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The Senegal River Basin Monitoring Activity

Hydrological Issues: Part I

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SUMMARY

The Senegal Valley has good long rainfall and river flow records. Some water level data has not been transformed into reliable flow data. There is much less data on evapotranspiration, infiltration, water levels in the flooded walo lands and the interaction of surface water and groundwater. The current groundwater study will be a focus for the field visit. River water and groundwater quality is little documented. There is little real data on flooding in the valley although information exists from models. Data on flood recession cultivation is extensive but sometimes contradictory. IDA's archive of flow data has some critical gaps which presently prevents an flood analysis on a daily basis. A major thrust of the field visit will be the collection of existing data, especially that for the period 1984-1990.

The severe drought years between 1972 and 1986 greatly influence the results of the water resource simulations. Water management in the Senegal Valley will be sub-optimal if it is organised to guarantee uninterrupted supplies during conditions such as 1980-84.

The artificial flood is a misnomer. It is usually only a topping up of natural runoff. Gibb (1987) is a competent study which defines three satisfactory artificial floods. The study is excessively oriented to hydro-power and exceeds its terms of reference which sought guaranteed energy in only nine years in ten. A more balanced programme with resources available 90 or 95% of the time is required and the artificial flood should not be guaranteed in the most severe droughts. Gibb does not analyze the residual natural flood after the planned cessation of the artificial flood.

The relationship of the three aquifer to the river and floods, and their potential for development for potable and irrigation supplies is well established qualitatively. The OMVS groundwater project should have provided quantification. Some land could be irrigated from groundwater with floods providing recharge. Irrigation water could be stored in the aquifers and in Manantali.

The relationships between the river hydrology, the area flooded and the area cultivated are not well defined but are central to the operation of the artificial flood. Monitoring of post 1987 flood extent and area cultivated is essential. A historical LANDSAT study would yield substantial benefits. There is evidence (SATEC, 1980) that, during small floods, water levels in the cuvettes can be up to two metres below the level of the bifurcation point on the river.

Existing analyses are inconclusive on Manantali's effect on groundwater recharge. Extensive irrigated perimeters with protective flood banks will substantially raise flood levels and will demand a major rehabilitation and raising of flood banks after 20 years. A full analysis of flood hydrographs will show big floods being higher in the future, but small frequent floods will be lower and rarer. Manantali, without an artificial flood, could reduce flood extent by an average of 33,000ha per year, i.e much more than 1.122 milliard FCFA per year.

Schemes are already underway to increase flows in the Dioulol and to retain water in the Diamel at the end of the flood. It is accepted that current developments will adversely affect the gonakier woodland. Two compensatory schemes for the woodland have been suggested. These involve gates on uncultivated cuvettes to simulate the flood regime and utilization of the 20% of the irrigated perimeters that are uncultivable. Gates on the entrances to the large cuvettes could enhance flood recession production by trapping flood water, releasing water to reveal land at a rate which can be planted, and by protecting the fields from subsequent flood peaks.

Predicted water quality problems in Manantali may require the bottom waters of the reservoir to be turned over regularly, perhaps in conjunction with a continued artificial flood.

Water planning in the valley needs a cross-sectoral and multi-disciplinary approach. It must seek to maintain the existing ecological basis of life in the valley whilst facilitating developments of a scale which do not threaten existing life support systems.

1.0 INTRODUCTION

This review is organised into four sections. The review of the status of the hydrological documentation concentrates heavily on the data that is available for the existing and future studies. The two main sections of the report discuss, first the issues that can be accepted from the literature, and second the issues about which there is still contention. The next section sets out a full programme for the forthcoming reconnaissance visit in terms of the reports that need to be sought, the people and agencies to be visited and the fieldwork to be undertaken. This section also develops some ideas for future field work that the SRBMA may be able to pursue. It lists further desk studies that should be undertaken within the framework of this mission and IDA's work for the forthcoming autumn seminar. The concluding section summarises the findings of this critical review.

2.0 STATUS OF THE HYDROLOGICAL DOCUMENTATION

2.1 Rainfall

The various hydrological reports present long term average rainfall data for a wide range of stations in the Senegal Valley within Senegal, Mauritania and Mali. There is no archive of daily or monthly data in machine readable form at IDA. Limited daily rainfall data for 1989-90 for Matam was collected from the local Meteorological Service during the field projects.

Gibb (1987) cites average rainfall data for Matam, Kayes, Podor and St Louis. Monthly rainfall for 1972 to 1987 for these station is given in the Appendices to Gersar et al (1988-Schema Hydraulique). It will be important to obtain daily data for Matam in relation to the estimation of the significance of rainfall in filling cuvettes.

There is no mention of rain gauges in Guinea in any of the reports analyzing the hydrology of the river or the operation of Manantali. Long, Dudley and Babcock (1976) said that "the watershed area of the Senegal River situated in Guinea is the key ... It contains only about 15% of the drainage area but generates over 50% of the runoff". They were correct to conclude that "every effort should be exerted to establish or improve communications and the transfer of hydrometeorological data between Guinea and OMVS and its member countries".

This issue must be explored during the field visit. A rainfall-runoff model of the upper basin will provide a much more secure forecast of the likely flow in the Bafing and Senegal. It may provide a forecast for weeks rather than the days available from a model based only on river flow within Mali.

2.2 Evaporation and Evapotranspiration

The published reports (eg Gibb, 1987) cite average evaporation for a range of stations without giving the period of record available. Gibb (1987) presents data for evaporation at Manantali and Lac du Guiers without giving the period of record or the method of measurement or estimation.

Potential evapotranspiration is mentioned only in the ADRAO reports (Huibers and Speelman, 1990). They state that the FAO Technical Handbook of 1979 is used to calculate potential evapotranspiration by the Penman method. This is then transformed into actual evapotranspiration by means of a crop coefficient which depends on the type of crop and its growth phase. They cite Table 2.2.1 from SAED (1985) for evapotranspiration in the Senegal Valley.

The inconsistency between the two sets of data for potential evapotranspiration and evaporation is strange. It is surprising that potential evapotranspiration is sometimes in excess of evaporation and at other times only a fraction of it.

There is no mention of any evaporation measurement at Matam but it will be important to visit the meteorological site at Matam to assess the range of data gathered. Gibb (1987, p2/24 of Volume 1D) assumes that the rate of evaporation at Matam is 2100mm per year.

Table 2.2.1 Evaporation and Evapotranspiration Data (after Huibers and Speelman, 1990; Gibb, 1987 (Vol 1D))

	J	F	M	A	M	J	J	A	S	O	N	D
Potential Evapotranspiration	200	170	150	180	160	170	180	190	250	260	270	220
Evaporation Manantali	157	184	234	236	234	198	76	68	110	103	103	99
Evaporation Lac de Guiers	142	173	179	241	239	235	166	170	152	201	153	149

2.3 Riverflow

A large set of computer files of riverflow data have been gathered at IDA but they do not represent a complete set of data available nor is there sufficient data to undertake all of the analyses required.

The file of monthly flow ($10^6 m^3$) from January 1952 to December 1984 for:

Bafing	Dakka-Saidou
Bafing	Soukoutali
Senegal	Bakel
Faleme	Kidira
Bakoye	Oualia

is central to the analysis and simulation of the operation of the upper basin including Manantali.

The only daily data available at IDA for the basin above Bakel is:

Bafing Dakka-Saidou 1 June 1965 - 31 May 1975
(The file is too large for Quattro and therefore the whole of it has not been viewed as yet)
Bakoye Oualia 1 June 1976 - 13 December 1987
Senegal Bakel 1 January 1904 - 31 December 1987

These machine readable files were obtained from the OMVS staff at the Manantali dam. The daily data file for Bakel has never been used at IDA. Comparison of the annual average flow in the data file with the data given in Gibb (1987, Table A1 Vol 1D) shows that the data held at IDA probably incorporates the corrected rating curve of M. Lamagat of ORSTOM (Table 2.3.1). Gibb (1987) shows that before 1965 the annual change as a result of the Lamagat algorithm was never more than 3% and usually between 0 and 2%. The data in Table 2.3.1 shows that there is normally accordance with 2 or 3 percent between the two sets of data but for 1966, 1967 and 1974 the difference appears to be unacceptably large. This is all the more important when studies are being undertaken to determine parameters with a 100% guarantee. The discrepancies in flow during the three years need to be examined.

Interestingly, a detailed cross check of the IDA monthly flow data file for Bakel and Soukoutali reveals an exact accord with the data published in Gibb (1987).

Finally, IDA has a large set of files, so far not examined in detail, which seem likely to contain the following daily data:

Senegal	Bakel	Water Level	1904-1987
Senegal	Kaedi	Flow	1919-1980
Senegal	Kaedi	Water Level	1913-1982
Senegal	Salde	Flow	1961-1987
Senegal	Salde	Water Level	1903-1904; 1939-1986
Senegal	Boghe	?	1919-1980
?	Diorb.?	Water Level	1938-1961
?	Aleg.?	?	1921-1980

Table 2.3.1 Annual average flow at Bakel (m^3/sec) in the IDA computer file of daily data and in Gibb's summary of the Bakel data after treatment by the Lamagat algorithm.

Year	IDA Data File	Gibb (1987)	% difference IDA/Gibb	% change wrought by Lamagat algorithm for Gibb's data
1960	missing data	628	---	+ 1
1961	934	953	-2.0	+ 1
1962	759	781	-2.9	+ 2
1963	656	675	-3.2	+ 1
1964	missing data	981	---	+ 2
1965	1061	1071	-0.9	+ 1
1966	842	1058	-25.7	+23
1967	1186	1317	-11.4	+26
1968	525	518	+1.3	+20
1969	932	927	+0.4	+22
1970	679	669	+1.5	+19
1971	734	729	+0.7	+21
1972	323	318	+1.5	+19
1973	451	447	+0.9	+21
1974	751	808	-7.6	+24
1975	609	605	+0.7	+22
1976	462	454	+1.7	+19
1977	334	330	+1.2	+15
1978 -	Lamagat's algorithm not applicable			

The priorities for riverflow data collection during the mission to Senegal are:

a) daily data for 1952 onwards for Soukoutali, Kidira and Oualia so that the operation of Manantali can be analyzed,
b) full sets of data for all hydrometeorological variables for 1984 to 1990 so that simulations can be brought up to date and so that observations in the valley can be related to the hydro-meteorological situation,
c) water level data for Matam since the beginning of the records will assist in understanding the patterns of flooding in the three case study cuvettes at Thiemping, Boyenadji Roumde and Doumga Rindiaw.
d) the inconsistencies between the IDA data file of daily flow data for Bakel and that held by OMVS at Manantali needs to be investigated.

2.4 Soil Moisture

No measurements of any description have been found in the IDA library. There does not seem to have been any simulation of soil moisture status in any of the studies.

Infiltration

The only data discovered on infiltration rates in the flood plain is published in Huibers and Speelman (1990). For a 1000m irrigation canal, carrying 80l/sec along a channel 1m wide and 0.7m deep the infiltration loss is given as less than 3%. They cited Table 2.5.1 from SAED (1985) showing infiltration rates for different types of soil from 0 to 3 mm/day for hollande soils through to 5 to 8 mm/day for fonde soils.

If an overall average of 4mm/day of infiltration is assumed over the 100,000ha to be flooded by the smallest artificial flood of 7,5 10^9 m^3 then over an assumed flood period of 30 days the maximum volume of infiltration will be 120 10^6 m^3. This is only a little over 1% of the artificial flood volume.

Table 2.5.1 Infiltration characteristics of flood plain soils (after Huibers and Speelman (1990): from SAED, 1985)

Soil type	Fonde	Faux-hollande	Hollande
% clay	10 - 30	30 - 50	>50
Permeability (mm/day)	5 - 8	3 - 5	0 - 3
Crop	Not rice	Rice and non-rice	Rice

Huibers and Speelman (1990) found that the farmers were both efficient and effective with their irrigation with an average efficiency of transport of water to the fields of 90% with a range from 83 to 95%. They studied 10 perimeters and found that the average lift necessary for irrigation was 9.35 m with a range from 5 to 12.5 m.

