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Physical Characterization and Evaluation of the Water Potential of the Watershed of the Ferlo Fossil Valley, Senegal: Louga Area

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Abstract

This study is an evaluation of the water potential of the Ferlo fossil valley in the Louga area in Senegal. It consisted in determining the volume of water that could be mobilized at the level of a confluence point of the waters according to the flow lines, where a dam would be placed to create a reservoir. This volume of mobilizable water was compared to the average water consumption of the area in order to evaluate its adequacy or not. To do this, a delineation, physical characterization and mapping of the Ferlo watershed was done using Google Earth, Global Mapper and Arc GIS softwares. A catchment area of 28,754 sq·km was obtained with a perimeter of 976 km, an average slope of 0.52% and a hydraulic length of 336 km. Then the decennial runoff of the watershed was calculated using the CIEH method, this flow is estimated at 1120 cm/s. On the basis of this flow, the annual volume of water that can be mobilized was estimated at 11,089,758 cm per year with a solid deposits of 93 cm per year. The conclusions reached are that there is a lack of mobilizable water resources in the area and that the entire fossil valley needs to be rewatered to provide a sustainable alternative water source.

Keywords

Ferlo, Fossil Valley, Watershed, Dam, Water Resources, Revitalization

1. Introduction

Integrated water resource management (IWRM) is an essential part of any country's development policy, especially for an emerging country like Senegal.

Water is a strategic resource that is the object of great covetousness in Sahelian countries plagued by recurrent droughts. Indeed, as water needs and uses increase, so do the difficulties of accessing this resource [1]. Water has become all the more precious in this context of climate change, which threatens the sustainability of the resource. Various solutions are being developed by governments to adapt to these changes. Senegal's FVRP (Fossil Valleys Revitalization Program) has been on the table ever since it was first mooted in the 1980s. The idea behind this project was to make better use of the river water (Senegal River) that flows into the sea [2].

In concrete terms, the program consists of replenishing several dead valleys in the interior of the country by transferring water from the Senegal River. The project began in 1988 with a test phase limited to the lower Ferlo valley (between Keur Momar Sarr and Linguere) [3]. This test phase led to the return of a more or less permanent water surface between Keur Momar Sarr and Doundodji at the end of the 1990s.

The Louga region has a very high surface water potential. It has the country's largest surface water reserve. The Lake "Lac de Guiers", with a surface area of 17,000 ha at low water and 30,000 ha at high water, and a storage capacity estimated at between 600 and 800 million cm per year [4].

The aim of this study is to physically characterize the watershed area of the entire Ferlo valley in order to calculate its runoff rate and the volumes of water that can be mobilized, and then to compare these with the area's water requirements for different uses. The results obtained would confirm the need to re-water the entire Ferlo valley.

2. Material and Methods

2.1. Material

2.1.1. Geographic Location

The Senegalese Ferlo belongs to the Sahelian region of West Africa, a strip of land that forms a transition, both climatically and biologically, between the Saharan domain to the north and the Sudanian domain to the south. It is a bioclimatic entity defined primarily by its arid to semi-arid tropical climate, controlled by the Gulf of Guinea monsoon and the maritime and continental trade winds [5].

This region's name is due to a small river in the area (the Ferlo). The Ferlo aeria touches on various regions of Senegal: Saint-Louis, Louga, Matam and a small part in the northern zone of Tambacounda region. **Figure 1** shows a location map of the Ferlo area.

