Chapter

Water Resources Management and Hydraulic Infrastructures in the Senegal River Basin: The Case Study of Senegal, Mali and Mauritania

Cheikh Faye

Abstract

The water resources of the Sahelian countries bordering the Senegal River basin (Senegal, Mali and Mauritania) are limited and unevenly distributed. To overcome the unequal distribution of water resources and to manage floods and droughts in the Senegal River Basin, hydraulic infrastructures have been built in the Senegal River Basin, starting with the Manantali dam. The paper reviews the current water storage capacity in the Senegalese, Malian and Mauritanian parts of the Senegal River Basin from a sustainable water resources management perspective. Data from the Manantali dam and from the water resources of the downstream countries (Mali, Senegal and Mauritania) in the Senegal River basin were employed to assess water storage capacity at country level in this basin. Water storage capacity was found to be lowest in the Mauritanian part and highest in the Malian part. These results led to the conclusion that despite the OMVS based heavy investment in the infrastructure of water storage capacity there is both need and potential for infrastructure increase. As the Senegal River Basin is a transboundary case the riparian countries sharing in order to promote integrated water resources management at the basin level, need to continue to develop additional storage to underpin and modernize the responsible use of water resources through the construction of other multifunctional water infrastructure.

Keywords: water storage, water infrastructure, dams, water use, water management

1. Introduction

Infrastructures are defined as "networks that enable the movement of goods, people or ideas and allow their exchange in space" [1]. The speed and direction of movement is influenced by their topology and physical form and from this point of view infrastructures are technological objects. Water distribution systems can be defined "as networks connecting water from rivers, lakes and storage sites to homes, farmers' fields irrigation systems and factory outlets empowering water's economic and social functions" [2].

The construction of dams is often linked to state policies seeking to meet the needs of populations. Among these needs, the multiplication of the number of structures is caused by regional development, increased access to drinking water and electricity, flood-fighting and irrigation development. Half of the world's rivers have at least one dam, and hydroelectric power plants produce more than 50% of the electricity consumed in a third of the world's countries [3].

Dams are works that block a section of a valley over the entire width and create a basin in a geological way and thus they usually are considered to be barriers. Its origin may be natural or catastrophic e.g., land slides or avalanches, or it can be the result of a disorganization of the river network with a change in the geomorphological system e.g., moranic or glacial dam. A dam is a project, and hence it has a pre-determined lifecycle after which it may end up being filled, or else by yielding, undermined by the infiltration waters.

Dams are the subject of many claims by members of civil society. The latter often criticize manufacturers and decision-makers for a lack of consideration towards them, a lack of transparency, and unfulfilled promises. From these concerns that animate the populations arise demands, forces to fight against dam projects accused of the flooding of forests, the acidity of water, the sterilization of agricultural land, and expropriations. These infrastructures also include the links between these machines that allow them to function as a system, as well as techniques of organization—companies, accounting, bureaucracies, etc. [4]. These infrastructures, of course, exist in society, and often embody, reflect and, in turn, shape their political, economic and social environment [2].

However, water is considered to be an economic good and is classified as a necessity [5, 6] and the economic motives for increase of agricultural/meat production via bulding dams are as below.

As seen above, if in-country production increases substantially Mauritania an Mali have a chance at a zero/positive BoP and Senegal could halve its negative BoP (**Figures 1**–**4**).

The first dams in the world date back to antiquity. Their objectives were to meet the water needs of the populations and for irrigation. "They are located in the Nile Valley, Mesopotamia, China and South Asia." The oldest known remains come from the Sadd-el-Karafa dam made in Egypt between 2950 and 2750 BC. Even in ancient Rome, more than adequately supplied with water and believing that flowing water was a sign of a high standard of living, water-saving devices (such as taps and storage tanks) were widely deployed [8]. Studies provide information on the mode of operation of dams, their history, as well as their consequences on the fragmentation of watercourses. These impacts are analyzed from several angles, in particular through the transformations of the landscapes, the displacement of populations, the changes of identity, the images projected on the disruptive dam, the economic contributions, the usefulness and the beneficiaries. These analyzes relate to cases of dams already built or projects.

Information also exists on the types of construction. They can be arch dams, gravity dams or buttress dams. This information provides knowledge on the world classification and according to the International Commission on Large Dams (ICOLD). The qualification of "large dam" is attributed to those that rise more than 15 meters above the foundations, according to the said commission.

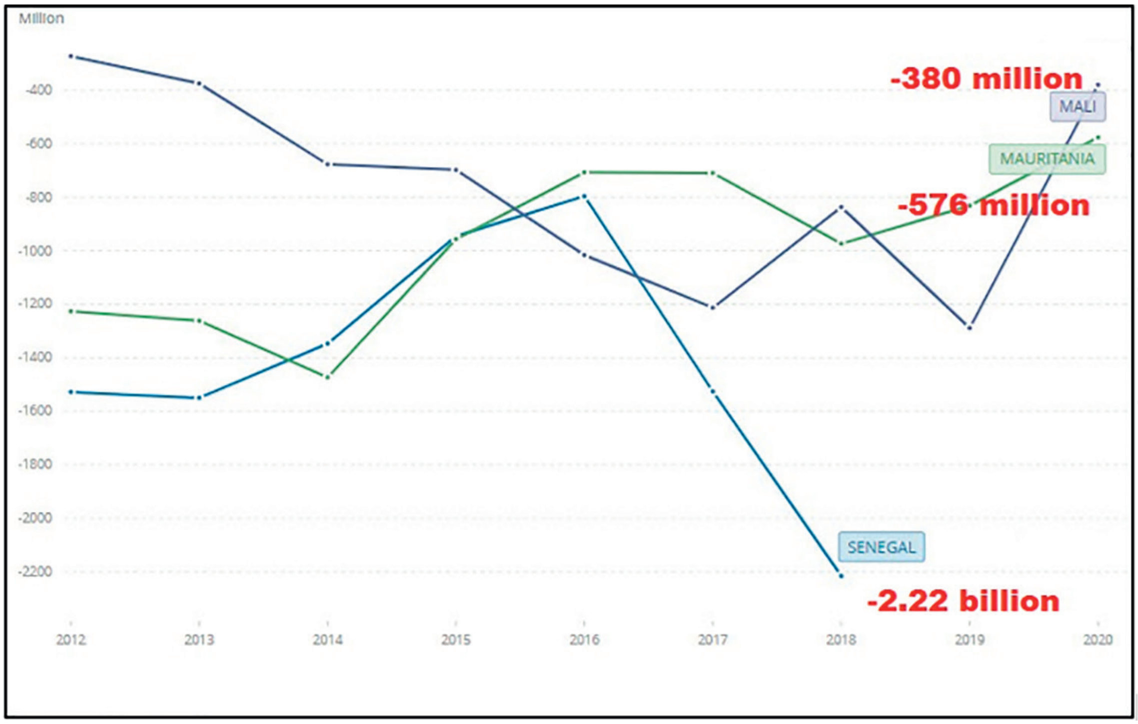

Figure 1.
Current Account (BoP) in Current USD [7].

