ARTIFICIAL FLOOD SUPPORT ON SENEGAL RIVER: A CHALLENGE TO PROTECT NATURAL RESOURCES IN THE VALLEY

Jean-Claude Bader*[1], Jean Albergel**[2]

1 IRD, UMR G-Eau, BP 64501, 34394 Montpellier cedex 5, France

2 IRD, UMR Lisah, Campus La Gaillarde 2, place Pierre Viala 34060 Montpellier Cedex 2, France

**jean-claude.bader@ird.fr*

***jean.albergel@ird.fr*

Summary Formed on the upper basin by the annual monsoon, the flood of Senegal River inundates a vast floodplain on its lower course, called 'the valley'. This one, several hundred kilometres long, can be regarded as an inland delta. This annual flooding, which offers ecosystem services and promotes traditional activities, must be maintained despite the presence on the Bafing of the Manantali reservoir dam, which controls since 1987 half of the river flows through the valley. In addition to its other objectives (energy production, low water support for irrigation and navigation, mitigation of too high floods), this dam therefore achieves a flood support, designed to maintain adequate flood in the valley. Here we present a decision support system dedicated to flood support that aims to: 1) define a flood hydrograph goal for Senegal river, according to a target area of recession crops; 2) define the optimal date for flood support, in order to penalize the least possible energy production at the dam; 3) calculate the discharges to release of the dam to support the flood, according to the real-time hydrological situation known. We finally analyse the respective impacts of natural climate hazard and of Manantali dam on the river's flood observed.

Keywords : dam management, floodplain, inundation, Manantali dam, recession crops

INTRODUCTION

In West Africa, the Senegal River drains a catchment's area of 343 000 km^2 (Michel, 1973) in the territories of Guinea, Mali, Mauritania and Senegal. Before reaching the Atlantic Ocean at St. Louis, Senegal, he travels 1 790 km from the source of its main parent branch, Bafing, located in the mountains of Fouta Djallon in Guinea (Fig. 1).

The natural flow regime of the river, pure tropicaly, is characterized by high water season from July to October and a low water season from December to June (Rodier, 1964). Monsoon rains in the upper basin produce most of this flow, which averaged 19.5 km^3 per year during the period 1950-2011 at Bakel station (Bader et al, 2014). Downstream Bakel, the river enters its lower course commonly called 'the valley', where it receives only negligible contributions. Then it travels about 800 km to its mouth, with a very slight slope (roughtly 0.0015%). Natural estuarine portion of the river is very wide, with a maritime influence that extends more than 150 km for the level and

350 km for the salinity, during low water.

In the valley, the annual flood inundates a major bed of 10 to 20 km wide, that contains multiple channels and floodplains and can be regarded as an inland delta. In the middle of a very arid region, this flooding provides very precious ecosystem services (biodiversity, aquifer recharge, maintenance of grasslands, forests and fish stocks), benefiting the riparian people (recession cropping, breeding, forestry, fishing, etc.).

Thanks to the OMVS (Organization for the Development of the Senegal River), which includes the four countries sharing the basin, two large dams were built on the river Senegal. Twenty eight kilometres upstream from St. Louis, Diama since 1986 prevents the rise of salt water and raises the river level upstream about 300 km along during low water. By creating a permanent reserve of fresh water available mostly without pumping, this dam favourites the development of irrigated agriculture in the region and secure drinking water supply to Dakar and Nouakchott. Operated since 1987, the Manantali dam creates a reservoir of 11 km^3 on the Bafing, 1 183 km upsteam of St. Louis. This dam, which controls about half the flow of the river in Bakel, has several objectives: production of about 800 GWh of electricity per year; mitigation of the too high floods to prevent their devastating effects; low flow support for navigation and irrigated agriculture in the valley and for drinking water supply; flood support ensuring adequate annual flooding in the valley for traditional agricultural practices and maintenance of the ecosystem.

The flood support consists in releasing sufficient discharge from Manantali reservoir, in order to obtain at Bakel a discharge greater than a flood hydrograph previously defined as objective. According to this goal and to the natural contributions received between Manantali and Bakel, this sometimes requires high releases, which can exceed the capacity of the dam turbines and substantially lower the water reserve. Thus, the flood support is clearly competing with the objectives of energy and low water support (Bader et al, 2003). Despite this, the Charter of Senegal river water adopted in 2002 by the OMVS members emphasizes its importance and the need to ensure it, except in extraordinary circumstances.

We present here a decision support system developed by the IRD (Institut de recherche pour le développement) to allow OMVS to best achieve flood support. This work (POGR, 1999 a, 1999 b, 2000, 2001-a, 2001-b), revised in the light of the recent hydrological monograph of the river Senegal (Bader et al, 2014), aims to: 1) set the objective of flood hydrograph based on a target area of recession crops in the valley, and determine the optimal date for flood support that penalizes the least possible energy production at Manantali; 2) determine the discharge to release from Manantali, in order to achieve the objective hydrograph at Bakel.

Finally, we assess the impact of the Manantali dam on river floods since 1987, with a particular interest for flood support operations performed.

DATA

The study uses the hydrometric database of OMVS that the IRD has recently verified, homogenized and supplemented by reconstructed data for some stations (Bader et al, 2014). Especially, we use daily averages chronics of:

- gauge levels He at Bakel, Matam, Salde and Podor in the minor riverbed for the observed regime (complete set of observed and reconstructed data on the period 1946-2013);
- gauge levels at Salde and Bakel in the minor riverbed for the natural regime (complete set of reconstructed data on the period 1987-2011);
- absolute level H in ten representative flood plains distributed over the major bed in the valley (fig. 2) for the observed regime (observed data on the period 1997-2000).

We also use some of the results of that study, concerning the calibration of the Bakel station and flow propagation between Manantali and Bakel.

Finally, we use the following data publicated by POGR(2001-b):

- flooded area S on each of the ten floodplains observed and Sv across the entire major bed between Matam and Dagana (98 km downstream Podor), measured from satellite images taken during the floods in 1986, 1987, 1988, 1992, 1997, 1998 and 1999 ;
- annual areas of recession crops grown between Matam and Dagana (incomplete series over the period 1946-1999), on the left bank, right bank or both sides of the river: agricultural statistics produced by the national services of Mauritania and Senegal, according Bonneau (2001).

METHOD

The computations made, detailed below, aim to: 1) provide a complete set of values on the 1946-2000 period for the annual area of recession crops grown on the floodplain between Matam and Dagana; 2) determine the relationships between these areas and some characteristic levels of the flood in river Senegal at Bakel; 3) use these relationships to define flood hydrograph objectives associated with different potential area of recession crops; 4) find the better date of the hydrograph objective in the year, so this one can be achieved by a flood support penalizing the least possible energy production at Manantali; 4) estimate the potential area of recession crops based on flood hydrograph in Bakel.

Reconstruction of missing data for the annual area of recession crops on the period 1946-2000

For beginning, we establish the relationship between the free surface level on gauges in the minor riverbed (He) and that on the major bed in all ten floodplains observed (H). To do that, we use a propagation model (Lamagat, 1983, 1987, 1990; Lamagat et al, 1993) justified theoretically by Morel Seytoux and al (1993), who used Saint Venant equations with the simplifying assumptions of the diffusive wave. This model doesn't require topographical data and can be used in the downstream or upstream direction. It describes the propagation of the flow between the two ends of a reach, using two relationships based on level or discharge data observed at these ends. Here, these relations give respectively the absolute level H in the floodplains and the propagation time T, according to the level He at the gauge in the minor riverbed. Model calibration, performed for each of the ten plains over the period 1997-1999, is shown in Figure 3 for the plain of Wawa, where the absolute level H is connected at the gauge level He at Podor with a standard error of 10 cm and NSE (Nash Sutclife efficiency coefficient) equal to 0.997.

Then we apply the propagation model (extrapolated up if necessary) for each of the ten floodplains, using the complete series of level He at the stations in the minor riverbed, for the observed regime on the period 1946-2000. Using the results to complete the values observed between 1997 and 2000, we obtain for each floodplain a complete series of daily average level H during flood, for each year between 1946 and 2000.

For each plain, Series H of observed and completed level is then used to determine the level at the precise date of each satellite view exploited. Pairs of simultaneous values H and S are thus obtained (four to eleven, according to the plain), from which we determine an average correlation between level and area of water, whose NSE is higher than 0.975 in all ten cases. This relationship is used to translate the chronicle of daily level H in flooded areas S, with which we finally obtain the maximum annual flooded area Smc of the plain for each year over the period 1946-2000.

Each satellite image shows the instantaneous flooded area S on each of the ten followed floodplains, and Sv across the entire major bed between Matam and Dagana. This shot can not coincide everywhere with maximum flood, which can reach Dagana more than one month later after Matam during the highest floods. Therefore, the Sv value must be corrected to give the maximum flooded area Smv of the year across the entire major riverbed. This correction is done by successive sections of the reach, by applying to each of them a multiplication factor higher or equal to 1, deduced from the ratio Smc/S found for the shot on the closest floodplains followed.

So for each of the seven floods followed by satellite images from 1986 to 1999, we have now the maximum annual Smv flooded area, which combines all the areas successively flooded from upstream to downstream on the entire major riverbed between Matam and Dagana . This area is closely linked to the amount ΣSmc of annual maximum area Smc of the ten representative plains. We therefore use the average relationship between ΣSmc and Smv (Fig. 4) to calculate non-observed values of Smv from ΣSmc, and finally obtain a complete set of Smv values over the period 1946-2000.