2.1.2. Relief and Soils

The Ferlo is a fossilized valley, its relief formed by a series of low plateaus with altitudes of no more than 15 m. The soils in this zone are poorly developed, with red soils in sandy areas, brown soils and tropical ferruginous soils with little leaching. The area thus belongs to the sandy Ferlo, characterized by a gently

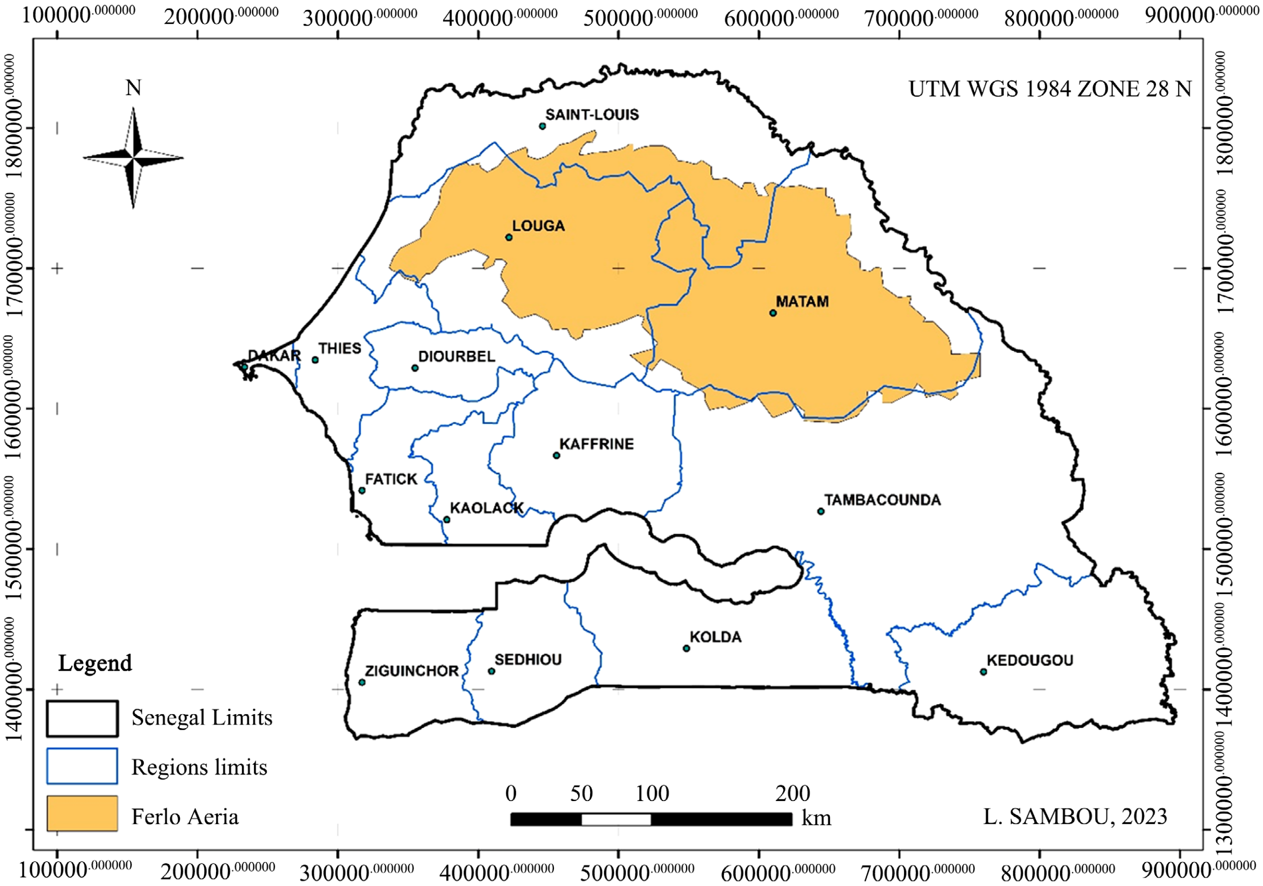

Figure 1. Location of the Ferlo area in Senegal.

sloping topography with light-brown, tropical subarid soils formed from clay-poor sandy materials. [6].

2.1.3. Climate

The Ferlo has a Sahelo-Sudanian climate characterized by a short rainy season from July to September or October with rainfall varying between 300 and 400 mm [7] [8]; a long dry season with temperatures varying between 35˚C and 40˚C. The very high climatic variability characteristic of this region refers more specifically to the rainfall hazard. Here, climate change is likely to result in highly irregular intra- and inter-annual rainfall, accelerating the degradation of vegetation cover and promoting soil erosion, thus triggering desertification mechanisms [9].