The lack of a reliable rating curve for the intermediate gauging station between Bakel and Dagana means that flows cannot be computed and therefore temporal changes in riverflow as a result of floodplain inundation and infiltration to groundwater cannot be computed.

Gibb (1987) in their simulation model for the valley assume that there will be an infiltration loss in the middle valley of 2% of riverflow. They state that this figure was chosen since that was the figure used for the simulation of the River Nile. However, given the simplistic calculation made above using the SAED (1985) data, it seems that Gibb's assumption is entirely safe.

2.6 Groundwater Level

The IDA Library has a limited number of reports that deal with groundwater. It does not have any of the detailed studies that are referenced in some of the overviews and syntheses.

No data of any description for groundwater exists in the IDA library. Several previous groundwater studies are mentioned in Gersar et al (1988) and these will have to be sought during the mission to Senegal. The OMVS/USAID groundwater monitoring project and its reports will obviously have to be a top priority task for the field work.

2.7 Flood Extent and Duration

Definitive data on flood extent and duration have yet to be published for the Senegal Valley. A project is underway to assess flood extent and area cultivated for 1986 onwards. IDA has an outline map of areas flooded in 1986 for a part of the valley and Gersar et al (1988) quote an area of flood recession cultivation of 64,350ha for 1986.

The very many figures for flood extent and duration that are to be found in the literature seem to be theoretical calculations based upon models. The most commonly used system is the UNE model which uses hypsometric data for each cuvette derived from the work of Chaumeny (1973) and an assumption that the level of flooding in the cuvette is equal to the level in the river. The evidence from the IDA field team is that cuvettes are of very varied morphology and they have a variety of types of connection to the river including no link at all. It will, therefore be essential to review Chaumeny's Atlas of UNEs from 1970 and Juton (1979) who also studied flood extent and flood recession cultivation.

Gersar et al (1988) refer to a study by SATEC et al (1980) which examined the relationship between water level in the river and in the major left bank distributaries the Dioulol and the Diamel. Some data is reproduced in Gersar et al (1988) but the SATEC study is not in the IDA library.

2.8 River water Quality

No data on river water quality has been found to date.

Dames and Moore (1989) comment at length on the water quality problems that will affect Manantali in the short term as the vegetation in the flooded area gradually decays. They also comment on the likelihood of a de-oxygenated hypolimnion which could be deadly for fish if hydro-power releases are made from this level of the reservoir.

2.9 Groundwater Quality

Whilst generalized maps for the dissolved content of groundwater in the whole of Senegal are to be found in BRGM (1982), no data has so far been found for the Senegal Valley aquifers specifically.

3.0 ISSUES GENERALLY AGREED

3.1 Hydrological Data

The quantity and quality of hydrological data for rainfall and riverflow for the Senegal Valley is exceptional. The various tabulations undertaken are excellent. The careful reworking of the data at Bakel by M. Lamagat has undoubtedly improved that record and Gibb's (1987) analysis of the consistency of the data for the upper valley suggests that there are few problems of any significance with that riverflow data.

.he existence of long records of water level at Matam, Kaedi, Salde, Boghe, Podor, Dagana and Richard Toll will need to be investigated further. Whilst these data have been transformed into flows, as in the computer files held at IDA, they have not been used as flows in any of the reports so far studied. The precise reasons for this need to be ascertained and the feasibility of applying M. Lamagat's correction algorithm must be investigated.

If reliable flow data were available for the listed stations then our understanding of flow, inundation, infiltration and evaporation processes on the flood plain should improve. Similarly it would be much easier to model present and future flows and patterns of inundation.

3.2 The drought of the 70s and 80s and Water Resources Management

The severity of the drought in 1980 to 86 has a serious impact on the analysis of hydrological data and the subsequent management decisions. Table 3.2.1 indicates that eight of the ten worst drought years this century occurred in the 1970s and 1980s. 1982 to 1986 saw the 7th, 2nd, 1st, 10th and 8th worst droughts this century in successive years.

Table 3.2.1 The severity of the 1980-86 drought in terms of the volume of flood flow at Bakel from August to October (** indicates record drought years that occurred in the 1970s and 1980s).

Average	1904-84	18,615 $10^6 m^3$
10th	1985 **	9578
9th	1976 **	9939
8th	1986 **	9022
7th	1982 **	8096
6th	1944	7907
5th	1972 **	7610
4th	1979 **	7468
3rd	1913	6207
2nd	1983 **	5108
1st	1984 **	4958

Gersar et al (1988), in a special sub-section on the recent dry years, has presented Table 3.2.2 to exemplify the severity of the problem where the maximum annual rainfall for 1972 to 1987 rarely reaches the mean for the period before 1972.

Table 3.2.2 Rainfall averages for the recent period and the long term (after Gersar et al, 1988) (mm)

Station	Average before 1972	Average 1972-87	% Reduction	Minimum 1972-87	Maximum 1972-87
Dagana	320	184	43	58	328
Podor	317	176	44	66	304
Matam	526	298	43	175	477
Bakel	683	477	30	320	602

Not surprisingly this succession of severe drought years has a large influence on the results of the water resource simulations. It will be important politically to decide if the proposed water management of the Senegal Valley must meet the severe conditions of the period 1970-86.

3.3 The Technical Competence of the Gibb studies

The studies by Gibb are thorough, competent and accurate. They have used a very long record of data carefully. They have paid attention to the totality of the hydrological cycle in the whole of the basin to Bakel. In their simulation model of the middle valley and delta they have used sensible simplifying assumptions. As far as can be discerned from their reports and their extensive appendices, there do not seem to be any errors. The absence of July from the column headings in Table 6.4 on page 6/11 of Volume 1B creates an unfortunate impression. The volumes needed for the "artificial" flood are, as a result, not typed beneath the columns in which they will occur and it appears that the probability of achieving these flows is very modest. However the error in the typing of the column headings does not appear to have caused any substantive error in the analysis or in the text. The Gibb analysis of the relationships between river hydrology, area flooded and area cultivated is weak and unconvincing, but as will be shown below, it results in an acceptable answer.

The problem with the Gibb study is that is seems to be pursuing virtually a 100% hydro-power strategy for Manantali rather than a more balanced and reasonable multi-purpose usage for the reservoir. It creates an impression of conflicts in water resource allocation when in reality a balanced scheme must be more desirable. These issues are discussed in the ensuing section on unresolved issues.

3.4 The Aquifers of the Middle Valley

Long, Dudley and Babcock (1976) reviewed the literature available and furnished the following succinct summary of the occurrence of groundwater in the Senegal Valley:

> "In the area from about 60km west of Bakel eastward, the basin is underlain by granite, gneiss and consolidated sedimentary rocks that can be expected to yield only small quantities of water ... many wells are unproductive.
>
> Westward from near Bakel, most of the basin is underlain by the Continental Terminal Formation, which in turn is underlain by the Maestrichtienne Formation. These units contain groundwater. The Continental Terminal Formation consists of sand gravel and clay that generally yield at least small quantities of ground water under water table conditions; however it is doubtful that a sufficient saturated thickness of the formation is present in most of the area to yield the quantities of water that are needed for irrigation.
>
> The underlying Maestrichtienne Formation consists of limestone, clay, and sand beds. The sand beds are quite extensive and generally are sufficiently thick and permeable to yield moderate to large quantities of water to wells. The water is under artesian pressure and generally rises to a level above that of the shallow water table aquifer. Well records ... show that ... wells yielding from 500-1000 gallons per minute can be developed. The Maestrichtienne and the Continental Terminal Formations extend for great distances north and south of the Senegal River drainage basin. The formations are regional aquifer

systems and probably are little affected by the Senegal River except in areas adjacent to the river".

BRGM (1982) comment on the existence of an alluvial aquifer in the Senegal Valley in addition to the Continental Terminal Aquifer. They say that the alluvial aquifer consists of sands, silts and clays. These are locally very permeable and they are recharged by the river floods and rainfall. Rainfall recharge is estimated at 13mm per year and it is thought that there is drainage to the Maestrichtienne aquifer. BRGM (1982) state in their Table 4 (p 53) that the alluvial aquifer in the Valley has a recharge of 50 10^6m^3 per year and an overall exploitable reserve of 210 to 410 10^6m^3.

Gersar et al (1988) comment on the clay lenses in the quaternary alluvial deposits of the valley but they believe that there is hydraulic communication between the permeable horizons. However, they propose a distinction between the unconfined surface aquifer and the deeper Maestrichtienne aquifer. The surface aquifer is in direct communication with the river and it is recharged during floods via the permeable deposits. This aquifer is used mainly for drinking water and it is found at 10 to 20 metres depth. The aquifer is very heterogeneous with permeabilities varying from 0.01 to 4.00 m/day. The sandy Maestrichtienne aquifer, found at -50m near Matam, is a good aquifer of high permeability. In some places, such as near Thilogne and between Matam and Semme, it is covered with sandy-clayey deposits and here it is not artesian in character.

BRGM (1982) have set the aquifers of the Senegal Valley into their national perspective. The Maestrichtienne aquifer is said to be the most important in Senegal because it is found at depth throughout virtually the whole country. In many parts of the country the aquifer's average thickness is 250m. It may contain up to 80,000 10^6m^3 of water.

Long, Dudley and Babcock (1976) say that "groundwater is used extensively for stock and village water supplies in Mauritania and Senegal ... a few irrigation well have been drilled in Senegal in an area east of Dakar ... the high cost of power has been a deterrent to well development". To exploit the surface aquifer in the Matam area, Gersar et al (1988) state that wells must cut through the 8 m of clayey deposits of low permeability. Gersar et al (1988) emphasize that the Maestrichtienne aquifer is very close to the surface near Thilogne and Matam-Semme.

Few details of the thickness of the aquifers at Matam are given in the reports held at IDA. Gersar et al (p14, 1988) state that the upper (Alluvial and Continental Terminal) aquifer is 70m thick whilst the Maestrichtienne is 75m thick.

3.5 The Relationship of the Aquifers in the Middle Valley to the River and its Floods

BRGM (1982) say that the alluvial aquifer in the Senegal Valley is recharged by the river floods and rainfall. Rainfall recharge is estimated at 13mm per year and it is thought that there is drainage to the Maestrichtienne aquifer.

Long, Dudley and Babcock (1976) say that "The Continental Terminal Formation is saturated under the river flood plain and to some extent away from the river flood plain. The saturated section would be expected to decrease progressively with increasing distance from the river".

Gersar et al (p M.10, 1988) state that the surface aquifer is in direct communication with the river and it is recharged during floods via the permeable deposits. More definitively in the overview report, Gersar et al (p14 1988) state that the recharge of all of the aquifers is generally from flood water rather than from rainfall.

The only suggestion that the recharge of all of the aquifers is not dependent directly on the inundation of the flood plain is in Long, Dudley and Babcock (1976). They say "recharge from the river to the Maestrichtienne formation probably is limited to areas where the sand beds in the formation may be in contact with the overlying Continental Terminal Formation or floodplain deposits. Near Matam tests run by the Bechtel Engineering Co indicate that there is little if any hydraulic connection between the upper saturated flood plain deposits or Continental Terminal Formation and the underlying Maestrichtienne Formation. However, this particular example is probably the result of a localized clay lens in the deposits and it does not seem to be applicable to the general recharge of the Maestrichtienne aquifer.

3.6 The potential for water supply and irrigation from groundwater

BRGM (1982) tabulated the number of boreholes in the Senegal Valley. There were 96 into the Maestrichtienne aquifer and 38 into other aquifers. 29 had motorized pumps, 35 were open wells and none were equipped with hand pumps. There were 22 boreholes which had not been equipped and one had been abandoned.