The annual area of flood recession crops grown between Matam and Dagana is known over the 1946-2000 period with incomplete sets of values on the left bank (SCg), the right bank (SCd) and both banks (SCv). These data can be linked by average relationships to the maximum flooded area Smv on the entire major riverbed (Fig. 5), with a standard error of 4 963 ha for the right bank and 8 138 ha for left Bank. These relationships are then used to complete the SCd and SCg series from the complete series of Smv. The complete chronicles of SCd and SCg obtained are finally used to reconstruct the missing values SCv of total area of recession crops on both sides.

We have now a complete chronicle of annual area SCv of recession crops on the period 1946-2000, containing observed values and values reconstructed by a modelling chain based on various observed data: levels in the minor riverbed; flooded areas and levels on the major riverbed. To each value SCv is attached an unknown uncertainty due to the inaccuracy of agricultural statistics or to the cumulative errors of the different models. Moreover, the flood recession crops not only depend on the maximum extent of the flooding, but also the duration of submersion and various human factors. In the following, we only use values of crop area SCv estimated from flooded area Smv, in order to smooth the effects of the various uncertainties and not hydraulic influences on crop areas. These values are calculated with the average relationship SCv(Smv), with a 90% confidence interval of $\pm$ 14 000 ha (Fig. 6).

DETERMINATION OF RELATIONSHIPS BETWEEN ANNUALLY AREA OF RECESSION CROPS AND CHARACTERISTICS OF THE FLOOD HYDROGRAPH OF THE RIVER SENEGAL AT BAKEL

For each year of the period 1946-2000, we calculate the average Hb(N) of the N highest daily levels observed at Bakel gauge, for values of N successively equal to 6, 10 and from 15 to 60 days with a 5 days increment. For each value of N, the Hb(N) chronicle obtained can be connected (fig. 7) to that of recession crops area SCv(Smv), with standard errors decreasing with N (36 cm for N = 6 days; 23 cm for N = 25 days).

Mean relations obtained above (Fig. 7) are used to calculate Hb from SCv(Smv). The Hb values thus obtained are used to determine average relationships between N and Hb for different values of SCv varying from 10 000 to 130 000 ha (Fig. 8). Each of these relationships, corresponding to an average area SCv of recession crops, is then used to calculate the mean Hb of the N highest daily levels of the year at Bakel gauge, for all N durations between 6 and 60 days.

DETERMINATION OF FLOOD HYDROGRAPH OBJECTIVES AT BAKEL, ACCORDING TO GOALS OF POTENTIAL AREA OF RECESSION CROPS

For a given value SCv of flood recession crops area, the corresponding Hb(N) series calculated above is used to determine a target flood hydrograph at Bakel, associated with this area. Arbitrarily, the 6 highest daily levels of this hydrograph (Hp(1) to Hp(6)) are set equal to Hb(6). The highest levels of higher ranks (Hp(N) for N greater than 6) are then determined by successive iterations:

$Hp(N) = N \times Hb(N) - (N-1) \times Hb(N-1)$

It is generally accepted that soil must have been submerged for at least 25 days to have accumulated sufficient water reserve for the success of a recession crop in the floodplains of the Senegal River. So we assume here that respect of the first twenty five Hp values is sufficient to allow recession crops on the expected area.

In order to preserve water, we also impose to the hydrograph objective a rapid rise and rapid decrease, within the limits of level gradient observed at Bakel in natural regime.

With these choices and assumptions, the hydrograph objective is thus constructed over a period of 41 days, with a level called H0 (i) for the chronological order i, imposed for ranks 1 and 41 to 0, that correspond to a null discharge:

- rise during 6 days, with : H0(1)=0 ; H0(5)=Hp(21) ; H0(6)=Hp(13). For the days 2 to 4, the level is calculated by linear interpolation between H0(1) and H0(5).
- stage during 6 days : H0(i) = Hp(i-6) for i between 7 and 12
- decrease during 29 days, with H0(N) = Hp(N-6) for N between 13 and 18 ; H0(N) = Hp(N-5) for N between 19 and 25 ; H0(N) = Hp(N-4) for N between 26 and 29 ; H0(41)=0. For the days 30 to 40, level H0 linearly decreases between H0(29) and H0(41).

Figure 9 shows the hydrographs determined for different objectives of recession crops area between 40 000 and 80 000 ha. The calibration of the Bakel station, which is non-bijective, is used to translate these hydrograph objectives in discharge with the method of water level gradient. Each hydrograph is finally represented in a simplified manner from the discharges at days 1, 5, 7, 12, 13, 29 and 41, with linear interpolation between these ones.

DETERMINATION OF THE OPTIMAL DATE FOR THE FLOOD SUPPORT

The above results concern the design of flood hydrograph objective at Bakel. We must now determine the optimal date of this hydrograph that permit to achieve this one by flood support with minimum lost of energy production at Manantali. We present here the results obtained by POGR (1999-b) for the optimal date of a former hydrograph objective called 'ORSTOM1', which is very close to the hydrograph determined above for an area of 65 000 ha of recession crops .

The analysis evaluates the volume that should have been released each year from Manantali dam to achieve this hydrograph at Bakel over the period 1973-1997. This volume vary according to the start date of the maximum stage of the objective hydrograph. We are especially interested in the part of this volume that cannot be turbinated (turbines capacity: 600 m^3/s), considered as the cost of flood support. Calculations are made in daily time step. They take into account the discharges observed in the Bakoye at Oualia and Faleme at Gourbassy, assuming a propagation delay of 3 days and no intermediate inputs from these stations and Manantali to Bakel. For each year, we determine a minimum cost for the flood support, obtained with an optimal date for the target hydrograph. For every other date tested, the difference between the cost obtained and the minimum cost of the year is then considered as a 'wasted' volume of water, due to non-optimal positioning of the flood hydrograph. The analysis determines the August 28 as the best date for the stage start of the hydrograph objective, that statistically minimizes the wasted volume (Fig. 10). This positioning of the flood hydrograph objective, that minimizes power production losses caused by flood support, also provides a flood early enough to permit full development of recession crops before the arrival of the cold season.

As a first approximation, the optimal date thus calculated for the hydrograph "ORSTOM1" is adopted for the different objective hydrographs whose form is determined above. These Hydrographs are shown on Figure 11.

INVERSE PROBLEM : EVALUATION OF A POTENTIAL AREA OF RECESSION CROPS IN THE VALLEY AS A FUNCTION OF THE FLOOD HYDROGRAPH AT BAKEL

Data used above to determine relationships between SCv(Smv) and Hb are used here to determine inverse relationships between Hb and SCV (fig. 12). These relationships are used in the following way to calculate a yearly potential area SC0v of recession crops from the daily levels observed at Bakel gauge during the year.

- For each j day of the year :
  - calculation of a level H0b(25) equal to the average of the daily levels of days j to j + 24;
  - calculation of a level H0b(N), equal to the maximum value of the average of the daily levels of days j+x to j+x+N-1 for x varying from 0 to 25-N. This level H0b(N) is calculated for N = 6, 10, 15, and 20 days;

- translation of levels H0b(25) and H0b(N) in recession crops area values (SC0a(25) and SC0a(N)) using the average relationships established over the period 1946-2000 between Hb and SCv (fig. 12);
- calculation of a single value SC0b of recession crops area by linear combination of SC0a(25) and SC0a(N) with the following formula wherein the factors K(6) to K(25) are constants defined below :

$$SC0b(j)=K(6)\times SC0a(6)+K(10)\times SC0a(10)+K(15)\times SC0a(15)+K(20)\times SC0a(20)+ K(25)\times SC0a(25)$$

- Determination of the annual area of SC0v recession crops, equal to the annual maximum of daily values SC0b(j)

The coefficients K(6) to K(25), to which we impose an amount equal to 1, are determined to minimize the standard error of the annual areas SC0v obtained, compared with the observed and completed values of SCv over the period 1946-2000. As shown in Figure 13, their optimized values (K(6) = 0.51873, K(10) = K(15) = K(20) = 0, K(25) = 0.48127) permit to assess precisely enough the recession crops area from the Bakel hydrograph (NSE = 0.938).

REAL-TIME ACHIEVEMENT OF THE FLOOD SUPPORT

For real-time management of the Manantali dam, OMVS uses the Progeman software (POGR, 2001-a) which calculates the discharge that has to be released from the dam (turbines, bottom gates, sluice gates). The calculation takes into account the safety rules and various management constraints of the dam, management objectives and the hydrological situation (level observed in the reservoir and on several gauges on the basin, transmitted by radio). The discharge that have to be released from the dam for flood support is calculated with the propagation model of Lamagat mentioned above, which is based on the assumptions of the diffusive wave (acceleration terms negligible compared to the other terms in the Saint Venant equations). This model is suitable when intermediate inputs are negligible on the modelled reach, or when they are sufficiently correlated with discharge at one of the ends of the reach.