2.1.4. Hydrography

The Ferlo is a fossil valley: in other words, it is traversed by a river that flows at depth. Several branches form at Linguere, joining "Lac de Guiers" lake before joining the Senegal River. Long used as a rainy-season pasture due to the absence of permanent water points before the 1950s, the Ferlo is today crossed by a fossilized hydrographic network [10] and is subject to permanent exploitation, made possible by the installation of numerous drills in the rangelands.

2.1.5. Vegetation

The dryness of this region and its morpho-pedological characteristics explain the fragility and precariousness of its forage resources. The pseudo-steppe in the north evolves towards savannah in the south, but with a good representation of the shrub layer and annual grasses. In the south-east, the vegetation takes the form of mosaics, sometimes quite dense, and scattered clumps of annual grasses that die out with the cessation of rainfall [10].

2.2. Methods

2.2.1. General Methodology of the Study

This study began with a literature search on the Ferlo Valley and the FVRP to gain a clear understanding of the context. The literature search also covered tools and methods for characterizing watersheds and calculating runoff.

A search for rainfall data for the area was also carried out at the Senegal National Civil Aviation and Meteorology Agency.

All the information and data obtained was then processed using a Windows computer as the main working tool, and software such as:

- Google Earth for zone location and visualization.
- Global Mapper and Arc GIS for watershed delimitation, mapping and physical characterization.

An evaluation of potential runoff flows was also carried out, followed by an estimate of the volumes of water that could be mobilized at the dike site.

2.2.2. Global Mapper Software Overview

Manual delineation of watersheds on topographic maps and conventional morphometric analyses were the very first quantitative measures used to define watershed geomorphology [11]. Nowadays, software such as Global Mapper makes it possible to do this work faster and more accurately using Digital Terrain Models.

Global Mapper is a mapping software package developed by BLUE MARBBLE GEOGRAPHICS to produce digital terrain model (DTM) maps, flow simulations, zoning maps and delineations of watersheds and sub-watersheds in a given location. Global Mapper also provides the physical characteristics of watersheds, such as surface area, perimeter, average slope, hydraulic length and more.

Figure 2 illustrates the Global Mapper interface.

The various stages on Global Mapper are summarized below:

- Locate the study zone;
- Download world imagery to confirm location;
- Download topographic datas (DTM SRTM);
- Generate the topographic contours of the aeria;
- Generate sub-watersheds and streams;
- Delineate the watershed by grouping sub-watersheds according to the outlet identified at the point where the waters meet;
- Calculate morphometric characteristics (surface, perimeter, slopes, etc.);