Long, Dudley and Babcock (1976) say "As (the Continental Terminal Formation) is capable of moderate to large yields ... it should be considered as a potential source of irrigation water under the flood plain and in areas adjacent to the flood plain. In these areas, the aquifer could be developed rather extensively because water withdrawn would be recharged continuously from the river (emphasis added)".

Long, Dudley and Babcock (1976) say "In the areas under and adjacent to the river floodplain, an opportunity would exist to develop irrigation water from both the Continental Terminal Formation and flood plain deposits water table system and the underlying Maestrichtienne artesian system"

Gersar et al (1988) report that the Government of Senegal in 1982 decided that all villages with more than 500 people should be equipped with a water supply system. Gersar et al (1988) suggest various levels of equipment for villages of up to 1000, 2000, 5000 and over 500 people and they suggest that the safest assumption is that the supply will be derived from wells. They give estimates of the numbers of villages and the costs (Table 3.6.1).

Table 3.6.1 Estimates of the costs of village water supplies in the Matam area (after Gersar et al (1988))

Population of villages	Number of villages	Cost per village (MFCFA, 1988)	Total Cost (MFCFA 1988)
100-499	64	20	1280
500-999	45	30	1350
1000-1999	43	40	1720
>2000	29	60	1740

Gersar et al (p14, 1988) state that on the edge of the Dieri the existing wells have a yield in excess of $1m^3$/hour/metre of drawdown. They state significantly that the constraint on development is the cost of the deep wells necessary.

3.7 Poor water quality in the deeper parts of Manantali Reservoir

Dames and Moore (1989) (p3-64) say that the construction of Manantali will bring with it a series of water quality problems that are already known from other reservoir sites in tropical forested areas. In their review they frequently cite a 1984 World Bank paper by Garzon.

There are both short and long term problems. Initially the rotting of the biomass of the flooded forest will deplete the oxygen content of the reservoir but after some years this problem should diminish in significance as the original biomass of the reservoir site rots away completely. A more serious and continuing long term problem with the reservoir may be the gradual formation of a deoxygenated zone at depth whose size and intensity may be exacerbated by eutrophic conditions in the upper part of the reservoir.

If water from the deoxygenated hypolimnion of the reservoir is used to generate hydro-power then there will be large fish kills in the zone downstream of the dam because of the deoxygenation of the water. The extent of the effect will depend on the self-purification properties of the river.

This issue is not irrelevant to the artificial flood because one way of managing water quality in reservoirs is to turn over the water regularly to prevent undesirable conditions developing. It may be that much of the bottom water of the reservoir could be released as part of the artificial flood with water from higher in the reservoir. It may be that the release of the reservoir's bottom water will become essential for water quality considerations and therefore its benefits as an element in an artificial flood should be borne in mind.

4.0 UNRESOLVED ISSUES

4.1 The relationships between the Flooding in the Walo and River Levels

Lericollais (1980) said that knowledge of the speed of filling of the cuvettes, and the level of water in the cuvettes compared to that in the river was missing. Gibb (1987) expressed surprise at the lack of data on the area of flooding and referred only to the SOGREAH simulation studies in relation to river flooding of the cuvettes.

Gersar et al (1988) refer to a study by SATEC et al (1980) which measured water levels in the Dioulol and the Diamel distributaries relative to that at their confluence with the river upstream and downstream of Matam respectively. Gersar et al (1988) assert that with large floods there will be equality of water levels in the river and the cuvettes although with a small time delay. However for smaller floods it is clear that there will not be equality in water levels in the river and in the cuvettes. Data is presented for the Dioulol and Diamel for 1978. This flood had a volume of 14,872 10^6m^3 from July to November. It was the third largest flood during the period 1972-84 and it is twice the size of the smallest artificial flood (A) and 50% larger than the largest artificial flood (C). Figure 6.3 in Gersar et al (1988) shows that at the 1978 peak river level the water in the Dioulol 25km into the cuvette was 1.60m lower than the river and 3.50m below the river at 60km into the cuvette. The Diamel is a more efficient channel than the Dioulol for the first part of its course and here Gersar show that the head loss along the Diamel in 1978 was up to only 1 metre. However the difference between the river level at the confluence and the water level in the walo at Thilogne at the downstream end of the Diamel was over 2 metres in 1978.

These findings for 1978, which were clearly unknown to Gibb (1987) since they are not referenced, throws some doubt on their calculation of the flooded area from river levels and UNE data. More importantly the data suggest that all of the data on flood extent computed with the UNE procedure is flawed at least for small floods of under 14,000 10^6m3 at Bakel.

It is interesting that earlier in Gersar et al (1988) (p48) the UNE model, "basant sur l'hypothese que la ligne d'eau du fleuve est similare a celle des UNE", had shown that the three artificial floods would inundate slightly more land than had been estimated by Gibb (1987). Clearly there must be greater attention paid to monitoring and modelling the levels and areas of inundation during modest flood flows in the river. The existing published data suggests that there is no reliable field data for area flooded and existing data on river levels and cuvette water levels during small floods invalidates existing methods of estimating flood extent for small floods.

4.2 The Relationship between River Hydrology, Flood Extent and Area Cultivated as Flood Recession Crops

The relationship between the hydrology of the river and the extent of flooding in the valley is central to an understanding of the hydrology of the floodplain system. Similarly it is essential to know the relationship between the area flooded and the actual area cultivated as flood recession agriculture. Gibb (1987) say (in french) "given the importance of this characteristic, we are surprised at the limited data available on the area inundated in the past. There are some tentative estimates of the area cultivated but there is not a relationship with the area inundated except for the years studied in detail by SOGREAH".

River Hydrology - Flood Extent Relationships

There is as yet no definitive data on the extent of flooding in the valley since all of the studies cite either estimated flood extent or the area of flood recession cultivation. It is to be expected that good data for the 1986 flood will emerge soon from the mapping that has been undertaken from Landsat imagery (LeBloas, 1986).

Gibb (1987) states that there have been three studies of flood recession cultivation:

a) that in 1970, 72, and 73 by Juton,
b) the 1970 inventory by Chaumeny in the context of his study of Unites Naturelles d'Equipement (UNEs), and
c) the surveys in 1976, 1977 and 1978 in the context of the socio-economic studies.

Each of these studies used air photographs and maps at 1:50,000, an overflight of the valley with the transcription of observations directly onto the photos at 1:50,000, transcription of the data onto 1:50,000 maps with subsequent colouring and planimetering with eventual presentation at a scale of 1 : 200,000.

The area flooded in 1968, 1969, 1970 and 1973 was estimated in the course of SOGREAH's simulation studies of the passage of natural floods down the Senegal River. The model was a modification of the Muskingum flood routing procedure and was fitted to water level data at a series of points down the river. There was absolutely no flood extent data used to validate the model.

The results of the simulations were within 11 to 16 cm of the observed water levels. The terms of reference of the study had demanded an accuracy within 10cm because of the very low slopes in the Senegal Valley. The areas computed by SOGREAH are estimates for a model which did not meet its contract specification. They will be discarded here.

Gibb (1987) used a much simpler procedure which linked the hypsometric curves (based on 1 metre contours) for each of the cuvettes (UNE) in the flood plain as determined by Chaumeny with the observed water level in the river. Essentially the water levels in the river were interpolated linearly and it was assumed that the water level on the flood plain would be equal to that in the river. Since the height/area relationship for each UNE is known then the area flooded can be computed (see Annex A in Gibb 1987 Volume 1B).

It is important to note that Chaumeny found in 1970 that only 89% of the flood recession cultivation was actually located in the "UNEs" that he mapped. Gibb (1987) ventured to suggest that their procedure produced an overestimate of the area flooded because, for example, it assumes an equality of levels on both sides of the river. However they balanced this view with the suggestion that the inundated areas outside of the UNEs make a very small contribution to the overall area of flood recession cultivation.

Whilst the flooded areas outside the UNEs may make a small contribution to flood recession cultivation, they may represent a large area flooded. In addition, because of the time taken to fill the cuvettes from the river, the area inundated early in the flood will almost certainly be less than that calculated by the Gibb procedure. Overall, it seems likely that the Gibb estimates are the best figures available and it is not possible to determine if they are under or over estimates of the actual area flooded. Gibb (1987) compare their estimates with those derived by SOGREAH and they conclude that there is good comparability. The UNE procedure produces slightly smaller estimates of flood extent in wet years and a slightly larger estimate of flood extent in dry years.

Gibb (1987) makes two separate efforts to relate flood extent to river hydrology. In Table 4.8 (page 4/20, volume 1B) the area of flooding in 1972, 82, 80, 73 and 75 is tabulated along with the number of days that the flow at Bakel is above 1500, 2000, 2500 and 4000 m^3/sec. They conclude that the table is not useful because the flood with more than 15 days of flow over 2000 m^3/sec produces a flood of over 100,000ha (147,000ha in fact)!

Gibb (1987) return to the relationship between river hydrology and flood extent in the next chapter, No 5. In Table 5.2 the floods for 1968 to 1984 are tabulated with volume of flow from July to November, peak flow, number of days over 2000m^3/sec and area flooded for at least 15 days (S15). Interestingly on the next page (5/13) there are two tables which abstract data from Table 5.2 but these are not numbered and Table 5.3 is on the next page.

The unnumbered table on page 5/13 shows data for 1982, 1977, 1980, 1981 and 1973. It is interesting to note that compared to the table used in the earlier chapter, data for 1972 and 1975 has been left out whilst data for 1977 and 1981 has been inserted.

The data in the un-numbered table shows that (in french) "the characteristics required to inundate the given areas, based on historic floods are (as shown in the following un-numbered table)". The area inundated is now just that and not the area inundated for 15 days in the previous table. The flood to inundate 150,000ha is very similar to that for 1981, that for 200,000ha is loosely related to that for 1973 whilst the flood to inundate 100,000 ha is based on 1977 but with the number of days with over 2000m^3/sec increased from 5 to 10 days.

On the following page (5/14) Table 5.3 presents the characteristics of the proposed artificial floods. Compared to the second un-numbered table on the previous page, the area inundated has changed to area to permit a certain area of cultivation and the volume of the natural flood (changed from volume July to November in the first un-number table) becomes volume August-October. The figures for volumes of flow have been reduced for each suggested flood, the peak flows for the two smallest floods have been increased but the durations of flow over 2,000m^3/sec remain unchanged.

Significantly, and setting aside the variations in the detailed headings given o the columns in each of the tables, it appears from a comparison of Table 5.3 (p5/14) with the second un-numbere : table (p 5/13) that exactly half of the area flooded is expected to be cultivated. That is <u>for artificial flood A, Gibb (1987) expect that 50,000ha will be cultivated out of a total area flooded of 100,000ha</u>.

Area Flooded - Area Cultivated Relationships

Gibb (1987) similarly address the question of Area Flooded - Area Cultivated Relationships in both Chapters 4 and 5. Once again an un-numbered table is used in Chapter 5. Table 4.5 presents the area cultivated and the area flooded for between 15 and 45 days (S15-S45 from the UNE methodology) for 1970, 72, 73, 76, 77, and 78. The ratio of area cultivated to area flooded is 1.3, 0.44, 0.69, 0.52, 0.2 and 0.74 respectively. They conclude that "(in french) this has not revealed a definitive relationship ... probably because of the simplicity of the hypothesis and special factors each year".

Highly significantly, on page 5/16 of the following chapter and following the un-numbered tables discussed above, another un-numbered table shows the area cultivated and the area flooded for between 15 and 45 days. This time 1973, 1978 and 1976 are included with 1970, 72, 76, and 77 left out. It is said that 1973 is included because "(in french) it represents the year where the area cultivated (87,000ha {this is an error in Gibb and should read 82,200}) corresponds the best to the area to be cultivated with an artificial flood".

