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Flood and drought: application to the Senegal River management

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Abstract In West Africa, reliable appraisals of water resources of large river basins encounter numerous difficulties due to decreasing yields since 1970. Water resource planning must be corrected according to new data on drought. This paper aims to show the importance of the reference period chosen when analysing the performance of a dam built for several uses. Firstly, runoff variability is studied on the upper Senegal, based on a complete homogenized data bank. Secondly, two scenarios of water resource monitoring of the Manantali dam are tested by numerical simulation using all available data. A statistic for the success rate of each aim and its priority is computed. The failure rate during the 1980s is alarming, particularly for the scenario which forecast an artificial flood each year. Excluding the possibility of climate change, this paper shows that to satisfy the most important objectives requires that certain objectives be renounced.

INTRODUCTION

How can the best possible use be made of a river's water, taking into consideration weather variations such as drought and flooding that may affect its regime? The many dam failures in West Africa show that it is important to estimate how the management of a dam affects its functioning. Defining the goals of a dam will not, alone, ensure its effectiveness.

Very long series of hydrological data are available on the Senegal River. The Bakel station for example, has been observed since 1903. An observation period such as this provides a good picture of the inter-annual variations of a tropical river, and of the impact of periods of drought on the performance of a multipurpose dam like that of Manantali. Numerical simulation of the dam's functioning shows the importance of the reference period selected in establishing water planning scenarios.

DATA

Geographic data

The Senegal River (Fig. 1) is formed by the confluence of the Bafing and the Bakoye. The source of the Bafing, its chief branch, lies at 900 m altitude deep in the Fouta-Djallon massif. Its long, narrow basin is located in the Guinean climatic region between the 2000 mm and 1300 mm isohyets, and in the Sudanese region (up to the 800 mm isohyet). The Manantali dam (27 800 km^2 watershed; 12 billion m^3 holding capacity), which regulates the water quantities from the Bafing (around half the flow passing through the Senegal), was inaugurated in 1988. It was built to meet the following medium and long term needs (Gibb *et al.*, 1987):

- the irrigation of 375 000 ha of crops along the Senegal valley;
- the generation of 800 GWh of electricity per year (power to be installed: 200 MW);
- navigation from the river mouth to Kayes;
- stabilization of very high water levels (protection from devastating flooding); and
- support for the river rising to optimize the growing of traditional crops.

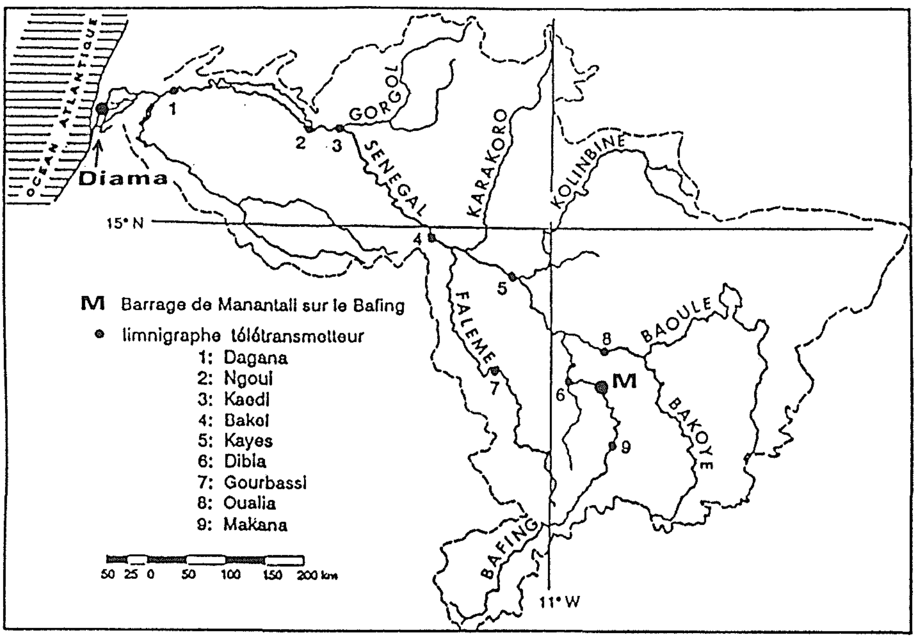

Fig. 1 Map of the Senegal basin.