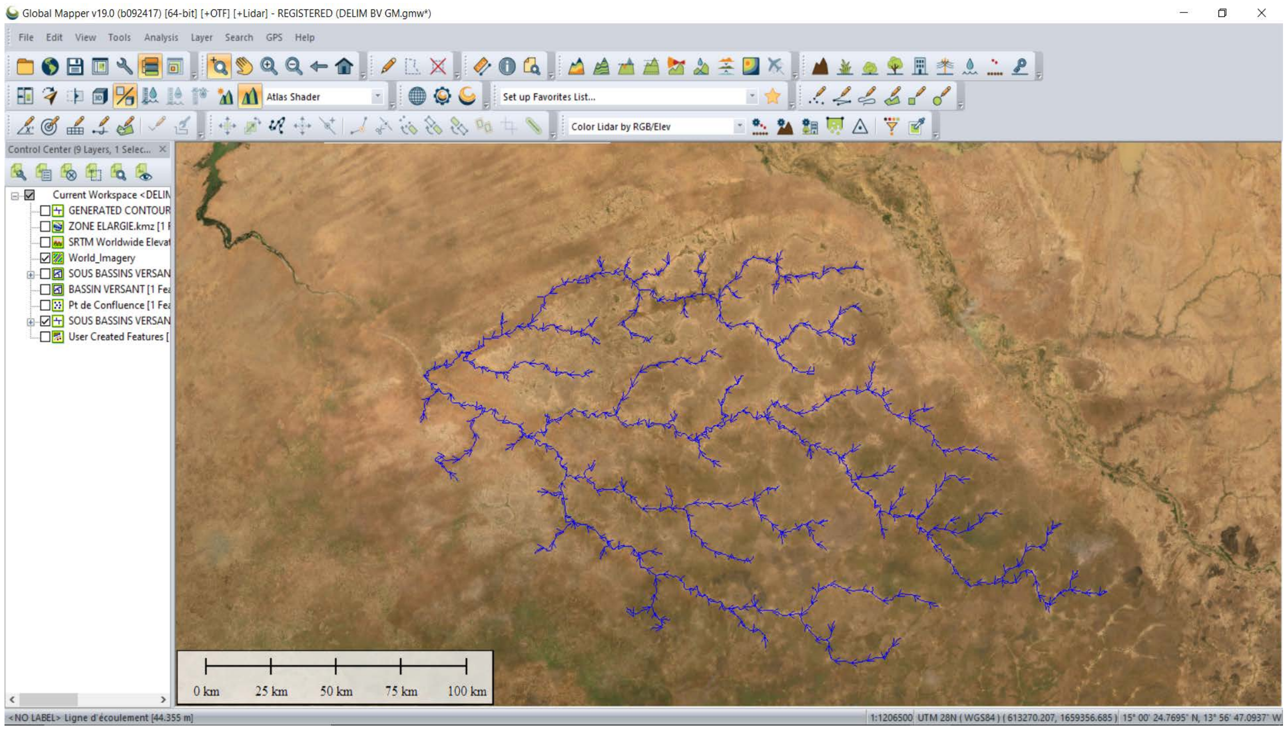

Figure 2. Global Mapper software interface.

- Display characteristics and export them as a table;
- Export necessary layers on shapefile format for the mapping on Arc GIS.

2.2.3. Arc GIS Software Overview

Arc GIS is a suite of geographic information system (or GIS) software developed by the American company ESRI (Environmental Systems Research Institute).

In general, the software contains numerous mapping modules and very useful functions in a number of fields, such as hydrology, topography, urban planning, etc. We are using it here to map the Ferlo area and the Ferlo watershed.

The various stages of work on Arc GIS are summarized below:

- Import on Arc Map de different shapefiles from Global Mapper;
- Do the symbology of each layer;
- Insert the map elements (legend, scale, orientation, coordinates grid, projection system and title);
- Export the map as an image.

Figure 3 illustrates the Arc GIS Arc Map interface.

2.2.4. Flow Estimation Methods

Determining flood flows is essential for assessing the volume of water that can be mobilized. Various methods can be used to determine the flow at the outlet of a watershed. In this study, we use the Office for Overseas Scientific and Technical Research (ORSTOM) method and the Interafrican Committee for Hydraulic Studies (CIEH) method, which are often used in hydrological studies of retaining dams in sub-Saharan Africa.

