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SUSTAINABILITY OF A HYDRAULIC FACILITY AND FLOOD RISK OF ITS DOWNSTREAM SECTION: THE CASE OF THE FOUM EL-GHERZA DAM (ZIBAN EAST, ALGERIA)

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Summary

Due to advanced silting, the Foum El-Gherza dam has lost more than two thirds of its initial capacity (47 hm^3) and is no longer able to withstand the floods that threaten its downstream section. Indeed, the damage recorded in recent years has confirmed the vulnerability of the man-made structures located on both banks of the Oued Labiod. Thus, we believe that the hydrological behaviour of the catchment area is no longer influenced by the dam. Therefore, the hydrological study involved a critical analysis (homogeneity tests) of the hydro-climatic data in order to highlight the characteristics of the historical events recorded during the period 1950–2019. The frequency study of the maximum daily rainfall and floods recorded at the dam allowed us to determine the rainfall and flow rates of the return periods (10, 25, 50, 100, 500 and 1000 years). The flooding of the 28 October 2011 were used as a standard for the calibration of the model calculated by the HEC-Ras software. After validation of the model, a prediction of the water levels and flood extent was made for the selected return periods. The results obtained show that a part of the town of Seryana (district located on the edge of the right bank) suffers from flooding proportionally to the return periods of the floods. In addition, some agricultural areas bordering the Oued are also affected by the floodings. The hazard modelling maps can be considered as a basis for a flood risk prevention plan (PPRI) and as a decision support tool.

Keywords

Foum El-Gherza dam • siltation • flooding • downstream section • modeling

1. Introduction

Ziban is located in the extreme north-east of the Algerian Sahara. A contact zone between two very different morpho-structural domains: The Saharan Atlas and the Sahara, a privileged agricultural area despite receiving less than 150 mm of annual rainfall [Aidaoui 1994]. The region is an exception due to its high water potential and the fact that it uses surface and groundwater from the SASS (Septentrional Sahara Aquifer System), which consists of a series of aquifer layers that have been grouped into two reservoirs called the Intercalary Continental (IC) and the Terminal Complex (TC) [Hamamouche et al. 2017, Amrani and Abdelhakim 2023]. Before the deep wells were installed in 2000, the Zab Chergui depended almost exclusively on water from the Foum EL-Gherza dam and some traditional wells [Cote 1991]. However, due to the very advanced silting of the dam's reservoir, which has lost more than 70% of its capacity, as indicated by the bathymetric surveys carried out in 2015 by the National Agency for Dams and Transfers (ANBT) [Remini and Maazouz 2018], the contribution of surface water has largely decreased. Today, the contribution of deep wells meets the water needs of the various sectors [Noui and Guesbaya 2022], particularly irrigation (80%) in the eastern Zab (W.R.M.P. Biskra 2003). In addition, the Foum El-Gherza dam, before its siltation, protected the agglomerations and agricultural areas from flooding in the downstream section of Oued Labiod [Ouamane et al. 2022].

Indeed, over the last decades, due to the decrease in the capacity of the dam, floods have become more and more threatening (September 1989, April 2004, May 2006 and October 2011). The volumes and flows are increasingly significant, hence the increase of flooding risk.

In fact, the flood of 28 October 2011, with a return period of only 50 years (ANBT, 2021), flooded a large area (1.6 ha) of the town of Seryana and its surroundings. These flood zones were certainly urbanized or cultivated during the period when the Foum El-Gherza dam protected the downstream part (the center of the eastern Zab). It should be noted that the fluvial dynamics of Saharan Oueds are characterized by an active erosion at the foot of the banks and a sedimentation in the axial part of the Oued [Ghachi and Ouakhir 2019]. This situation leads to the retreat of the banks which are already occupied by orchards and urbanization.

This situation raises concern about the long-term sustainability of the hydraulic facility. It calls for a detailed hydrological investigation leading to hydraulic modeling based on fieldwork, satellite images and the use of Arc-GIS and HEC-Ras software [Army Corps of Engineers 1997] for the determination of the flood zones at different return periods affecting the downstream section of the dam, and in particular the agglomeration of Seryana and its surroundings.

The Oued Labiod catchment area and the Foum El-Gherza dam have been the subject of several studies, including the work of [Benkhaled et al. 2013]. They presented analytical study of the temporal distribution of extreme events recorded at the dam from 1950 to 2010. Other studies, such as [Souanef 2015, Hachemi 2017], focused on the flows at various temporal scales, specifically the maximum daily floods, using probabilistic statistical methods, while working on an uninfluenced flow.

Our contribution is to use these studies to monitor the hydrological behavior of the catchment area from the date the dam was built (1950), and to follow the evolution of the capping role with the rate of silting of the dam (see Fig. 3). Thus, we demonstrate that the sustainability of this hydraulic facility and theimpact of its condition on its downstream section poses a threat to the region.

The lack of regulation of the Oued Labiod has resulted in the loss of a water reservoir that is essential for the eastern Zab throughout the year. This has led to a situation in which more and more deep wells are necessary to meet the demands of the region, especially for irrigating the arable lands [Miled Zohra 2019].