Hydrometric data

The natural flow regime of the Senegal River as a whole is characterized by a high water season from July until the beginning of October, and a low water season from early December to the beginning of June. The flooding is followed by a regular drying out extending through the entire low water season, ensuring almost each year a consistently weak flow starting from Kayes. To analyse the natural regime at Bakel, we used observed and homogenized data for the period 1904-1986, and reconstructed data for 1987-1992 using a propagation model and the data of Makana, Oualia and Gourbassy, which are not affected by Manantali. Figure 2 shows trends in average and median flows for the Senegal at Bakel between 1904 and 1992. We see a great inter-annual variability

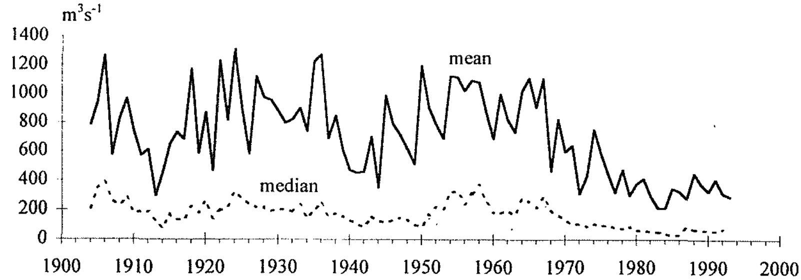

Fig. 2 Flow of the Senegal River at Bakel (modules, annual median values).

of the regime, with a variation coefficient, *Cv* of 0.45 on the modules. Like many other rivers of West Africa (Nicholson, 1981; Albergel *et al.*, 1984; Sircoulon, 1987), there are wet periods separated by three periods of shortage: 1911-1915; 1940-1944; and 1972-1992. The latter of these, remarkable for its length and for the magnitude of the deficit (average module of 379 m^3 s^{-1}, compared with 716 for the period 1904-1992, or a deficit of 47%), concentrates 18 of the 20 weakest annual modules observed between 1904 and 1992. The year 1984, with a module of 212 m^3 s^{-1}, is the most disastrous.

METHOD

Numeric management model for the Manantali dam

The management model (Bader, 1992) permits one to assess the effect of certain rules for management on the degree of satisfaction of the different goals that had been assigned the structure. It first simulates one type of dam real time management, using specifications of the dam and lake components, a flow propagation model and the configuration of the measurement station network equipped with telemetransmitting recording gauges (Fig. 1) where the flows are known in real time. That generates records of flow (as far as Bakel), water level in the reservoir and electric power generation, which are then statistically analysed to determine the rate of satisfaction of the different expressed goals. The simulations are made at a daily rate between 1904 and 1992.

Each calculation is carried out in respect of the physical limits imposed on the release of water by the size of the discharge components of the dam and respect of the maximum allowable level for dam safety, and for a combination of management rules chosen from the following list of operating constraints and requirements, freely classified in order of priority:
- the requirement that a minimum or maximum limit be respected regarding the level in the reservoir, which varies according to the time of year;
- the requirement for flood stabilization at Bakel or where the water leaves the dam;
- the requirement regarding electricity generation; and
- the requirement regarding water supply for various needs (irrigation, navigation, supply to urban centres), expressed as the flow to be achieved at Bakel.

Each of these rules permits one to define a minimum value Qmin, a maximum value Qmax, or both, for the total flow to be released from the dam during the day (drained + discharged + harnessed for the turbine). Most of these limits correspond either to the values of flow released (written $Qmin_a$ or $Qmax_a$) permitting one to satisfy the related demand directly, or to the values (written $Qmin_b$ or $Qmax_b$) that bring the lake level back to the stock or safety margin level necessary to ensure the possibility of satisfying the related demand 49 years out of 50 (Bader, 1992).

Every day, the successive application of the different rules in decreasing order of priority is expressed in a narrowing of the bracket of limit values for the total flow, until all the rules have been taken into consideration or until one has proven incompatible with the limits set by the preceding rules. In the latter case, the bracket is narrowed to the limit value nearest the flow required for the rule which cannot be satisfied. In all cases, the lower limit of the bracket is finally adopted as the total flow to be released.

Management scenarios chosen for the Manantali dam

The tests were made using two standard scenarios which differed from each other essentially in taking or not taking flood support into consideration. Flood support consists in producing an artificial flood every year in the valley, whose characteristics are close to those of an average flood observed in the natural river regime. The rules chosen were, in decreasing order of priority: A, B, C, D1, E, F for scenario 1, and A, B, C, D2, E for scenario 2. They are given below.

Rule A: Stabilization of the Senegal River maximal water level at Bakel at 4500 $m^3 s^{-1}$ daily flow. A limit $Qmax_a$ and a limit $Qmin_b$ are associated with this rule.