In fact the flooded area was probably much more than the 118,000ha listed because of the neglect of lands flooded for less than 15 days or for more than 45 days and the 82,200ha of cultivation is not equivalent to the 50,000ha for flood A, the 75,000 for flood B or the 100,000 for flood C.

An alternative approach

Data was trawled from the literature for the area flooded (various definitions accepted), the area cultivated, the peak flow at Bakel, the volume of flow from August to October at Bakel and the number of days per year that the flow at Bakel was above 1500, 2000 and 2500 m^3/sec. The spreadsheet formulated (Appendix A) includes data from Reizer (1974), Gibb (1987), Guerber (1985), Groupement Manantali (1985) and Gersar et al (1988). The data for area flooded in 1944, 1950 and 1953 in Reizer (1974) is quoted from Cheret. Reizer's data for 1967 to 1972 is calculated according to the UNE model after Juton. Gibb's S15 and S45 data are calculated according to the UNE system. Gibb's area cultivated is derived from Chaumeny, Juton and the "socio-economic studies". Guerber (1985) does not describe the origin of his area cultivated data whilst the Groupement Manantali data is said to derive directly from OMVS. The hydrological data for Bakel was derived from the daily and monthly flow data for Bakel which is held at IDA.

The compilation of data in Appendix A allows some exploration of the relationships between river flood hydrology, area flooded and area cultivated. It is essential to emphasize at the outset that the data used in this analysis is of variable quality and reliability. The area flooded is always a theoretical calculation. The area cultivated may be grossly in error. IDA experience is that the recession cultivators move steadily over the landscape as the flood recedes. Therefore any aerial or ground survey is in danger of measuring simply the area cultivated up to that time. Only surveys undertaken in mid to late January are likely to give a reasonable estimate of the area cultivated. The graphs shown in this analysis must be regarded as indicative and not definitive.

Figure 4.2.1 shows the relationship between the peak flow at Bakel and the area flooded in the valley. Whilst there is a fairly good relationship shown over the whole dataset, it is important to note that peak flows of around 2,000 m^3/sec have resulted in areas flooded of between about 40,000 and 160,000ha with an outlier of 300,000ha flooded in one year. This analysis suggests that, as long as the artificial flood has a peak of 2,000m^3/sec, the actual peak flow is not critical in determining the area flooded in the lower range of observed values.

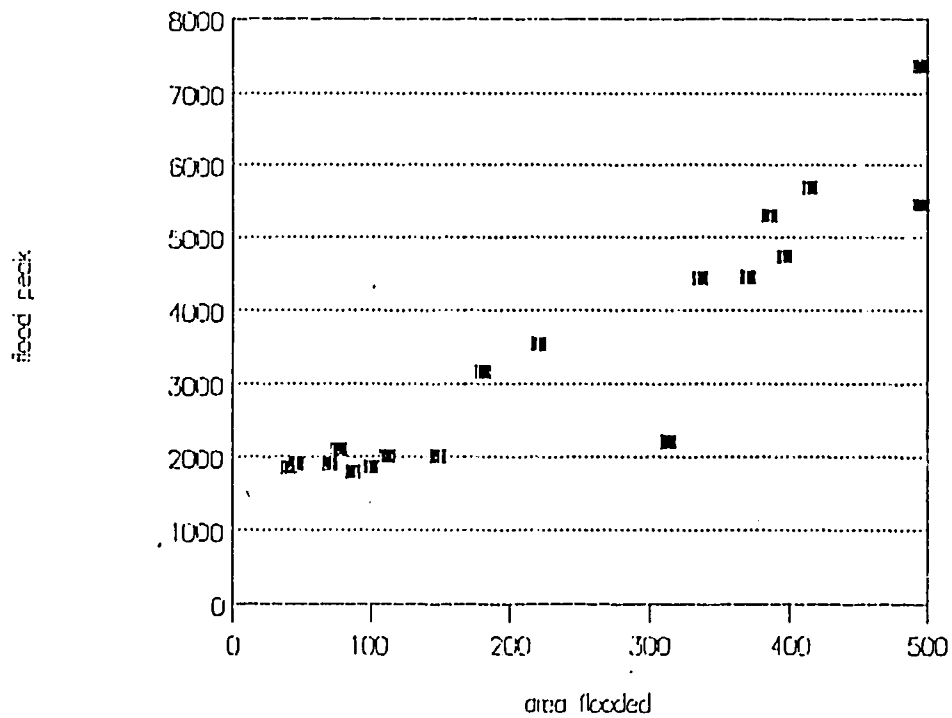

Figure 4.2.1 Relationship between area flooded (000 ha) and the flood peak at Bakel (m3/sec)

There is a strong relationship between the area flooded and the number of days that the flow is over 1500m^3/sec (Figure 4.2.2). The figure suggests that a little less than 20 days at over 1500 m^3/sec is needed for the flooding of 100,000ha. The suggested Gibb hydrographs A, B, and C have these flows for about 20, 23 and 27 days respectively.

The relationship between flooded area and the number of days over 2000 m^3/sec is generally quite strong with 10 days at over 2,000m3/sec being equivalent to 100,000 ha flooded, although no actual flood has had those characteristics (Figure 4.2.3).

The relationship between the area flooded and the volume of flow during the months August to November is very strong, curvilinear and without major outliers. Figure 4.2.4 shows that 10,000 $10^6 m^3$ is required to flood 100,000 ha and 7,500 $10^6 m^3$ will inundate 50,000ha approximately. This is broadly in line with Gibb's figures for artificial floods A, B and C but as discussed above Gibb uses the terms area flooded, area cultivable and cultivated area rather loosely.

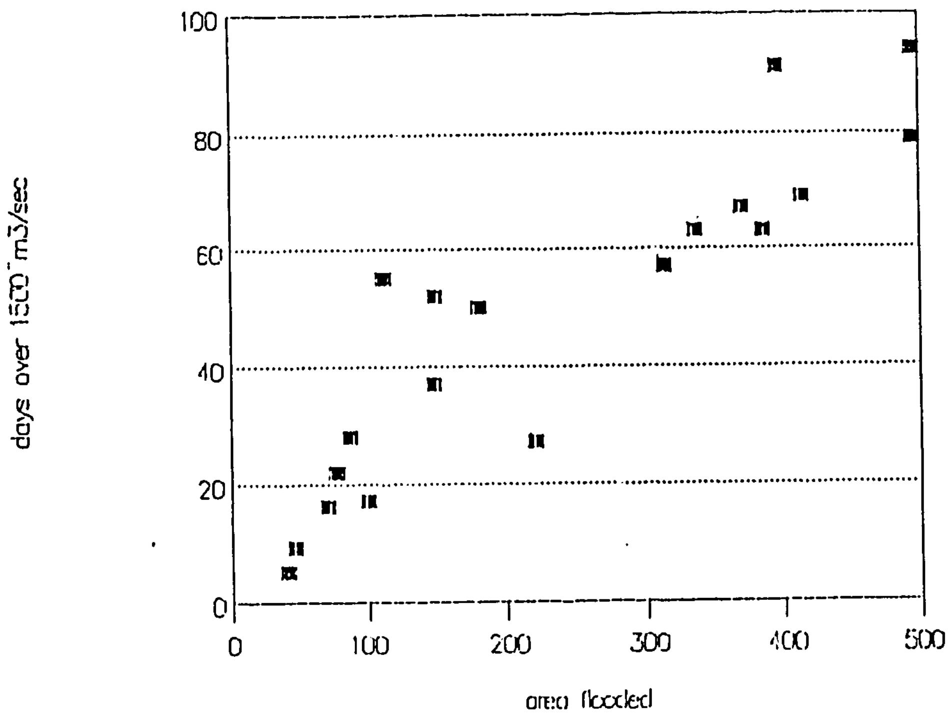

Figure 4.2.2 Relationship between area flooded (000 ha) and the number of days that flow is over 1500 m3/sec at Bakel

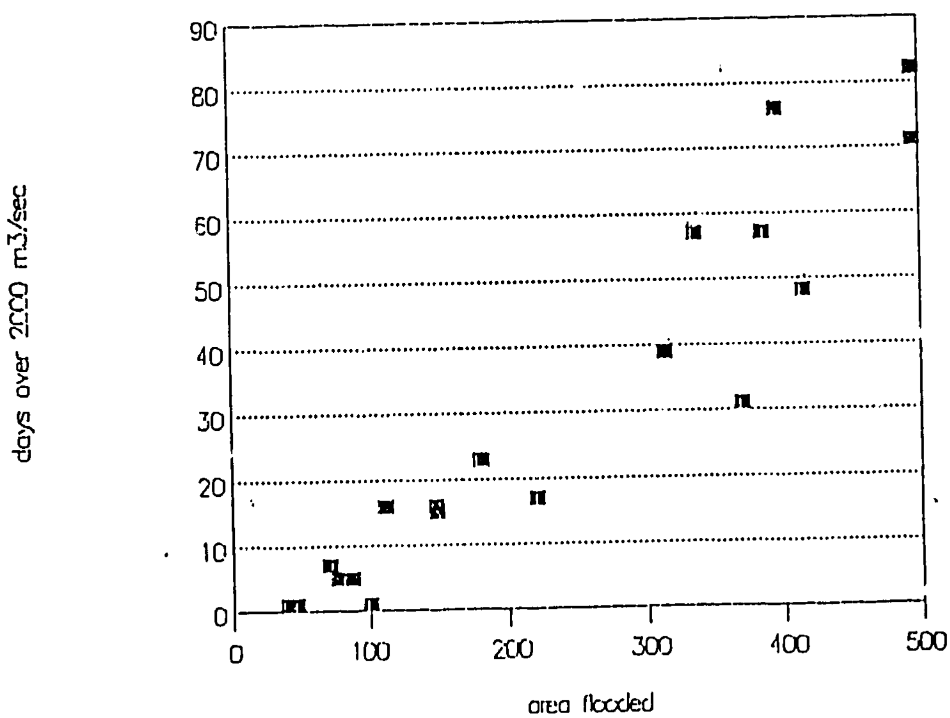

Figure 4.2.3 Relationship between area flooded (000 ha) and the number of days that flow is over 2,000 m3/sec at Bakel

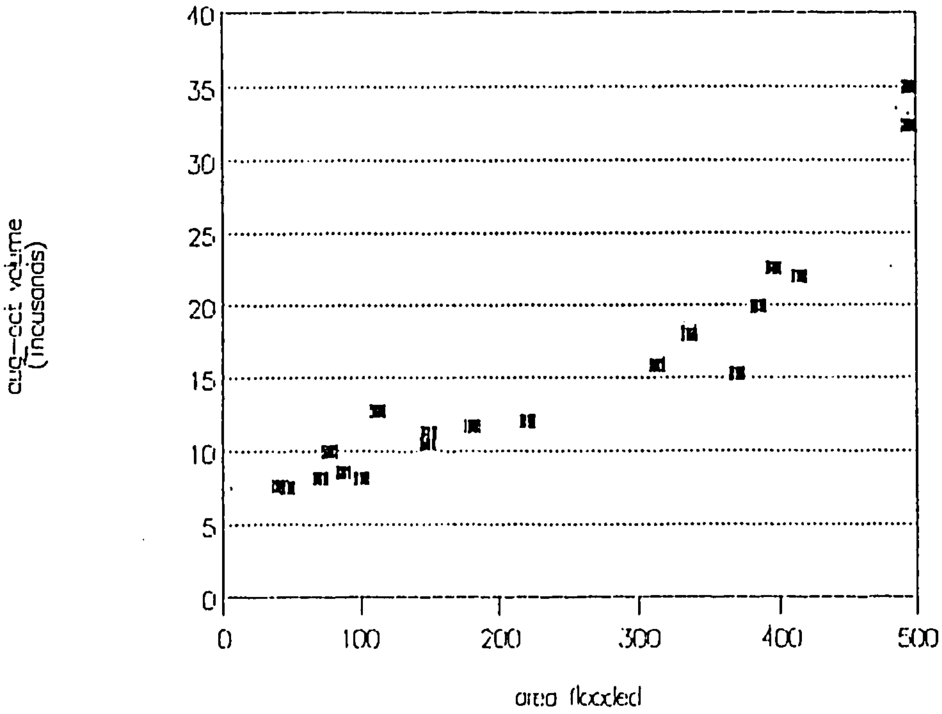

Figure 4.2.4 Relationship between area flooded (000 ha) and the volume of flow (000 $10^6 m^3$) from August to October at Bakel

The various sources often give different data for the area cultivated during the same year. The differences in 1970, 72, 76, and 78 are modest. In 1978 the estimates are 97,000ha, 97,000ha and 82,200ha. More remarkably in 1977 the figures vary by a factor of almost 2, whilst in 1980 the figures range from 13,740ha to 30,000ha to 66,000ha. In 1983 the range is from 5,240ha to 17,000ha whilst in 1984 Gersar et al imply that there was no flood at all whilst Groupement Manantali give an area cultivated of 16,000ha. Gersar et al (1988) comment on their figures from regional officials for 1979 to 1985 being less reliable than the satellite derived figure for 1986. These variations in estimates of the area cultivated are reflected in the ensuing graphs by symbols for each of the figures shown in Annex A.

