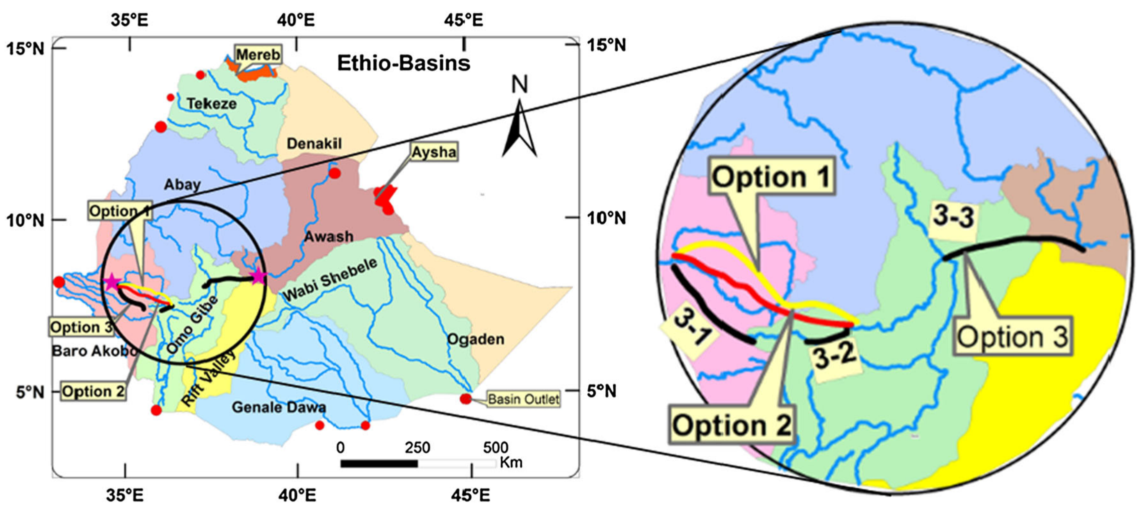

Fig. 8 Three different options of water transfer routes

Identification of water transfer routes from the Baro Akobo to the Awash basin

Different options are identified and assessed for the water transfer from the Baro Akobo to the Awash basin. These options are shown in Fig. 8. The diversion point in the Baro Akobo basin is selected as the confluence of Sore and Birbir rivers, which is about 45 km upstream (to the east) of Gambela Town. The location of the point is 7°30′0.45″N latitude and 35°15′42.06″E longitude. This location is just upstream of a wildlife reserve and is also away from any habitat or settlement. At this point, there is sufficient water. The elevation of the diversion point is 1595 m amsl. The max, min and average discharge at the point of diversion are 120, 2110 and 388 m^3/s, respectively. This is taken from the long-term historical discharge data (1980–2012) of Gambella station downstream of the diversion point.

Likewise, the receiving point in the Awash basin is also identified. It is at the Awash *Melkakunture* about 12 km west of the *Melkakunture* prehistoric site. Its geographical location is 8°42′02.88″N latitude and 38°36′30.6″E longitude. The elevation of the receiving point is 2264 m amsl. The nearest flow gauging station is at Mojo Town and the max, min and average discharge at this station is 9.3, 150, and 47.2 m^3/s, respectively. It is taken from a long-term historical discharge data (1980–2012) of the Mojo station. The receiving point is nearer to city centres where it can be utilised for different purposes.

The topographic map of the basin is used for the purpose of route identification. As far as the terrain topography allowed, the shortest route is followed to transfer water either under gravity or by pumping. Accordingly, the total conveyance under gravity and pumping is identified for each route. Further, settlement conditions of the enroute villages are assessed so as to minimise the number of people to be displaced during the implementation. Option 1 and 2 join at the Gibe River course after a distance of 380 and 252 km, respectively. They use the natural conveyance for about 137 km and then deliver the water to the receiving point through an open channel. The routes impact some of the villages when they are conveyed inland. Route 3 enters and leaves the natural waterways in two locations. Its impact on the enroute villages is minimum. It crosses the wildlife reserve in the natural waterway. So its impact on wildlife reserve and other natural environment is negligible. In all the three options, to overcome the overflowing and inundations of natural waterways due to additional volume of water, the time of water transfer can be planned when the flow of water in the natural waterway is minimum, i.e., during the lean period. Reshaping of the