Rule B: Stabilization of the Bafing maximal water level upon exiting the dam to 1500 $m^3 s^{-1}$ daily flow. Like rule A, this rule introduces a limit $Qmax_a$ followed by a limit $Qmin_b$.

Rule C: Satisfaction of the water demand to irrigate 200 000 ha in the valley and to supply water to the city of Dakar through Lake Guiers. It is taken that a flow of 20 $m^3 s^{-1}$ must be provided at Lake Guiers (near the mouth), partly to provide the Dakar area with water, to which is added an average evaporation loss of 30 $m^3 s^{-1}$ after Bakel. With the flows required to irrigate 200 000 ha of land for the types of crops envisaged by Gibb *et al.* (1987), these different needs reveal a flow demand expressed at the level of Bakel, which is described in Table 1. Rule C consists in taking into consideration the associated limits $Qmin_a$ then $Qmax_b$.

Rule D: The demand to generate Pd = 90 MW of electrical power, with a threshold S of turbine action of 186 m IGN. S is the limit level of the lake below which the release of flow solely for the generating of electrical power is not profitable. This rule consists

Table 1 Flow demand ($m^3 s^{-1}$) to irrigate 200 000 ha and supply Dakar with water.

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
102	198	237	239	215	191	181	311	374	344	242	132

in considering the associated limit $Qmin_a$, then a limit $Qmax$ which is lower for rule D2 than for rule D1. The daily power P to be produced is taken as equal to the maximum that can be produced when the lake level exceeds the dam discharge threshold, and as equal to Pd in the opposite case. Qm and QM are the minimum and maximum values of the total flow discharged from the dam that make it possible to produce the power P, with $Qm = QM = 0$ when P cannot (too low lake level). $Qmin_a$ is then defined by $Qmin_a = 0$ if the level of the lake is less than S, and $Qmin_a = Qm$ if it is not.

Rule D1: the value of $Qmax$ is defined by $Qmax = QM$;

Rule D2: the value of $Qmax$ is defined in the following way, using the limits $Qmax_a$ and $Qmax_b$:

- $Qmax_a = 0$ if the level of the lake is less than S, and $Qmax_a = QM$ if it is not;
- $Qmax_b$ is calculated for the days between 1 December and 15 June. This limit is directly related to a minimum reserve that must be retained in the lake, to ensure the possibility of producing Pd until 15 June. It is calculated taking into consideration the level of the lake, the flow entering the dam, and the corresponding drying up factor, as well as the daily evaporation losses.
- Finally: $Qmax = Qmax_a$ between 16 June and 31 November, and
  $Qmax = \min(Qmax_a, Qmax_b)$ between 1 December and 15 June.

Rule E: support for a minimum flow of 200 $m^3 s^{-1}$ at Bakel, for navigation. ($Qmin_a$ only).

Rule F: support for flood flows permitting traditional cropping on 100 000 ha in the valley. This rule takes into consideration the limit $Qmin_a$ associated with the flow demand needed to reproduce, at Bakel, the "artificial type A flood" (Gibb *et al.*, 1987). This artificial flood, with the average characteristics of a natural flood, has been recommended for a transition period that would enable the valley's farmers to move from traditional crop growing methods to irrigated cultivation as developments are set up. Horowitz *et al.* (1990) show the importance of conserving this artificial flooding, with respect both to conserving ecosystems and to maintaining balance among the social systems of riverside dwellers in Senegal.

RESULTS

The results obtained for the two management scenarios envisaged are studied in terms of functions of annual distribution of the following parameters: daily flow deficit at Bakel (irrigation and other needs, support of drying up for navigation, flood support); power generated; and level of the lake. For each of them, Dn is the value reached or exceeded during n days of the year, and NDn is the value not exceeded during n days of the year.

Results obtained for irrigation and related needs

The requirement regarding water supply for irrigation and related needs is given high priority in both cases, and in addition includes a limit set on the release of water, to preserve a stock which is compatible with a failure rate of one year out of fifty. This guarantees nearly 100% satisfaction of this type of need for both management scenarios. The only year showing a real failure of supply is 1985, when the total depletion of the reserve at Manantali led to null flow at Bakel for some 35 days between May and June, and a deficit characterized by $D35 = 191\ m^3\ s^{-1}$.