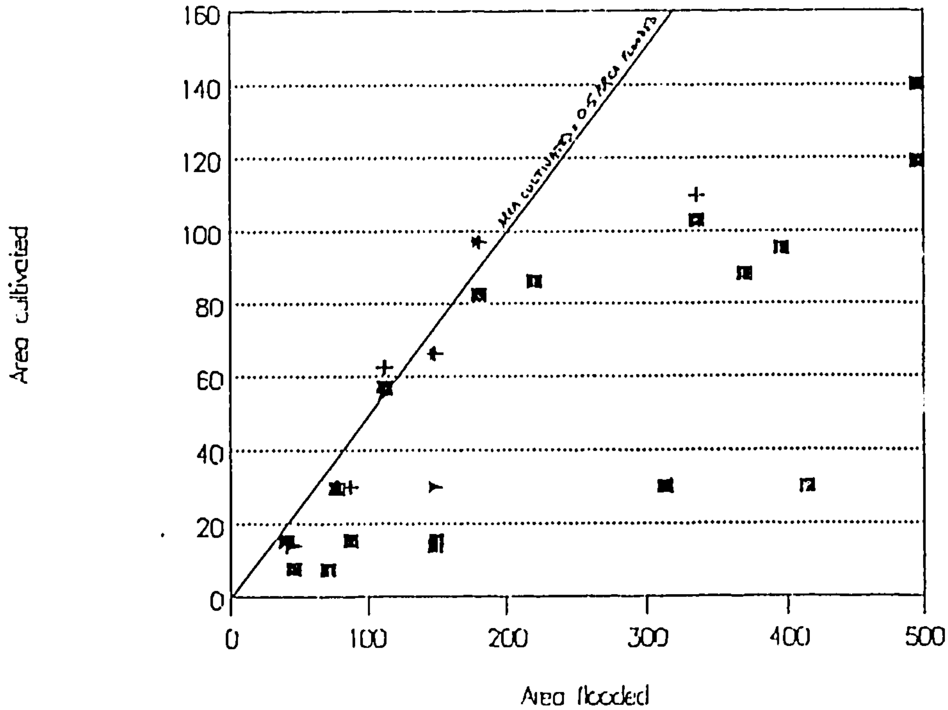

Figure 4.2.5 Relationship between area flooded (000 ha) and the area cultivated (000 ha)

Figure 4.2.5 shows that, in the published data, the area cultivated does not approach the area flooded. In general the area cultivated approaches a maximum of 0.5 of the area flooded but in many years the area cultivated is only a tiny fraction of the area flooded. This conclusion is at odds with the field observations in the IDA villages in 1989-90 where it was observed that all of the land flooded was in fact cultivated.

Gibb (1987) recognized that not the whole of the area flooded was actually cultivated. They argued that the area flooded for less than 15 days was not able to absorb sufficient soil water to make cultivation possible. The areas flooded for more than 45 days were only available for cultivation so late in the season that the growing season for sorghum was too short for a successful crop. Therefore Gibb (1987) defined the area flooded between 15 and 45 days (S15-S45) as the cultivable area. Figure 4.2.6 shows that there is a very weak relationship between area cultivated and S15-S45. In addition, the available data does not suggest a consistent limiting value since in 1970 the area cultivated was greater than S15-S45. However, it must be noted that 1970 had an exceptionally large flood with Reizer giving a flooded area of 335,000ha.

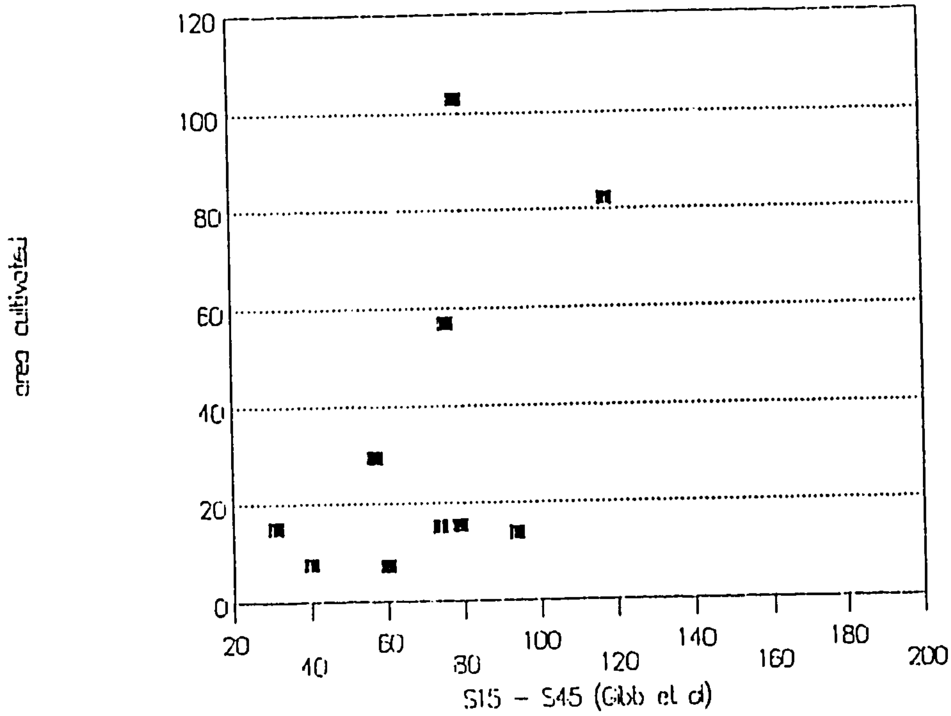

Figure 4.2.6 Relationship between area flooded (000 ha) and the area flooded for between 15 and 45 days (000 ha)

Conclusion

As others have already identified, there is a very urgent need for the monitoring of the areas actually flooded and the areas cultivated with flood recession agriculture. It is essential that this data is derived for each of the floods which takes place after the commissioning of Manantali in 1987. It will probably be essential to use high resolution satellite imagery (TM or SPOT) along with extensive ground truthing. Imagery will be needed for September/October to assess the flood extent and for January to measure the true extent of recession agriculture.

There is no historical data on flood extent. The figures that exist are calculations based upon several models. The historical data for the area cultivated derives from numerous methodologies. The published sources sometimes give wildly different figures for individual years. The SATEC et al (1980) data for river levels and cuvette water levels suggests that the estimation of flood extent from river levels using the UNE model may over estimate the area flooded substantially for small floods.

The analyses of the relationships between river flood hydrology, area flooded and area cultivated suggest that the Gibb artificial hydrographs A (7,500 10^6m^3 for 50,000ha cultivated), B (8,500 10^6m^3 for 75,000ha cultivated) and C (10,000 10^6m^3 for 100,000ha cultivated) are satisfactory for the continuation of flood recession agriculture in the Senegal Valley. However, it would be highly desirable for the historical databank of LANDSAT images to be used to establish firm relationships and to map the actual areas likely to be inundated by the proposed artificial floods. It will be important to endeavour to link the LANDSAT imagery to a digital terrain model of at least some of the cuvettes to establish the precise magnitude of the difference in water levels identified by SATEC et al (1980).

Gersar et al (1988), whilst quoting the SATEC et al (1980) studies towards the end of their report, ran the artificial floods A, B, and C from Gibb (1987) through the ORSTOM model of flows in the river. The resulting levels within the UNE model for flood extent give the results in Table 4.2.1.

Table 4.2.1 The Flood Extent for Artificial Floods A, B, and C using the ORSTOM hydrological model and the UNE model for flood extent. (after p 48 in Gersar et al (1988)

Flood	A	B	C
The area inundated for 15 days on the left bank of the river (Ha)	98,000	109,000	130,000

These analyses confirm the adequacy of the proposed artificial floods since they indicate clearly that almost as much land (in hectares) will be flooded as has ever been cultivated. However, there remains the question of the SATEC et al (1980) relationships.

The adequacy of the proposed artificial floods for the floodplain fishery remains to be determined. It is possible that the fishery will require a larger area and longer duration of inundation than that expected from the artificial floods. Indeed, Dames and Moore (1989) comment (p 3-66) that one of the adverse effects of Manantali will be the loss of 350,000ha of fish habitat.

4.3 The Impact of Manantali and the Cessation of the Artificial Flood on Groundwater Levels

All of the groundwater literature reviewed agrees that the groundwater in the middle valley is recharged primarily by river floods with rainfall playing only a minor role. The literature is almost unanimous in believing that the surface alluvial aquifer, the Continental Terminal Formation and the deeper Maestrichtienne aquifer are linked and receive water from the river flood. The river is known to be in direct hydraulic communication with the groundwater.

No literature has been discovered which even mentions the adverse effects of Manantali or the cessation of the artificial flood on groundwater recharge. There appears to be no concern in the literature for any potential decline in water levels.

At first sight, it might be expected that the closure of Manantali and the termination of the artificial flood would have an adverse effect on groundwater in the valley. The creation of a reservoir of up to 600 km^2 ought to attenuate flood flows in the Bafing and reduce water levels downstream. The storage of 11,000 10^6m^3 of water in the reservoir ought to reduce the volume of flood flows downstream of the dam and so reduce the levels of floods downstream. The cessation of the artificial flood ought to reduce the frequency of moderate flooding in the valley. The cumulative effect of attenuation, the reservoir storage and the cessation of the artificial flood ought to be one of lower water levels for all floods, a large reduction in the frequency and duration of small floods, and a modest reduction in the peak discharge of large floods. These changes ought to lead to a reduction in groundwater recharge in the valley and a consequent lowering of water levels. In the lower part of the valley this reduction in hydraulic head could lead to a landward movement of the salt water which occurs under the delta.

However, other developments in the valley could offset some of these adverse effects. The creation of irrigated perimeters should lead to drainage of water to groundwater, albeit of probably lower quality than natural percolation. The creation of flood protection embankments around irrigated perimeters will restrict inundation of the floodplain and cause water levels to rise in the unprotected parts of the valley. This rise in flood stage may cause new areas to be inundated and may increase the duration of inundation on unprotected areas. The net effect of these changes may be to increase the recharge of groundwater.