In natural regime, the discharge of rivers in the upper basin of the Senegal River is entirely related to monsoon rains, which are highly seasonal. Intermediate inputs between two stations are thus fairly correlated to the upstream station discharge. This permits to use the model with fairly good results. From Manantali to Bakel, we use the following two sub-models where the upstream discharge Q1n and the downstream discharge Q2n are respectively defined in this manner:

- upstream sub-model: Q1n = sum of natural discharges of Bafing at Manantali and Bakoye at Oualia; Q2n = natural discharge of Senegal at Kayes
- downstream sub-model: Q1n = sum of natural discharge of Senegal at Kayes and Falémé at

Gourbassy; Q2n = natural discharge of Senegal at Bakel

Each sub-model is then defined by two functions f and g calibrated on observed data, which give the downstream natural discharge Q2n and propagation delay D from the upstream natural discharge Q1n (fig. 14) :

D = g(Q1n(t))

Q2n(t+D) = f(Q1n(t))

In first approximation, the difference between Q2n(t+D) and Q1n(t) can be considered as discharge Qi(t+D) of intermediate inputs on the reach :

Qi(t+D) = Q2n(t+D)-Q1n(t) = f(Q1n(t))-Q1n(t)

In artificial regime, there is no reason that intermediate inputs are correlated with observed upstream discharge Q1. The sub-model is then adapted in order to estimate the downstream discharge Q2 in this manner :

D = g(Q1(t))

Q2(t+D) = Q1(t)+Qi(t+D) = Q1(t)+f(Q1n(t))-Q1n(t)

In real time, the raw results of the propagation model can be corrected by taking into account the recently observed modelling errors (differences between the values predicted by the model and the observed values of the discharge). This correction is made according to the principle of the closed loop, which uses some persistence (or autocorrelation) of these errors. The Progeman software calculates a corrected modelled discharge for Bakel, equal to the raw modelled discharge to which is subtracted 80% of the most recent recorded raw error.

Every day, the discharge that has to be released from Manantali dam for flood support is determined by successive frames. We thus calculate for each value tested a corrected modelled discharge at Bakel, until this one coincides best (value and time) with the hydrograph target at this station. Sometimes the Faleme, Bakoye and other natural tributaries produce a discharge that exceeds the target at Bakel, and no discharge released from the dam is then necessary for flood support. In this case, the dam only releases the discharge required by the other objectives (energy production, etc.).

RESULTS

RULES USED FOR FLOOD SUPPORT

Since the beginning of its operation in 1987, the Manantali Dam has supported flood of river Senegal many times, in order to achieve different target hydrographs at Bakel that all were supposed to create a sufficient flooding for 50 000 ha of recession crops. Since 2001, the target chosen by OMVS is the hydrograph which was calculated by the IRD with the method described above (POGR, 2001-b). This hydrograph is very close to that which is recalculated here for 50 000 ha of recession crops (Fig. 11).

Otherwise, the rule chosen since 2001 is to decide each year whether to support or not the flood of river Senegal, according to the stock of water available in the Manantali reservoir on August 20th. If this level is higher than some threshold, flood support is decided. Until the end of September, the achievement of the target hydrograph at Bakel is then integrated among the management objectives of the dam. If the threshold is not reached on August 20th, the flood support is abandoned for the current year and the dam only releases the discharge required by the other management objectives.

IMPACT OF CLIMATE HAZARD ON THE POTENTIAL AREAS OF RECESSION CROPS IN THE VALLEY

To analyze the impacts of the Manantali dam and climate hazards on the potential area of recession crops in the valley, we apply the method described above to calculate this area SC0v in function of the flood hydrograph of river Senegal at Bakel. The calculation is performed for each year on the period 1944-2011, both for observed and natural regime (the latter being entirely reconstructed by Bader and al (2014) since 1987).

The climatic hazard itself leads to substantial variations in the yearly potential area of recession crops. Three successive periods can thus be distinguished since 1945 in natural regime (Fig. 15 and 16):

- 1945-1975 : mean = 103 573 ha ; higher than 50 000 ha 30 years in 31.
- 1976-1993 : mean = 39 976 ha ; higher than 50 000 ha only 4 years in 18
- 1994-2011 : mean = 83 341 ha ; higher than 50 000 ha 17 years in 18

These results follow the trend of observed natural flow of the river, mostly high before the mid-1970s, then very low until the mid-1990's and finally quite mean since, until now.

IMPACT OF MANANTALI DAM ON THE POTENTIAL AREAS OF RECESSION CROPS IN THE VALLEY

Three successive periods can be distinguished for the impact of the dam on the annual flooding of major riverbed in the valley and potential area of recession crops associated (fig . 17).

- From 1987 to 1991, the Manantali reservoir is filled gradually to the overflow level. However, the dam supports moderately low water and also quite high discharges are sometimes released during floods, probably to limit the reservoir filling rate and test the dam equipments. In most cases, these released discharges seem not to be destinated to flood support in the river Senegal, except perhaps in 1988 and 1991 when they contribute significantly to the flooding in the valley.

During this transitional period, the gradual filling of the reservoir results each year in reduction of the potential area of recession crops, compared wit natural regime. This yearly reduction amounts on average to 13 675 ha.

- From 1992 to 2003, support of low water is systematic and strengthened compared to the previous period. Specific discharges are also released each year to support the flood of the river Senegal, except in 1999 and 2003 when the dam must on the contrary store the maximum amount of water during the flood to limit the catastrophic effects of too high floods in the valley. This leads, these two years, to fill the reservoir higher than its overflow limit. With the flood support, the annual potential area of recession crops remains greater than 50 000 ha in most cases, and 40 000 ha in all cases. However, this area is each year less than that of natural regime (in average, yearly decrease of 5 243 ha), except in 1993, 1994 and 2000, when it is on the contrary slightly higher.
- From 2004 to 2011, the management of the Manantali dam is dedicated to hydropower and low water support and performs no flood support. This results in a very strong regulation of the discharge in the Bafing : this one always remains below 450 m^3/s at the outlet of the dam, instead of exceeding 2 500 m^3/s in natural regime. This regulation mitigates very efficiently too high floods in the river in 2007, 2009, 2010 and 2011, with a level never exceeding the overflow limit in the reservoir. Compared with natural regime, the management done results in strong and systematic decrease (26 331 ha on average) of annual potential area of flood recession crops. But except in 2004 and 2006, when it is lower than 30 000 and 15 000 ha respectively, this area still remains quite high most of the time, thanks to substantial contributions of natural tributaries received downstream Manantali (mainly Bakoye and Faleme).

DISCUSSION

In the Senegal River Valley, submersion of floodplains by the annual flood of the river is necessary for maintenance of ecological balance and for many traditional activities. Some studies have investigated the impact of the flood on fish resources (Roche, 2000) or groundwater recharge (Bader et al, 2014). But an accurate assessment of the ecological benefits of the flood is still very difficult. On the other hand, agricultural statistics permit to link the annual area of recession crops to characteristics of the annual flood of the river in Bakel. Therefore this area, which directly concerns the riparian communities, is used here to define flood hydrograph objectives based on.

The target of 50 000 ha of recession crops chosen by the OMVS for flood support is very low compared to the annual potential areas observed from 1944 to 1975 (over 100 000 ha in average). But it is beyond most natural annual potential areas for the period 1976-1993 (average lower than 40 000 ha), whose weakness correspond to the natural decline of discharges observed during this period. So, the flood support aims a modest but significant goal.

To be satisfied, the objectives of energy and low water support require a sufficiently high level in the Manantali reservoir at the end of the rainy season. Using the natural discharges observed on the upper Senegal basin, the Simulsen software (Bader and al, 2006) can provide a statistical evaluation of this level, depending on the level in the reservoir to August 20th (optimal date for flood support beginning) and planned management rules. The decision to achieve or not the flood support is thus taken each year around August 20th, depending on the level observed in the reservoir on that date, which is compared with a threshold chosen by OMVS : if the level is higher than the threshold, the flood support is decided ; if it is lower, the flood support is abandoned for the current year. Dam management is thus very influenced by the value of this threshold: a high threshold promotes the production of energy and scarce the flood support, while a low threshold allows more frequent flood support and weakens production.

Since the complete installation of its turbines in 2003, the Manantali Dam has not achieved any flood support and has only released discharges through the turbines (excluding overflow discharges after complete filling of the reservoir in September-October 2003). The floods observed at Bakel can be classified into two categories:

- In 2004 and 2006, the very low floods observed show that OMVS decided not to support the flood those years, despite a relatively high level in the reservoir on August 20th 2004 (200.96 m).
- In other years (2003, 2005 and 2007 to 2013), flood support was not necessary to achieve the objective of a potential area of 50 000 ha of recession crops, because Faleme and Bakoye provided sufficiently high contribution. But level was quite low in reservoir on August 20th of these years and even mostly lower than that one of 2004 (fig.18). It is thus quite likely that flood support was abandoned these years, and that it wouldn't have been achieved, even if it had been necessary to reach the goal of crops area.

In fact, significant discharges are released through the turbines during the dry season to meet energy demand, which causes a strong lowering of the level in the reservoir. Except in cases of strong inflows into the reservoir at the beginning of monsoon, this results mostly in a low level in the reservoir to August 20th, which could be considered insufficient for flood support. This type of management could therefore lead OMVS to abandon quite often the flood support, while the Charter of Senegal river water emphasizes the need to ensure it, except in extraordinary circumstances.

In the SDAGE (master plan of development and water management of the Senegal River) realised in 2011 by IUCN/CACG/SCP, OMVS presents several large dam projects that could be added to that of Manantali on the upper basin of the river Senegal in the coming years. Some of these new dams will create large reservoirs, especially on the Faleme (Gourbassy) and Bakoye (Badoumbe). It therefore will be possible to almost completely regulate the flow of the river Senegal if all these projects come true. But in the same study, OMVS promotes ecological management of water and reaffirms its commitment to maintain the flood support. Then this will be an entirely artificial flood that must be generated in a concerted manner from several dams located on the Bafing, Falémé and Bakoye. Further studies will be necessary to determine how to achieve this flood support, in order to penalize the least possible the energy production of these dams.

AKNOWLEDGEMENT

The authors want to acknowledge all the parties involved in the studies on the water management and the hydrological following of the River basin. They thank the OMVS and its different departments working in partnership with IRD. They thank the Hydrological Service of Senegal and particularly the brigades of Saint Louis and Bakel.

