Agricultural systems and transnational water management in the Senegal River basin

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Abstract

This paper examines the relationship between hydrology and the functioning of traditional and modern agricultural systems in the Senegal River valley in West Africa. It will be demonstrated that the traditional flood recession agriculture, relying on the natural floodings of the wide river valley, is declining because of a strong reduction of the inundated area. This is due to both the reduction in rainfall since the early seventies and the construction of the Manantali Dam, controlling the discharge in the Bafin branch of the river. The operation of the dam is presently optimized to satisfy the needs of modern irrigated rice cultivation, yet the development of this cultivation has not entirely lived up to expectations, mainly because of economical and management problems. Therefore, farmers still express a preference for flood recession agriculture, whenever the floodings are suffiently large. In the future, water availability for both the flood recession and irrigated agriculture will be influenced by two major projects: Firstly, it is planned that hydro-electric power production will be initiated at Manantali, which will change the principles of dam operation. Secondly, it is planned to dam the Faleme branch of the Senegal River in order to divert water into the dry 'fossil' valley system in northern-central Senegal, whereby the discharge in the main river is reduced. It will be argued that hydrological modelling coupled with an economic assessment of costs and benefits of all the effects, including the environmental impacts, are necessary in the decision making process concerning major projects that affect water availability and management in major transnational river basins, such as the Senegal River basin.

Keywords

Agricultural systems, flood recession agriculture, irrigation, water management, Senegal.

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The research project 'Integration of Earth Observation Data in Distributed Agrohydrological Models' (INTEO), funded by the Earth Observation Programme of the Danish Research Councils, was initiated in 1997. The main objective of the project is to develop methods to integrate remotely sensed data in hydrological models, with the perspective of improving water resource management. The project was implemented in the Senegal River basin in West Africa (Figure 1) for which a large scale distributed hydrological model has been set up. Once tested, the model can be used to study the effects of changes in natural conditions, in particular rainfall, and the impacts of human water management, e.g. in the form of dam construction and operation as well as expansion of irrigated agriculture.

The main purpose of this paper is to describe the context in which the research performed in the INTEO project should be seen, with emphasis on how the different water resource management practices have influenced the agricultural production systems in the basin.

The Senegal River basin has been affected by two major dam construction projects, the building of the Diama and Manantali dams. These dams serve a number of purposes, including hydro-electric power generation (which is yet to be implemented) and provision of a stable water supply for irrigated agriculture in the delta and the valley. Plans for the future include the 'Fossil Valleys Project', which will involve the building of a dam on the presently uncontrolled Faleme branch of the Senegal River and the consequent diversion of river discharge into a dry valley system inside Senegal. This is expected to have considerable effects on both the flood recession and the irrigated agriculture in the valley. As with the construction and management of the Diama and Manantali dams, the economic, environmental and social gains and losses associated with the project are not very well known. It is the intention with this paper to point out the necessity of using integrated hydrological models and environmental economic assessments, as tools for the analysis and resolving of the conflicts of interests inherent in transnational water management on the scale of the Senegal River basin.

The paper is divided into two main sections. Firstly, the characteristics of the Senegal River basin will be presented, including a description of the general issues related to water management within the basin. Secondly, the relationship between the hydrology and agricultural production systems in the river valley will be studied, and the impacts of changes in the water management on agricultural systems will be discussed. The paper will be concluded by suggestions as to how future work within the INTEO-project may contribute to decision making concerning water management.

The Senegal River basin

The Senegal River has its source in the Fouta Djalon mountains in Guinée in West Africa and provides water resources to the semi-arid parts of Mali, Senegal and Mauritania. The basin has a total drainage area of approximately 350.000 km^2 and the main tributaries are Bafin, Bakoye, and Faleme (Figure 1). The rainfall within the basin is characterized by a large north-south gradient, with the highest rainfall in the source area in the Fouta Djalon (up to 2000 mm/year), and the lowest towards the north where the annual precipitation amounts to less than 200 mm (Figure 2).

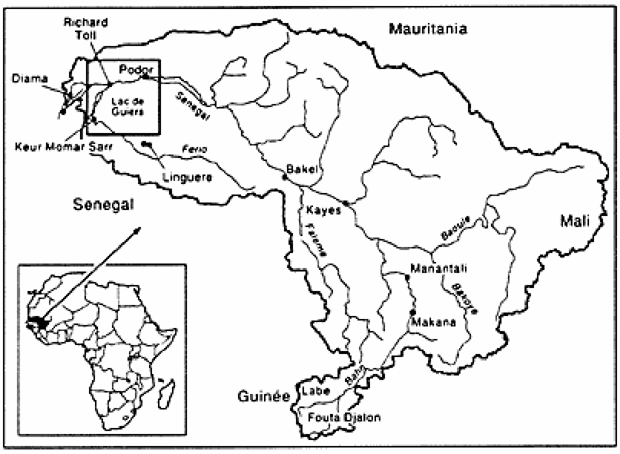

Figure 1: The Senegal River basin. The small frame shows the area studied in more detail in Sandholt et al. (1999).