Fig. 9 Water transfer route for option 1

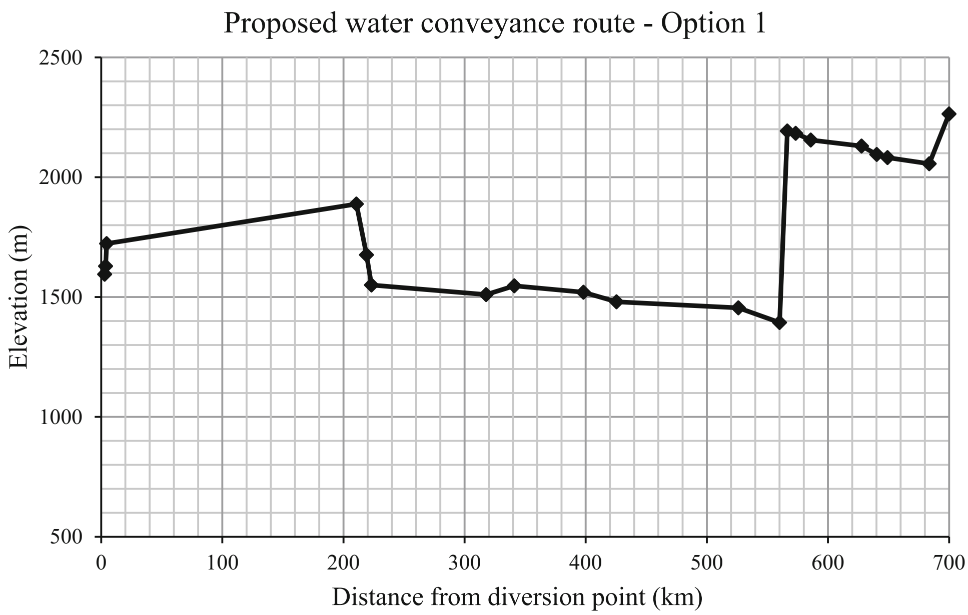

Table 9 Details of conveyance route for option 1

No.	Elevation (m)		Difference (m)	Distance (Km)	Mode of conveyance		Discharge, Q (m^3/s)	Pump capacity (MW)	No. of stages	Number of pumps[a]
	From	To			Gravity	Pump				
1	1595	1629	−34	2.87		Pump	8.6	1.5	1	2 + 2
2	1629	1723	−94	0.81		Pump	8.6	5	2	4 + 4
3	1723	1888	−165	0.82		Pump	8.6	5	3	6 + 6
4	1888	1676	212	206.19	Gravity		8.6			
5	1676	1550	126	8.35	Gravity		7.31			
6	1550	1510	40	4.15	Gravity		6.214			
7	1510	1547	−37	94.65		Pump	6.214	4	1	2 + 2
8	1547	1520	27	23.23	Gravity		6.214			
9	1520	1480	40	57.15	Gravity		5.99			
10	1480	1455	25	27.24	Gravity		5.09			
11	1455	1394	61	100.64	Gravity		4.33			
12	1394	2193	−799	34		Pump	4.33	5	5	10 + 10
13	2193	2183	10	6.39	Gravity		4.33			
14	2183	2155	28	6.88	Gravity		3.89			
15	2155	2130	25	12.43	Gravity		3.5			
16	2130	2095	35	41.98	Gravity		3.35			
17	2095	2082	13	12.5	Gravity		3.22			
18	2082	2056	26	8.95	Gravity		3.1			
19	2056	2264	−208	34.45		Pump	3	5	4	8 + 8

[a] 100 % standby pumps

Total distance of the transfer route = 685 km

Conveyance by gravity = 518 km

Conveyance by pumping = 167 km

waterway and river training measures can also increase the carrying capacity of the waterway. The other advantage of the stabilised natural waterway is that it can decrease the infiltration losses of water. It is believed that the conveyance stream channel can easily carry an additional 11.2 m^3/s of water along its own natural discharges.

The cost estimates of these routes are presented in the form of the present worth of the cost and the same are compared to evaluate the economic feasibility of the project.