They thank the organisers of the African floodplains and deltas conference held in Dar Es Salaam 27-30 May 2014. They allow the presentation of this topic and encourage us to present this paper for publication.

REFERENCES

Bader J.C., Lamagat J.P., Guiguen N. (2003). Gestion du barrage de Manantali sur le fleuve Sénégal. Analyse quantitative d'un conflit d'objectifs. Hydrol. Sci. J., 48(4) : 525-538

Bader J.C., Rolland D., Pouget J.C. (2006) Simulsen. Logiciel de simulation de gestion d’un barrage à objectifs multiples, au pas de temps journalier. Manuel de référence et d’utilisation. IRD, Montpellier. 85 p.

Bader J.C., Cauchy S., Saura P., Duffar L. (2014) Monographie hydrologique du fleuve Sénégal. IRD, Montpellier. (sous presse)

Bonneau M. (2001) Programme d’optimisation de la gestion des réservoirs. Phase 3. Besoins en eau de l’agriculture irriguée et de l’agriculture de décrue dans la vallée du fleuve Sénégal. OMVS, IRD, Dakar. 185 p.

Lamagat J.P. (1983) Analyse de la vitesse de propagation des crues. Application à la prévision des crues et des étiages : delta central du Niger, modèle provisoire de propagation. Bondy, ORSTOM, 42 p multigr.

Lamagat J.P. (1987) Modèle de propagation des crues du Niger entre Koulikourou et Niamey. Niamey, ORSTOM, 93 p multigr.

Lamagat J.P. (1990) Analyse de la vitesse de propagation des ondes de crues. In : The state-of-the-art of hydrology and hydrogeology in the arid and semi-arid areas of Africa. Proceedings of the Sahel Forum (1989/02/18-23). Urbana : International Water Ressources, 291-305.

Lamagat J.P., Morel-Seytoux H.J., Albergel J. (1993) Analyse de la propagation des ondes de crue. *Hydrol. Continent.*, **8**(2) 113-137

POGR (1999-a) Programme d'optimisation de la gestion des réservoirs. Phase 2, tome 3. Mise en eau du lit majeur. OMVS, IRD, Dakar. 43 p.

POGR (1999-b) Programme d'optimisation de la gestion des réservoirs. Phase 2, synthèse. 117 p.

POGR (2000) Programme d'optimisation de la gestion des réservoirs. Phase 3, rapport intérimaire. OMVS, IRD, Dakar. 155 p.

POGR (2001-a) Programme d'optimisation de la gestion des réservoirs. Phase 3, synthèse. OMVS, IRD, Dakar. 151 p.

POGR (2001-b) Programme d'optimisation de la gestion des réservoirs. Phase 3. Crue artificielle et cultures de décrue. Synthèse finale. OMVS, IRD, Dakar. 68 p.

Michel P. (1973) Les bassins des fleuves Sénégal et Gambie. Etude géomorphologique. Mémoires ORSTOM, n° 63. ORSTOM, Paris. 752 p. + planches hors texte + cartes

Morel-Seytoux H.J., Fahmy H., Lamagat J.P. (1993) A composite hydraulic and statistical flow-routing method, *Water Resour. Res.*, **29**(2), 413-418

Roche (2000) Etude des ressources ichtyologiques du fleuve Sénégal. Roche International, OMVS, ACDI, Soned, SainteFoy (Quebec). 294 p. + annexes

Rodier J. (1964) Régimes hydrologiques de l'Afrique noire à l'ouest du Congo. ORSTOM, Paris. 137p.

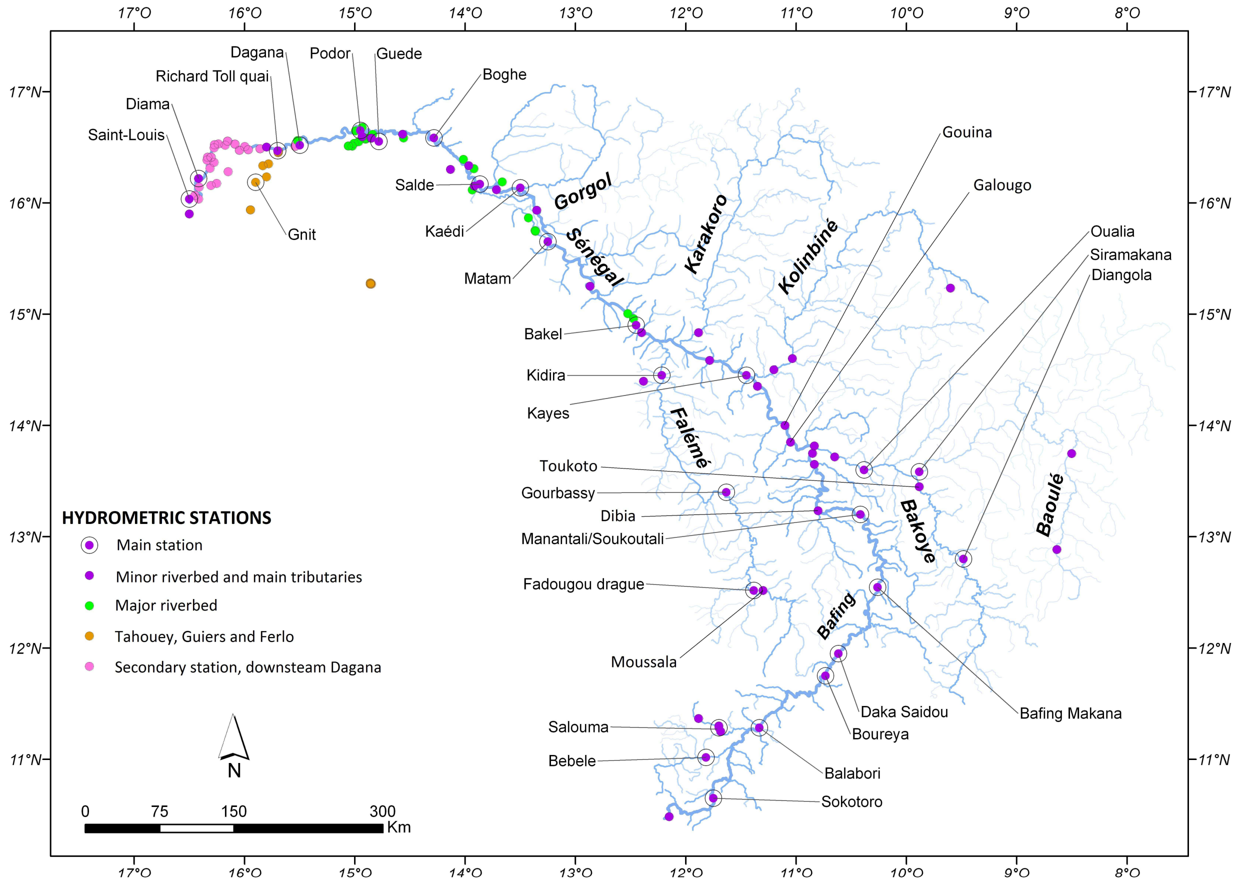

Figure 1: hydrometric stations and hydrographic network on the Senegal River Basin

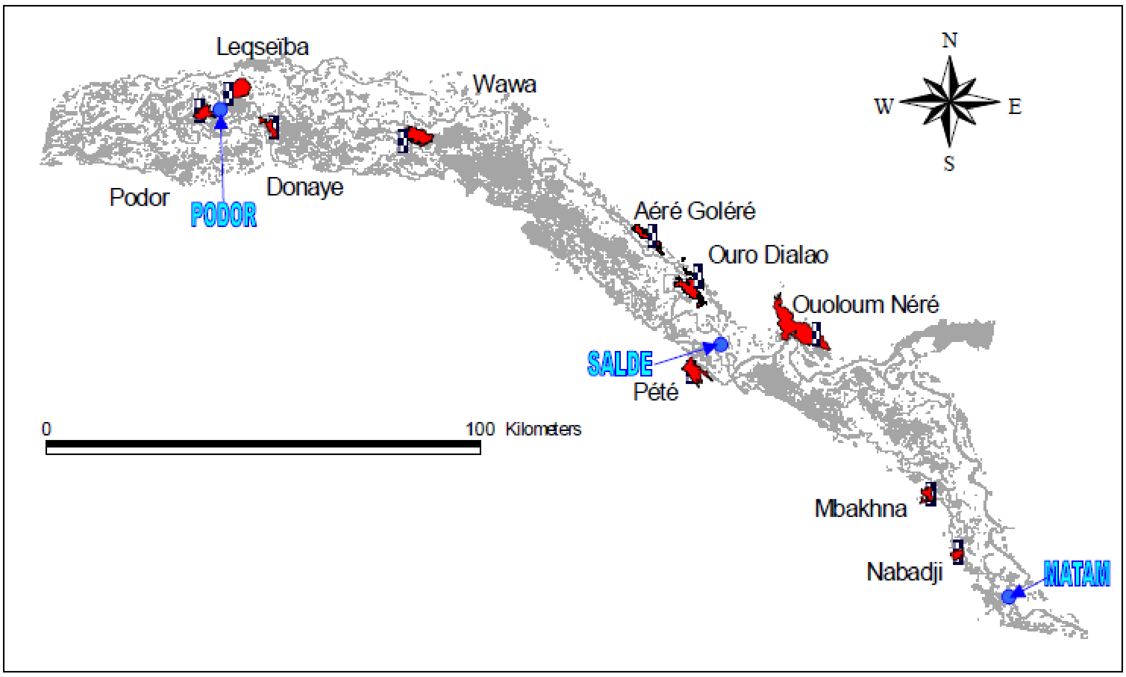

Figure 2: position of hydrometric stations on the main channel (bold) and the floodplains of the river. (Source: POGR)