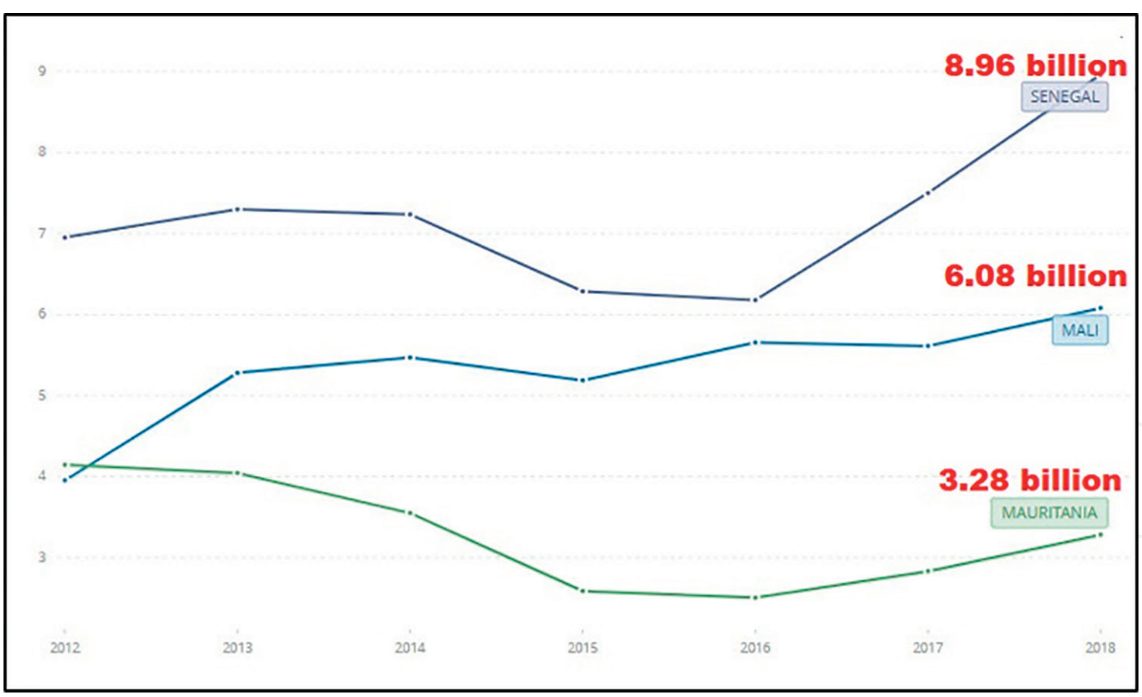

Figure 2.
Imports in Current USD [7].

Dams are installed with a run-of-river or pumped storage reservoir. They are classified into two categories according to the type of material: concrete dams (gravity dams, buttress dams, arch dams) and embankment dams (earth dams, rockfill dams). A third type combining the first two is called hybrid or compound. ICOLD considers that there are 24,395 large earth dams, 3065 rockfill dams, 6688 gravity

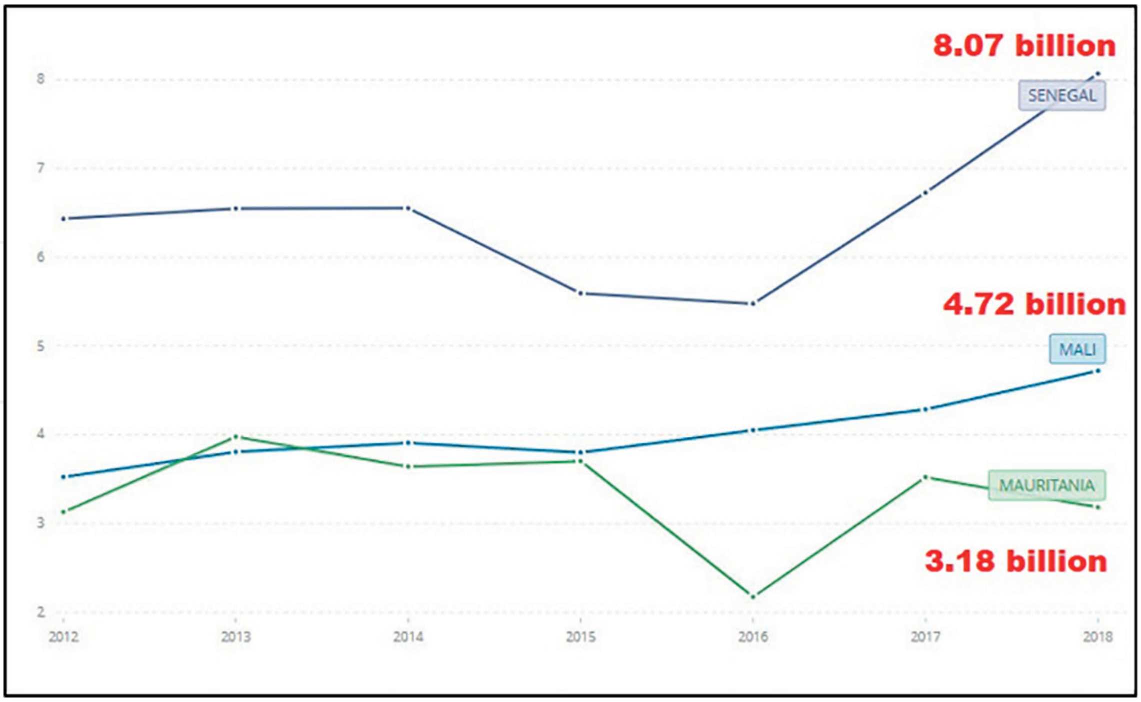

Figure 3.
Merchandise Imports Current USD [7].

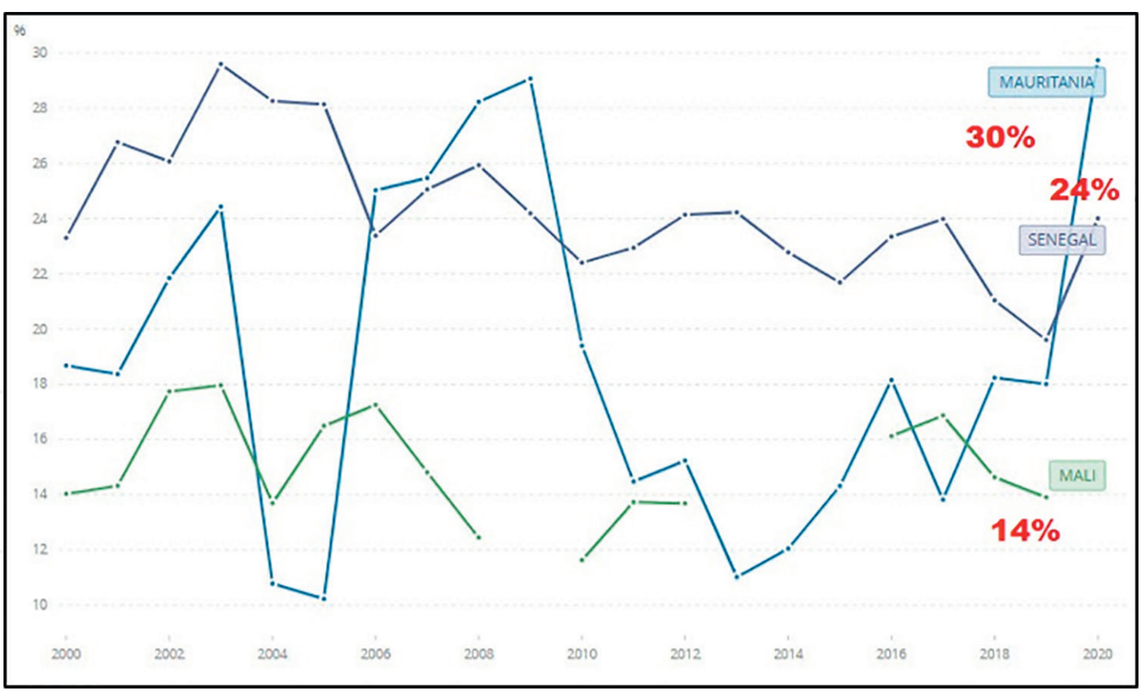

Figure 4.
Food imports as percentage of Merchandise Imports [7].

dams, 426 buttress dams, 1839 arch dams, 172 multi-arch dams and 2603 of another type. Embankment dams are in the majority and constitute nearly 63% of the total number of dams recorded. It is obviously the oldest type of dam and there are traces of embankment dams dating from the oldest civilizations. In addition, this type of dam can be adapted with many types of foundations.