Economic evaluation of the identified routes

The present worth method is used to compare mutually exclusive three alternatives. The costs of the alternatives consist of capital, equipment, equipment replacement and operation and maintenance. The cash flow diagram is prepared for these options and the future amount of expenditure is converted into equivalent present worth using a particular discount rate. In this study, a discount rate of 6 % is taken.

Option 1

Option 1 is about 685 km long. The total length of the route where gravity is used for water conveyance is about 516 km. This includes the natural waterways, whereas for the rest of the distance (about 167 km) water is to be pumped against gravity as shown in Fig. 9.

Wherever topography allows, gravity flow is considered and it is assumed that the water is conveyed through an open lined channel. The maximum and minimum pumping head is about 159.8 and 34 m, respectively, while the maximum gravity head available for water conveyance is 212 m. Referring to Table 9, the first column No. 12, the corresponding head difference in (M) of column 3 is −799 m. 159.8 m is achieved through five stages of pumping, so as to reduce the capacity of the pumps. Therefore, the maximum head comes from 799 m divided by 5 = 159.8 m for each pumping stage. The distance of each segment and the available head are shown in Table 9.

Pumps and fittings of pipes are assumed to be replaced every 10 years throughout the project. Considering the various cost components, a cash flow diagram is prepared and shown in Fig. 10. It is assumed that the construction of

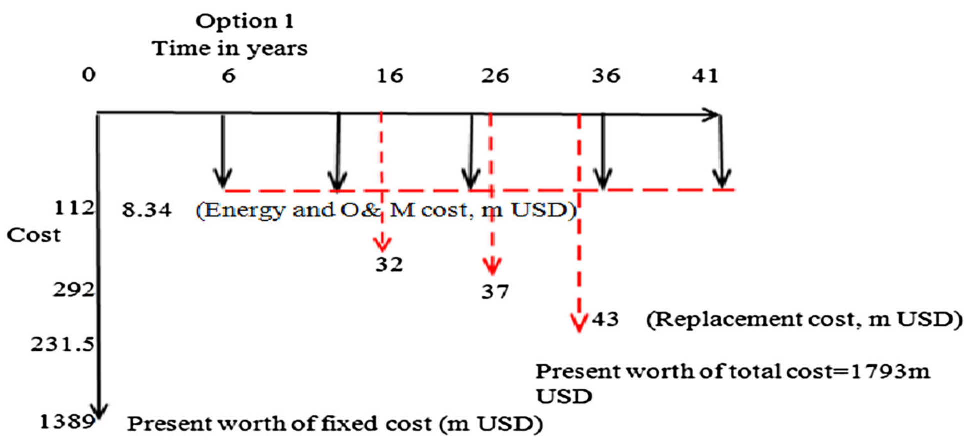

Fig. 10 Cash flow diagram for option 1

Table 10 Estimated present worth of the cost for option 1

No.	Cost element	Estimated present worth of the cost (in billion USD)
1	Dam construction	0.543
2	Pipes + saddles + anchors	0.488
3	Pumps and powerhouse	0.034
4	Open channel + open chambers, etc.	0.119
5	Access road	0.205
6	Present worth of energy cost for pumping	0.058
7	Present worth of replacement cost	
	(a) after 10 years	0.032
	(b) after 20 years	0.037
	(c) after 30 years	0.043
	Sub-total	1.559
8	O and M and administrative charges (15 % of sub-total)	0.234
	Present worth of total cost	1.793
	Cost per unit of water ($/m^3)	1793/(116 × 35) = 0.442