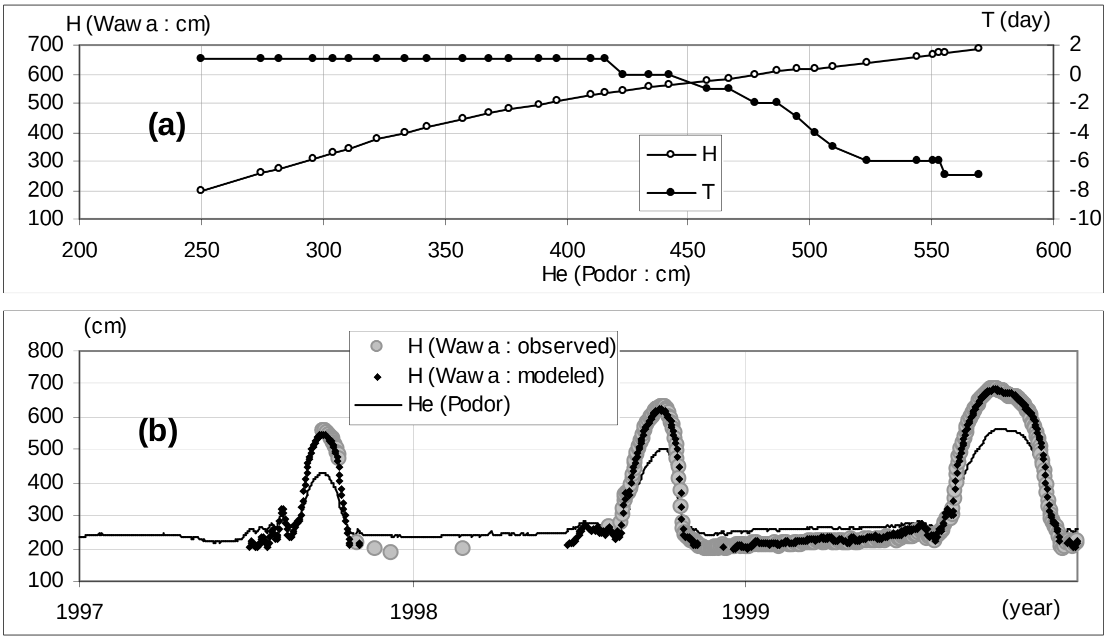

Figure 3: propagation model of Lamagat. Example of calibration (a) and application (b) of the model over the period 1997-1999, between Podor in the minor riverbed (level He on gauge whose zero absolute altitude is -44 cm IGN) and Wawa in the floodplains (level H in absolute altitude)

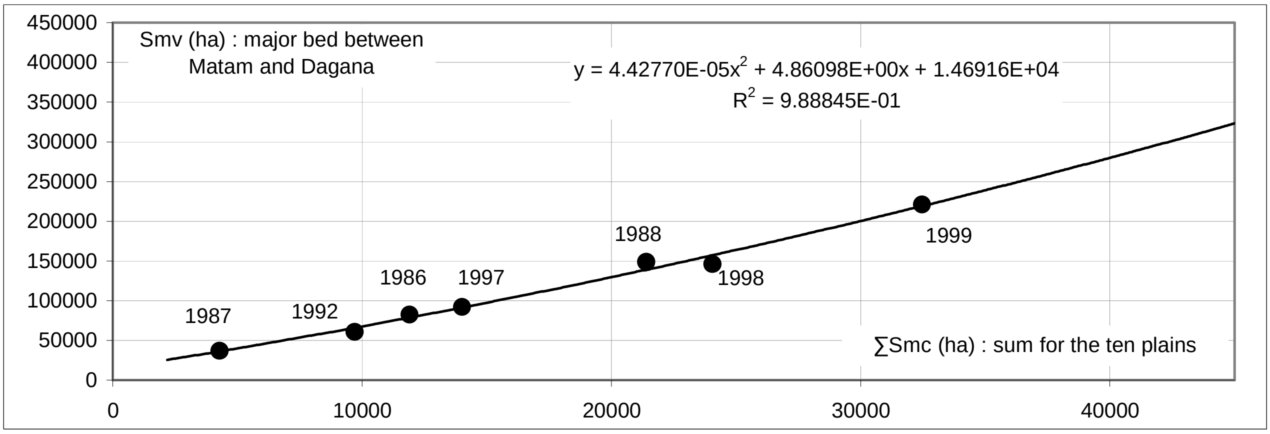

Figure 4: relationship between the sum of annual maximum flooded area of the ten floodplains and the maximum annual flooded area on the entire major bed between Matam and Dagana

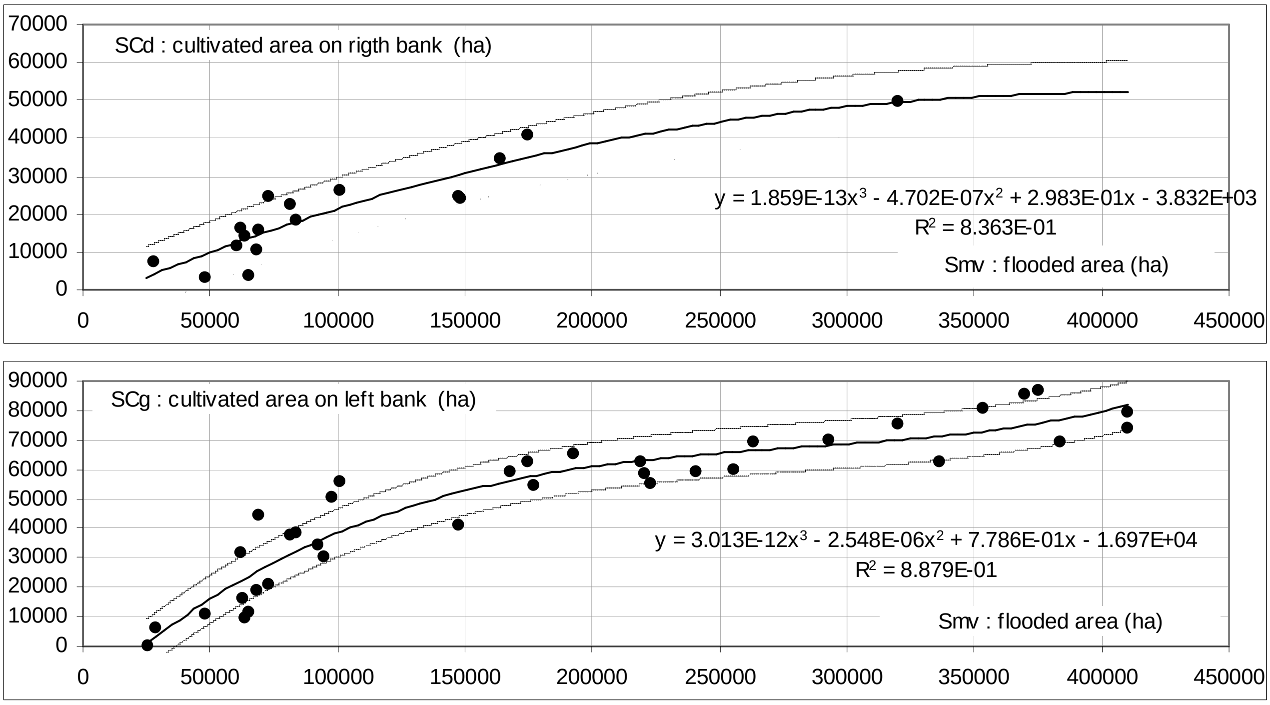

Figure 5: average relationships (with 90% confidence intervals) between the maximum annual flooded area Smv on the entire majorbed and flood recession crops areas observed on the right bank (Scd) and left bank (Spc) between Matam and Dagana

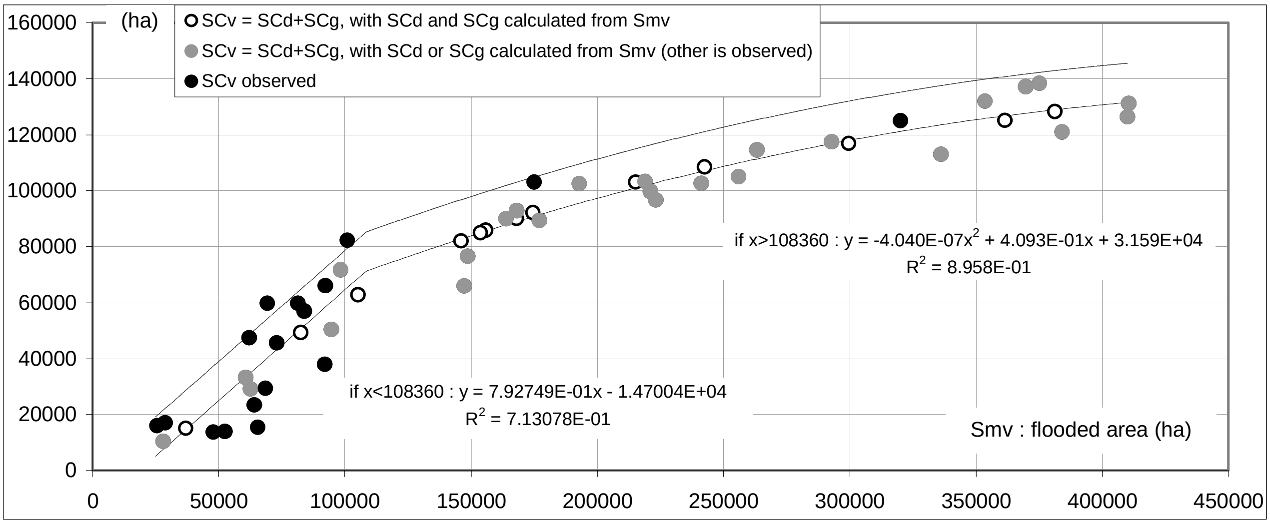

Figure 6: average relationship (with 90% confidence interval) between the annual Smv flooded area on the entire major bed and SCv area of flood recession crops grown between Matam and Dagana over the period 1946-2000