The Senegal River, which is the second largest river in West Africa, owes its formation to the joining of the Bafing and the Bakoye rivers at Bafoulabé, Mali. Its 300,000 km^2 watershed is divided into three subsets [9]: the upper basin, the valley and the delta as seen in (**Figure 5**). The Senegal River runs through four distinguishable climatic zones:

- Guinean (very humid)
- South Sudanian (humid)
- North Sudanian (semi-humid)
- Sahelian (semi-arid).

At 1500 mm/year in the Guinean part the rainfall gradient remains poweful compared to 200–250 mm/year in the northern part leading to an annual average of 550 mm/year, a pluviometric contrast that is a a main basin characteristic which is attenuated to a ceratin extent as billions of m^3 of water are transferred annually by the river from the the upper basin wet regions to the the valley and the delta arid Sahelian regions [10, 11], which explains the great wealth of biophysical environments in the basin and their great diversity.

The impacts of the dam are often examined without taking into account the forms of knowledge of the inhabitants who experience them. The weakness of the

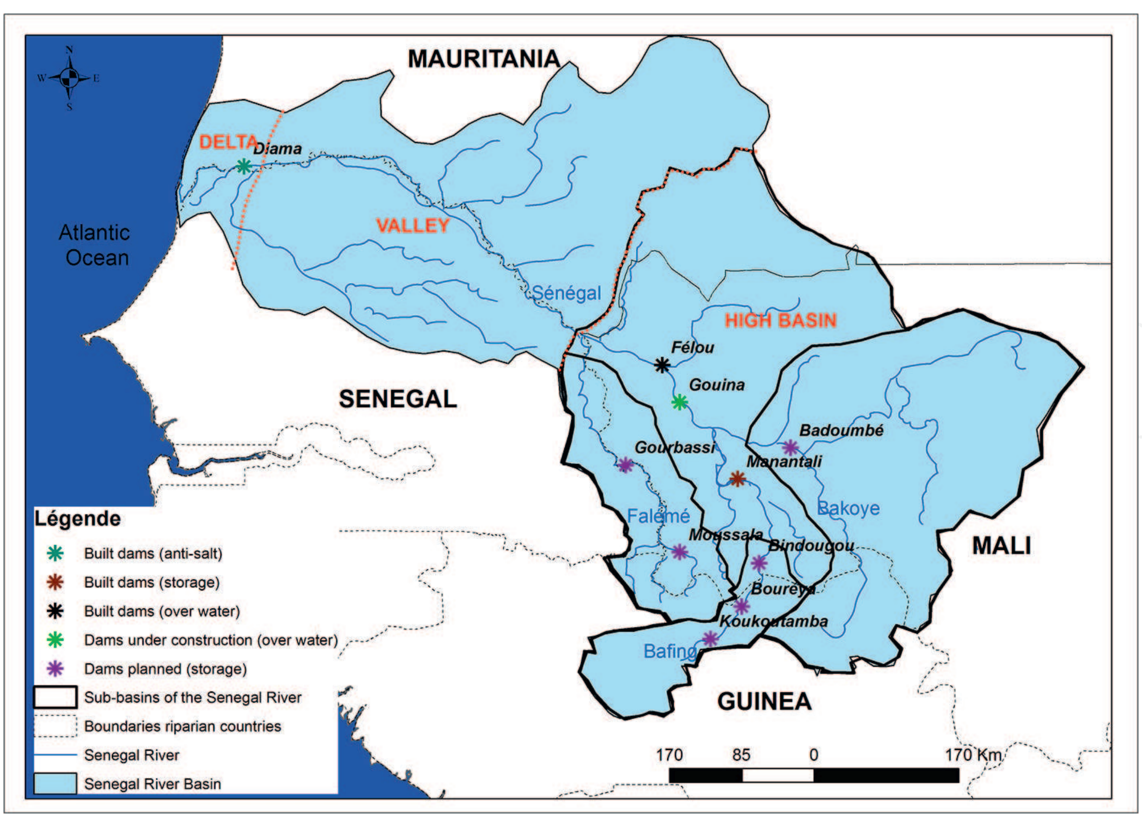

Figure 5.
Situation of the Senegal River watershed and the dams built and planned.

approach to social questions in a context of research into sustainable development is denounced by sociologists, anthropologists, agrogeographers, historians, economists and geographers. On the Manantali dam, the first studies date back to the 1970s. They focused on calculations and simulations before and after the construction of the dam and the hydroelectric power station. The creation of the reservoir, the fish population, the quality of the water, the flows, and the regime of the river were thus questioned. Legally, the status of the Manantali dam is qualified as co-ownership. The specific role of the Organization for the Development of the Senegal River (OMVS) in the operation of the Manantali dam is underlined in certain studies, and the success of the bet on regional integration around the Senegal River is particularly mentioned.

Water withdrawals vary by country. In Senegal, in 2000, withdrawals from water resources amounted to 1591 million m^3 including 1435 million for agriculture (93%), 98 million for communities (4%) and 58 million for industry (3%). In Mauritania, in 2000, water withdrawals were estimated at 1698 million m^3 including 1.5 billion for agriculture (88%), 150 million for domestic use (9%) and 48 million for industry (3%). In Mali, the current withdrawals of the irrigation sector are of the order of 5.0 km^3 in 2006, or 96.4 percent of the total withdrawal [12], and come almost entirely from water resources, surface and almost entirely over a period of 6 months. In the Senegal River Basin water resource availability and distribution are influenced by factors such as: population dynamics, extremely variable climatic conditions ecosystem maintentenance water-affecting environmental issues, and political/socio-cultural issues e.g., food security, and the problem of economic development [13].

Based on the OMVS agreements framework it is seen that via the Manantali dam management a minimum low water flow at the Mali/Senegal border is guaranteed and the Mali, Senegal and Mauritania agreed sharing of stored water is ensured. Thus, a sectoral plan declining master frameset for the development of the Senegal River (SDAGE) is applied in order to attempt the promotion of the watershed's sustainable and concerted development [9].

The water-scarce Sahelian countries, Senegal, Mali and Mauritania, lying on the border of the Senegal River basin have invested in water storage for a long time so as to increase water availability to satisfy their socio-economic/environmental needs. This leads to the question raised here, whether current storage capacity is sufficient to cover the future development needs of these three countries. To be more precise, the Senegal River basin water storage capacity must be assessed taking into consideration whether the OMVS supported potential of these countries is realistically capable to increase this capacity. This paper assesses the the Sahelian countries bordering the Senegal River Basin current water storage capacity from the poin of view of integrated water resources management.

2. Materials and methods

This article is based on data from literature searches and secondary data collection. The main data on water resources were collected from the FAO global database AQUASTAT available at: https://www.fao.org/aquastat/statistics/query/index.html?lang=fr. For the case study on the Senegal River Basin, the databases of the Direction de la Gestion et de la Planification des Ressources en Eau (DGPRE) and of the Organization pour la Mise en Valeur du fleuve Sénégal (OMVS) were used. The combined approach to data collection (on dam issues) is favored here. It consisted first of all of a consultation of unpublished documents (books, reports, dissertations, theses, articles, etc.) which are of great interest for the present. This in-depth review of the literature allowed us to collect different data and information available on the impact of dams in areas where similar studies have been conducted.

3. Results and discussion

3.1 Water availability

Table 1 shows the quantity of wavailable water as seen in FAO [6]. The 2014 three renewable water resource classesi.e., surface water, groundwater, internal water and external water vary according to country. Te estimation results for Mali are at 120 km^3/year compare to those for Senegal, 38.97 km^3/year and for Mauritania, 11.4 km^3/year. For Mali there is a dependency index of 50% between surface renewable water resources and internal renewable water resources estimated at 110 km^3/year and 60 km^3/year repspectively which is explained, in the case of the importance of surface renewable water resources, by the water availability of the Niger River. In Senegal, surface renewable water resources are estimated at 36.97 km^3/year and internal renewable water resources of around 25.8 km^3/year i.e., a dependency index of 33.8%. In the particular case of the the weakest availability country, Mauritania, 97.4% of all water resources is represented by 11.1 km^3/year renewable surface water resources, which essentially are comprised of reservoirs dams distributed widely in the southern and central parts of the territory and of the Senegal River along with its tributaries.