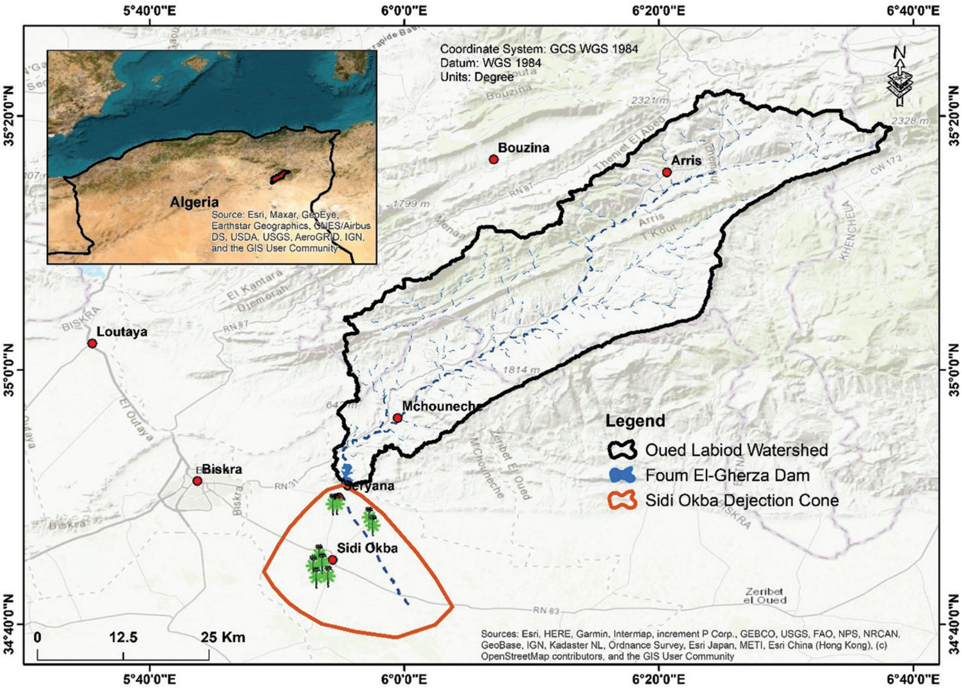
It has been determined that the SASS does not reach the eastern Zab. Thus, the drilled wells exploit the phreatic aquifer of the conglomerate, which is the result of the degradation of the Aurès massif during its recent uplift. The thickness of these formations has limited the depth of the drillings (800–900 m) [Guiraud 1973, 1990; Chebbah 2007, 2016]. The recharge of this phreatic aquifer is linked to the Chabet flowing down the southern flank of the Aurès, and particularly the Oued Labiod. This contribution is far from being sufficient to meet the needs of the agricultural sector, hence the drawdown observed during the summer season [Khomri et al. 2022]. The government's support for the development of the agricultural sector has made Ziban a pioneering region, particularly in the fields of phoeniciculture and market gardening. Due to the constraints of the region (climatic and edaphic), caution in the management and exploitation of water resources remains an unavoidable rule.

2. Presentation of the study region

The study area is subdivided into two physiographic units, the upstream unit constituting the catchment area of the Foum El-Gherza dam located entirely on the southern flank of the Aurès (1300 km^2) and characterized predominantly by secondary formations, mainly represented by limestone and marlstone, with a limited presence of soft Miocene formations [Brinis et al. 2021]. The course of the Oued Labiod (82 km) is significantly determined by active tectonics (uplift), which has favoured the subsidance of the Oued Labiod, forming gorges over several kilometres (Ghoufi balconies). The second, downstream unit crosses the eastern Ziban. It is made up of Quaternary alluvial formations that cover the lowlands and show, in places, very significant thicknesses reaching up to 800 m. These formations contain a reservoir of underground water that is fed by the Chabet and drains the southern flank of the Aurès. The northern boundary of this unit is marked by the South-Atlasic flexure [Guiraud 1973, 1990; Chebbah 2007, 2016]. This unit is further characterized by the conjunction of several flattened and buried alluvial fans resulting from subsidence. After the Oued Labiod was regulated (the impoundment of the dam in 1950), the eastern Zab experienced a fairly intense agricultural activity, which depended largely on the releases from the dam. By ensuring the safety of settlements and cultivated areas against the risk of flooding, the dam has created the conditions for significant development (Fig. 1).

3. Materials and methods

To carry out this work, we used cartographic and photographic data to delineate the catchment area, characterize its relief and slopes, identify geological formations and vegetation cover. The collection of hydro-climatic data which allowed us to analyze the hydrological behavior at different time scales in order to deduce the risk of flooding after the dam's silting. All this data is processed according to the requirements of the modeling software used, namely Hyfran, Arc-GIS, HEC-Georas and HEC-Ras [Army Corps of Engineers 1997].



Source: Authors' own study

Fig. 1. Location of the study area

However, a high-resolution digital terrain model (DEM) with a resolution of 12.5 m was used. Converting it into the Triangular Irregular Network (TIN) format is essential in order to provide a topographic support for the creation of oued geometry and flood simulation.