Gersar et al (1988 - Schema Hydraulique) examined flood flows in connection with the perceived need for flood protection works. They showed that, using the flood hydrograph for 1967 for Soukoutali and the operating rules that have been developed for the bottom gates and the upper sluices of Manantali, there is no attenuation effect in Manantali at all. Moreover, assuming a constant release of 250 m^3/sec during the dry season, it was found that the volumetric reduction in flood volume for extreme floods was under 5%

Gersar et al (1988) went on to examine the effects of the constriction of flows because of the flood protection embankments around irrigation perimeters. They used the SOGREAH model and found substantial rises in flood levels (Table 4.3.1)

Table 4.3.1 The increase in water levels for the 100 year flood in the Senegal Valley as a result of flood protection embankments around irrigated perimeters (metres) (after Gersar et al, 1988)

Station	130,000ha of development	230,000ha of development
Matam	+0.73	+1.05
Kaedi	+0.66	+1.44
Salde	+0.77	+1.64
Boghe	+0.55	+1.11
Podor	+0.82	+0.87
Dagana	+0.63	+0.69

Gersar et al (1988) (p 73, Scheme Hydraulique) say that embankments will have to be built to the full height with the ultimate development, however for the next twenty years such high banks are not necessary. In a rare admission of the need of such schemes for continued capital investment, they say that their experience on the left bank of the river is that flood protection banks need rehabilitation every 20 to 30 years. They say that the decision to raise the flood banks to their full height in a one or two stage process is primarily an economic question. It will be interesting to examine the economics of schemes, such as ITALTEKNA at Matam, to assess the extent to which the scheme's cost benefit analysis has taken the future elevation of flood levels into account.

A deeper examination of the Gersar et al (1988) analysis reveals that it is not directly applicable to the full range of flood flows in the river. The large flood of 1967 consisted of 40% of its volume from the very flat hydrograph at Soukoutali and 60% of its volume from the very peaked flow in the Faleme and Bakoye. Whilst it is well established that the Bafing makes a minority contribution to big floods at Bakel, floods at Soukoutali do not normally arrive with flat topped hydrographs. It is almost certain that Manantali would have a significant attenuating effect on smaller and more peaked floods such as that for 1982 shown on p3/19 of Gibb (1987, Volume 1D). In addition these smaller floods have a greater % of their flow from the Bafing; that for 1982 has 61% of its flow from the Bafing (Table 3.4 in Gibb (1987) Volume D). Whilst such floods are of little relevance to Gersar et al (1988) in their design of flood protection works, such floods are probably of significance for groundwater recharge, the maintenance of the gonakier forest etc.

Similarly, whilst Gersar et al (1988) found only a 5% decline in the volume of extreme floods because of Manantali's storage, their diagram 5.5 (p 67) does show that smaller floods will have the greatest percentage decline in volume. 37% of floods (< 15,000 $10^6 m^3$ Aug-Oct) will decline in volume by around 20% and 11% of floods (< 10,000 $10^6 m^3$ Aug-Oct) will decline in volume by around 40%. On this basis the flood of 1982 would have been reduced to 5,816

10^6m^3 which makes it more than 1,000 10^6m^3 smaller than the record low flood during the 1984 drought.

Table 4.3.2 makes a very preliminary attempt to synthesize dat from a number of sources to estimate the area of walo land not flooded between 1968 and 1984 if Manantali had been in operation. The volumes of the floods are taken from Gibb (1987) as is the extent of the S15 flood. The % impact of Manantali in reducing flood volumes is estimated from a generalised line inserted on Figure 5.5 in Scheme Hydraulique of Gersar et al (1987). These % impact are then applied to the flood volumes and these are then transformed in to flood extents using Figure
4.2.4 in this report. A subtraction of the flood extent after Manantali from that given by Gibb shows the approximate impact of the dam year by year. It is clear that the transformation of flood volume into flood extent gives some problems in certain years. However the overall result is clear. A more analytic derivation of this table of impacts will be possible once there is an effective simulation model available for daily flow at Bakel and a more rigourous relationship between area flooded and flood volume

Table 4.3.2 Reduction in the size of floods and area inundated as a result of the operation of Manantali (based on Figure 5.5 in Gersar et al (1988 Scheme Hydraulique), Table on p 5/12 of Gibb (1987 Vol 2A), & Figure 4.2.4 in this report)

Year	Flood volume (10^9 m^3)	Flood extent (000ha) (S15)	% impact	Post dam flood volume (10^9 m^3)	Post dam flood extent (000ha)	Walo land not flooded (000ha)
1968	14.3	160	-30	10.0	90	70
1969	27.7	400	-8	25.5	410	+10
1970	19.7	340	-12	17.3	320	20
1971	22.2	380	-11	19.7	370	10
1972	9.2	40	-40	5.5	0	40
1973	13.3	180	-25	10.0	120	60
1974	24.9	410	-8	22.9	400	10
1975	18.3	313	-15	15.5	290	23
1976	13.6	80	-25	10.2	110	+30
1977	9.7	90	-39	5.9	0	90
1978	14.9	110	-29	10.6	125	+15
1979	9.0	50	-42	5.22	0	50
1980	11.8	150	-30	8.26	70	80
1981	13.0	150	-24	9.9	100	50
1982	9.3	70	-40	5.6	0	70
1983	6.5	c30	-50	3.3	0	30
1984	6.5	?20	-50	3.3	0	20

Average area of Walo land not flooded each year 33,000ha

One preliminary conclusion from this brief review is that falling groundwater levels are not likely to be a problem. However, development in the valley may cause a rise in extreme flood levels with some areas being flooded more frequently than at present. This may result in a need to relocate some settlements or to provide protective embankments for existing settlements. The implication in Gersar et al (1988) that rehabilitation and raising of the flood banks around irrigated perimeters after about 20 years of operation may seriously undermine the profitability of such schemes. Perhaps more significantly the patterns of use on the non-irrigated parts of the floodplain may have to change.

An different preliminary conclusion is that groundwater levels will tend to decline in dry periods because of the reduction in the height and duration of small floods.

In the first instance, the existence of Manantali will reduce flood volumes and therefore flood extent. A very preliminary analysis has estimated the lost flood area as 33,000ha per year on average. In the terms used by Gibb (1987) this represents a financial loss of 34,000

FCFA/ha. At 1.122 milliard FCFA, this loss must be added to the presently projected price of electricity. However IDA are in the process of estimating the true value of all aspects of production on flooded walo lands. Therefore the true total loss as a result of the adverse effect of Manantali on flood extent is likely to be much more than 1.122 milliard FCFA.

It is clear that much more attention will have to be given to a broad spectrum of hydrological effects of Manantali. Some modelling of river - groundwater relationships will probably be very useful once the OMVS/USAID project has produced a usable database. A definitive conclusion from this review is that the hydrological modelling of the valley will have to be extended to include the spatial patterns and impacts will have to be examined at least on the basis of individual cuvettes and major villages.

4.4 The Fate of Flood Water and Rain Water in the Walo

Apart from an observation in Gibb (1987) that Chaumeny's 1970 study of the UNEs showed that 89% of flood recession agriculture was created by flooding from the river, there appears to have been no attention given to rainwater or other flooding of the walo. Chaumeny found only 11% of his flood recession outside the UNE's but this represented 11,300ha which is a significant percentage of the area likely to be cultivated during the artificial flood regime.

The IDA field team has identified deep cuvettes near to the river that do not flood at all because they have no direct channel linking them to the river. Similarly the University of Arizona video coverage of the walo in 1989 depicts many walo depressions which the IDA field team identify as having been filled with local runoff from the land around the depression.

Gibb (1987), in their simulation model for the whole valley, made some necessary simplifications of the hydrology of the walo. They calculated evaporation on the basis of a river 400m wide and evaporation did not vary with the level of river flow. They admitted that some water must be lost due to infiltration, but without any data on the subject available, they assumed infiltration to be 2% of river flow. They assumed that some of the water flooding the walo would be lost according to Table 4.4.1. There was no data on which to base these simulations.

Table 4.4.1 Floodwater on the walo which does not return to the river in the Gibb (1987) simulations

Volume of the flood at Bakel in 000 $10^6 m^3$/month	Volume lost in the UNEs 000 $10^6 m^3$/month
15	6
8	4.5
6	2.5
4	1
3	0

For the sound management of the walo cultivation and for the successful implementation of water management simulation models, it is important that an understanding of the water balance of the walo lands is developed. The SAED (1985) study presents infiltration rates for irrigated perimeters on various walo soils. It will be important to examine the scientific basis of that study. It is arguable that it is as important to ask "What happens to the water?" as it is to ask "What do the people do?"!

4.5 The Interpretation of the Results of the Gibb Studies

Dames and Moore (1989) exemplify how the technical results of one study can become "absolute truth" for a subsequent piece of work. On page 3-36 they say that the size of the artificial flood and the quantity of hydro-power produced are intimately linked and they reproduce a Table 4.5.1 from Gibb et al (1987).

Table 4.5.1 The relationship between flow, flood and hydro-power for the Manantali Dam

Artificial Flood (000 10^6m^3)	0	7.5	8.5	10.0
Flow at Bakel				
1904-78 (m^3/sec)	320	210	170	130
1904-84 (m^3/sec)	250	90	50	0
Power guaranteed 100% (MW)	86	34	17	5
Average annual production 1970-84 (GWh)	830	640	550	450

This exposes one of the major reservations about the orientation of the Gibb analysis and the style of results which they have presented. Article 1.2 of their Terms of Reference (quoted on p1/2 of Vol 2A) says that the aims of the management are:

- irrigation of 373,000ha
- navigation throughout the year from St. Louis to Kayes
- production of 800 GWh of electricity nine years out of ten (my emphasis)
- reduction of exceptional flood risks
- maintenance, for a transitory period, of an artificial flood for flood recession agriculture
- prevention of saline intrusion at Diama
- partial control of water levels in the delta
- improved flow to a series of specific depressions in the floodplain
- reduction in the pumping height in the delta
- maintenance of acceptable ecological conditions in the reservoirs, the river and the delta.

However throughout their analyses there is a disproportionate focus on hydro-power generation. Their conclusions, as illustrated by Table 4.5.1, emphasize the conflicts in water utilization in the basin and focus on the "problems" created by the release of water from Manantali for the artificial flood.

Nowhere in Volume 2A on the Water USe Scenarios do they work to 800 GWh of energy in nine years out of ten, as set out in their terms of reference. Their conclusion (p6/16 of Volume 2A) is based on data for 1970 to 1984 and they are quoting figures for 100% guaranteed power:

"Flood 000 10^6m^3	0	7.5	8.5	10.0
Average Annual energy (GWh)	830	640	550	450"

Their Table 6.6 shows that when data for 1904 to 1984 is used and 95% guaranteed power is quoted (not the 90% demanded in their terms of reference) then the result is :

"Flood 000 10^6m^3	0	7.5	8.5	10.0
Average Annual energy (GWh)	1015	912	883	837"

This table shows that they can meet their terms of reference for power generation and release a flood of 10 10^9m^3.

The repeated use of the term artificial flood is also symptomatic of the problem because the clear impression is given to the non-technical reader that the whole of the 7.5 to 10 10^9 m3 of water is being released artificially from Manantali. The reality, of course, is that Manantali is simply required to top up the flood discharges which are occurring naturally in the uncontrolled tributaries.

Clearly the simulation models, including IRIS at IDA, need to be run again to establish tables showing the interactions amongst the following priorities:

minimum flow at Bakel - 12 months per year - 100% probability (terms of reference)
- 95% probability

power guaranteed (MW) - 100% probability
- 90% probability

mean production (Gwh) - 100% probability
- 90% probability (terms of reference)

area irrigable under each scenario (000 ha)

for a flood including releases from Manantali of:

7.5 000 10^6m^3- 95% of the years
10.0 000 10^6m^3- 90% of the years (actual natural figure for 10 000 10^6m^3 flood!)
15.0 000 10^6m^3- 85% of the years

There is support for a more balanced approach to the simulation and development of the Senegal Valley from Dames and Moore (1989). They argue (p 3.36) that the Gibb analysis is prejudiced because the flooding of the river provides many other advantages than the simple cultivation of Sorghum.