Renewable water resources	Mali		Senegal		Mauritania	
	Quantity	%	Quantity	%	Quantity	%
Total inland water resources (km3/year)	60	50.0	25.8	66.2	0.4	3.5
Total external water resources (km3/year)	60	50.0	13.17	33.8	11	96.5
Surface water resources: total (km3/year)	110	91.7	36.97	94.9	11.1	97.4
Total groundwater resources (km3/year)	20	16.7	3.5	9.0	0.3	2.6
Total renewable water resources (km3/year)	120	100	38.97	100	11.4	100
Dependency index (%)	50		33.8		96.5	
Total water resources per capita (m3/year/capita)	6290		2458		2589	
Total withdrawals (km3/year)	5186		2221		1.3502	
Exploitation index (in %)	4.32		5.70		11.84	
Total capacity of dams (km3)	13,795		0.25		0.5	
Total capacity of dams per inhabitant (m3/inhabitant)	723.09		15.77		113.55	

Source: [6].

Table 1.
Renewable water resources available in 2018 in the three countries.

Internal renewable water resources coorespong to 0.4 km^3/year, which leads to a very high dependency index at 96.5% (**Table 1**) while the total withdrawal estimation regarding Senegal is 2.22 km^3. The exploitation index is relatively low at 5.70% if it is justactaposed to potential of water reserves in the country.

Rural areas and many cities in Mali have to rely exclusively on groundwater as the main source of reliable and safe drinking water while Senegal and Mauritania have to rely on the same for huge tracts of arable land irrigation and livestock watering as well as for the supply of many mines and industries. In terms of total volume of available renewable groundwater, the contrast is sharp between Mali (20 km^3/year) and Senegal (3.5 km^3/year) and Mauritania (0.3 km^3/year).

Regarding the Senegal River the inflows are significant, variable, interannually irregular and in an average year around 20 km^3 while in the wet year of 1924 they reached 41 km^3 in the dry year of 1987 went down to 6.15 km^3 [14] and due to the Sahelian climatic deterioration the average inflow went down to 13 km^3/year. However, user requirements are met due to the water draining by the ricers cris-crossing these countries e.g., the Senegal River. In **Table 1** it is seen that total withdrawals estimation is: in Mali 5.19 km^3/year, in Senegal 2.22 km^3/year in Senegal and in Mauritania 1.70 km^3/year. The exploitation index is relatively low taking into consideration the great potential of water reserves and amounts to 4.33, 5.75 and 14.9% correspondingly.

At the existing socioeconomic circumstances in these three countries, social development invitably causes an increasing demand for water as most national planning initiatives e.g., mining, industry, agricultural development, municipal water supply, energy security, tourism and recreation, and municipal water supply [13]. The demographic and urban growth of these countries exerts strong pressure on the often limited available water resources in these countries.

According to the AQUASTAT database [6], renewable freshwater resources per capita (in m^3) continued to decrease between 1958 and 1962 and 2018–2022 at the level of the three countries. They thus fell from 22,301 m^3 in Mali, 12,538 m^3 in Mauritania and 11,612 m^3 in Senegal in 1958–1962 to only 6290 m^3 in Mali, 2589 m^3 in Mauritania and 2458 m^3 in Senegal in 2017–2022. These results show the tendency of these differences towards a situation first of water stress (below 1700 m^3/inhabitant/

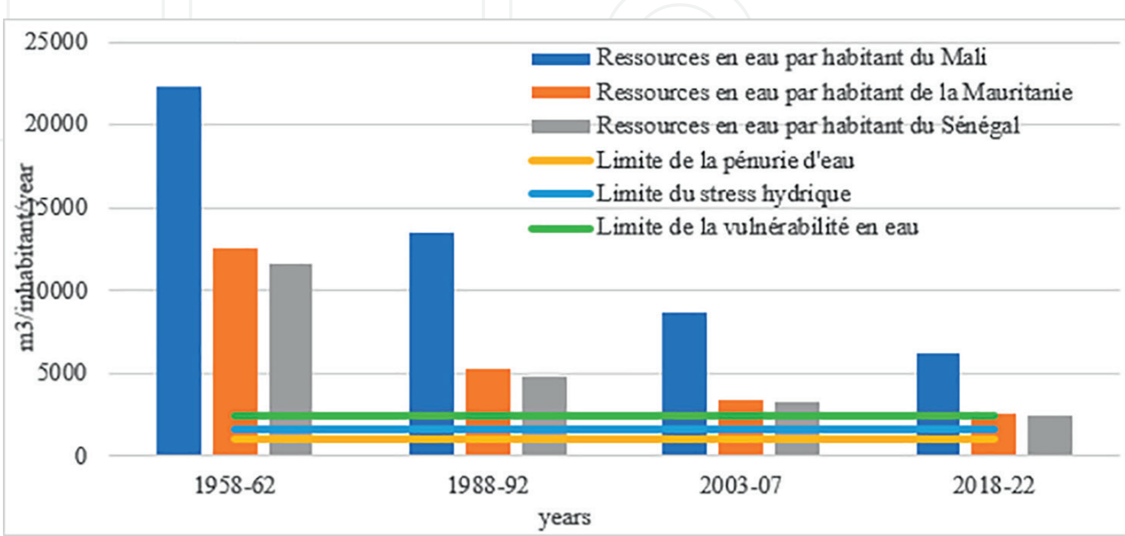

Figure 6.
Evolution of total renewable water resources per capita between 1958 and 1962 and 2013–2017 in the three countries (Source: [6]).

year) and then of water shortage (below 1000 m^3 /inhabitant/year). A country like Senegal is already in a situation of water vulnerability (below 2500 m^3 /inhabitant/year), while Mauritania is not far from such a situation.

As can be seen in the **Figure 6** above in the countries bordering the Senegal river water consumption is increasing at an exponential rate due to population increase leading to the creation of a state of competition for water [15]. According to this these countries will target water uncertainty reduction in-border river flow regulation via dams which is detrimental to the other contesting countries. This leads to peace fracture as high transnational river water import dependent countries e.g., such as Mauritania which is 96.49% dependent, will consider water to be a matter of national security justifying the use of force for its safeguarding [16].

3.2 Shared water systems

Most sub-Saharan Africa freshwater resources are parts of either shared river basins or transboundary watercourse systems. The Senegal River Basin in conjunction with the Organization for the Development of the Senegal River (OMVS) has noted that a strong commitment to regional collaboration must form the basis of the management and protection of these shared systems as the hydrosystem comprised by the Senegal River basin and its tributaries covers a 289,000 km^2 area. The proportions this is shared between Mali, Mauritania, Guinea Conakry and Senegal are 53.5, 26, 11, and 9.5% respectively. The Falémé basin, like the Senegal River, is spread by13,800 km^2 or 47.8% over Mali, 11,500 km^2 or 39.7% over Senegal and 3600 km^2 or 12.5% over Guinea Conakry [17] while Mali and Guinea share the 22,000 km^2 Bafing and the 85,000 km^2 Bakoye basins.

The organization of the Senegal River Basin (OMVS) has as main goal to realize an integrated transnational vision of the Senegal River Basin development where, on the basis of analysis of the basin's water resources/ecosystems, the integration of sectoral objectives will be achieved e.g., hydroelectricity, drinking water and sanitation development, navigation and transport, rural development, mining and industry will be achieved. As seen in **Table 2**, interest in the major components of the OMVS program- energy production, irrigation and navigation-varies according to the riparian country's point of view [18]. Mauritania and Senegal are the two riparian States which exploit nearly 90% of agricultural developments in the basin but whose dependency factor (the total share of water resources produced outside their borders) is the highest in the basin while Mali and Guinea have abundant water resources incommensurably high relative to their agricultural development [19, 20].