A land cover map derived from the land cover map (Sentinel 2) produced by Esri was also integrated to determine the Manning roughness coefficient for each soil type to be assigned to the HEC-Ras model. The spatial (10 m) and temporal (5 days) resolution proposed by Sentinel 2 perfectly meets the requirements of this work [Phiri et al. 2020].

In addition, several visits to the Foum El-Gherza dam allowed us to collect data on water balances, bathymetric surveys and recorded hydrological events (1950–2019), as well as the exceptionally severe flooding of 28 October 2011.

The approach adopted required a field study of the area in order to characterize the elements that impact the hydrological behavior of the upstream section and the flood risk of the downstream section. A survey was also carried out to collect testimonies from the inhabitants at the overflow locations and to locate raw water channels using GPS. This field work made it possible to identify the overflow areas which will help calibrating the model to determine the water levels and the extent of the floods.

4. Results and discussion

4.1. Flow and water potential of the catchment area

The inflow of the Oued Labiod has been observed at the level of the Foum El-Gherza cluse by the road and bridge department since 1924 (ANBT, 2021). Thus, the analysis of the annual inflows observed over a period of 96 years shows the important contribution of the autumn season, mainly in the form of floods, and the irregular nature of the Oued Labiod (Fig. 2).

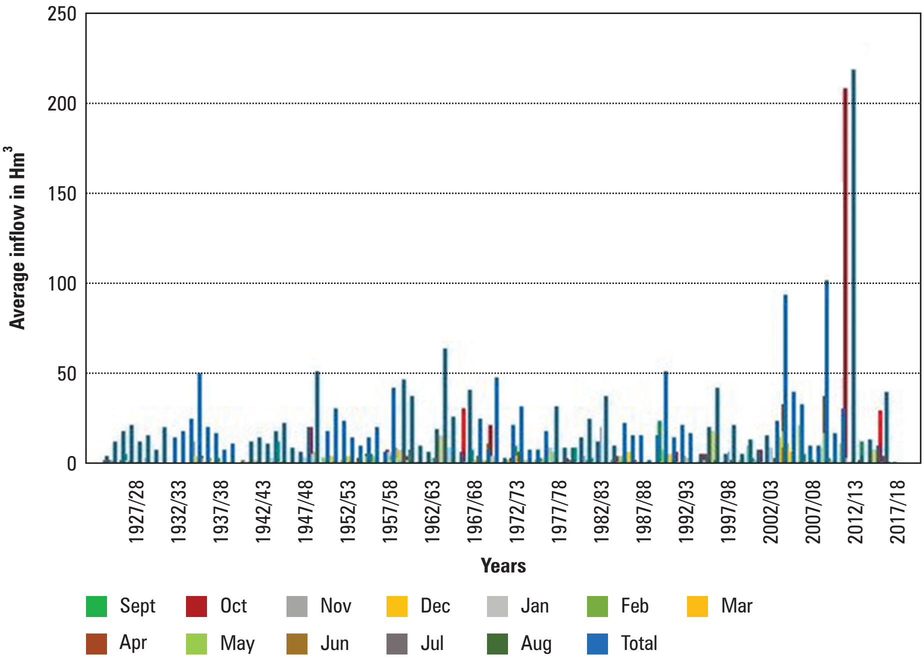


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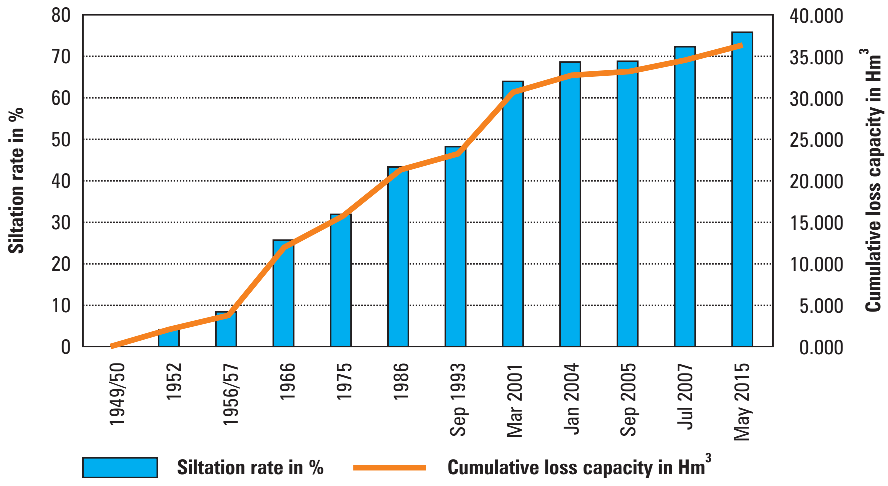
Fig. 2. Average monthly and annual inflow of the Oued Labiod (ANBT, 2021)