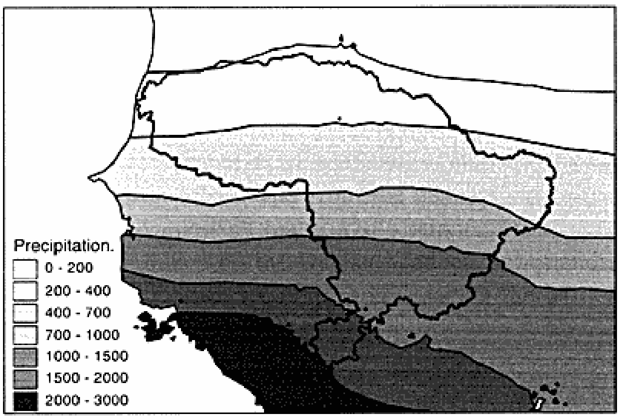

Figure 2: Annual average rainfall, 1960 - 1990. Modified from Corbett and O'Brien (1997).

Substantial agricultural activities depend on water supplied from the river, based either on natural flooding as in the traditional flood recession agriculture, or on pump-based irrigation. The climate is characterised by one rainy season lasting two to six months, resulting in a strong seasonal variation in river discharge. This imposes limitations on the crop choices and the number of crops that can be grown annually.

Since the early seventies the discharge of the Senegal River has been affected by the reduced rainfall (Figure 3), and in addition, the two dams, constructed in the eighties, have had considerable impact on river discharge over the years. The Diama dam was built in the river delta, with the purpose of hindering the intrusion of salty seawater in periods with low discharge. In 1987 the construction of the Manantali dam on the Bafin tributary in Mali was com-

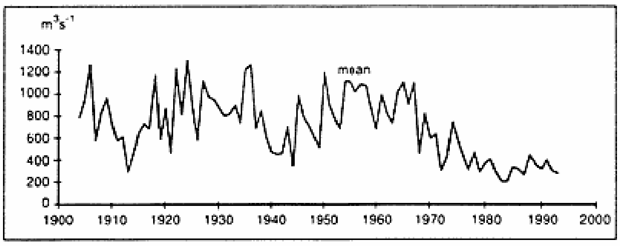

Figure 3: River discharge at Bakel. Adapted from Albergel et al. (1997).

pleted. The dam controls approximately 50% of the total river discharge. The Manantali dam was built to facilitate hydro-electric power production and to regulate river discharge in order to provide a stable water supply for the pump-based irrigation in the river valley. However, the hydro-electric turbines have yet to be installed. Ideally the operation of the Manantali dam should be optimized to allow for artificial floods, affecting 100.000 ha in the river valley, and in addition allowing for navigation on the Senegal River. The dam operation, combined with the drought, has resulted in inundations that have been smaller than planned, as shown in a later section.

Conflicts of interest in transnational water management in the Senegal River basin

As in the cases of several other transnational river basins (Acreman, 1996), the management of the water resources of the Senegal River has caused controversy, between the countries involved, and between the interests associated with hydro-electric power production, agriculture and the environment. Resolving these conflicts of interests is a demanding task. A proper understanding of the hydrological regime of the river basin must be established to allow decision makers at national and supranational levels to predict the effects of changes in water demands, construction of dams, diversions of water, land cover change and climatic change. This requires the establishment of a suitable hydrological model of the basin.

The differences of interest involved in water management may concern (1) the allocation of and access to water for irrigation or drinking water, (2) the quality of the water and (3) the balancing of management objectives for the operation of dams, taking into consideration both modern and traditional agriculture (see below), hydro-electric power generation, navigation on the river, the replenishment of aquifers and conservation of biologically interesting wetland ecosystems.

A supranational authority, the 'Organisation pour le Mise en Valeur du Fleuve Senegal' (OMVS) has been established to decide on water allocation and dam management principles within the Senegal River basin. Mali, Mauritania and Senegal are members of OMVS, whereas Guinée, from where most of the river discharge originates, is not. In order to support the decision-making, OMVS operates three non-distributed hydrological models, each with a specific application (Ouattara, 1998), allowing for the effects of various changes in water demands to be studied.

