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Senegal River Basin
Monitoring Activity

Hydrological Issues: Part II

A report based on discussions and bibliographical work
in Senegal, fieldwork around Matam and subsequent data analysis

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1. Integrated Management of the River Basin

The present atmosphere of suspicion, distrust, secrecy and competitiveness which exists between several of the organizations involved in planning the future of the valley will have to be changed for effective integrated management to take place.

Integrated development must involve the local population directly. The aspirations, immediate needs and views of the village people of the Valley need to be better known by planners. There should be a freer two way process of consultation between organizations operating in the Valley and the local people.

Approaches should be made to Guinea with regard to obtaining hydrometeorological data for use in managing the river system.

2. Groundwater Recharge from the Flood

An artificial or augmented flood should become a permanent feature of the water management of the valley because the groundwater in the alluvial, surface and deeper aquifers of the valley, and probably those over wide areas of northern Senegal, are recharged predominantly by the infiltration of flood water through the floodplain. Wells drawing upon these aquifers are critical for the supply of water to villages and stock.

The water quality effects of enhanced groundwater recharge through the percolation of irrigation water should be monitored through the existing Groundwater Monitoring Network.

3. Availability of Groundwater for Irrigation

Irrigation schemes should not be fed from the large volumes of groundwater in the valley's aquifers until there is an appreciation of the full effects of such a scheme on village wells in the wider region, floodplain woodlands, regional groundwater flows, etc.

When groundwater - river relationships are better understood, consideration should be given to the conjunctive use of surface and groundwater resources.

4. Management of the Artificial Flood

The management rules for Manantali should aim at the augmentation of the natural flood from the uncontrolled portion of the upper catchment rather than endeavouring to follow the hydrograph of Artificial Flood A. This will require less water, will normally lengthen the growing season for flood recession crops and will usually permit the effective management of undesirable double peaked hydrographs.

The present OMVS/ORSTOM real time forecasting model cannot be used to augment natural flood flows because it gives only a one to three day forecast of river flow at Bakel. The present OMVS/ORSTOM real time forecasting model will lose its utility as increasing areas of irrigated and embanked perimeters change the relationship between river discharge and water level in the valley below Bakel.

A real time hydrological forecasting model should be developed which will furnish forecasts of flow at Bakel for, at least, two weeks ahead. This model will inevitably have both a rainfall/runoff component and a hydraulic component based on river levels as at present. Such a model could be used to manage an augmented flood in the Senegal River.

The feasibility of extending the existing METEOSAT based telemetering of real time climatological data should be investigated.

Links must be established with Guinea to obtain an adequate supply of rainfall and flow data for the uppermost parts of the Senegal catchment.

5. Flooding Mechanisms in Cuvettes

The blockage and restriction of flow into cuvettes and along distributary channels should be investigated prior to an inexpensive programme of dredging and excavation at critical points. These works will assist both cuvette inundation and water supplies for irrigation.

Plans for the construction and management of sluices at the points where distributaries leave the main river should aim at the integrated management of water levels for the benefit of fishermen, flood recession cultivators, irrigation schemes and any other people with an interest in water levels in the distributaries.

The complexity and variability of flow directions on the floodplain, together with the significant flows along the floodplain in some places, requires that embankments must not obstruct floodways. The placing of irrigated perimeters on the higher and sandier lands within cuvettes will reduce the costs of embankments and reduce the rise in flood levels caused by the reduction in floodplain storage produced by embanking perimeters.

The construction of temporary roads across distributary channels should only be undertaken when there will be no adverse effect on downstream irrigators and where the whole structure will be fully dredged away before the ensuing flood season.

6. The ITALTEKNA Irrigation Perimeter at Matam

The plans for the construction of this perimeter must be changed because:

a) the planned drainage of the parcels into the existing marigots and then into the cuvettes within the scheme's embankment will cause rapid salinization of the cuvette, groundwater and eventually of large parts of the perimeter,

b) the replacement of the bridges on the Matam-Ourosogui road with a continuation of the embankment will seriously impede flood flows down the floodplain. During a large flood there is a danger of floodwater passing through Matam town which is lower than the crest of the embankment.

The ITALTEKNA scheme should:

a) dredge the marigots so that drainage water can discharge via non-return flaps into the Diamel,

b) leave an extensive floodway through the perimeter so that floodwater from the Dioulol, Navel and Thiemping cuvette can pass through to the Diamel and beyond.

These hydrological modifications to the scheme should be incorporated with the ideas of other specialists for the improvement of this project.

7. Hydrological Studies

A real time flow forecasting model with a forecast horizon of, at least, two weeks must be developed for Makana and Bakel, as described above. (Top Priority)

There should be test releases of sustained base flows from Manantali to permit studies of the fate of the released water. Special attention will have to be given to water levels in the river between existing gauging stations, water levels in distributary channels and the current metering of rates of flow at critical points. (Very high priority)

Stage boards should be established in each of the study's cuvettes and at strategic locations along the distributaries and marigots. These boards should be read daily by an observer resident in a local village during the flood season and during test releases of dry season flows from Manantali. The stage boards will have to be carefully levelled to yield elevations in m IGN. (High priority)

The volumes of flow into critical cuvettes and long important channels must be current metered repeatedly during the passage of the flood so that volumes of water movement can be calculated and relationships established between the slope of the water surface between stage boards and the discharge. (Medium priority)