Fig. 11 Water transfer route for option 2

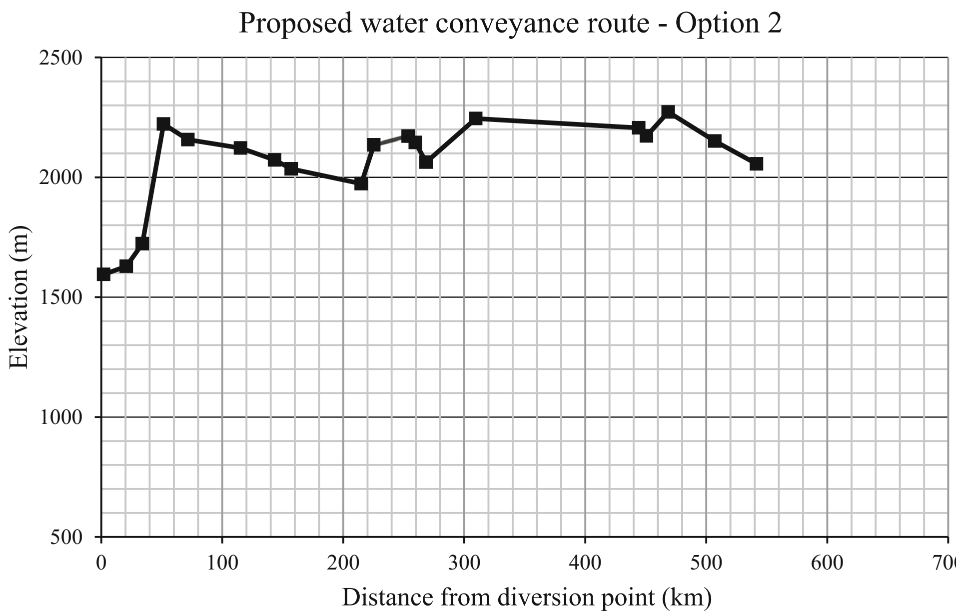

Table 11 Details of the conveyance route for option 2

No.	Elevation (m)		Difference (m)	Distance (km)	Mode of conveyance		Discharge, Q (m^3/s)	Pump capacity (MW)	No. of stages	No. of pumps[a]
	From	To								
1	1595	1629	−34	2.00		Pump	8.6	1.5	1	2 + 2
2	1629	1723	−94	18.75		Pump	8.6	5.5	2	4 + 4
3	1723	2222	−499	13.19		Pump	8.6	4.5	5	10 + 10
4	2222	2157	65	17.51	Gravity		7.31			
5	2157	2122	35	20.16	Gravity		6.21			
6	2122	2072	50	43.60	Gravity		5.74			
7	2072	2035	37	28.11	Gravity		5.45			
8	2035	1973	62	13.80	Gravity		5.4			
9	1973	2135	−162	57.82		Pump	5.4	2	3	6 + 6
10	2135	2172	−37	10.34		Pump	5.4	2	1	2 + 2
11	2172	2145	27	28.30	Gravity		5.4			
12	2145	2063	82	6.09	Gravity		5.12			
13	2063	2245	−182	8.82		Pump	4.33	3.8	3	6 + 6
14	2245	2206	39	41.09	Gravity		4.33			
15	2206	2172	34	134.64	Gravity		3.89			
16	2172	2272	−100	6.39		Pump	3.89	2	2	4 + 4
17	2272	2151	121	17.99	Gravity		3.59			
18	2151	2056	95	38.58	Gravity		3.2			
19	2056	2264	−208	34.45		Pump	3.0	5	4	8 + 8

[a] 100 % standby pumps

Total conveyance = 541.6 km

Conveyance by pumping = 151.76 km

Conveyances by gravity (including natural waterways) = 389.87 km

this option shall be completed in 6 years and thereafter the annual operation and maintenance, and replacement cost will be as shown in the cash flow diagram. The summary of the present worth of estimated cost is shown in Table 10.

Option 2

The volume of water to be transferred to the Awash basin will be delivered to the Gibe River natural waterway as in