Two prospective major projects will lead to significant changes in the principles of the management of water resources and dam operations. These are:

- The planned installation of hydro-electrical power generators at the Manantali Dam by year 2000.
- The 'Fossil Valleys Project', involving the diversion of water from the Senegal River into a fossil valley system inside Senegal.

Economically optimal hydro-electrical power generation will require a relatively stable flow of water through the Manantali Dam, and thus the current management objectives, which focus on water provision for irrigated agriculture, will have to be changed. Originally, the construction was rated to generate 800 GWh/year. In addition, plans for the operation of Manantali after the installation of the hydro-electrical power turbines have included assuring enough water discharge all year to allow navigation on the Senegal River all the way up to Kayes (Figure 1).

The 'Fossil Valleys Project' aims at developing the agricultural potential of a dry valley system in northern (and in a proposed later phase, the central) part of Senegal, by diverting water from the currently uncontrolled Faleme tributary of the Senegal River at Bakel, where a dam is planned. The perennial river system of Senegal includes only the Senegal, Gambia and Casamance rivers, leaving the central parts of the country without any active river channels. Therefore, the Senegalese Government has proposed a project concerned with revitalization of the fossil river system in the central part of the country (Republique de Sénégal, Ministere de l'Hydraulique, 1998). The objectives of this project are to permit irrigation in the central parts of Senegal, facilitate reforestation, the development of continental fishing, regeneration of wildlife and flora and (last but not least) create new jobs. In the first phase of the project, water will be diverted into the Ferlo tributary, upstream from Lac de Guiers. This is obtained by deepening the lower part of the Ferlo Valley, thus creating a 125 km long channel from Keur Momar Sarr towards Linguère (Figure 1). The channel was completed in 1992.

The next phase, which has not yet been finally approved, involves the pumping of water from the Senegal River at Bakel into a channel between the river and the upper end of the Ferlo Valley, with a peak rate in the rainy season of 150-200 m^3/s. According to the plan, this should make the irrigation of 30.000 ha of land in the Ferlo Valley possible. From Ferlo, water is planned to fill the tributaries of the fossil valley system. During the dry season, a minimum flow of 10 m^3/s will allow the replacement of water in the fossil valley. The plans for this second phase has created disagreement between Mauritania and Senegal, as it involves reallocating water to the benefit of Senegal at the expense of river discharge, and thus irrigation potential, in the main river valley, shared by Mauritania and Senegal.

Several problems associated with the Fossil Valleys project need to be analysed. With respect to the hydrology, it is essential to know what will be the additional loss of water due to evaporation and infiltration.The topography of the fossil valley system can possibly result in high evaporation losses. With respect to agriculture, it is necessary to study whether the diversion of water into the fossil valley system will lead to a higher crop production, relative to using the same amount of water for irrigation in the Senegal River valley. Further, the control of the discharge in the Faleme tributary by a dam at Bakel may further reduce the peak flow downstream in the main Senegal River valley, which will make flood recession agriculture even more difficult.

All problems in this category have technical, agricultural, environmental and political aspects. The establishment of a suitable, distributed hydrological model, allowing for the objective analyses of the consequences of the various scenarios, is one of the elements involved in resolving the conflicts, yet other elements are also required. Balancing the costs and benefits of major projects, like the two mentioned, require that all the effects, including the environmental impact and effects on non-commercial agriculture, such as flood recession agriculture, have to be accounted for.

Agricultural systems in the river valley

Historical trends in agriculture in the middle and lower valley

A great variety of agricultural systems, rainfed, flood recessional and irrigated, may be found within the basin. In the middle and lower valley, where the average rainfall is less than 300 mm per year, flood recession and irrigated agricultural systems dominate. The importance of rainfed agriculture has decreased substantially since the drought of the early seventies, especially in the lower valley and will not be dealt with in this paper. Traditionally, flood recession agriculture has been the most important agricultural system in the middle and lower valley, supporting a relatively high population. Already in colonial times, the potential for increasing the agricultural output by introducing modern irrigated agriculture was recognized. With the drought of the seventies, policies of the Senegalese government and of major donor agencies focused on obtaining a higher level of national self-sufficiency in food production by promoting irrigated rice cultivation, especially in the delta. The construction of the Diama and Manantali dams should be seen in this context, since the provision of water resources for irrigation was the most important management objective of these dams. The expansion of irrigated agriculture in the valley, however, has not lived up to expectations.