The mean annual inflow calculated from this series is equal to 22,705 Hm^3, or a mean annual flow of 0.72 m^3/s. However, maximum flows are often recorded during the autumn season (Fig. 2). The driest year recorded only 3,033 Hm^3 (1987) and the wettest year reached an inflow of 217,644 Hm^3 (2011). This irregularity leads to periods of drought with dramatic consequences for population of the eastern Zab. The floodings that are caused by such irregular climate have an adverse effect on the habitat and agriculture. This situation motivated the Romans to try to build a dam (traces of such attempt were found) at the level of the Foum El-Gherza cluse. The same site was chosen by the French for the construction of the current dam in 1950. The capacity of the dam is 47 Hm^3, with an annual regulated volume of 17 Hm^3. It is interesting to note that the highest monthly inflows are recorded mainly in September and October, followed by March, April and May. This order is maintained with regard to the size and number of floods. Thus, the highest risk of flooding is in the early autumn. Spring shows a medium risk. In contrast, winter and summer floods are much less dangerous.

4.2. Siltation of the dam

The Oued Labiod drains the southern flank of the Aurès (a mountain range from the Quaternary period) with a difference in height of about 2000 m, which means that the torrential flow develops sufficient hydraulic energy to contribute to the erosion of the low resistance rocks. Indeed, the twelve (12) bathymetric surveys carried out during the years 1949–2015 (1949, 1952, 1956, 1966, 1975, 1986, 1993, 2001, 2004, 2005, 2007, and 2015) indicate a constant decrease of the capacity of the Foum El-Gherza reservoir (Fig. 3).



Source: Authors' own study

Fig. 3. Evolution of the volume and siltation rate of the Foum El-Gherza dam (ANBT, 2022)

The evolution of the siltation curve of the reservoir (Fig. 3) shows the rate of siltation during the period of operation of the dam (65 years). During this period, the volume of sedimentation reached 35.45 Hm^3. The average annual sediment supply is 0.6 Hm^3. It is worth noting that some de-silting operations have been carried out since 2007. The quantity of silt removed is estimated at 5 Hm^3 [Boudjerda et al. 2022]. However, without the intervention of these two operations, the total siltation would reach 40.45 Hm^3, or a loss of 86 % of the initial capacity of the reservoir. Thus, including the volume of silt removed, the average annual sediment supply becomes 0.622 Hm^3 and the specific degradation reaches 478. 10^3 m^3/km^2/year. The reading of the curve (Fig. 3) also shows two periods of more active erosion (1957–1966 and 1993–2001), where the specific degradation reaches 1.5 times the average specific degradation (0.86 Hm^3). These two periods are characterized by instability and drought, resulting in poor land management and frequent forest fires. This situation is certainly at the origin of the accelerated erosion. Given the severity of the floods and the reduction in the capacity of the reservoir, the floods are less and less capped; at 80% siltation, the dam loses its essential capping function [Michalec 2022].

4.3. Flood risk

4.3.1. Frequency of maximum daily rainfall

The number of stations (03) monitoring the catchment area is insufficient. However, their distribution from upstream to downstream is very satisfactory. The data series (1969/70–2015/16) used have been subjected to a critical analysis which has shown their reliability. The dispersion of the values recorded at the three stations justifies their adjustment to the Gumbel law [Mohamed et al. 2022]. It is clear that the altitude largely determines the rainfall recorded at each station (Table 1).

Table 1. Frequential maximum daily rainfall (Medina, Tkout and Foum El-Gherza stations)

Station	*x*	*y*	*Pj* max average [mm]	*Pj* max [mm] *T* = 10 years	*Pj* max [mm] T = 50 years	*Pj* max [mm] *T* = 100 years	*Pj* max [mm] *T* = 1000 years
Medina	6°31’02” E	35°19’46” N	40	74.2	99.8	111	146
Tkout	6°18’22” E	35°08’42” N	35	59.7	83.5	93.5	127
Foum El- Gherza	5°55’33” E	34°51’12” N	20	52.10	73.3	82.3	112

Source: Authors’ own study

Overall, the progression of frequent rainfall is slow, as the calculated values only reach twice the maximum ten-year rainfall at the millennial frequency. Nevertheless, the 50-year rainfall can generate floods with daily volumes exceeding 100 Mm^3. Figure 4, by illustrating the spatial distribution of the centennial rainfall, synthesizes the characteristics of the frequent rainfall in the Oued Labiod catchment area.