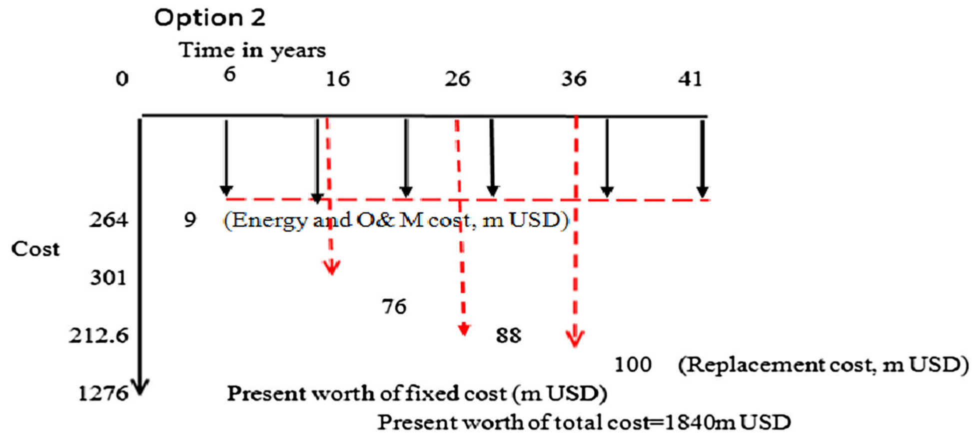

Fig. 12 Cash flow diagram for option 2

the case of option 1. The major difference in this option is that the environmental impact, the number of people to be displaced and the construction of pipelines and open channels is less, as it is a shorter inland route. The total distance including natural waterway, where gravity is used for water conveyance, is about 390 km and the total distance from the point of diversion to the point of delivery is about 542 km. The distance to be pumped against gravity will be about 152 km as shown in Fig. 11. The distance of each segment and the available head is shown in Table 11.

Considering the various cost components, a cash flow diagram is prepared and shown in Fig. 12. The summary of the estimated cost and its present worth is shown in Table 12.

Table 12 Estimated cost and its present worth for option 2

No.	Cost element	Estimated present worth of the cost (in billion USD)
1	Dam construction	0.543
2	Pipes + saddles + anchors	0.435
3	Pumps and power house	0.03
4	Open channel + open chambers, etc.	0.105
5	Access road	0.163
6	Present worth of energy cost for pumping	0.061
7	Present worth of replacement cost	
	(a) after 10 years	0.076
	(b) after 20 years	0.087
	(c) after 30 years	0.1
	Sub-total	1.6
8	O and M and administrative charges	0.24
	(15 % of sub-total)	
	Present worth of total cost	1.84
	Cost per unit of water ($/m^3)	1840/(116 × 35) = 0.453

Option 3

This option is the shortest route among all the options suggested in this study and involves water conveyance of about 519 km. It uses a natural stream channel of the Gojeb and Gibe rivers. In this option, water enters and leaves the natural waterway at two different points. For 315 km of transfer distance, gravity can be employed while for 204 km water is pumped against gravity. The transfer route is shown in Fig. 13. The details of the conveyance are shown in Table 13.

Considering the various cost components, a cash flow diagram is prepared and shown in Fig. 14. The summary of the estimated and its present cost is shown in Table 14.

Discussion of results

It may noticed that each of the options involves the construction of storage through the construction of a dam. This will serve a double purpose. Besides the purpose of meeting the demand in the dry season, it will also make the project self-sustaining as it will generate electricity as well. That is why the cost of the turbine is also included in option 3. As can be observed in Fig. 13, the head falls abruptly from 2222 to 2022 m. One can use the fall in head for hydropower generation which can compensate the energy requirements during pumping.

The total present worth of cost for the options 1, 2, and 3 is 1.793, 1.84 and 1.637 billion US $, respectively. The water to be transferred in 35 years will be about (35 × 116 MCM) 4060 MCM. This means that the cost of water transfer by the three options is 0.44, 0.45 and 0.4 US $ per m^3, respectively. This shows that option 3 is the best from the economic point of view. It may be argued that economics is an important issue, but not the only one. Therefore, the options were examined from the social and environmental point of view as well. Figure 15 show the