Flood recession agriculture

Flood recession agriculture is traditionally carried out on the wide flood-plain, inundated during peak flow periods. The area inundated depends strongly on the flood level, as outlined in Figure 6, and the river level is, of course, closely related to the river discharge. Both the size of the inundated area and the duration of the inundation determine the potential for flood recession agriculture in any given year. The crops grown are mainly millet, sorghum, corn and beans (Gibb, 1987). Mineral fertilizers are rarely used. The average yields obtained are in the order of 400 kg/ha for cereals, yet vary strongly in both time and space (Gibb, 1986). It is not known whether average yields have changed significantly over time. Yield may be limited by either water availability, plant density, plant nutrient availability, plant diseases and insects or attacks by birds. The plant density is low, and this may be seen as an adaptation to the limited water or nutrient availability. The nutrient availability may have been influenced by changing patterns of inundation involving a reduced deposition of mud on the flood-plain after the construction of the Manantali Dam. The inundated area has been considerably reduced since the early seventies, and this, in combination with a considerable increase in the population in the valley, has meant that the flood recession agriculture can no longer ensure a stable and sufficient local food supply, let alone contribute to national food self-sufficiency.

Irrigated crop production

Pump-based irrigated crop production has increased dramatically since the seventies, supported by national policies and subsidies to agricultural inputs (Seck, 1991). Large external donors, such as the World Bank, have funded this expansion. A Senegalese institution, Société Nationale d'Aménagements et d'Exploitation des Terres du Delta du Fleuve Sénégal, SAED, has been responsible for the establishment of irrigation schemes on the Senegalese side of the river. Two main types of irrigation schemes exist: (1) Large (>500 ha) schemes, until recently operated by SAED itself and equipped with separate feeding and drainage channels, and (2) village schemes, often smaller than 200 ha, constructed without proper, separate drainage channels. The large schemes have typically proved uneconomical, in particular when subsidies on inputs were removed. Some of these schemes are currently being rehabilitated and subsequently transferred to private operators or village management. The village schemes are often abandoned and need rehabilitation after some years, frequently due to salinisation, caused by absence of a proper drainage system. Other factors, including inappropriate land allocation and management, malfunction of pumps (and lack of funding for maintaining or replacing them) and unsound economy, may also contribute. In general, privatization of the operation (but not necessarily the establishment) of irrigation schemes is favoured by external funding agencies, and SAED is supposed to serve mainly in a technical and advisory capacity, rather than operating the schemes.

Rice is the main crop. Only one rice crop a year is grown in the major part of the area. In addition, a dry season crop, often onions, may be cultivated. Rice yields vary widely, depending on the quality of the scheme, the amount of fertilizer applied and the quality and quantity of the labour input. Yield levels between 1 - 6 t ha^{-1} have been recorded, the latter only in newly established or rehabilitated, well-functioning schemes. The rice cultivation is based on large inputs of mineral fertilizers, and reductions in fertilizer inputs immediately lead to decreasing yields.

There is presently no lack of suitable land for rice cultivation in the valley upstream from Richard Toll (Figure 1), and the river discharge in and just after the rainy season is large enough to support an expansion of rice cultivation, as has also been predicted in the optimistic plans of past decades (Kane, 1998)

Irrigated versus flood recession agriculture

The reduction in the inundations has made flood recession agriculture relatively less attractive, yet if a satisfactory inundation occurs, most farmers will allocate labour to flood recession agriculture. This has to do with several factors, the most important probably being that labour productivity is relatively high and the capital input is low in flood recession agriculture. Since irrigated rice cultivation involves numerous risks, practising flood recession agriculture may be part of a risk adversion strategy. In the future the relative importance of flood recession agriculture versus irrigated agriculture may, therefore, be partly controlled by the extent (in time and space) of inundations.

A case study, illustrating the interdependency of river flow dynamics, dam operation and the potential for flood recession agriculture, will be presented in the next section.

Influence from the Manantali Dam on the floodings between 1986-96

Studies previously done on this subject (Bader (1992, 1997) and Albergel et al. (1997)) have mainly focused on the multi-purpose operation planning of the Manantali Dam, including the forthcoming implementation of hydro-electrical power production in year 2000. Here we will focus on the question of what has been the influence of the dam to date. Has the dam had any severe impact on the floodings, and thus on flood recession agriculture, in the river valley ?