Indeed, unlike Mali and Guinea, which border the Niger River basin and have relatively abundant water resources, the Senegal River remains the only source of fresh

Country	Hydroelectric power	Irrigation	Navigation	Flood recession agriculture
Guinea	Potentially high	None	None	None
mali	High	Weak	Very high	Weak
Mauritania	Very high	Very high	High	High
Senegal	Very high	Very high	High	High

Table 2.
Priorities of the riparian States compared to the components of the current OMVS program.

water for Mauritania and Senegal, which exploit nearly 90% agricultural developments in the basin. This situation has led to rivalries for control of the resource, which have resulted in the establishment of a climate of hostility and mistrust between the two neighboring countries for more than two decades now.

In this way the OMVS, in order to manage and develop in a joint way these shared resources, has encompassed a set of instruments specific to this purpose since cooperation is required to achieve sustainable management of the sum total of external resources and as a result e.g., life-improving cross-border hydraulic infrastructures were developed. According to this arrangement, OMVS member countries are obliged to aknowledge its commitments to cooperative management of international waters with its neighbors with goal od promoting the regional interest in terms of peace, security and economic integration.

3.3 Water use in the three countries

While irrigated agriculture is the largest water consumer in these countries water withdrawals vary by country and by sector of activity. Current withdrawals of the irrigation sector in Mali are around 5 billion m^3 in 2006, or 96.4% of the total withdrawal [12], and come almost entirely from mineral resources. Surface water (**Table 3**). In addition, the supply of water to livestock takes about 75 million m^3 industry 4 million and local authorities 107 million (2.06%) in 2006. According to **Table 4** in Senegal (2000), water resources withdrawals were 2221 million m^3 apportioned: for agriculture 2065 million amounting to 93%, for communities 98 million amounting to 4.41% and

Abstraction in millions of m3	**Mali**		**Senegal**		**Mauritania**	
	Value	**%**	**Value**	**%**	**Value**	**%**
Water withdrawal for agriculture (10^9 m3/year)	5075	97.9	2065	93.0	1223	90.6
Water abstraction for industrial uses (10^9 m3/year)	0.004	0.1	58	2.6	31.8	2.4
Water withdrawal for municipalities (10^9 m3/year)	107	2.1	98	4.4	95.4	7.1
Total water withdrawal (sum of sectors) (10^9 m3/year)	5186	100	2221	100	1350.2	100
Progress in water use efficiency	**Mali**		**Senegal**		**Mauritania**	
SDG 6.4.2, Water Stress (%)	8003		11.81		13.25	
SDG 6.4.1, Water use efficiency (US$/m3)	1859		7571		3933	
SDG 6.4.1, Efficiency of water use by irrigated agriculture (US$/m3)	0.047		0.095		0.352	
SDG 6.4.1, Efficiency of water use by industries (US$/m3)	787.1		81.27		47.67	
SDG 6.4.1, Efficiency of water use by services (US$/m3)	58.41		121.5		35.25	
Source: [6].						

Table 3.
Water use by main economic sectors in these countries.

Country	Costs assumed	Benefits withdrawn
Mali	35.3%	• 52% of hydroelectric production • opening up thanks to the navigation pane
Mauritania	22.6%	• 15% of hydroelectric production • 33.6% of the 375,000 ha of land made irrigable
Senegal	42.1%	• 33% of hydroelectric production • 64% of the 375,000 ha of land made irrigable

Source: [21].

Table 4.
Cost and benefit distribution key.

for industry 58 million amounting to 2.61%. Similarly, as seen in **Table 3**, in the case of Mauritania (2000), total withdrawals were 1698 million m^3 of which 1500 million went to agriculture amounting to 88.3%, 150 million went for domestic use amounting to 8.83% and 48 million to industry amounting to 2.83%.

Through the UN-Water Initiative for the Integrated Monitoring of Sustainable Development Goal (SDG) 6, the United Nations is committed to supporting countries in monitoring issues related to water and sanitation as part of the 2030 Agenda for Sustainable Development, and in compiling national data to report on global progress towards achieving SDG 6 [19]. Thus the progress made at the scale of the Senegal River basin towards the achievement of SDG 6 is indicated in **Table 3** which shows the values calculated at the national level for the efficiency of water use. While the efficient use of water resources averages just over US$ 15 /m3 worldwide, the countries of the Senegal River Basin record values below this average. Senegal, which records the highest water use efficiency, among the 3 countries in the downstream part of the basin, is at US$ 7571 /m3, against 1933 for Mauritania and 1859 for Mali. However, the situation remains variable depending on the country. Indeed, for the efficiency of water use by industries, Mali is positioned ahead with 787.1 $US /m3, against 81.27 for Senegal and 47.67 for Mauritania. As for the efficiency of the use of water by the services, Senegal stands in front with 121.5 $US /m3, against 58.41 for Mali and 35.25 for Mauritania [20]. At basin scale, the lowest values in this regard are noted in Mauritania.

3.4 Contributing to climate change adaptation from water storage

As the challenges posed by global warming are increasingly understood, it is widely accepted that water is the primary medium through which the societal stresses of climate change will manifest. Although the exact impacts remain uncertain, in many places, even where total precipitation is increasing, climate change will most likely increase precipitation variability. Undoubtedly, those who will be hardest hit are the poor, who are already struggling to cope with the existing variability. It will be increasingly difficult for them to protect their families, their livelihoods and their food supply from the negative effects of seasonal rainfall, droughts and floods, all of which will be exacerbated by climate change.

According to the Intergovernmental Panel on Climate Change [22], climate change is expected to have an impact on the level and variability of rainfall in Africa. Climate change potentially has a significant impact on both water availability and needs in countries bordering the river. Likewise, it alters the hydrological systems and water resources of the Senegal River Basin and reduces water availability. Monitoring the evolution of runoff coefficients at multi-annual, seasonal and monthly scales over the period 1960–2014 clearly shows changes in runoff dynamics and changes in hydrological regimes [23]. Climate change forecast scenarios indicate that climate change will have the effect sometimes of a gradual decrease in runoff from the 2030 horizon to the 2090 horizon, sometimes of a gradual increase in runoff over the basin [24]. What is certain is that climate change will likely lead to more intense and more variable weather events, and will likely lead to more intense and prolonged periods of drought and flooding. The jointly managed water resources of the Senegal River are at the center of climate adaptation strategies, and improved and expanded water storage capacities create buffer zones for periods of water scarcity [25].

Water storage (in all its forms) has a key role to play both in terms of sustainable development and climate change adaptation water storage (in all its forms) plays a key role. Water storage leads to risk reduction risk and, by providing a buffer zone, reduces population vulnerability by offsetting some of the negative impacts induced by climate change. While climate change may impact any water storage option, in general water storage, as seen in **Figure 3**, leads to the improvement of both agricultural productivity and water security.

By altering both water availability and demand, climate change will affect the need, performance and suitability of different water storage options. In some situations, some storage options will be rendered completely impractical while the viability of others may be increased. Storage in ponds, tanks and reservoirs can also be reduced more quickly due to increased evaporation and/or greater sediment inputs. In addition, large and small dams as well as ponds and reservoirs may be at increased risk of eutrophication and flood damage.

In any case, the externalities associated with the different types of storage are also likely to be affected by climate change. Climate change requires fundamental rethinking of how water resources, and in particular water storage options, are planned and managed. In all situations, maximizing the benefits and minimizing the costs of water storage options will, as in the past (but not commonly), require consideration of a wide range of hydrological, social, economic and complex and interdependent environments. However, unlike in the past, planning needs to be much more integrated across a range of levels and scales with greater consideration of the full range of possible options.

The key to planning and managing water storage is determining current and future needs and making appropriate choices from the suite of storage options available. In a given situation, this requires understanding a range of biophysical and socio-economic issues that influence the *need, the effectiveness* and *suitability* of different water storage options, both in isolation and within systems comprising several types. In the past, there has generally been little explicit consideration of these issues, even for the construction of large dams. For the other options, where the planning is generally less formalized, the needs are generally taken for granted and alternative options are only very rarely considered.