Results obtained for electricity generation

Figures 3 and 4 show the annual distribution of daily power generation for the two scenarios. The curve of annual medians shows that 1985 was the most disastrous, with zero generation in both cases more than one day out of two. During the periods 1914-

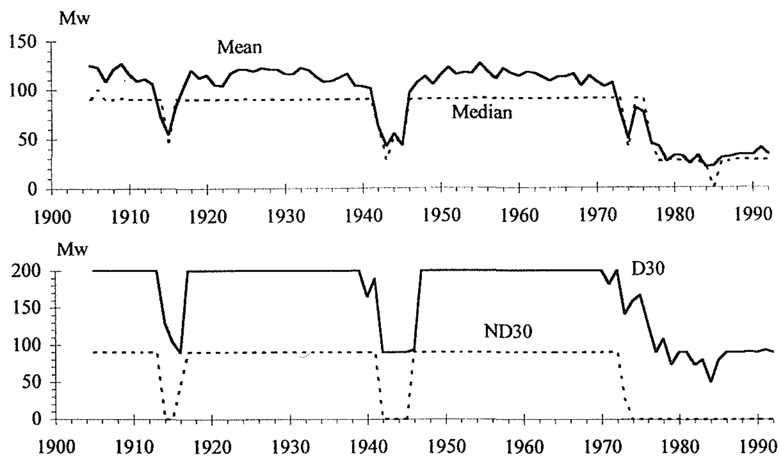

Fig. 3 Daily electrical power generation (daily values, medians, reached or exceeded [*Dn*] during *n* days, and not exceeded [*NDn*] during *n* days) for scenario 1.

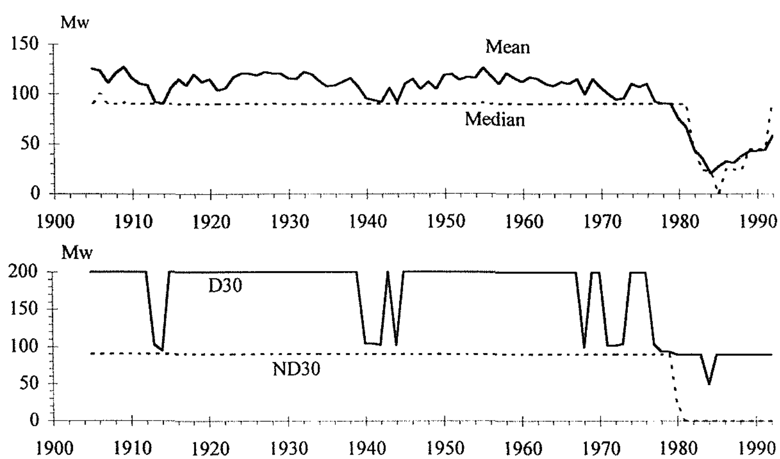

Fig. 4 Daily electrical power generation (average values, medians, reached or exceeded [*Dn*] during *n* days, and not exceeded [*NDn*] during *n* days) for scenario 2.

1916, 1942-1945 and 1973-1992, the water shortage caused a drop in power generation that was much greater for scenario 1 than for scenario 2, and was visible for all quantiles except *D*10, pertaining to peak production. Zero generation for more than 4 months of the year (*ND*120) is, for example, observed between 1982 and 1992 only in the second case, while it is observed in the first in 1915, 1943, 1945, 1974 and from 1978 to 1992. Outside the periods of water shortage, electricity generation is identical for both scenarios. These observations show that the cost of flood support estimated in average power generation loss varies enormously depending upon the reference period chosen (Table 2).

Table 2 Loss of electricity generation due to flood support.

Reference period	1905-1992	1950-1969	1970-1992
Average power, scenario 1 (MW)	92.3	115	48.0
Average power, scenario 2 (MW)	101	115	67.7
Difference (loss due to flood support)	8.7	0	19.3

Level of the lake

The distribution of levels obtained in the lake is shown in Figs 5 and 6 for the two scenarios. The drop in level observed for the different periods of drought is, of course, the direct cause of the lowered electrical generation mentioned above for the same periods. The trends in levels are almost identical for the two scenarios, outside these periods of lack, which bring about a much faster and greater exhaustion of the stock for scenario 1 than for scenario 2. The considerable drop in level noted in the first case for the periods 1913-1917 and 1941-1946 is scarcely discernible in the second case. Similarly, exhaustion of reserves, which began in 1973 and 1978 respectively, and reached a peak in 1985 (level below the bottom drainage level that lies at 155.28 m IGN) was followed in the first case by a near stagnation at a very low level from one year to the next, while the second case shows a slow but steady replenishment of the stock.