To study this question, a time series of the natural river flow at Bakel has been reconstructed. As there is a good accordance between the measured flow at Manantali and Makana (Figure 4) in 1986 (before the dam was in operation) the Makana data was chosen to be representive of the natural discharge at Manantali in the period 1987-96. A reconstructed natural discharge at Bakel has the been com-

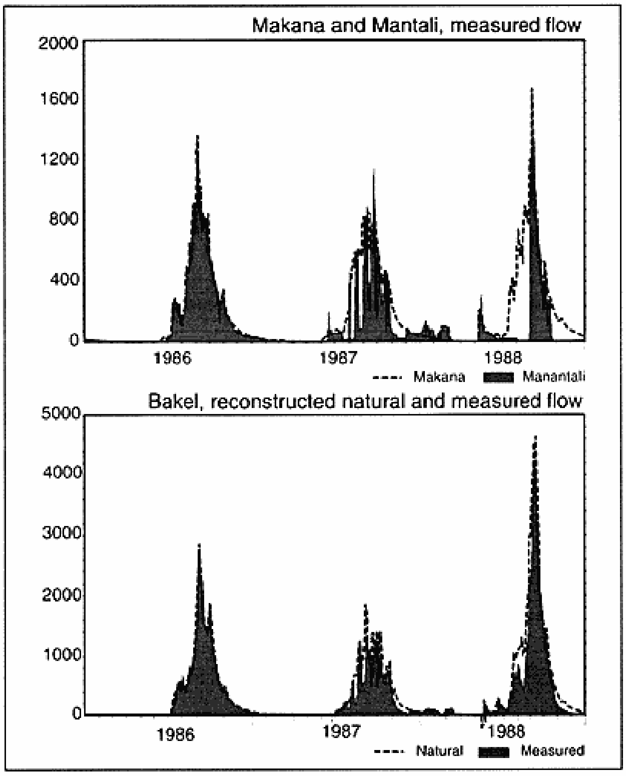

Figure 4: Measured discharge at the Manantali outlet and measured inflow to the Manantali lake at the Makana station (top) and 'reconstructed natural' and measured discharge at Bakel (bottom).

puted as the measured discharge at Bakel minus the measured artificial outlet from Manantali and added the measured discharge at Makana. The discharge time series from Manantali and Makana are given a time delay of six days relative to the Bakel time series. This method for reconstructing the natural discharge is based on the assumptions that (1) Makana and Manantali are sufficiently close, so that the delay between the two stations is small, (2) precise records of the outlet from Manatali are available, and (3) using a fixed six days delay between the flows at Manantali and Bakel is realistic, which implies that the 'smoothing out' of the discharge is insignificant. While the two former assumptions are realistic, the validity of the latter will depend on the time variation of the outlet from Manantali: If very sharp peaks occur, these are likely to be smoothed considerably before reaching Bakel.

According to Bader (1997) a criteria for a succesful flooding (seen from a recession agriculture point of view) is a period of at least six days with a discharge of at least 2500 m^3/s at Bakel. In Figure 5 this criteria is used to