3.5 Water storage infrastructure

3.5.1 Investment in water infrastructure

The lack of storage infrastructure has significant negative social and economic impacts, especially in a drought-prone region where water is inadequately stored [13]. Water storage facilitates the supply of water for domestic and industrial use, irrigation for sustainable agriculture, hydropower generation, infrastructure and job creation, improvement of accessibility of regions where large dams are built, the promotion of ecotourism through fishing, canoeing and tourism, and enabling the sale of water to thirsty regions and communities inside and outside of national borders, which constitutes a strong increase in the revenues of local and national governments [26].

Investment in infrastructure for the development and distribution of water resources has shown significant human and macroeconomic benefits. On the other hand, countries that have limited water storage capacity experience damaging shocks from droughts and floods [25]. Investing in improved water storage to even out access to water during and between rainy seasons and being prepared to support flood management are also primal implements in a flood and poverty reduction strategy. A number of declarations has recognized the important role of dams and reservoirs played in sustainable development: The 2002 World Summit on Sustainable Development, The 2004 Beijing Declaration on Hydropower and Sustainable Development, The 2008 Dams and Hydropower for Sustainable Development in Africa and The Ministerial Declarations of the Fifth and Sixth (2009/2012) World Water Forums [27].

As seen in Article 12 of the joint works agreement there is a "key" (**Table 4**) which determines, on the basis of benefits accrued for the individual country, the distribution of investment and operating costs and operating costs. This phase, limited to consultation alone, consists of allocating quotas (water volumes) to the riparian States for the implementation of national development plans for their respective portions of the river [21].

This legal framework testifies to the fact that the political project of the OMVS goes far beyond mere consultation. It aims at regional integration through the development and pursuit of a basin-wide water resources development plan. *A priori,* it therefore surpasses as much the concept of management at the basin scale (just fixed by the doctrine through the Helsinki rules) that of Integrated Water Resources Management (IWRM), which was only formulated in 1992, at the end of the Dublin Ministerial Conference.

3.5.2 Large dams in the Senegal river basin

The OMVS riparian States invested heftily in billions of m^3 storing dams for the dual purpose of overcoming the inequitable water distribution of water and flood/drought management in the basin. As can be seen in **Table 5** an OMVS data-based plan has been set in motion targeted on the construction of water control 'first generation'structures, the Diama and Manantali dams along with their auxiliary structures, which succeded in their target of water availability in guaranteed all year-round sufficient quantity which supports both agricultural development and natural environmental restoration. Case in point, as seen in [28], the Manantali dam, not only accommodates the storage of 11.3 billion m^3 leading, along with Diama Dam to the irrigation capacity of 255,000 ha but also produces 800 GWh/yearand regularizes river flow at Bakel at 300 m^3/s in Bakel along with river navigation.

In **Table 5** can be seen the next generation hydroelectric works planned by OMVS which, as seen in [19], from 2012 onwards targeted the increase the energy supply and full control of basin waters via major hydroelectric dam construction projects. For example, two secong generation structures built along the river, the

Country	Barrage	Watercourse	Storage capacity (Millions of m^3)	Installed power (MW)	Functions
Mali	Manantali	Bafing	11,300	200	Hydroelectricity + Regualtion
	Felou	Senegal	0 (over the water)	70	Hydroelectricity
	Gouina	Senegal	0 (over the water)	140	Hydroelectricity
	Mussala	Faleme	3000	30	Hydroelectricity + Regualtion
	Bindougou	Bafing	2000	49.5	Hydroelectricity + Regualtion
	Boudofora	Bakoye	to be determined	30	Hydroelectricity + Regualtion
	Marela	Bakoye	3000	21	Hydroelectricity + Regualtion
	Badoumbe	Bakoye	10,000	70	Hydroelectricity + Regualtion
Guinea	Koukoutamba	Bafing	3600	280	Hydroelectricity + Regualtion
	Boureya	Bafing	5500	160	Hydroelectricity + Regualtion
	Balassa	Bafing	0 (over the water)	180	Hydroelectricity
Senegal	Gourbassi	Faleme	2100	30	Hydroelectricity + Regualtion

Table 5.
Dams and dam projects in the Senegal River Basin and their storage capacity.

currently operational Félou dam and the under construction Gouina dam, have no water storage capacity. These two dams are said to be second generation structures. Finally, the other planned works (known as third-generation works) in the Senegal River basin consist of two run-of-river hydroelectric works and eight multi-purpose reservoir works. A good part of these structures will therefore be dams with water storage capacity (Badoumbé, Boureya, Moussala, Gourbassi, etc.). Among these planned storage structures, some are in the funding research phase (Koukoutamba, Boureya and Gourbassi) and others are in the study and identification phase (Badoumbé).

Insofar as these developments will create a water reservoir, as is the case for the Gourbassi project (storage volume of 2.1 billion m3 of water), they will contribute to better water control, flowing further downstream and which are not currently controlled (Falémé and Bakoye). They will therefore play an important role in the fight against floods, but require rigorous management and coupled with that of Manantali. On the other hand, run-of-river hydroelectric dams (Félou and Gouina) will not play any role in flood risk management because, being used exclusively for hydroelectricity production, they do not have a sufficient storage volume to rolling floods. In the estuary part, it is planned to extend the embankments of the river upstream from Rosso as far as Dagana, to enable the level of management of the Diama reservoir to be raised to the 250 cm IGN level in the dry season. The fresh water reserve thus created would meet the water needs of 120,000 ha of irrigated crops in the region.

On the technical level, the two major challenges ahead concern the satisfaction of energy and food demands. It is indeed expected that these data will experience an exponential evolution under the effect of the strong demographic growth of the basin: with a rate of 2.7%; the population is expected to double every 25 years. The potential for hydroelectric production and irrigated cultivation is considerable (1200 MW; 375,000 ha) and should make it possible to meet these demands, but this requires developing its potential, which has so far been largely under-exploited: only 25% in the first case, just over 30% in the second. This is the purpose of the medium- and long-term planned projects presented in **Table 5** (the map locating the second-generation projects can be consulted in **Figure 7**). The challenge of the success of these developments does not depend solely on technical factors. The challenge lies in reconciling competing uses, between tradition and modernity, between regional economic integration and sustainable local development. With regard to the first point, the orientation towards multi-use projects responds to the concern of the riparian States to share the benefits according to the interests of each. However, it appears that certain aspects of the OMVS program have suffered from competition between uses for funding. As a result, some States have not obtained satisfaction. One thinks in particular of Mali which had obtained that its opening up be ensured by means of the "navigation" component, from which we have seen that, for lack of funding, nothing or almost nothing has been achieved.