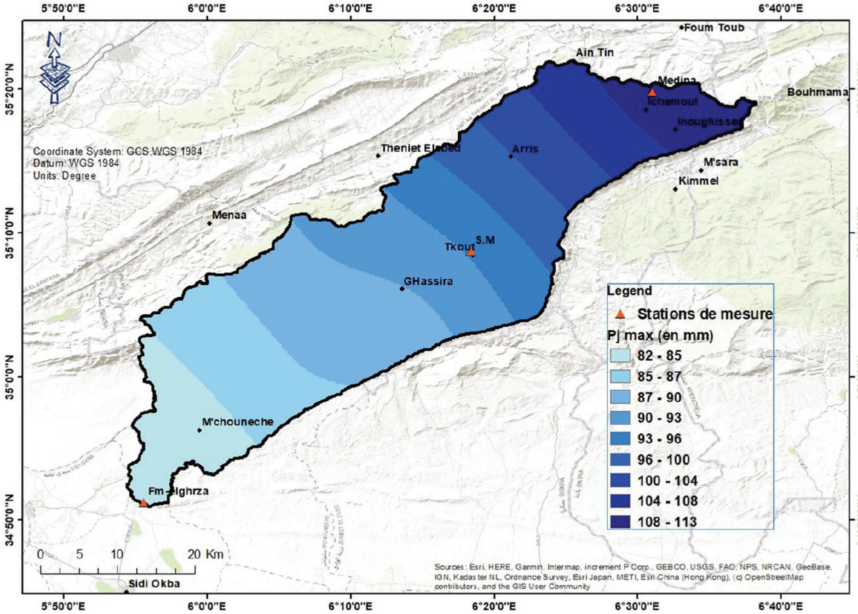


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Fig. 4. Daily maximum 100-year rainfall in the Oued Labiod catchment area

4.3.2. Frequency study of maximum annual floods

The maximum instantaneous flows recorded since the dam was impounded in 1950 until 2019 (70 years) have been critically analyzed and tested, allowing us to choose the most suitable distribution law, namely the Weibull law [Nguimalet 2021]. The length of the series makes it possible to forecast return periods of up to 1000 years (Table 2). The quantiles of the different return periods according to the Weibull distribution are summarized in Table 2.

Table 2. Flow values for different return periods

Law of distribution	Max flows [m³/s] *T* = 10 years	Max flows [m³/s] *T* = 25 years	Max flows [m³/s] *T* = 50 years	Max flows [m³/s] *T* = 100 years	Max flows [m³/s] *T* = 500 years	Max flows [m³/s] *T* = 1000 years
Weibull	1410.143	1850.207	2160.261	2470.317	3150.454	3430.515

Source: Authors' own studies

The records of the damages show that floods only become dangerous after a return period equal to or greater than twenty-five years. For this reason, the flood of 28 October 2011 is adopted as the basis for the model built using the HEC-Ras software [Puno et al. 2020].

4.3.3. One-dimensional hydraulic modeling

4.3.3.1. Calibration and validation of the model

The purpose of calibration is to ensure the accuracy and precision of the model by comparing the observed measurements and field surveys corresponding to the 28 October 2011 flood with the equivalent data calculated and simulated by the model [Abbas et al. 2020]. However, after integrating a series of values of the Manning coefficient (*n*) ranging from 0.020 to 0.025, we obtained the highest value of the Nash criterion (0.983), which coincides with n equal to 0.022 [Soualmia and Gharbi 2014]. Table 3 summarizes the Nash criterion values for the simulations performed.

Table 3. Nash criterion values of simulations performed for different values of Manning *n*

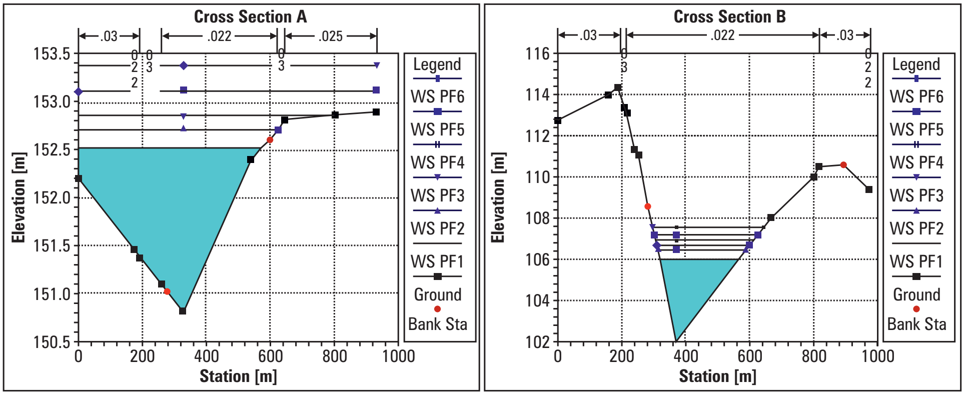
	n = 0.020	n = 0.022	n = 0.023	n = 0.024	n = 0.025
Nash criterion	0.974	0.983	0.982	0.982	0.976

Source: Authors' own studies

Thus, we note that the model constructed has generated largely acceptable results. Therefore, it will be used for the prediction of water levels and overflows for different flood return periods (10, 25, 50, 100, 500 and 1000 years).

4.3.3.2. Flood modeling for different return periods (10, 25, 50, 100, 500 and 1000 years)

The use of the one-dimensional hydrodynamic model combined with geospatial approaches allowed the water levels of the selected cross-sections to be determined efficiently and accurately [Pathan and Agnihotri 2021]. Therefore, field observations led us to define two cross-sections at Seryana (section A) and Garta (section B) respectively, to confirm the results (Fig. 5).