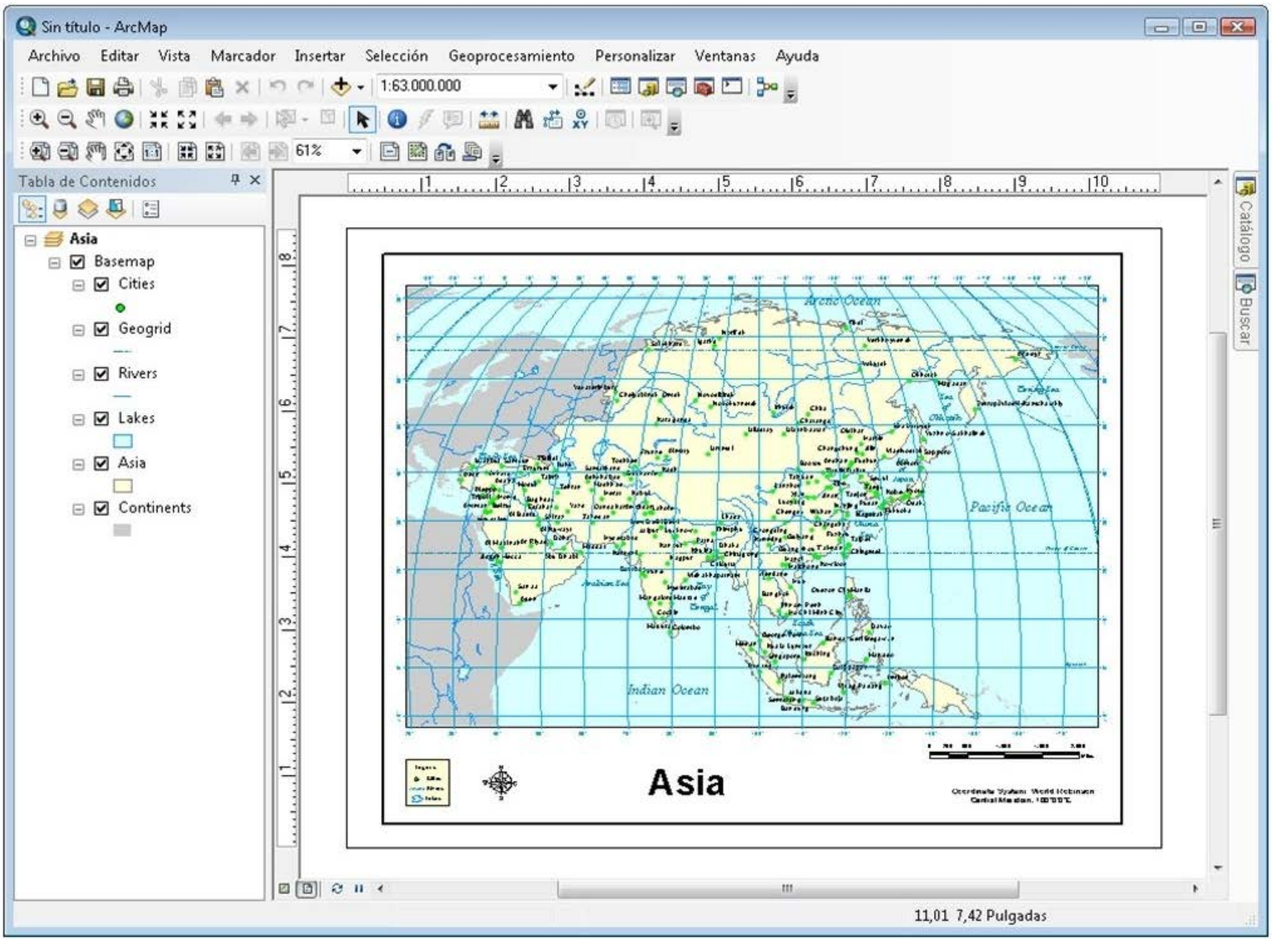

Figure 3. Arc Map software interface.

1) ORSTOM method

This method applies to catchments of less than 1500 sq·km in West Africa. Beyond this limit, the authors consider that it becomes difficult, if not impossible, to determine the decadal-frequency rainfall from the point shower of the same recurrence [12] [13].

$$Q_{10} = (1.15 \text{ à } 1.20) \times \frac{A \times P_{10} \times K_{r10} \times \alpha_{10} \times S}{T_{b10}} \quad (1)$$

Q_{10}: Total decadal frequency runoff flow;

α_{10}: peak coefficient;

A: coefficient of attenuation;

P_{10}: decennial daily rainfall in mm;

K_{r10}: runoff coefficient corresponding to the ten-year flood as a percentage (%);

S: watershed surface aeria in sq·km;

T_{b10}: base time corresponding to the ten-year flood.

These various parameters are determined using abacuses or formulas. In many cases, only α_{10} can be considered a constant.