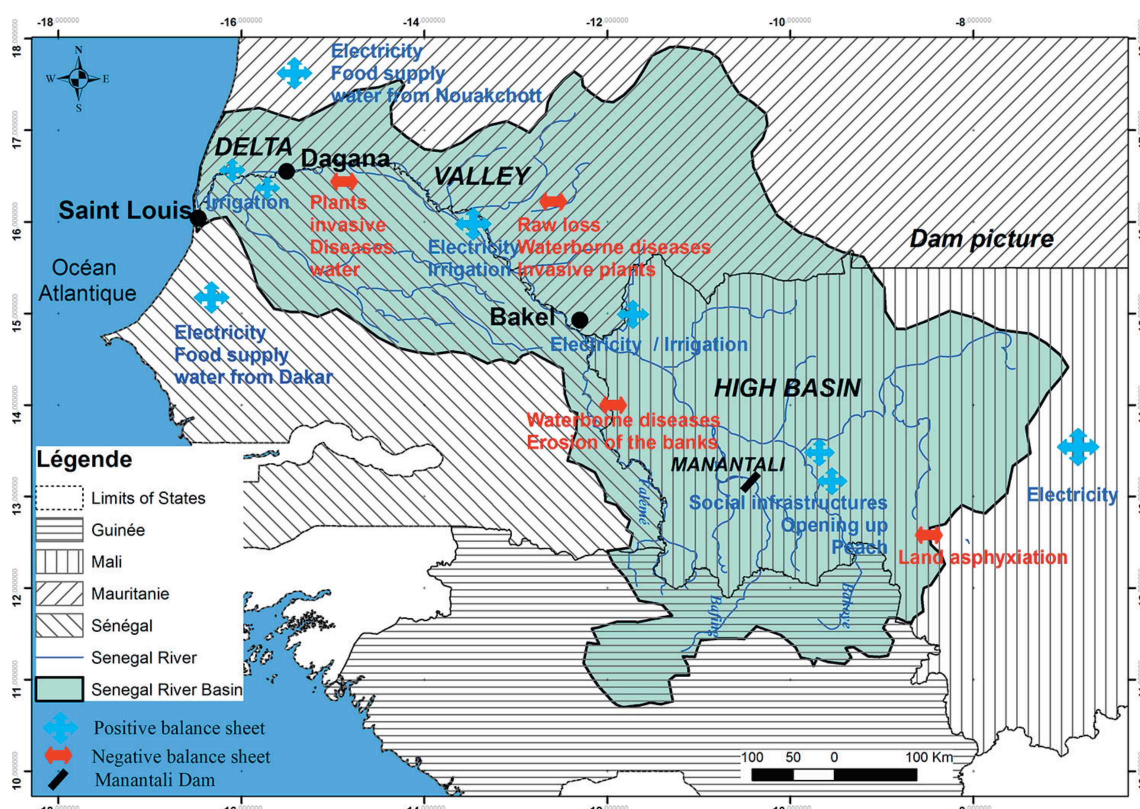

Figure 7.
The Senegal River basin: Perceptions of the results of the program according to the zones of the basin and at the level of the countries bordering the river (Source: [29] modified).

3.6 Water storage capacity

Improved water resource management and water storage capacity makes the economy more resilient to external shocks, such as variability and drought, and thus provides a stable and sustainable basis for productivity and food production and industrial scale [13]. The riparian states, within the framework of the OMVS, continue to develop a large amount of water storage infrastructure, which still needs to be increased in order to improve the water storage capacity in the basin. This storage capacity is 11,300 million m^3 at the level of the Manantali dam and will be around 10,000 million m^3 for Badoumbé, 5500 million for Boureya, 3600 million for Koukoutamba, 3000 million for Moussala and Maréla, 2100 million for Gourbassi and 2000 million for Bindougou. These various facilities should make it possible to store nearly 23 billion m^3 of water, and thus achieve almost total control (more than 97%) of the flows of the Senegal River, by doubling the storage capacities of Manantali and Diama together [19, 30, 31].

At riparian state national level, the largest storage capacity of 13,790 million m^3 is in Mali, the lowest at 250 million m^3 in Senegal while in between lies Mauritania at 500 million m^3. As seen in **Table 1**, in terms of total capacity of dams per inhabitant, Mali is again at the top with 783.5 m^3/inhabitant, Senegal at the bottom with 16.52 m^3/inhabitant and in-between lies Mauritania with 122.9 m^3/inhabitant. Regarding planned storage structures, as seen in **Table 5**, Mali will get the largest one at 29,300 million m^3, Senegal a 2100 million m^3 one and Mauritania none while national rainwater harvesting programs should be supported in all riparian states.

3.7 Water storage for multiple uses

The purpose of water storage includes "water supply for domestic use, industry, livestock and irrigation, hydropower generation, flood and drought protection, fishing and aquaculture, transportation, flood recession cultivation and grazing sites, sinks for pollutants, biodiversity-based tourism, landscape or sporting activities, cultural and religious uses, and biological diversification sites" [32]. According to [13] rural area domestic supply water is used for various samall scale purposes e.g., small businesses, vegetable gardens and stock watering besides cooking and washing. In the case of the Senegal River Basin, water storage is multi-purpose to be distributed in food production irrigation and fisheries, power generation, industrial, drinking, environmental services and mining water supply, as well as in flood management and drought mitigation. In order of importance hydroelectricity production, irrigated agriculture, navigation and other minor activities e.g., fishing and breeding, water supplyand ecological needs are the the main areas of development associated with storage structures.

3.7.1 Hydroelectricity

Throughout the OMVS area, access to electricity is a real obstacle to development. The member countries of the OMVS are, in their entirety, confronted with shortages and growing demands for energy. And yet the watershed has the hydroelectric potential necessary to meet the needs of its populations. Current electricity production represents 16% of the basin's production capacity. The current demand of the riparian states of the basin is estimated at 4400 GWh/year. If the growth rate is maintained on all the Member States' electricity networks, energy needs will be around 15,000 GWh in 2040. The Manantali power station, which is currently the only facility operating for energy production can meet 18% of the energy needs of Mali, Mauritania and Senegal [19].

3.7.2 Drinking water supply (DWS)

The member states of the OMVS and more particularly the local populations of the basin mostly use groundwater for their drinking water supply. The weight of abstractions for the DWS is low compared to the volumes of water available on the river. The rate of access to drinking water in the states bordering the river is still very low. Studies carried out by the OMVS in 2008 showed that on average nearly 25% of the population of urban towns and nearly 45% of the population living in rural areas do not have access to drinking water meeting the Objectives of the Millennium Development Goals (MDGs). To date, surface water from the basin is limited to supplying the growing urban population of the cities of Conakry, Bamako, Nouakchott and Dakar. Withdrawals intended for the agglomerations of Dakar from Lake Guiers and Nouakchott from the Aftout Es Sahel, estimated at 27 hm3 per year and water withdrawals intended for the industrial and mining sector, currently estimated at around 40 hm3 per year in the basin, remain negligible compared to withdrawals from irrigated agriculture.

3.7.3 Irrigation

Agriculture is the main activity developed in the basin and irrigation is made possible thanks to the regulation of the hydrological regime since the commissioning of the Manantali and Diama dams. It was the trend deterioration in climatic conditions observed from the 1970s that led the neighboring countries to adopt irrigation as the preferred means of intensifying and securing agricultural production. Irrigated agriculture is thus the sector of activity that consumes the most water in the basin. With 20,000 ha in Guinea, 10,000 ha in Mali, 125,000 ha in Mauritania and 240,000 ha in Senegal, the potential for irrigable land is estimated at 395,000 ha over the entire Senegal River basin [33]. Current surface water withdrawals for irrigated agriculture amount to approximately 1.88 km3 per year, with a peak flow of around 110 m3/s in August [34]. The developed areas are today estimated at 120,000 ha with actual exploitation of 60%. The commissioning of the Manantali dam also made it possible to increase Mali's agricultural potential to more than 10,000 ha/year [35]. Senegal and Mauritania share more than 90% of agricultural development in the basin. The OMVS aims to increase agricultural holdings to 255,000 ha by 2025 in order to improve and secure the productive base of the Senegal River basin.

3.7.4 Navigation

Another major objective of the commissioning of the Manantali dam is to create an uninterrupted waterway (12 months/12), from Saint-Louis to Kayes in Mali over a total distance of 900 km. As Navigation is currently very limited on the basin while there is a desire for expansion, there is currently no concrete plan for its development in the basin. However, as seen in [36], it is foreseen to implement a plan for the development of a 55 m wide navigable channel 55 m wide connecting the towns of Ambidédi (43 km downstream of Kayes in Mali) and Saint-Louis at the mouth of the river. River transport would make it possible to open up priority development areas such as the current and future sites of dams, agricultural and mining production areas, towns isolated from the Atlantic Ocean and between them, and to facilitate the transport of merchandise. Although being a non-consumptive request, navigation still requires a minimum draft of 300 m^3/s at Bakel.