Source: Authors' own studies

Fig. 5. Sections A and B showing the levels and overflows of the Oued Labiod

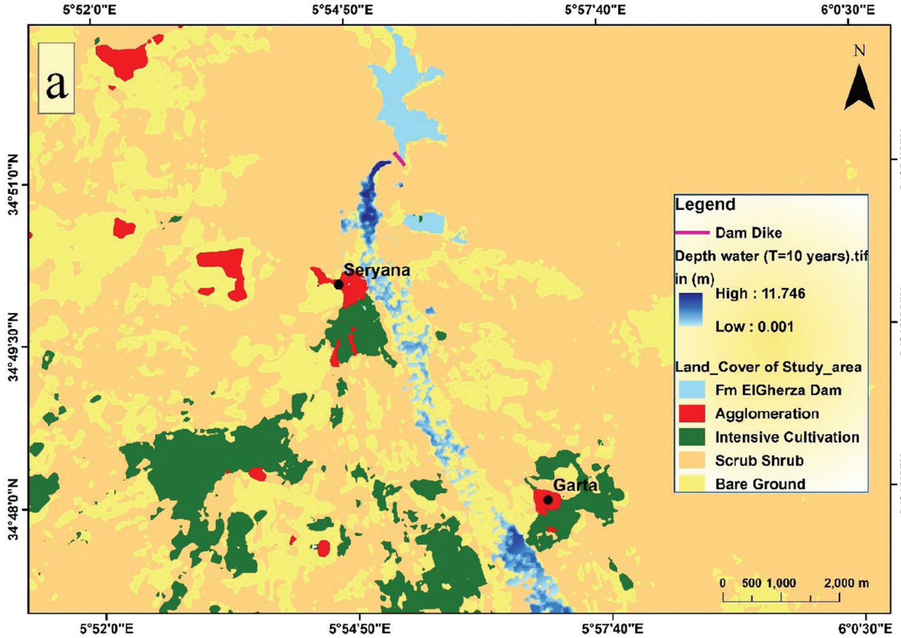
The following Table 4 summarizes the simulated water levels and overflows for floods of different return periods for the Seryana and Garta sites.

Table 4. Simulated water levels and overflows

	Seryana			Garta		Agricultural areas
	Water level [m]	Overflow level [m]	Flooded area [ha]	Water level [m]	Overflow level [m]	Flooded agricultural area [ha]
T = 10 years	1.73	0	0.12	4.03	0	1.7
T = 25 years	1.92	0.12	0.15	4.45	0	1.9
T = 50 years	2.05	0.25	0.17	4.71	0	2.05
T = 100 years	2.19	0.39	0.18	4.95	0	3.7
T = 500 years	2.33	0.55	0.20	5.42	0	27.65
T = 1000 years	2.59	0.79	0.23	5.59	0	35

Source: Authors' own studies

The town of Seryana, located on the right bank of the Oued Labiod, suffers from flooding at different return periods, with the exception of the decennial floods. The overflow levels vary from 0.12 m for a 25-year period to 0.79 m for 1000-year period. However, the flood range reaches 350 linear metres in the town, where the overflow level drops to 0.10 m. On the other hand, the town of Garta, located on the left bank of the Oued Labiod, will not be affected even by the millennial flood (height 107.5 m), due to its location on a hill (110–112 m high). Thus, the expansion of the town towards the lower levels would expose it to the risk of flooding. However, the agricultural land at risk of flooding is about 35 ha and stretches on both banks of the Oued. In addition, the retreat of the banks due to the severity of the floods causes a significant loss of agricultural and/or urban land. Figure 6 illustrates what will happen during the above-mentioned floods. Nevertheless, the DEM used with a resolution of 12.5 m does not achieve the resolution required by the HEC-Ras software in order to generate very detailed maps that can show the limits reached by a given frequency of flood [Huţanu et al. 2020]. Nonetheless the reading of the cross-sections of the selected sites presents the height and overflow of the waters with precision.