4.6 The Role of Groundwater in Water Resources Management in the Valley

The idea of using the surface water and groundwater resources of the Senegal Valley in an integrated manner does not seem to be on the agenda for any of the studies so far reviewed.

There is a clear conclusion abroad that Manantali cannot meet all the demands of maximum hydro-power generation, irrigation, navigation <u>and</u> the production of an artificial flood. There is some doubt that the dam can meet the ultimate long term demands of hydro-power and very substantial irrigation development. The groundwater resources of the area are known to be large and to be available over a very wide area. However, groundwater is only discussed in the context of improving supplies of drinking water to small villages.

The greatest stress is put on the simulated water resource system during the dry years of 1980 to 1984 because during these successive years of low rainfall river flows were particularly low. However, if a system of conjunctive use were developed using both surface water and groundwater resources there would be a greater amount of water resources available and there would be greater security of supply.

4.7 Means of Enhancing Production in the Walo System

Gersar et al (1988) state (p M.9) that work is underway on the Dioulol distributary of the Senegal River near Matam to improve the water flow into the area for irrigation. They say that the situation will represent a considerable improvement on the last few years.

Whilst this work needs to be investigated in the field, it seems likely that there has been deepening and clearing of the channel to maintain water in the area even when the river level is low. It is probable that these works will also have the effect of allowing a freer inflow and outflow of water to the walo zones of the area too. It remains to be determined if a faster inflow and faster outflow will be beneficial to the recession cultivators.

Gersar et al (1988) also describe works underway at the point where the Diamel joins the main river. They state that $300m^3/sec$ at Bakel guarantees 8.3m IGN at Matam and $50m^3/sec$ gives 6.6mIGN. However given the modest improvement to the bed of the channel it will only be able to maintain levels of 6.5m. Therefore, in order to maintain higher water levels, it is planned to trap water in the Diamel to stop it draining back to the river. These works are incorporated into the development project for Matam and Nabadji and they will be finished in 1990.

One development option that has not been explored in the literature is that of enhancing the walo flood recession cultivation. Since several large areas of cuvettes are fed by distinct channels diverging from the main river, eg the Dioulol and Diamel, it is feasible to consider structures at these points. Gates or sluices would trap flood water in the cuvette and guarantee an appropriate length of flood on the rich bottomland soils. The gate could be opened to allow the flood to recede at such a pace that the farmers could just manage to plant the recently emerged soil. The gates would have the additional advantage that should a second flood pass down the valley than it would be possible to safeguard the already planted fields.

Ideas similar to these have been advanced in the forestry section of Gersar et al (1988) in connection with establishing gonakier woodlands on uncultivated walo land. Whilst such proposals have merit, it is probablv even more important to maintain staple food supplies to the valley.

4.8 Relationship between the Flood and Acacia nilotica (Gonakier) Woodland

Skinner and Pomerleau (1989) state that Gonakier woodland requires regular flooding and/or a good supply of groundwater. Van Lavieren et al (1988) say that it is essential to have surface flooding for gonakier woodland and they go on to list many of the other species of plants associated with this woodland type. Skinner and Pomerleau (1989) and Gersar et al (1988) agree that the regeneration of gonakier from seed requires surface flooding. The limited information in the IDA library on the ecology, extent and utilization of gonakier woodland suggests that this ought to be given some priority.

Gersar et al (1988) state (p J.57) that a Gonakier woodland can produce 3.2 tons of wood per hectare per year. The productive potential of the woodlands of the valley is estimated at 160,000 tons per annum (40,000 tons of charcoal). Skinner and Pomerleau (1989) emphasize that in addition to wood, the forests also provide wood that is good for building because it is resistant to termites; tannin for preparing leather; dyes; nutritious seed pods for animals; and good dry season grazing where the trees stay green because of a supply of groundwater. Gersar et al (1988) also list the importance of the gonakier woodland as habitat for several species of mammals and birds including several breeding birds. They state that the loss of the woodland will be negative for the fauna of the region.

Amongst the reasons that Gersar et al (1988) give for the recent decline in the productivity of the forests is the elimination of good floods and the consequent inundation of the forests. They say that "(in french) in the long term, the losses of forests resulting from the construction of dams, the regulation of the water regime of the river, the construction of embankments and the development of irrigated agriculture will have a negative impact on the productivity and survival of the forests".

In considering the management options available for sustaining or expanding the productivity of gonakier woodland in the middle valley, Gersar et al (1988) list amongst their ideas "irrigated forests" and "water conservation to favour gonakiers". For the former it is said that there are many small parts of irrigated perimeters that cannot be cultivated for various reasons. A CAB estimate from 1986 is quoted to show that 20% of the irrigated perimeters may be uncultivable which would result in 24,000ha of gonakier woodland. It is said that the experience at Nianga shows that $20m^3$/year/ha can be produced. The conservation of water in favour of gonakiers involves using the cuvettes which are not used for agricultural production (p J.69). The idea is that the manipulation of simple gates at the mouth of the cuvettes will simulate the effect of the flood and so recreate conditions necessary for the spontaneous regeneration of gonakier woodland. "This management will compensate in part for the loss of forests that were formerly inundated by the natural flood which will have disappeared"!

It is surprising, given the unlikely economic viability of using capital intensive schemes to grow gonakiers, that Gersar et al (1988) did not take a more obvious course and recommend consideration of the continuation of the artificial flood.

One other important point deriving from this review is the point that 20% of irrigated lands will never be cultivated. Does this point feature in their internal cost/benefit evaluations?

4.9 Feasibility of Generating and Managing an Artificial Flood

A major part of the work in Senegal will be the review of methods and procedures for the timing of the release of the artificial flood. The documents at IDA do not give a detailed insight into the operation details of the release.

The experience of the artificial flood regime does not seem to have been very positive to date. There was no artificial flood release in 1987 when the dam was closed. 1989 had the unfortunate occurrence of a second peak in the release hydrograph which caused serious problems for many flood recession farmers. A cynic might observe that there have been two bad years out of three and that the operators of Manantali are not trying to produce successful results with the artificial flood. It would be entirely in keeping with the highly pro-electricity generation orientation of Gibb's (1987) report that the actual operation (as opposed to the theoretically planned operation) of the dam would be organized to limit the apparent value of the artificial flood.

The problems associated with operating the artificial flood relate to:

i) knowing the flows in the Faleme and Bakoye in good time such that releases from Manantali can be made to top up the natural flows, if necessary, to guarantee the achievement of the artificial flood,
ii) knowing the likely flows through the wet season so as to determine the likely timing of the flood peak comprising flows from the Faleme and Bakoye and essential releases from Manantali as a result of very high water levels being achieved,
iii) knowing the likely flows into the dam next year since this influences operation of the dam this year,
iv) having the means to convey information about the timing of the artificial flood, or the large "natural" flood, to the people downstream,
v) having the people downstream trust the flood forecasts.

The Gibb (1987) proposal to have the artificial flood peaking in mid September has the benefits that the chances of a second larger peak are reduced and water will not be released from the reservoir before it has filled to some extent. However, the mid-September peak carries with it twin dangers. First, the totality of the artificial flood may have to be released from the reservoir if earlier high flows in the tributaries have not been augmented. Second, if flows have been low in the Bafing it may be judged impossible to release an artificial flood.

This section will require a lot more reading during the mission to Senegal and experimentation with the daily flow data when it is obtained.

4.10 The optimization of the whole water resource system

The introduction to Gibb (1987) Volume 2A (English Summary) states that the "main functions of the project are:

- agriculture - irrigated and flood regression cropping
- navigation
- power production
- water supply
- flood attenuation
- environmental protection".

Environmental protection and flood attenuation receive scant attention in the Gibb studies and groundwater is not a major feature of their consideration. Gersar et al (1988), which incorporates Gibb as part of the team, demonstrate that far from attenuating floods, the whole development scheme of the valley will elevate the levels of the most extreme floods. Gersar et al (1988) also suggest a range of capital intensive measures to maintain or enhance the productivity of the (essential) gonakier woodlands which will be otherwise destroyed by the other development actions foreseen in their work. Whilst reproducing the Gibb analysis which purports to show what a disaster the artificial flood will be for the development of the valley, Dames and Moore (1989) do attest that the Gibb analysis is prejudiced because the flooding of the river provides many other advantages than the simple cultivation of Sorghum. This report has, however, shown that Gibb's own analysis, when examined closely, shows that the artificial flood does not conflict with the element in their terms of reference which demands 800 GWh nine years in ten.

The future planning of the water resources development of the Senegal Valley requires a broader cross-sectoral approach. It demands inter-disciplinary teams with a greater input from economists. A greater effort is needed to consider the direct (tangible) costs and benefits of certain strategies, the indirect costs and benefits and the intangible existence values of, for example, the features of the valley which are of environmental importance. Consideration, and due weight, must be given to the maintenance of the ecosystem upon which the people of the valley depend.

5.0 FUTURE RESEARCH

Lericollais (1980), a geographer, devoted to the SOGREAH model a large part of his review of the hydrological constraints on flood recession farming. However he finished by saying that "(in french) without a knowledge of the speed of filling of the cuvettes, the level of water in the cuvettes compared to that in the river, the effective date for the retreat of the water, and in view of the lack of precision in the ancient topographic survey of the areas, the true potential of the lands cultivable by flood recession techniques remains very poorly known". Sadly, a further ten years of intensive work in the Senegal Valley does not seem to have provided much useful hydrological data with which to deny Lericollais's assessment, save the limited circulation SATEC et al 1980 study.

5.1 The Reconnaissance Visit August-September 1990

A large part of the visit will be devoted to office meetings, interviews with people and collecting data and reports.

Existing Reports to be Sought

A major task of the mission will be to become acquainted with the OMVS Projet Eaux Souterraines. An interim report from this project is already circulating but it is not yet available. It will be important to see this report in Senegal. Gersar et al (p13, 1988) suggest that the OMVS study has confirmed the results of previous studies by ILLY, AUDIBERT, BECHTEL, SATEC/BRGM and GERSAR. Bibliographical details of these reports are missing from the photocopy of Gersar et al (1988). It will be useful if copies of these earlier reports can be obtained during the mission to Senegal.

Similarly it will be important to obtain a copy of what appears to be the only study of water levels in the river and in the distributary channels, i.e. SATEC - SCET - SONED 1980 Projet d'Amenagement Hydroagricole dans le department de Matam.

None of the SOGREAH studies are available at IDA nor is there any documentation on the ORSTOM hydrological model of the valley. Copies of these documents will be sought during the mission to Senegal.

The SAED (1985) report will be important for its information on infiltration and perhaps for other scientific hydrological aspects of the flooded walo lands.

The limited information in the IDA library on the ecology, extent and utilization of gonakier woodland suggests that this ought to be given some priority.

It will be essential to review Chaumeny's (1973) study of the UNEs from 1970 and that of Juton which seems to contain data on flood extent and flood recession cultivation for several years during the 1970s. The 1960 report by Cheret on flood extent and area cultivated will also be interesting.

It will be interesting to examine the economics of schemes, such as ITALTEKNA at Matam, to assess the extent to which the scheme's cost/benefit analysis has taken the future elevation of flood levels into account. It will also be important to assess the extent to which they have allowed for 20% of their perimeters to be uncultivated as stated in general terms in Gersar et al (1988).

Existing data to be collected

The following flow records will be sought:

- Daily flow since records began (1952) for Soukoutali, Kidira and Oualia so that the operation of Manantali can be analyzed,
- Full sets of data for all hydrometeorological variables for 1984 to 1990 so that simulations can be brought up to date and so that observations in the valley can be related to the hydro-meteorological situation,
- Water level data for Matam since the beginning of the records will assist in understanding the patterns of flooding in the three case study cuvettes at Thiemping, Boyenadji Roumde and Doumga Rindiaw.
- The inconsistencies between the IDA data file of daily flow data for Bakel and that held by OMVS at Manantali needs to be investigated.