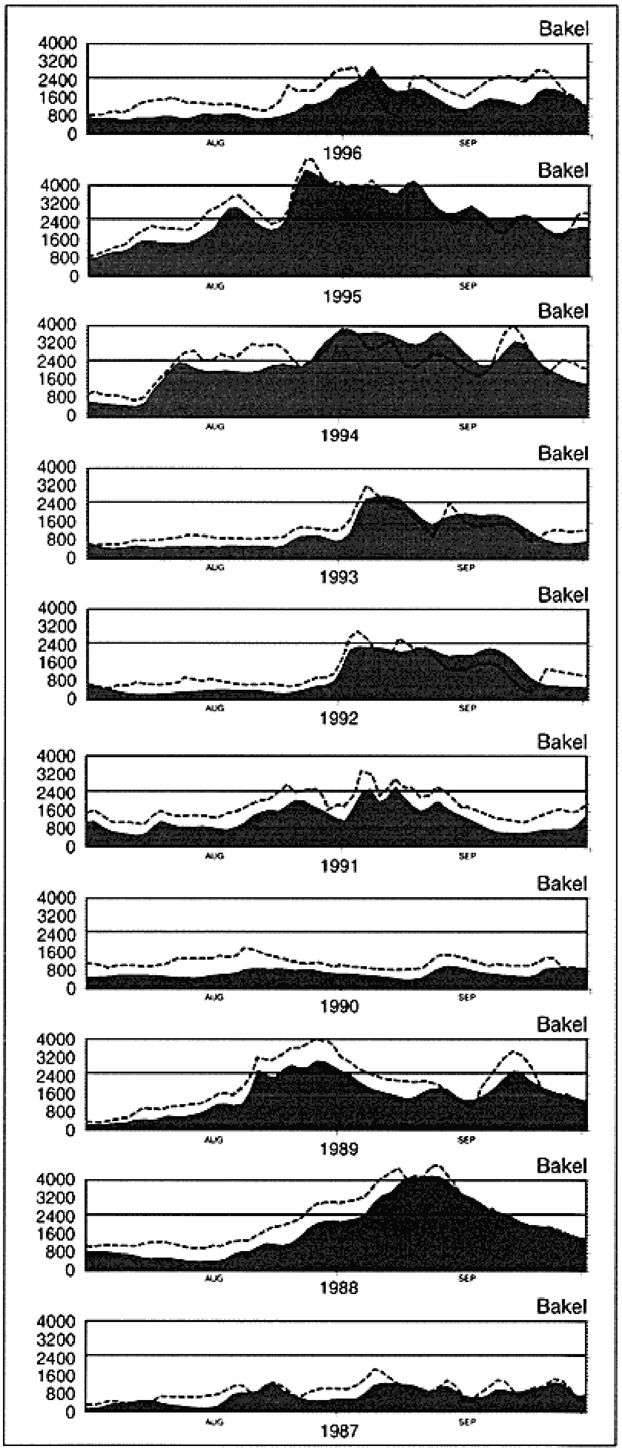

Figure 5: Comparison of the reconstructed natural and the measured discharges at Bakel in August and September 1987 - 1996.

compare the floodings created by the natural discharge and the dam-controlled flood (measured). In two out of ten years, 1987 and 1990, the discharge was so low that inundations would have been absent, even without Manantali. It should be noted that the effects of the droughts in 1987 and 1990 were quite visible in the following years. In two years, 1992 and 1993, the discharges were close to the critical limit of 2500 m^3/s, and Manantali did not appear to have a significant impact. In one year, 1995, the flooding was quite extensive and not strongly affected by Manantali. All in all, in five out of ten years, the operation of the Manantali dam seems to have had little negative impact on recession agriculture. In the years 1988, 1989, 1991, the operation of the Manantali dam has either reduced peak flow to below the critical limit or significantly reduced the total volume of water available for inundations. In 1994, the effect of Manantali may be seen to be quite significant, but it is difficult to know whether the shorter and more intensive flooding observed was inferior, seen from a recession agriculture point of view, as compared to the natural flooding, which would have lasted longer and fluctuated more. The same may be said about the situation in 1996.

The effects of river discharge on agriculture in the lower valley: A village level case study

A detailed study of three villages was made in order to examine the consequences of river flow dynamics on agriculture in the lower and middle river valley covering the period from before the drought of the 1970's until 1997. The study was carried out in three villages all located within 10 kilometres from Podor (Figure 1). The villages of N'Gaoulé and Diatar are located on the bank of the Senegal River, east and west of Podor. The third village, Goumel, is located on the bank of the Doué river, a river branch south of the Senegal River.

The study included detailed semi-structured interviews with a small number of households in each village, in combination with field visits and GPS-measurements of fields. The households were selected to represent both the 'rich' and the 'poor' households. In addition, interviews with agricultural extension officers and village leaders were carried out.

Village history

All three case villages were severely affected by the drought in the early 1970's. Prior to the drought, the livelihood strategies of the villages were different, involving a combination of fishing, herding, rainfed and flood recession farming. All of these productive activities were affected by the drought. The drought reduced the potential for rainfed farming, leading to a serious reduction in livestock, and limiting the extent and productivity of fishing and flood recession agriculture. By the end of the 1970's, the standard of living was very low and Diatar received food aid. Since most livestock died and fishing was extremely limited, flood recession agriculture became the main livelihood strategy and was practised in all three villages despite the limited extent of the yearly floods. In this period, a great number of the male population migrated to larger cities in Senegal or abroad in the search for work.

By the beginning of the 1980's village based irrigated agriculture was introduced in all three villages. None of the villages had any prior experience or knowledge of irrigated agriculture. The villages adopted the farming system under strict control and management by SAED, which supplied the villages with the machinery, know-how, credit and marketing services considered necessary. Thus irrigated rice cultivation existed alongside flood recession agriculture, which was still performed whenever possible.