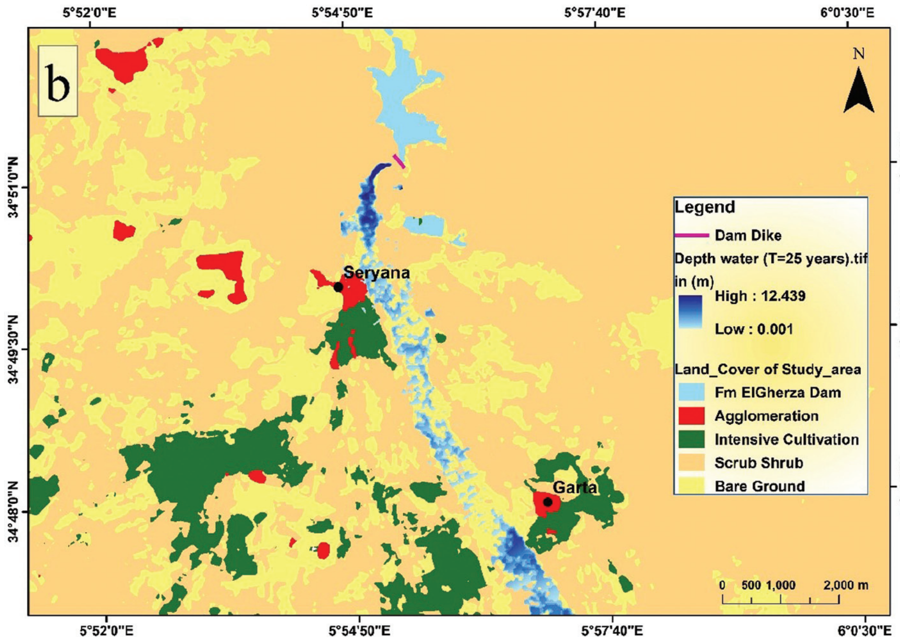


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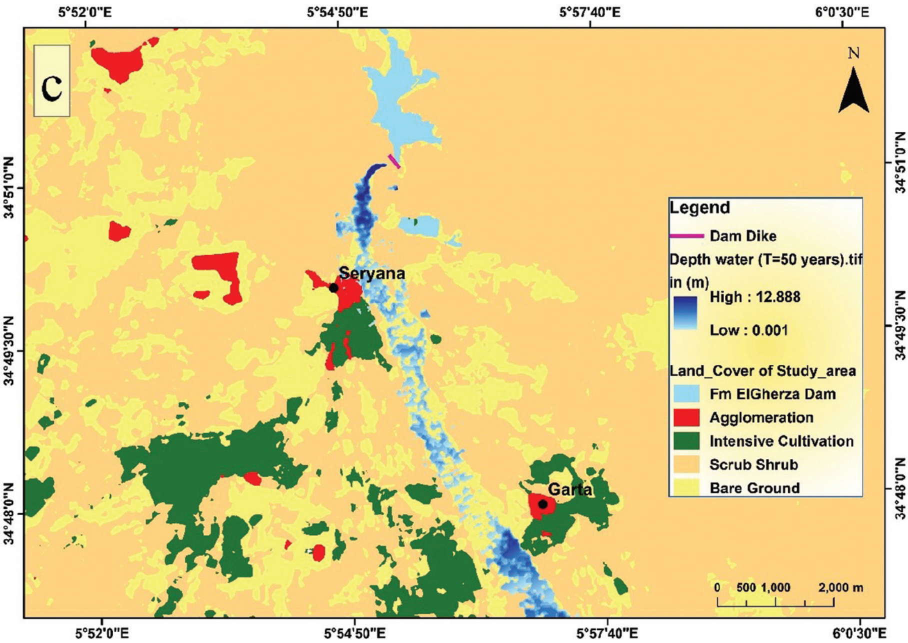
Fig. 6. Flood map: a. 10-years return period, b. 25-years return period, c. 50-years return period, d. 100-years return period, e. 500-years return period. f. 1000-years return period



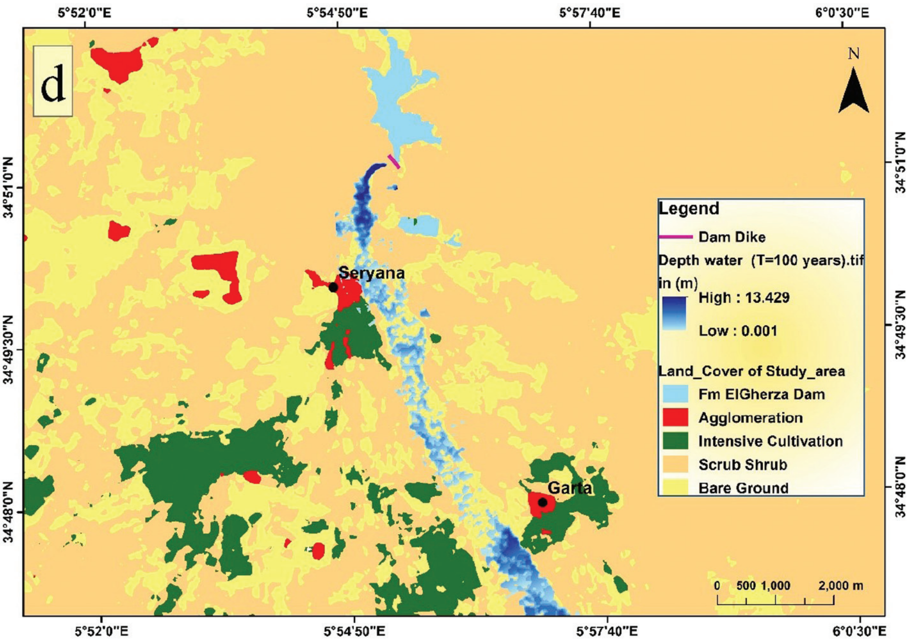


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Fig. 6. cont.