3.7.5 The mines

The mining resources of the river remain very little exploited, being limited to the mines of Mali. These weaknesses are explained by the constraints linked to the permanent availability of water, energy and means of transport. The Falémé mining project relied on the supply of cheap hydroelectric power from the Manantali power station. The reality today is that the energy produced by the dam is intended to satisfy other more pressing needs. The current water needs of the mining sector are estimated at 13 Mm3. They will reach a gross volume of 235 Mm3/year by 2025, 85% of which will be reinjected into the ore processing process. These volumes, although very modest (representing less than 5% of the volumes of water available in the basin) are totally taken from the tributary of the Falémé which, due to a lack of regulation, can restrict access to water during the low water season. The completion of the future river navigation project would propel the mining sector, which could in the long term be one of the basin's development poles. The commissioning of the future development of Gourbassi, although making it possible to reduce the energy deficits of this sector, will not have significant impacts on the reduction of water deficits in the sense that the increase in exploitations is essentially concentrated on the upstream part of the plant.

3.8 Water needs

On the river, irrigation is the sector consuming the most water. The developed perimeters are mainly sown with rice. There are also 10,000 ha of industrial crops [19]. Current irrigation water needs are estimated at 1437 Mm3/year, mainly distributed between Senegal and Mauritania. The combined requirements of Senegal and Mauritania, located on either side of the valley and the delta, represent more than 90% of the total demand of the four countries. The objective of increasing the irrigated area to 255,000 ha will bring irrigation water needs to 5200 Mm3/year by 2025. 90% of agricultural developments in the valley and the delta. The development of irrigation will still remain very low in the upper basin. The areas developed in this part of the basin will represent less than 10% of the total irrigated area. Taking navigation into account in the development objectives of the valley will require having a guaranteed minimum flow of 300 m3/s at Bakel. The combined needs of drinking water supply, livestock and mining are very low and account for less than 10% of the basin's water needs. Demands remain constant throughout the year.

The valley and the delta concentrate more than 90% of low water support requests. The management of resources in this part of the basin is therefore a major challenge for the socio-economic development of the basin. Particular attention will be paid to the Manantali reservoir and later to that of Gourbassi for their locations in relation to the valley and the delta, but also the importance of their mobilizable volumes and which constitute a key variable for low water level support at the level of the valley and the delta and for the overall management, present and future, of the waters of the river.

On the legal level, the Charter specifies the principles which must govern the distribution of water resources (and this in a more detailed manner than the New York Convention since it is a question here of governing a specific situation, and not of establish a framework agreement for the current distribution of the resource by State and by sector (**Table 6**).

3.9 Case study of the large Manantali dam on the Senegal river

The Manantali dam is located on the Bafing River, the main tributary of the Senegal River, 90 km upstream from Bafoulabé (**Figure 7**). Built between 1982 and 1988, the Manantali dam consists of a dam 1460 m long and has a height of 66 m at the foundation. At the IGN filling level of 208 meters, its reservoir has a capacity of 11.3 billion m^3 and covers an area of 477 km^2 [37]. At its minimum operating level (187 m IGN), the reservoir has a volume of 3.4 billion m^3 and covers an area of 275 km^2. The Manantali dam regulates the flow of the Senegal River and makes it possible to irrigate a potential 255,000 ha of land and, in the long term, should allow the navigability of the river over approximately 800 km from the mouth. Added to this is an energy production function [29, 38]. For this, a 200 MW power station was installed and a network made up of 12 transformer stations and approximately 1650 km of high voltage transmission lines of 225,150 and 90 kV, interconnected with the networks of Mali, Mauritania and the Senegal [39].

The Manantali dam is a project multifunction which offers many huge benefits such as flood prevention and surface water availability, power generation, navigation, aquaculture, ecological protection, development-oriented restocking, food self-sufficiency, water transfer and supply in neighboring countries and irrigation [40–42]. Good that the usefulness of the dams is not called into question [43] in intertropical countries whose rivers, while having respectable annual flows, experience wide seasonal and interannual variations, their erection involves a set of irreversible changes. Despite the importance of the advantages, the Manantali dam has its own disadvantages. The impoundment of the Manantali and Diama dams, as well as the resulting developments (embankments, hydro-agricultural developments, etc.) have had negative impacts on the functioning of certain ecosystems in the basin. These impacts are numerous and quite diversified and boil down to the modification of the quantity and quality of water, the pollution of groundwater, the proliferation of aquatic plants, drainage, sedimentation, recurrent diseases), the effect on local culture and the traditional economy [40, 44]. Besides, soil erosion increased, causing collapses of banks and landslides.

Sector/State	Mali	Mauritania	Senegal
Agriculture	1319	1499	1251
Domestic uses	27	101	68
Industry	14	29	41
Total	1360	1630	1380

Table 6.
Current distribution of water resources by State and by sector (in millions of m^3).

Point sight environmental impacts, the dam of Manantali show the proof that there is more advantages than disadvantages. So, he may well be compatible with an ethic of sustainable development and preservation from ecological balances.

4. Conclusions

The variability of precipitation is an important development factor and translates directly into a need for water storage. In Africa, the existing variability and insufficient capacities to manage it are at the root of much of the prevailing poverty and food insecurity. These continents are expected to experience the greatest negative impacts of climate change. By making water available at times when it would not be naturally available, water storage can significantly increase agricultural and economic productivity and improve human well-being. Water storage capacity per person is often cited as an indicator of water security and a measure of large and small scale water infrastructure development [45]. Well-planned and well-managed water storage infrastructure is important to provide a safe and secure water supply for households, agriculture and industry.

In the past, water resources planning has tended to focus on large dams, but dams are only one of many possible water storage options. Other options include natural wetlands, underground aquifers, ponds and small reservoirs. The type of storage to be used in a given location should be suitable for the intended use. Under the right circumstances poverty reduction may benefit by the contribution of each option, while neither is a complete solution since their benefits carry costs and location altering influences poverty reduction in a different way.

There has been very little systematic analysis of alternative storage options in terms of their role in climate change adaptation and poverty reduction. While large dams are the result of central planning and are part of an integral scheme, smaller dams, which are not, result in a piecemeal structure based on local initiatitive and the resulting non-integrated minimal planning based on incomplete data management, erroneous local stakeholder and water resource authorities' interactive communication leading to the expected result of non-optimal investments.

Improved water storage capacity and water security are particularly required in climatic zones characterized by low rainfall and high rainfall variability, such as Mali, Senegal and Mauritania. One of the purposes of water storage in the Senegal River basin is the production of hydroelectricity. Future population growth, combined with climate change, will increase the importance of water storage in many developing countries such as OMVS member countries. However, as water resources are increasingly used and climate variability increases, planning will become even more difficult. Without a better understanding of which types of storage are best used under specific agroecological and social conditions, and without much more systematic planning, there is a risk that many water storage investments will not produce the expected benefits. In some cases, they can even make the most unpleasant impacts of climate change worse.

The need for water storage to support socio-economic development in the countries bordering the Senegal River cannot be overstated. Infrastructure development and management strategy applied in water inbestment is the basic OMVS policy aimed at the support of economic development. Within the OMVS framework these three countries have already invested a lot in the development of the Manantali, Diama and Félou water storage infrastructures in the Senegal river and as there clearly

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exists more potential for additional infrastructures since these existing dams cannot capture and control all the potentially available water, the OMVS plans for its future exploitment via the programmed dam projects of Koukoutamba, Gourbassi, Bouréya, Balassa and Badoumbé.

Current research aims to better understand water resources and their storage under different social and ecological conditions. This will provide information on the potential impacts of climate change on water supply and demand; the social and environmental impacts of different storage options; the implications of scaling up small-scale interventions; and the reasons for the success/failure of past storage programs. Systematic methods for evaluating the suitability and effectiveness of different storage options are being developed to aid in planning and to facilitate comparison of storage options, individually and within systems.

Conflict of interest

The author declares that there is no conflict of interest.

Author details

Cheikh Faye
Department of Geography, U.F.R. Sciences and Technologies, Assane Seck University of Ziguinchor, Geomatics and Environment Laboratory, Ziguinchor, Senegal

*Address all correspondence to: cheikh.faye@univ-zig.sn

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