2) CIEH method

The method developed by CIEH is based on the fundamental principles of statistical studies using current data and measurements. This method, established by PUECH & CHABIGONNI in 1983 and revised in 1994, is based on the initial statistical study of 162 watersheds with surface areas ranging from 0.07 to 2500 sq·km, and on 414 watersheds during the 1994 revision, for annual rainfall ranging from 100 to 2500 mm [12] [13].

The ten-year recurrency flow (Q_{10}) in cm/s is given by Formulas (2) and (3):

$$Q_{10} = a \times S^{s} \times P_{an}^{p} \times I_{g}^{i} \times K_{r10}^{k} \times D_{d}^{d} \quad (2)$$

a, *s*, *p*, *k* and *d* are coefficients to be determined.

S: watershed surface aeria in sq·km;

I_g: slopes global index in m/km;

P_{an}: average annual rainfall in mm;

K_r: coefficient of runoff in percentage (%);

D_d: drainage density in km^{-1}.

The list of parameters to be used is not exhaustive and depends on the calculation model used. These coefficients are determined using a multiple linear regression method, taking into account several variables. In a study of sub-watersheds in Mali and Senegal, Albergel and *et al.* (1991) selected the first three parameters as the most significant, with the coefficients shown in Formula (3), to ensure that the formula was appropriate for the area studied [14]:

$$Q_{10} = 131 \times S^{0.68} \times P_{an}^{-0.68} \times I_{g}^{0.56} \quad (3)$$

For our study, the watershed flow will be calculated for a 10-year return period (decennial flood), given the scarcity of rainfall in the area and in order not to overestimate the quantities of water that can be mobilized. We will use the result of the applicable method according to the results of the delimitation and characterization of the watershed, since the ORSTOM method is restricted to an area of less than 1500 sq·km.

2.2.5. Methods for Estimating Reservoir Inflows

1) Water inflow to the reservoir

The ten-year flood volume that can be mobilized at the reservoir is given by the Formula (4) [12]:

$$V_{10} = Vr_{10} + Vret_{10}$$

With

$$Vr_{10} = A \times P_{10} \times Kr_{10} \times S \quad \text{et} \quad Vret_{10} = Qret_{10} \times Tb_{10} \quad (4)$$

For the Sahelian zone, the following Formulas (5) and (6) can be found:

For an *I* infiltrability index:

$$V_{10} = \left(A \times P_{10} \times Kr_{10} \times S\right) + \left(0.029 \times Q_{10} \times Tb_{10}\right) \quad (5)$$

For a *P* infiltrability index:

$$V_{10} = \left(A \times P_{10} \times Kr_{10} \times S\right) + \left(0.056 \times Q_{10} \times Tb_{10}\right) \quad (6)$$

2) Solid input to the reservoir

Because of the difficulties involved in measuring solid transport, in suspension and by bottom scouring, data concerning this section should be treated with great caution. Some authors (and particularly C PUECH in his book "Methods and references for the design and analysis of hydro-agricultural schemes" Volume 1 Hydrology of small dams—CIEH, 1984) reduce the problem of reservoir silting to the determination of two terms [15]:

- Annual specific degradation, *i.e.*, the quantity of material likely to land in a reservoir each year.
- The number of years required to fill a reservoir in proportion to its useful volume.

Gottschalk established the equation given by Formula (7):

$$D = 260 \times S^{-0.1} \tag{7}$$

D: Specific degradation (volume of solids) in cm/sq·km/year;

S: Watershed surface area in sq·km.

3. Results and Discussions

3.1. Watershed Delimitation and Physical Characterization

Figure 4 shows the map of the Ferlo watershed, produced using Arc GIS after delimitation and characterization using Global Mapper software.