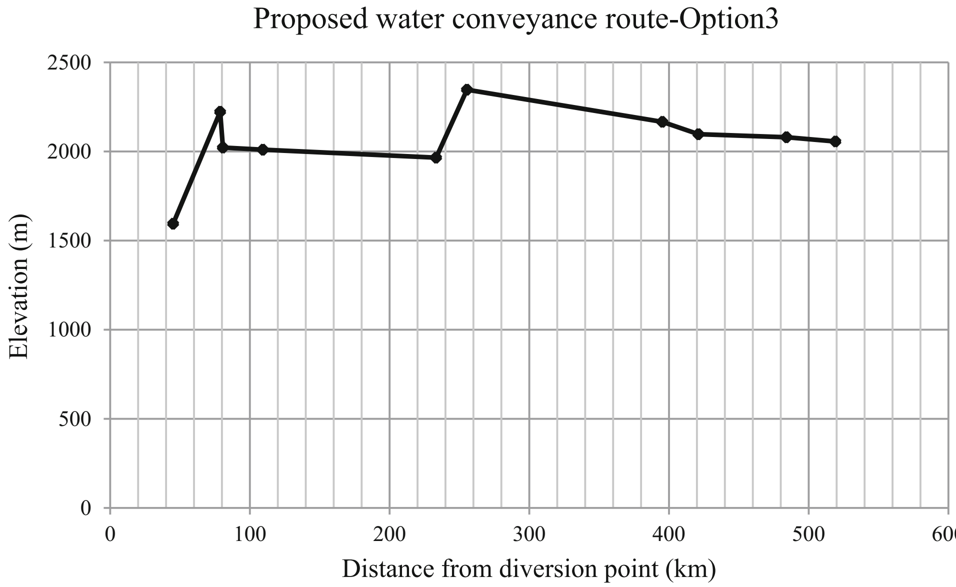

Fig. 13 Water transfer route for option 3

Table 13 Details of conveyance route for option 3

No.	Elevation (m)		Elevation difference (m)	Distance (km)	Method of conveyance	Discharge, Q (m^3/s)	Pump capacity (MW)	Number of stages	No. of pumps[a]
	From	To							
1	1595	2222	−627	45	Pump	8.6	5.5	5	10 + 10
2	2222	2022	200	2	Gravity	8.6			
3	2022	2010	12	33.7	Gravity	7.3			
4	2010	1965	45	28.6	Gravity	6.6			
5	1965	2346	−381	124	Pump	5.6	2.3	5	10 + 10
6	2346	2166	180	22.1	Gravity	4.8			
7	2166	2097	69	139.9	Gravity	4			
8	2097	2080	17	25.8	Gravity	3.4			
9	2080	2056	24	63.1	Gravity	3			
10	2056	2264	−208	35	Pump	3	1.2	4	8 + 8

[a] 100 % standby pumps

Total distance from the point of diversion to the point of delivery = 519 km

Conveyance by pumping = 204 km

Conveyances by gravity (including natural waterways) = 315.9 km

routes of options 1, 2 and 3 as well as the settlements, national parks and sanctuaries, and wildlife reserves that the possible routes may possibly affect.

Further, it may be noticed that the proposed option 3 uses natural waterways of the Gojeb and Gibe rivers for a significant portion of flow. It crosses the wildlife reserve through a natural waterway without causing any adverse impact. Also, there is very little settlement along the route of option 3. Appropriate compensation mechanism can be adopted for the affected villagers (if any). Therefore, from the social and environmental impact point of views also, option 3 is the best. Thus, it can be concluded that the water resources development through option 3 has the low adverse impact which can be easily absorbed by the enroute area, especially when the benefits will be very high. One can suggest an environmental management plan (EMP) while preparing the detailed project report.