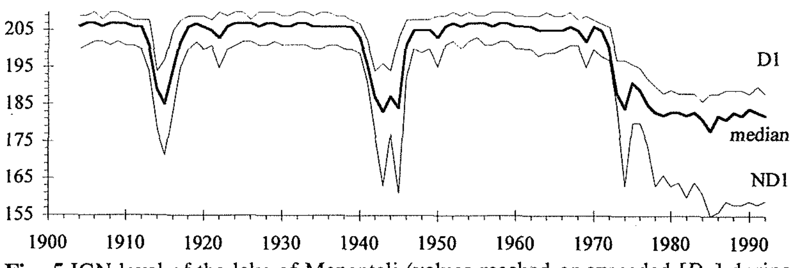

Fig. 5 IGN level of the lake of Manantali (values reached or exceeded [*Dn*] during *n* days of the year, and not exceeded [*NDn*] during *n* days of the year) for scenario 1.

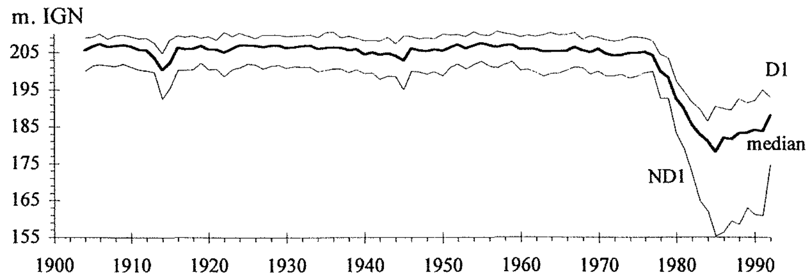

Fig. 6 IGN level of the lake of Manantali (values reached or exceeded [*Dn*] during *n* days of the year, and not exceeded [*NDn*] during *n* days of the year) for scenario 2.

Results obtained to support drying up for purposes of navigation

Under the natural regime, the flow is distinctly lower than 200 $m^3 s^{-1}$ for more than 140 days of every year observed between 1904 and 1992. This limit is, however, reached almost throughout the year with a considerable success rate for the two management scenarios. Once again, scenario 2 gives the better results, with only 6 years, from 1983 to 1988 (against 15 for scenario 1 on the entire period) showing a shortage of over 50 m^3 for more than 30 days.

Results obtained for flood support

To estimate the satisfaction rate of this goal, we compared the $D15$ values obtained with those corresponding to the desired flood support ($D15$ = 1955 $m^3 s^{-1}$) and natural regime. Scenario 1, which refers explicitly to the flood support demand in the management requirements, offers very much better results than scenario 2 for this objective, with a success rate almost equal to that of the natural regime. The number of years where the deficit is greater than 300 $m^3 s^{-1}$ on the desired value of $D15$ is 15, 31 and 10 for scenarios 1 and 2 and the natural regime, respectively.

Results obtained for flood reduction

The two management scenarios give very good and quasi-identical results, with an effective reduction of natural flooding both upon leaving the dam on the Bafing and at the level of Bakel on the Senegal. The number of years in which the average daily flow reached or exceeded certain thresholds for 5 days, is 0, 1 and 31 for scenarios 1 and 2 and natural regime, respectively, for a threshold of 5000 $m^3 s^{-1}$ at Bakel; and 0, 1 and 20 for a threshold of 1700 $m^3 s^{-1}$ upon leaving the dam.

CONCLUSION

The effect of periods of drought on the performance of a multi-purpose structure such as the Manantali dam depends greatly on the length and magnitude of the water shortage, and at the same time on the management practices applied. The useful volume of the Manantali dam (11.3 billion m^3 at the discharge threshold, 12.8 billion m^3 at the maximum operating level), which is slightly greater than the average annual flow volume of the Bafing at right angles to the dam (9.5 billion m^3 for the period 1951-1989 under natural regime) permits a considerable reduction in the impact of inter-annual variations in flow coefficient. As a result, isolated years of shortage (1921, 1949, 1968) do not decrease the level of satisfaction of the goals set for the dam, even when flood support, which consumes very large quantities of water, is envisaged. The series of dry years from 1911 to 1915, 1940 to 1944, and 1972 to 1973, which were relatively short, exert a negative effect only when flood support is envisaged. In these cases, the impact of the water shortages is felt one or two years after the shortage occurs, because of the absorption related to the volume of the dam. The period of drought from 1976 to 1992 was of record magnitude and duration, and caused a disastrous decrease in the dam's performance. Only the supply of water for irrigation and related needs, which was given top priority with a rule for preservation of stock, continued to be provided in a satisfactory fashion. A slow but steady replenishment of the dam water stock is observed after 1985 in the case of management excluding flood sustaining, which also permits operation to come closest to achieving the goals of electricity generation in periods of low flow.

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