The effects of hydrology on flood recession agriculture at the village level

Hydrological models have been used to study the relationship between the size of the flood and the extent of the inundation in the river valley, with varying results (Gibb, 1986). Seguis (1990) cites different sources for estimating the size of an average inundation, with results ranging from 370.000 ha to 1.000.000 ha. The effect of the river level on the extent of the inundation is shown in Figure 6 (Seguis, 1990). A small flood (river level at 3,58 m.I.G.N.) will inundate 100.000 ha, a medium size flood (river level at 4,88 m.I.G.N.) will inundate 370.000 ha, and a large flood (river level at 5,95 m.I.G.N.) 500.000 ha. Furthermore Figure 6 illustrates that a maximum river level at Podor below 3,42 m I.G.N. will result in no significant inundation. The variations in the model results call for caution, especially when using the results as the basis for decision-making and planning purposes. However, the shape of the relation is likely to be correct.

At the village level, details of the local topography are important when studying the effects of river level on the

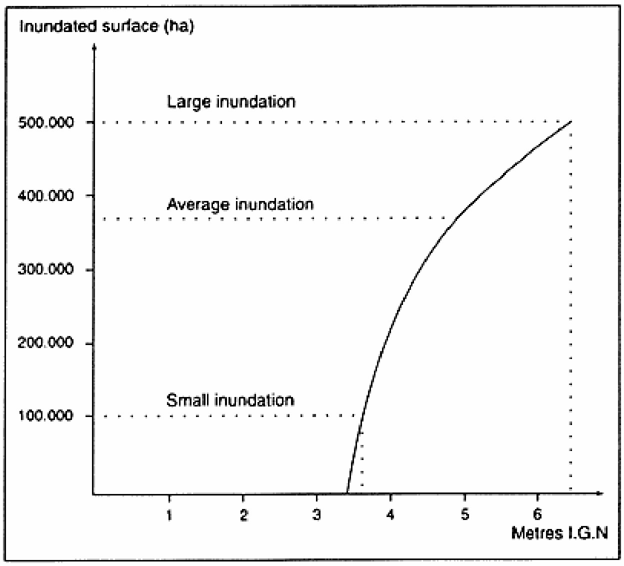

Figure 6: The relationship between the maximum river level at Podor and the inundated area in the Senegal River valley. Modified from Seguis (1990).

inundated area, since this determines the threshold above which the river has to rise before water enters the areas ('cuvette') used for flood recession agriculture. A topographical transect between the Senegal river and the river branch Doué approximately 4 kilometres east of Diatal shows that the base level of the cuvette is located in 4 m I.G.N.. When this base level is compared to historical river levels at Podor from 1903 until 1969 the river level has been below base level in 6 out of 67 years. From 1970 until 1986 the river level has been below base level in 13 years out of 17 years, whereas it has been below this level in 8 out of 11 years since 1987. The farmers interviewed in Diatar confirmed that the inundations never regained the pre-drought dimensions. The levels of the flood recession land of the villages of N'Gaoulé and Goumel are found to be significantly lower than that of Diatar, implying that these villages have been able to maintain flood recession agriculture up until this day, but at a reduced scale.

If the water remains only briefly in the inundated area, the soil water reserves are not fully replenished, and may be insufficient to sustain crop growth until maturity. On the other hand, if the water remains longer than 12 weeks, the soil microbiological conditions may become unfavourable to flood recession cultivation (Euroconsult, 1990). Seen from a flood recession cultivation point of view, the optimal duration of the inundation period is approximately three to four weeks. Thus, the duration of the inundation may be expected to influence the fraction of the inundated land actually cultivated.

Many other factors may be important determinants of the area used for recession agriculture, not the least labour constraints. At the times of peak labour demand, the various production systems and other income generating activities will compete for labour. However, in the three villages studied all suitable inundated land was used for flood recession agriculture, which was not the case in the pre-drought period. Thus, during the last decades, water availability seems to have become the factor limiting the cultivated area, and changes in inundation extent, associated with changes in rainfall or in management principles of the Manantali dam, may therefore be expected to have a proportional effect on the cultivated area.

Generally, the farmers in the river valley are not able to distinguish between the effects of the Manantali dam from those of the drought. However, hydrological data, as presented above, show that whereas reduced rainfall certainly caused a very substantial reduction in flood recession agriculture from the early seventies to 1986, the operation of the Manantali dam has played a major role from 1987 until 1996. Other effects of the dam are more difficult to quantify. These include the effect on the nutrient supply caused by the sedimentation associated with the floodings.