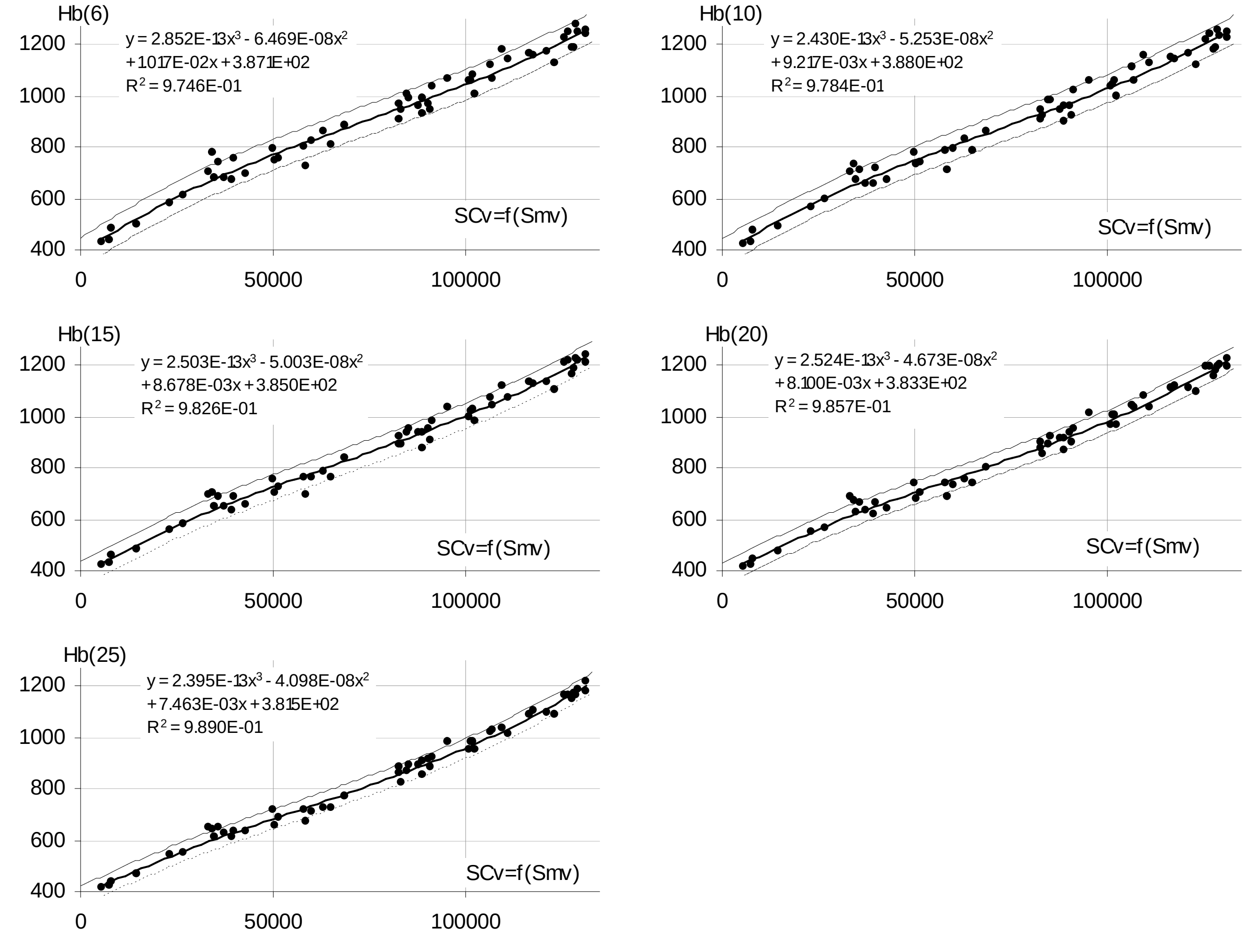

Figure 7: relationship between annual SCv area of recession crops and the average Hb(N) of the N highest daily levels observed in the year at Bakel gauge, over the period 1946-2000 for different N values between 6 and 25 days

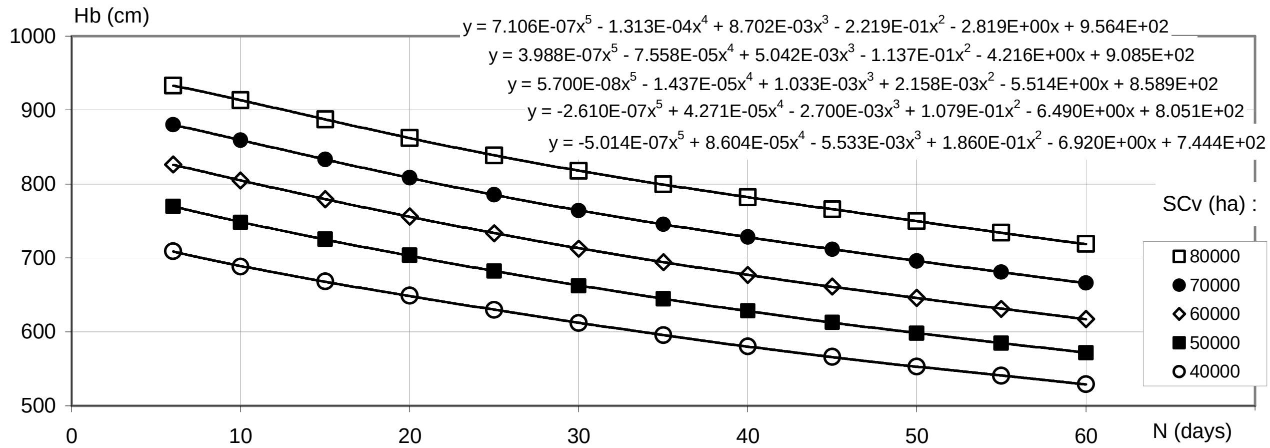

Figure 8: examples of average relationships (period 1946-2000) between the length N and the mean Hb of the N highest daily levels of the year at Bakel gauge, for values of recession crops areas SCv varying from 40 000 to 80 000 ha

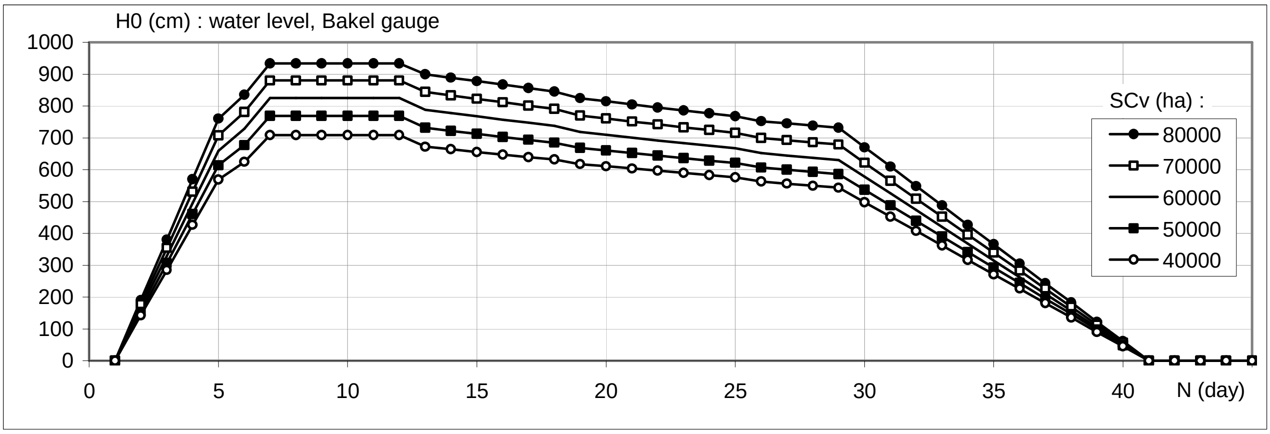

Figure 9: hydrograph objectives at Bakel gauge, determined for different recession crops areas between 40 000 and 80 000 ha in the valley between Matam and Dagana

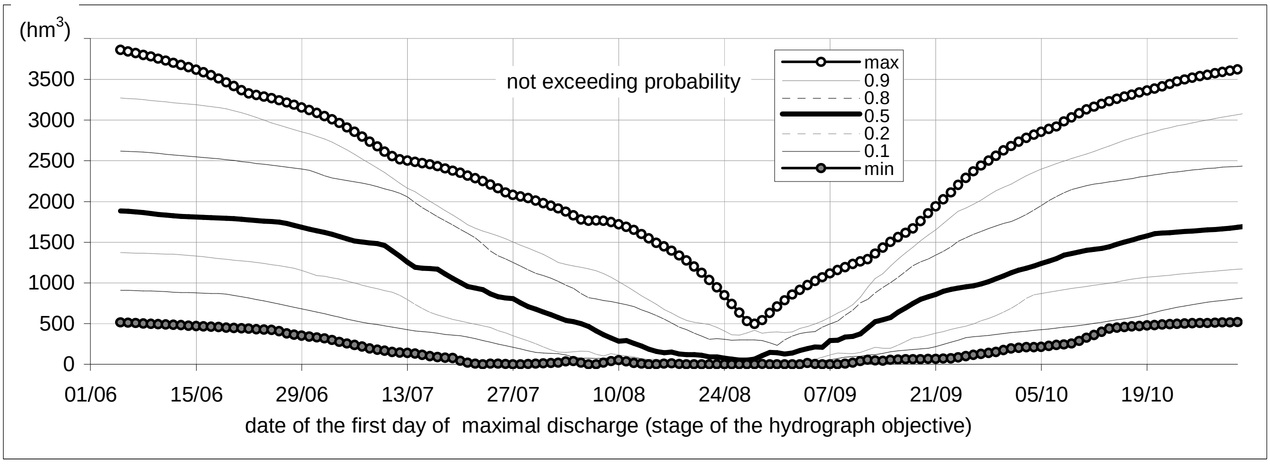

Figure 10: theoretical iso-frequency values over the period 1973-1997 of the volume annually ‘wasted’ at Manantali, caused by non-optimal date of the hydrograph objective "ORSTOM1" in Bakel, depending on the start date of maximum discharge of this one.