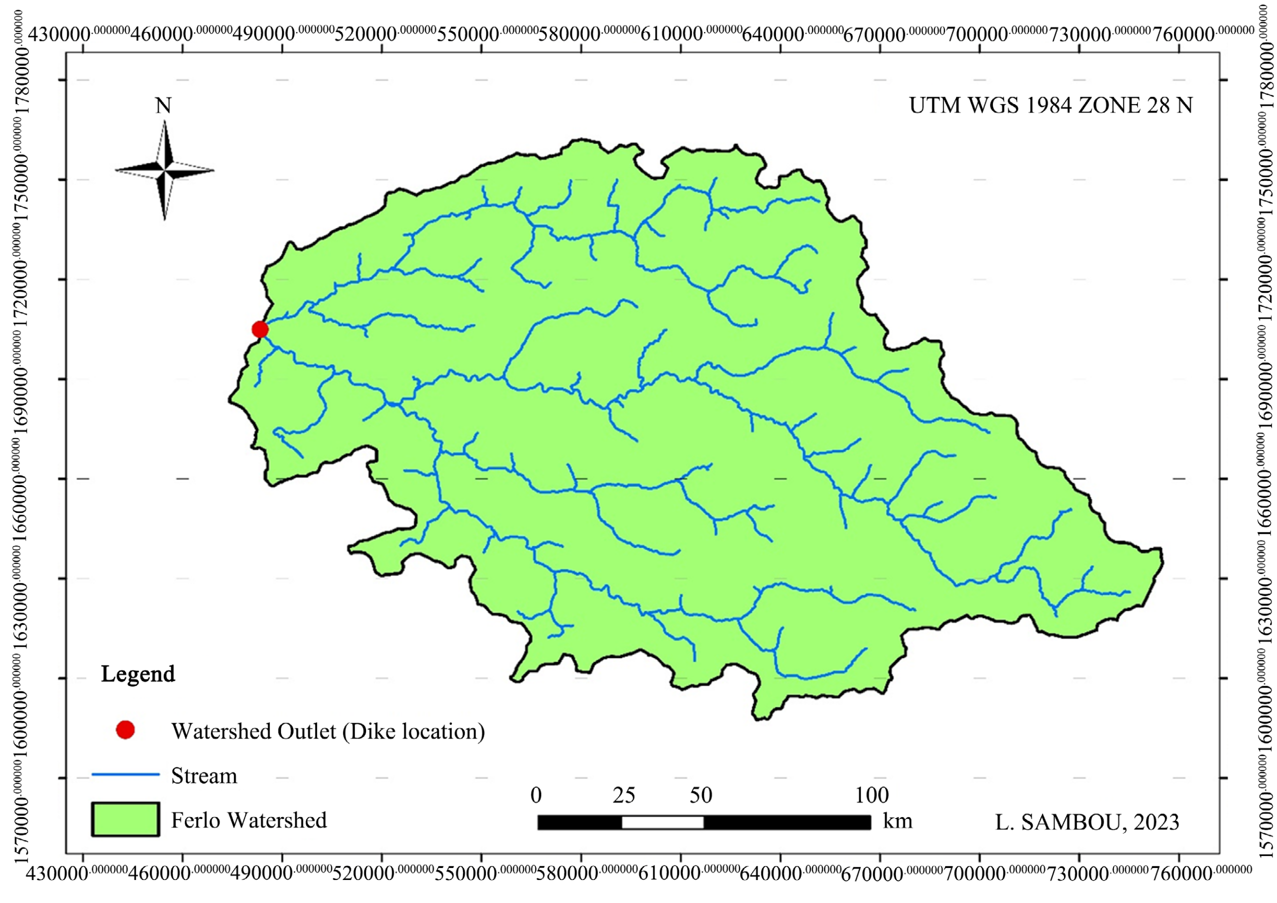

Figure 4. Map of the Ferlo fossil valley watershed.

Table 1 shows the morphometric characteristics of the watershed, extracted from the Global Mapper software.

The watershed is very large, with a surface area well in excess of the reference 2000 sq·km. This means that the ORSTOM method cannot be used to calculate flow, since the surface area is greater than 1500 sq·km. The morphology is rather elongated, with a compactness index of 1.61, which is confirmed by the watershed map in Figure 4. The specific vertical drop of 43.26 m, between 25 and 50 m, represents a relief class R3, *i.e.*, fairly low.