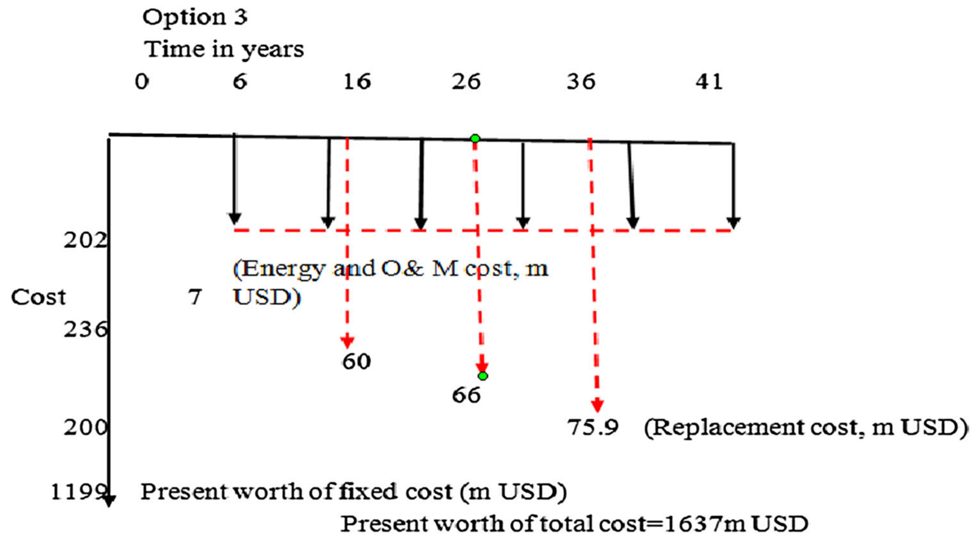

Fig. 14 Cash flow diagram for option 3

Table 14 Estimated cost and its present worth for option 3

No.	Cost element	Estimated present worth of the cost (in billion USD)
1	Dam construction	0.543
2	Pipes + saddles + anchors	0.372
3	Pumps and power house	0.025
4	Open channel + open chambers, etc.	0.09
5	Turbines	0.013
6	Access road	0.156
7	Present worth of energy cost for pumping	0.022
8	Present worth of replacement cost	
	(a) after 10 years	0.06
	(b) after 20 years	0.066
	(c) after 30 years	0.076
	Sub-total	1.423
9	O and M and administrative charges (15 % of sub-total)	0.214
	Present worth of the total cost	1.637
	Cost per unit of water ($/m^3)	1637/(116 × 35) = 0.403

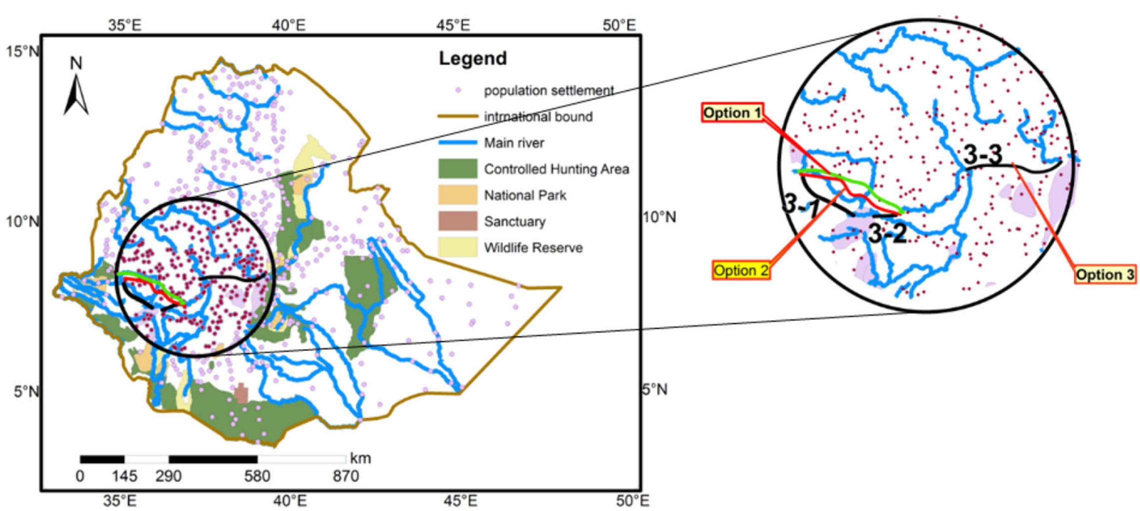

Fig. 15 Population settlement of the basin and the proposed transfer route

Conclusions

The Awash basin of Ethiopia is in a critical condition from a water resource point of view. To improve the water resources in the basin and to have somewhat equitable water distribution, it is desired to transfer water from the water surplus basin. Baro Akobo is a water surplus basin in Ethiopia. In this study, water resource potential of the Baro Akobo basin is assessed using the SWAT model and is estimated at about 23 BCM. Further, the Awash basin has little over 4.5 BCM. To meet the water requirements of the Awash basin, this study advocates the transfer of about 116 MCM of water per year through the proposed inter-basin water transfer link. Three alternative routes are identified and compared for their economic sustainability and social and environmental viability. Finally, the best possible route has been identified and recommended for the inter-basin water transfer from the Baro Akobo to Awash basin. The proposed water transfer period shall be during dry season (December–March), i.e., 116 MCM during 120 days, which is ~ 1 MCM per day. It should be noted that a dam is proposed to store this water during the wet season (June–September) and this stored water will meet the requirements of the proposed water transfer and also of the downstream. It will not affect the dry seasonal flow at the downstream, but will rather improve it. Another advantage of water transfer is that it can produce hydropower enroute. Depending on the topography of the transfer route, mini- or micro-hydropower plant can be designed. The proposed inter-basin water transfer will have dual advantage of reducing the gap between the demand and supply in the Awash basin as well as help mitigate the flood problem in the Baro Akobo basin.

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