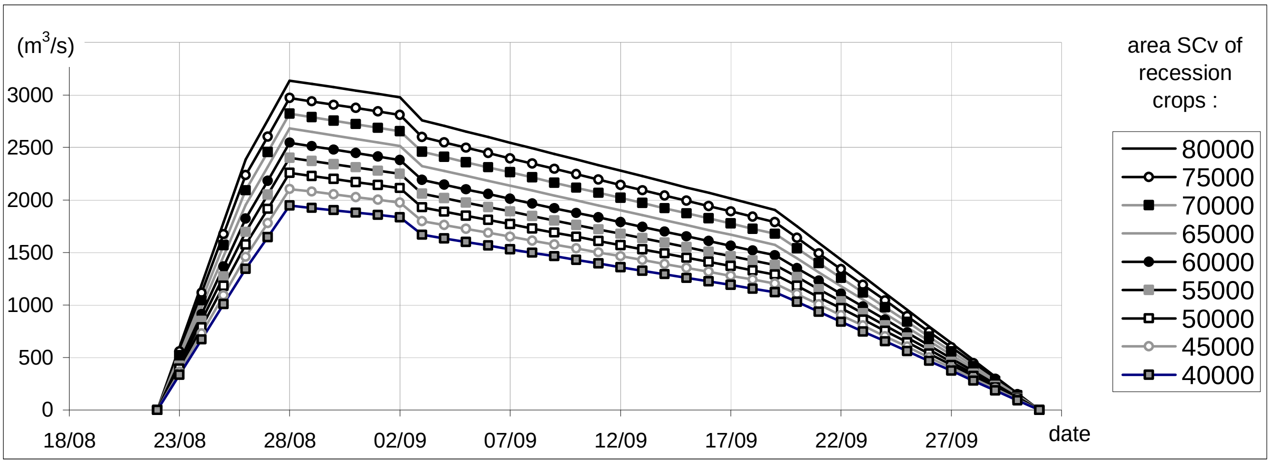

Figure 11: flood hydrograph objectives of the river Senegal at Bakel gauge, associated with different areas of recession crops

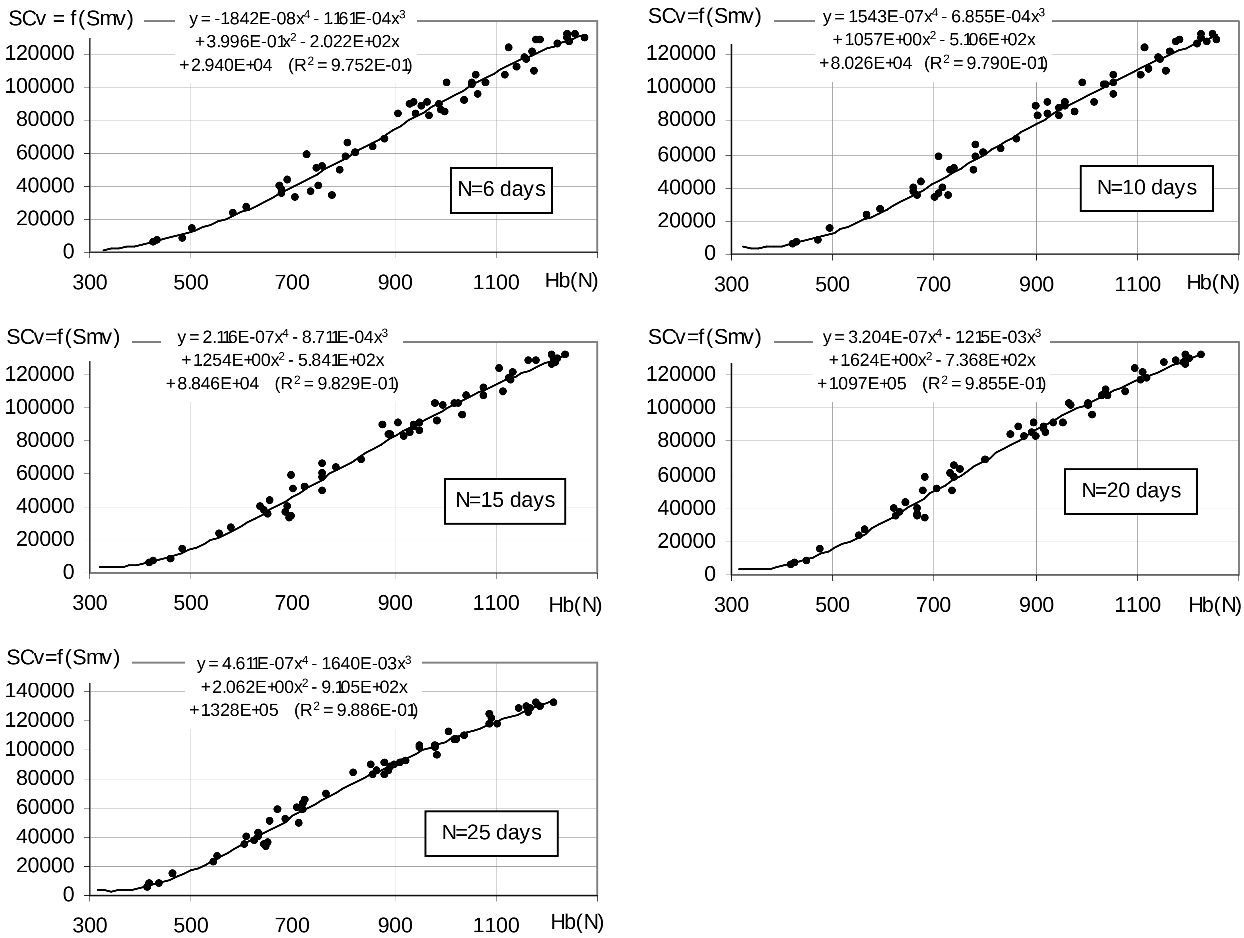

Figure 12: relationship between the mean Hb(N) of the N highest daily levels of the year at Bakel gauge (cm) and the area SCv of recession crops (assessed in hectares, from the flooded area Smv), over the period 1946-2000

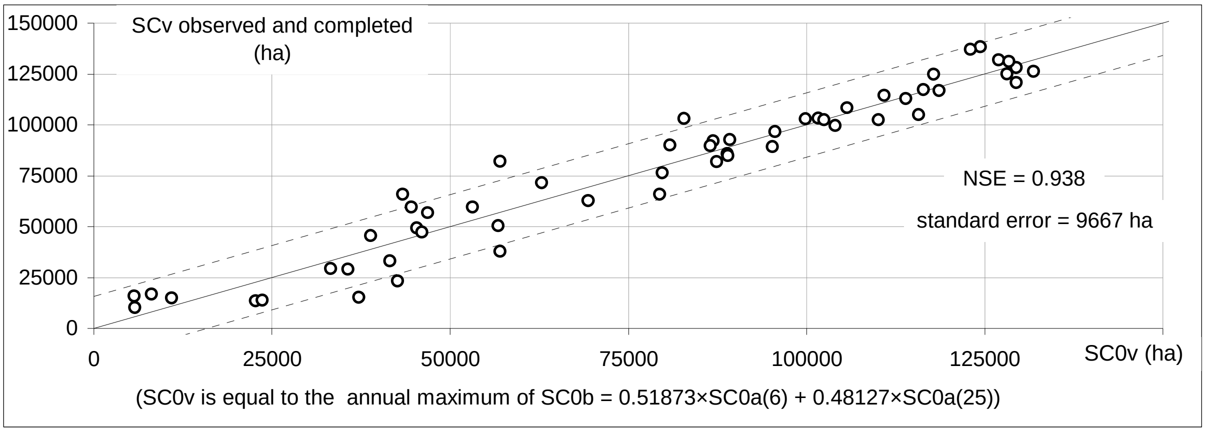

Figure 13: Annual recession cropping area for the regime observed over the period 1946-2000. Comparison between SCv (observed and completed values) and SC0v (calculated from the observed hydrograph at Bakel gauge), with confidence interval of 90% framing the mean relationship SCv = SC0v