3.2. Ten-Year Flood Flow Estimates

Table 2 shows the results of the CIEH method for estimating the ten-year discharge of the Ferlo fossil valley watershed.

3.3. Estimation of Mobilizable Water Volume and Solids Input

Table 3 shows the results of the calculation of annual water inflows to the reservoir.

Table 4 shows the results of the calculation of annual solid inputs to the reservoir.

Table 1. Morphometric characteristics of the Ferlo fossil valley watershed.

Watershed	Surface aeria (sq·km)	Perimeter (km)	Average slope (%)	Maximum Elevation (m)	Oulet Elevation (m)	Vertical drop (m)	Maximum length (km)	Compacity index	Equivalent rectangle length (km)	Slopes global index (m/km)	Specific vertical drop (m)
Ferlo	28,754	976	0.52	111	5	106	336	1.61	416	0.26	43.26

Table 2. Calculation of decennial watershed flow using the CIEH method.

Watershed	Surface aeria (sq·km)	Average annual rainfall (mm)	Slopes global index (m/km)	Decennial watershed flow Q10 (cm/s)
Ferlo	28,754	398	0.26	1,120

Table 3. Calculation of annual water inflow to the reservoir.

WATER INFLOW INTO THE RESERVOIR							
Watershed	Surface aeria S (sq·km)	Maximum dayly rainfall P10 (mm)	Coefficient of attenuation A	Kr10	Waterhed decennial flow Q10 en cm/s	Tb10 (sec)	Reservoir Water inflow V10 (cm/year)
Ferlo	28,754	111	0.36	0.55	1,120	322,347	11,089,758

Table 4. Calculation of solids input to the reservoir.

SOLID INPUTS TO THE RESERVOIR		
Watershed	Surface aeria S (sq·km)	Reservoir solid inputs (cm/year)
Ferlo	28,754	93

We therefore have a volume of water of around 11 million cm mobilizable per year, with solid inputs of 93 cm per year. The area of arable land, estimated on the basis of the area of degraded forest, is 1,349,000 ha [4]. An irrigated crop may require up to 9 cm/ha in the dry season. This would make a total potential water requirement for agriculture of 12,141,000 cm per year, which exceeds the quantities of water that can be mobilized. In addition, if we take into account the area's high soil infiltration (fossilization of the valley) and evapotranspiration, which is around 4000 mm per year at the Linguere station [10], the volumes of water actually usable would not even reach 10 million per year. What's more, other uses (livestock farming, drinking water) have not been taken into account when estimating requirements. This is all the more important given that the area's water tables are heavily exploited, to the point of exceeding permissible thresholds.

To sum up, mobilizing water at the level of a retaining dam would certainly make it possible to store a volume of water that would be a supplement to meeting the area's water needs. However, this is far from sufficient, and revitalizing the entire valley would enable part of the river's waters to be diverted to supply not only the Louga area, but also the Matam and Saint-Louis zones if necessary.

4. Conclusion

To sum up, in this study we used Global Mapper and Arc GIS softwares to delineate and characterize the Ferlo fossil valley watershed. Then we used CIEH method to estimate the ten-year flood flow that can occur at the dike location on the watershed outlet. Finally, we estimated the mobilizable water inflow and solids input volumes to see if the water resources can cover the water needs. The results have shown that the water needs estimated are superior to the estimated mobilizable water volume, what clearly shows that the complete revitalization of the Ferlo fossil valley is more than necessary to fully cover the area's water needs, especially in the near future when the area is set to expand. The various uses of water (agriculture, livestock farming, consumption) will continue to grow as the area develops. In perspective, re-watering the other fossil valleys, as planned by the FVRP, would therefore be very important in ensuring the sustainability of water resources throughout the country. This would be a major step towards achieving the objectives of IWRM (Integrated Water Resources Management). However, the geopolitical stakes linked to the interests of the various member countries of the Senegal River Development Organization (OMVS) with regard to the management of the Senegal river's water resources remain obstacles to be overcome in order to make this project viable.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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