Daily rainfall records from Matam will be sought to examine their utility in assessing the importance of local rainfall and runoff for filling certain cuvettes.

People and Offices to be Visited

A major effort will be devoted to the real time forecasting procedure that is being used to control the release of the artificial flood. One specific item that will need to be discussed is the feasibility of using hydrometeorological data from Guinea to improve the forecasts of flows into Manantali and the other tributaries at Bakel.

In addition, the agency and researchers undertaking the mapping of flood extent and area cultivated for 1986 onwards from satellite imagery will need to be visited.

Niasse has provided the following list of people and agencies to be contacted:

Agency	Person	Information
In Dakar:		
USAID	LeBloas	Extensive collection of reports and studies including the OMVS Groundwater Study.
ORSTOM	Lericollais	Studies and liaison with the hydrology department of ORSTOM.
ORSTOM	Lamagat	Hydrology of the River Senegal and the methodologies utilized especially in relation to real time forecasting of river flows. The feasibility of treating the intermediate gauging stations between Bakel and Dagana with the Lamagat algorithm will also need to be explored.
ASECNA	-	Hydrological data for the River Senegal and for Climatological stations.
Geography Dept University	Sall, Kane, Sow	Hydrological studies of the River Senegal
Dir. Nationale de l'Hydraulique		Annual hydrological reports, groundwater data. National hydrometric network.

OMVS/Infrastructure	Deme	Groundwater project, management of Manantali and Diama
Cellule Apres Barrage (CAB)	Sylla	Reports and political hydrology.
Projet Canal de Cayor	Ndiaye	Preliminary hydrological studies.

In St. Louis:

ADRAO		Water needs for irrigation.
OMVS	Seck	Documents and reports.
SAED	Keila	SAED programmes and studies underway.
Dir. Regionale de l'hydraulique		State of knowledge on aquifers.

In Matam:

ASECNA	Diop	Recent hydrological and climatological data
SAED	Diop	Hydrological studies in the region
ITALTEKNA		Details of their major irrigation scheme

Fieldwork

a) Observing the filling of the Walo lands around Matam during the 1990 flood

b) Observing changes in Groundwater levels and quality during the passage of the 1990 flood

c) Reconnaissance of the gonakier woodland to determine ecological and hydrological conditions in the remaining woods.

5.2 Priority Field Studies

a) Collection of ground truth data on flood extent and cultivated area for use in the interpretation of satellite imagery. This must include the field mapping of these areas.

b) Measurement of the relative levels of water in the river, Diamel and Dioulol channels and in the walo fields before, during the rise of the flood and during the recession.

c) Measurement of the inflow and outflow of surface water along the Dioulol and Diamel channel to check the assumptions of the Gibb model

d) Measurement of the volume of water retained in the floodplain after the end of the flood recession.

e) Development of reliable rating curves for the rising and falling limb of the hydrographs for the intermediate stations along the valley.

f) Water balance of three selected cuvettes with special reference to soil moisture, evapotranspiration, infiltration, groundwater level and surface water/groundwater exchanges.

g) Water relationships for Acacia nilotica woodland, investigation of its ecology, mapping of areas that have good conditions for regeneration if social and economic conditions are suitable.

5.3 Future desk studies

a) Updating the Gibb findings with the hydrological data for 1985-1990. It will be important to determine the extent to which the problems which crippled the final years in Gibb's analysis were a transitory drought interlude or the start of prolonged period of water shortage.

b) Analysis of the groundwater monitoring data for the middle and upper parts of the Valley.

c) The use of the IRIS model to define feasible and balanced scenarios for the development of the water resources of the Valley. Is it feasible for it to simulate the middle valley as well as the upper basin above Bakel? If so, it would be possible to examine the benefits to be derived from some conjunctive use of groundwater and surface water. The Gibb (1987) model is quite simple for the middle valley so long as IRIS can simulate the flooding and drainage of the cuvettes using the UNE hypsometric data. IRIS should have a flood extent algorithm added to it and SATEC style findings about the relative levels of small floods should be incorporated.

d) Analysis of the daily data for the Bafing, Faleme and Bakoye with regard to the:

i) extent of double peaked hydrographs,
ii) synchroneity of the Faleme and Bakoye,
iii) predictability of September's flow from that of July and August,
iv) the saving of water in Manantali through beginning releases for an artificial flood on an opportune day before the beginning of September as in Gibb's model (ie use the daily data not the monthly averages),

e) Comparison of the UNE model with SATEC's observations in 1978 and field observations in 1990.

f) A historical analysis using MSS and TM to determine the area flooded and the area cultivated using images from September and January for 1972 to 1990. A digital terrain model could be developed from the 1 metre contours on the existing 1:50,000 topographic maps. With this topographic data the results could be presented for each UNE and for each level.

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7.0 MISSION ITINERARY

This report has been prepared in three stages. The first phase took place in England during the first two weeks of July and involved introductory reading about the Senegal Valley and the Project. A large number of summary documents in English, were provided by IDA for this phase. The second phase from July 14th to 22nd took place at IDA in Binghamton. This involved "immersion" in the IDA Senegal Valley Library and extensive discussions with staff at all levels in IDA. The report was finalized in England at the end of July.

8.0 APPENDIX A

The spreadsheet of data used to examine the relationships between river hydrology, area flooded and area cultivated with flood recession crops.

Flood Year	Flooded Area	Cultvted Area 000ha	Source	Cultvted Area No2	Source for No2	Cultvted Area No3	Source for No3
1944.00	100.00						
1946.00		100.00	Guerber85				
1947.00		105.00	Guerber85				
1950.00	500.00	119.00	Guerber85				
1951.00		116.00	Guerber85				
1952.00		98.00	Guerber85				
1953.00	370.00	88.00	Guerber85				
1954.00		131.00	Guerber85				
1955.00		101.00	Guerber85				
1956.00		142.00	Guerber85				
1957.00		143.00	Guerber85				
1961.00		78.00	Guerber85				
1963.00		94.00	Guerber85				
1964.00		109.00	Guerber85				
1965.00		123.00	Guerber85				
1966.00		117.00	Guerber85				
1967.00	500.00	140.00	Guerber85				
1968.00	220.00	86.00	Guerber85				
1969.00	396.00	95.00	Guerber85				
1970.00	336.00	103.00	gibb1B	110.00	Guerber85		
1971.00	385.00						
1972.00	41.00	15.00	OMVS/Reiz	13.70	Gibb1b	15.00	G.Man85
1973.00	180.00	82.20	gibb1B	97.00	Guerber85	97.00	G.Man85
1974.00	414.00	30.00	G.Man85				
1975.00	313.00	30.00	G.Man85				
1976.00	77.00	29.40	gibb1B	30.00	Guerber85	29.00	G.Man85
1977.00	86.00	15.40	gibb1B	30.00	Guerber85	15.00	G.Man85
1978.00	112.00	56.90	gibb1B	62.50	Guerber85	55.00	G.Man85
1979.00	46.00	7.46	gersar88			14.00	G.Man85
1980.00	147.00	13.74	gersar89	66.00	Guerber85	30.00	G.Man85
1981.00	149.00	15.26	gersar88			66.00	G.Man85
1982.00	70.00	7.15	gersar88				
1983.00		5.24	gersar88			17.00	G.Man85
1984.00		0.00	gersar88			16.00	G.Man85
1985.00		6.62	gersar88				
1986.00		64.35	gersar88				

Flood Year	Flood Year	Flooded Area 000ha	Source	S15 000ha	s45 000ha	s15-s45 000ha	Source
1944.00	1944.00	100.00	Reizer				
1946.00	1946.00						
1947.00	1947.00						
1950.00	1950.00	500.00	Reizer				
1951.00	1951.00						
1952.00	1952.00						
1953.00	1953.00	370.00	Reizer				
1954.00	1954.00						
1955.00	1955.00						
1956.00	1956.00						
1957.00	1957.00						
1961.00	1961.00						
1963.00	1963.00						
1964.00	1964.00						
1965.00	1965.00						
1966.00	1966.00						
1967.00	1967.00	500.00	Reizer				
1968.00	1968.00	220.00	Reizer	164.00	43.00	121.00	Gibb 1b
1969.00	1969.00	395.00	Reizer	396.00	320.00	76.00	Gibb 1b
1970.00	1970.00	335.00	Reizer	336.00	257.00	79.00	Gibb 1b
1971.00	1971.00	380.00	Reizer	365.00	257.00	128.00	Gibb 1b
1972.00	1972.00	20.00	Reizer	41.00	10.00	31.00	Gibb 1b
1973.00	1973.00			180.00	62.00	118.00	Gibb 1b
1974.00	1974.00			414.00	275.00	139.00	Gibb 1b
1975.00	1975.00			313.00	127.00	186.00	Gibb 1b
1976.00	1976.00			77.00	20.00	57.00	Gibb 1b
1977.00	1977.00			86.00	7.00	79.00	Gibb 1b
1978.00	1978.00			112.00	36.00	76.00	Gibb 1b
1979.00	1979.00			46.00	6.00	40.00	Gibb 1b
1980.00	1980.00			147.00	53.00	94.00	Gibb 1b
1981.00	1981.00			149.00	75.00	74.00	Gibb 1b
1982.00	1982.00			70.00	10.00	60.00	Gibb 1b
1983.00	1983.00						
1984.00	1984.00						
1985.00	1985.00						
1986.00	1986.00						

Flood Year	Peak m3/sec Bakel	Aug-Oct Volume Mm3	Days > 1500m3sc	Days > 2000m3sc	Days > 2500m3sc
1944.00	1860.00	8097.00	17.00	0.00	0.00
1946.00	4593.00	19530.00	67.00	57.00	38.00
1947.00	4729.00	17950.00	57.00	33.00	21.00
1950.00	7361.00	32335.00	79.00	71.00	62.00
1951.00	5995.00	19750.00	93.00	63.00	23.00
1952.00	5454.00	18650.00	60.00	53.00	33.00
1953.00	4437.00	15236.00	67.00	31.00	17.00
1954.00	6652.00	26900.00	79.00	73.00	62.00
1955.00	5706.00	27500.00	82.00	75.00	71.00
1956.00	6353.00	25850.00	72.00	64.00	50.00
1957.00	5994.00	26310.00	86.00	79.00	70.00
1961.00	7018.00	25200.00	77.00	67.00	56.00
1963.00	3747.00	16870.00	73.00	50.00	15.00
1964.00	7172.00	25850.00	82.00	52.00	40.00
1965.00	7074.00	28760.00	76.00	68.00	60.00
1966.00	5808.00	27290.00	70.00	52.00	41.00
1967.00	5460.00	34923.2	94.00	82.00	68.00
1968.00	3526.00	11947.8	27.00	17.00	9.00
1969.00	4732.00	22511.4	91.00	76.00	58.00
1970.00	4431.00	18047.0	52.00	56.00	52.00
1971.00	5303.00	19834.8	63.00	57.00	52.00
1972.00	1849.00	7608.2	5.00	0.00	0.00
1973.00	3149.00	11658.6	50.00	23.00	7.00
1974.00	5695.00	21918.7	69.00	48.00	36.00
1975.00	2200.00	15844.4	57.00	39.00	27.00
1976.00	2100.00	9939.5	22.00	5.00	0.00
1977.00	1800.00	8504.2	28.00	5.00	0.00
1978.00	2000.00	12715.0	55.00	16.00	4.00
1979.00	1896.00	7466.9	9.00	0.00	0.00
1980.00	2000.00	10465.5	37.00	16.00	8.00
1981.00	2000.00	11171.2	52.00	15.00	2.00
1982.00	1900.00	8095.8	16.00	7.00	0.00
1983.00	1211.00	5106.8	0.00	0.00	0.00
1984.00	903.00	4956.6	0.00	0.00	0.00
1985.00	2439.00	9578.2	37.00	7.00	0.00
1986.00	2732.00	9022.3	30.00	11.00	4.00