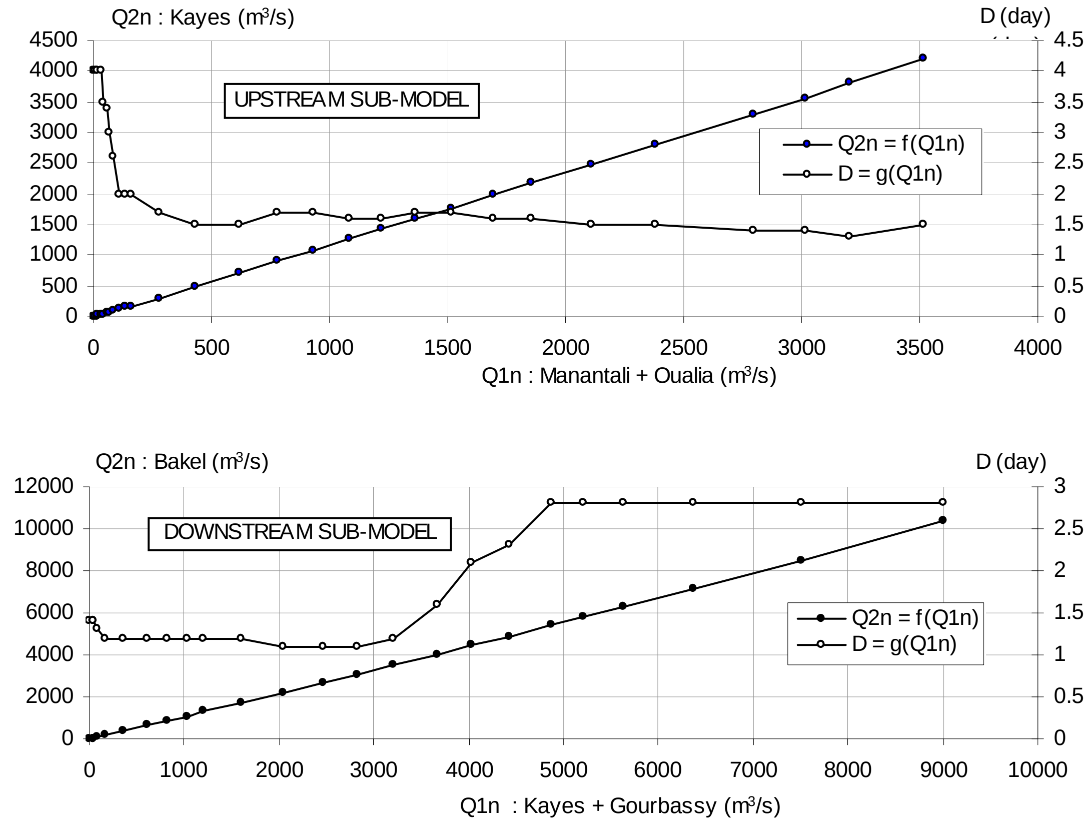

Figure 14: propagation model of Lamagat fitted between Manantali and Bakel (from Bader et al (2014))

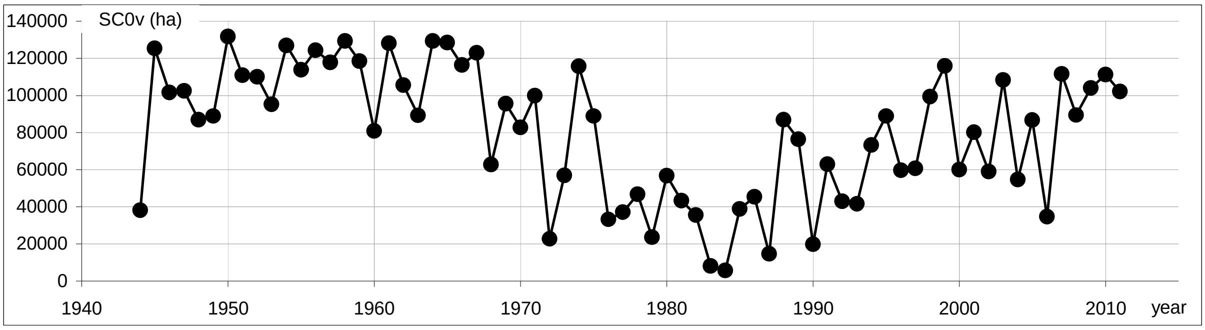

Figure 15: chronological evolution of annual SC0v potential area of recession crops calculated from flood hydrograph at Bakel gauge for natural regime, over the period 1944-2011

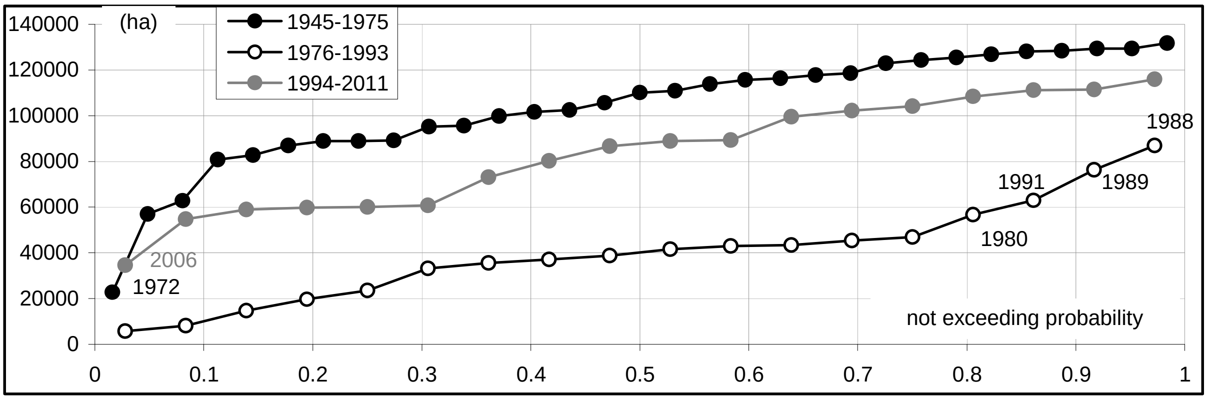

Figure 16: distribution function of the annual potential area SC0v of recession crops for natural regime over the periods 1945-1975, 1976-1993 and 1994-2011

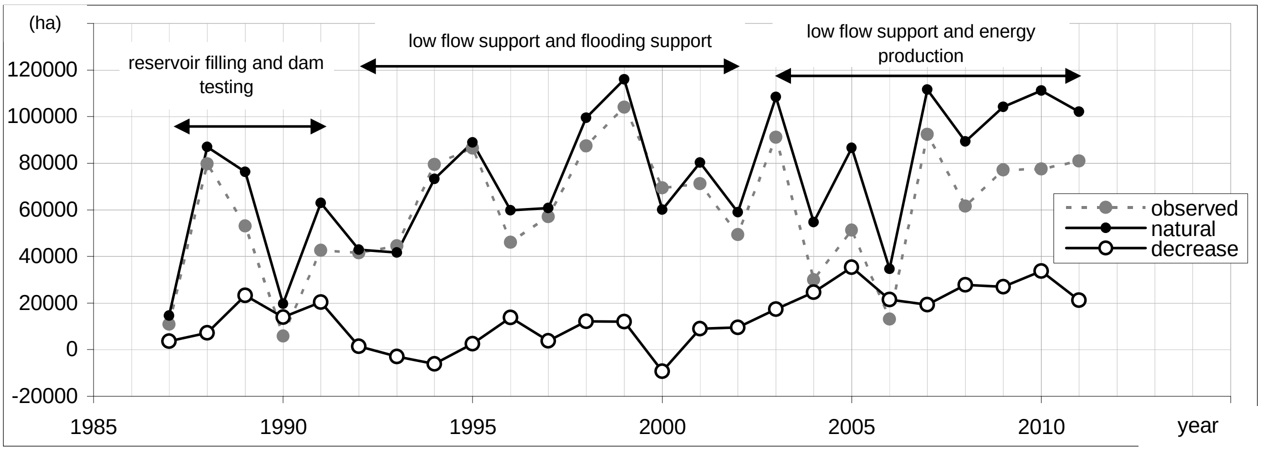

Figure 17: annual potential area SC0v of recession crops for natural and observed regime over the period 1987-2011, and decrease of this area caused by the Manantali dam (difference between the previous two areas)

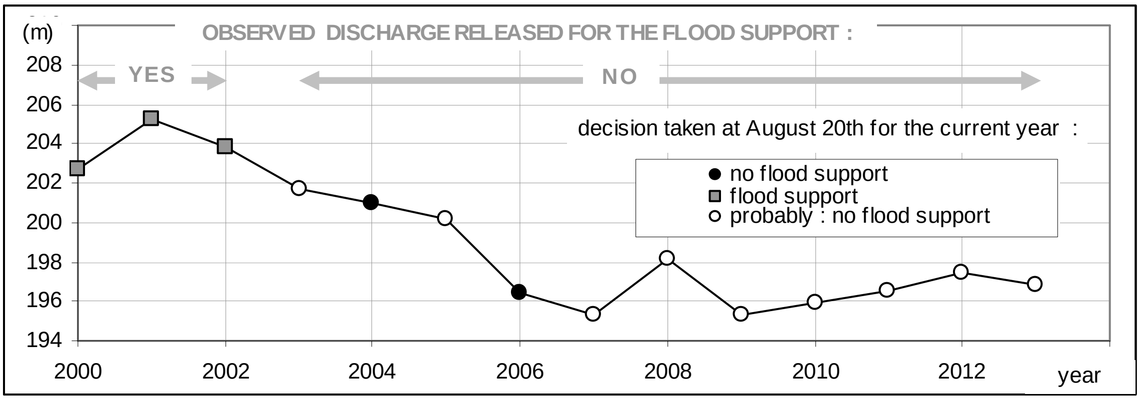

Figure 18: level observed August 20th in the Manantali reservoir, each year over the period 2000-2013