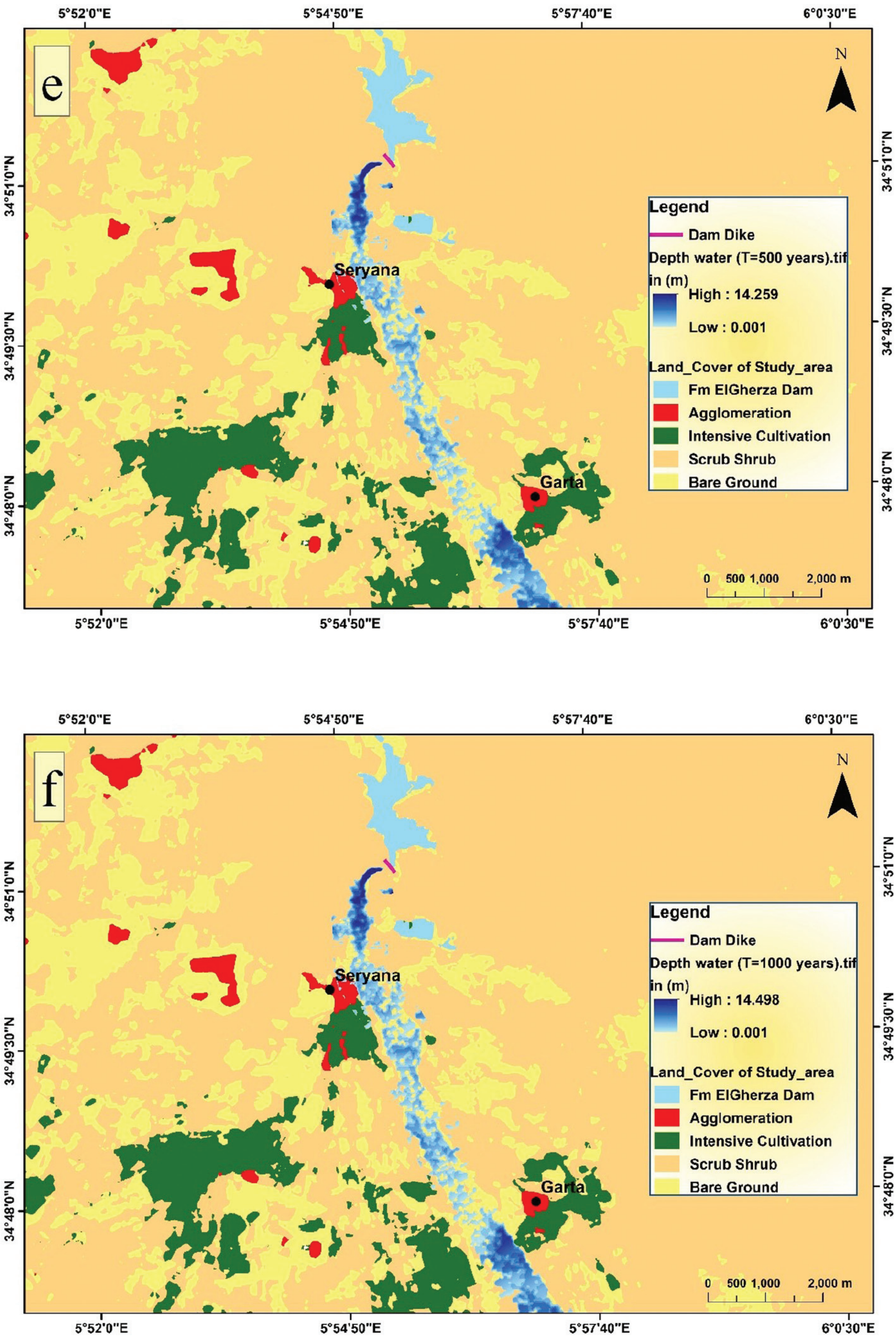

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Fig. 6. cont.

5. Conclusion

The construction of the Foum El-Gherza dam had an impact on the organization of human activity and space in its downstream section (eastern Zab). This hydraulic facility has made it possible to protect this downstream area from the risks of flooding, while at the same time releasing enough water to meet the needs of the population and agriculture in the eastern Zab. The latter was mainly used for livestock transhumance, despite its fertile agricultural land. In this way, the regulation of the Oued has allowed a significant agricultural development based on phoeniciculture and market gardening, stimulating the development of the surrounding agglomerations (Sidi Okba, Garta and Seryana). This situation remained for over fifty years. However, the progressive siltation of the dam's reservoir and the reduction in water released for irrigation has led to the multiplication of deep wells (800 to 900 m) exploiting the phreatic aquifer fed by the Oueds and Chabet draining the southern flank of the Aurès. This solution made it possible to meet the water needs of the entire eastern Zab. Meanwhile, the siltation (80%) has eliminated the flood control provided by the dam, increasing the flood risk in the downstream section, which now is vulnerable to extensive rainfall.

Our work consists of hydraulic modeling using the HEC-Ras software, which has enabled us to map the flood zones according to the frequency of the floods that threaten the development of an important part of the eastern Zab. The results show the damage already caused by 50-year floods and the floods expected at longer return periods. The case of the Seryana agglomeration is instructive; the recurrent floods and the annual loss of arable and/or building land. The settlements (Garta), which are now considered safe, may be threatened if they expand. Their development plans must inevitably take into account the risk of flooding. It should be noted that underground dams are better adapted to the harsh conditions of the Saharan climate, especially to intensive evaporation, and can replace surface dams in terms of water supply and flood protection. This work can serve as a decision-making tool.

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