The effects of hydrology on irrigated agriculture

Even before the dam construction, all three villages were practising irrigated agriculture, cultivating rice and most often harvesting once a year. After the dam constructions this changed and the villages began cultivating rice twice a year. However, yields started to decline after a few years, despite the use of chemical fertilizers, mainly because of, among other things, increasing salinity of the soil. Subsequently, the farmers mostly stopped double cropping their fields. After the construction of the Manantali dam, water availability was not the controlling factor of irrigated agriculture in the region in the early dry season. Economic profitability, management difficulties and in particular the problems with maintaining and replacing pumps appeared to be the more important factors. Later on in the dry season, river discharge may become the limiting factor, if the double-cropped area in the valley, as a whole, was increased. Likewise, the 'Fossil Valleys Project', if fully implemented, may limit water availability for a second irrigated crop in the valley.

Implications of the findings
This village level study demonstrates the importance of hydrological information as an input for assessing the agricultural development options in the Senegal River valley. The peak flow of the river has a direct impact on the potential for flood recession agriculture, and yet the sensitivity to flow variations will differ strongly between villages, due to small variations in topography. Presently, the river discharge does not limit the extent of irrigated agriculture, since the economical and management factors appear to be more critical. The removal of subsidies on fertilizers and crop prices will tend to make input-intensive irrigated agriculture relatively less attractive, and thus there is likely to be a strong interest among farmers in increasing flood recession cultivation. However, this will depend heavily upon three factors; the rainfall, the principles of operation of the Manantali dam, and whether or not the 'Fossil Valleys Project' is implemented.

The need for assessing costs, benefits and risks in transnational water management

Rational transnational river basin management requires a hierarchy of institutions at different levels. In the case of the Senegal River valley these include institutions at the village level, at the level of institutions, such as SAED, at the national level and at the transnational level. The interests of institutions at different levels are likely to be in conflict. In the present case it is obvious that the interests of farmers in the lower and middle valley, involved in both irrigated rice cultivation and flood recession agriculture, will be different from those of the national institutions, focused on national food supply, as well as those of OMVS. Ways of assuring that the priorities of the farmers are taken into account, in transnational water management, must be sought.

Institutions at the higher levels need tools allowing for the analysis of the effects of management practices and infrastructural projects. As argued above, a suitable hydrological model of the river basin is required in order to allow analysis of consequences of changes in climate, dam operation and land use. This will be further elaborated in Sandholt et al. (1999). However, hydrological modelling alone cannot resolve the political, economic and environmental conflicts of interest. The optimal decisions on water management, e.g. those associated with the operation of the Manantali and Diama Dams, as well as a possible future dam on the Faleme, at Bakel, can not be entirely based on hydrological reasoning. Also broader agronomic, economic, social and environmental aspects need to be taken into account.

As a first step, the economic gains and losses associated with all the consequences of major water management projects need to be accounted for when balancing the costs and benefits. So far, only costs and benefits directly associated with hydro-electric power generation and irrigated agriculture have been taken into account. Examples of the economic losses, which may be associated with other effects of the regulation of river flow, and which have not been taken into account in standard cost-benefit analysis, are:

(1) the above mentioned reduction in flood recession agriculture,
(2) the loss of riparian woodlands and wetland ecosystems in the valley,
(3) the reduction of the fertilisation effect of the reduced floodings and
(4) the reduced replenishment of both shallow and deep aquifers.

The size of these losses are not well known, and there are considerable methodological problems associated with their estimation. Irrespective of these problems, an analysis of hydrological impacts, carried out by use of hydrological models, should be coupled with environmental-economic assessment of the costs and benefits, as listed above.

Conclusions

The main findings concerning the agricultural impacts of water management in the Senegal River basin are:

- Pump-based irrigated agriculture has expanded while the traditional flood recession agriculture has been in retreat since the early seventies. However, provided that the flooding is adequate, most farmers prefer to invest labour in the low-input, low-output flood recession agriculture.
- The extent of flood recession agriculture is presently controlled by the size of the inundated area, and thus by the peak discharge. The extent of irrigated rice cul-

tivation in the early dry season is limited by economical and management constraints rather than by water availability.

- The decrease in flood recession agriculture since the early seventies may be ascribed to both drought, primarily in the seventies and the early eighties, and to the establishment and the operation of the Manantali dam. It has been demonstrated that in the period from 1987 to 1996 dam management has had a negative impact on recession agriculture in the middle and lower valley in 5 out of 10 years.
- There is a need to take into account a wider range of factors when assessing whether or not to implement large projects, such as the construction of the Diama and Manantali Dams and the 'Fossil Valleys Project', and when deciding upon water management and allocation principles. It appears that neither the benefits of flood recession agriculture nor the adverse environmental effects of reduced peak discharge have been properly evaluated.

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