A new physically based model of the hydrology of the valley needs to be developed and calibrated with the existing wealth of data for the river and the, scanty but adequate, data on water levels in distributaries and cuvettes, groundwater levels, and the extent of flooding. The new model will have to take into account the flooding and drainage processes for individual cuvettes; groundwater-surface water relationships; withdrawals of water, including irrigation, that are foreseen; and the return of drainage water to the river. The main aims of the model will be the determination of the water levels which will be attained in the dry season under different development scenarios and the extent of flooding during the release of the artificial, or augmented, flood from Manantali. There is sufficient data on the physical hydrology of the river and floodplain to begin this modelling work immediately but new data will be needed for the testing and verification of the model. (Medium Priority)

Monitoring of the OMVS/USAID Groundwater Network should be continued and the data entered into the existing data base. (High Priority)

A report should be prepared on the groundwater resources in the Middle Valley using the OMVS/USAID Groundwater Monitoring Project's database. The study should include consideration of the effects of changing the flood regime of the river on groundwater in the wider region. (High Priority)

There should be some investigation of the soil moisture in the Waalo lands with particular emphasis on the recharge/drainage relationships, the significance of rainfall amount and timing, and the processes of evaporation and transpiration. (Low priority)

Whilst flows from the uncontrolled parts of the upper basin are reported to have exceeded Artificial Flood A in 52 years out of the 68 years from 1903 to 1971, there is some evidence that the drought years have significantly reduced the proportions of flow at Bakel which come from the Faleme and the Bakoye. A study of temporal trends in relationships between rainfall and runoff and between the relative contribution of each tributary is needed. It should accompany the present investigation of the effects of different operating regimes at Manantali on the actual flood at Bakel. (Medium priority)

An overview should be prepared on sediment movement because little attention seems to have been given to sediment transport on the floodplain, and to sediment and nutrient deposition in the cuvettes of the middle valley. (Low priority)

8. Remote Sensing and GIS Studies

The existing work of mapping flood extent from SPOT imagery should be continued in 1990 and thereafter for at least 5 more years. Satellite image(s) for the valley for 1989 should be obtained and analyzed for flood extent. The existing image for 1987 should be analyzed for flood extent since it depicts areas inundated by rain water and local runoff.

Serious consideration should be given to the analysis of old LANDSAT scenes from 1972 to create a fuller understanding of floodplain inundation. In particular LANDSAT MSS data should be used to map the area inundated during the 1978 flood, if possible, at several stages of the flood. This year is especially important because the flood hydrograph was similar to that likely to result from the artificial flood and good water level data exists for the distributaries and cuvettes around Matam.

A digital terrain model of the valley should be created within, for example, the ARC-INFO system. This will serve as a basis for both the OMVS GIS system and for the hydrological modelling proposed.

9. Senegalese Involvement in Projects

Every effort should be made to involve, and where appropriate train, Senegalese staff in project activities. There are a number of staff at the University of Dakar who could usefully contribute to the programme of work suggested. Some of the hydrological data collection which is recommended can most effectively be undertaken by the employment of educated members of village Communities.

Summary

This brief study involved literature review, discussions, field work and analysis.

Thirty-two recommendations are made. The most important is that Manantali's long term operation should be changed to include the release of water to augment the natural flood in the valley. A new real time forecasting model will be required to facilitate this. Other important recommendations seek modifications to the ITALTEKNA irrigation project and the continuation or extension of data collection programmes.

In 1986, the area of inundation at Thiemping and Boyenadji was $58.3 km^2$ and $12.3 km^2$ respectively. The flow at Bakel was 8819 $10^6 m^3$ with a peak of $3145 m^3/sec$. In 1988, the flood extents at Thiemping, Boyenadji and Doumga Rindiaw were $71.9 km^2$, $28.9 km^2$ and $5.2 km^2$ respectively. The flow a Bakel was 12,504 $10^6 m^3$ with a peak of 4585 m^3/sec.

The river flood provides most of the recharge of the aquifers under the valley. The deeper aquifers extend over a wide area beyond the valley. A narrow riverine zone has recharge during the flood and discharge to the river after the flood.

There have been measurements of water levels in cuvettes using stage boards and flows on the floodplain have been current metered. The cuvettes around Matam are inundated by flows from the river direct; from distributary channels; from marigots fed by distributary channels; and by direct discharges down the floodplain. Modest and relatively inexpensive excavations of selected channels and the installation of simple sluices could enhance the extent of flooding and provide some control.

Large pumping stations will deplete downstream flows in the dry season. There is limited existing knowledge of the interaction of baseflow releases from Manantali, pumping, and changed groundwater relationships. The embanking of irrigated perimeters will change floodplain flow patterns and raise extreme flood levels.

Artificial flood A can be achieved with the existing forecasting model and experience gathered to date. However, other factors have been most powerful in determining releases from Manantali. A flood released to augment the natural flood, rather than forming the artificial flood, would have saved, had the dam existed, 66% of the water between 1954 and 1964 and 19% of the water from 1986 to 1989. It is possible to achieve forecasts of flow at Bakel at least 14 days in advance with a rainfall-runoff model using existing technology to gather the rainfall data.

Much daily hydrometeorological data exists and it is beginning to be used. The Bafing contributed 35 to 50% of the flow at Bakel before the closure of Manantali. The contribution from the Bakoye has fallen since 1972. That from the Faleme has fallen a little.

Runoff from the lower parts of the upper basin has grown from 5% in the 1950s to 30% in the 1980s before the closure of Manantali.

Without the Bafing's flow, there would have been a flood at least equal to the artificial flood from 1954 to 1964 save for two years. There would have been no significant flooding in 1986, 1987 and 1989 whilst in 1988 there might have been minor inundations. There is sufficient existing information to construct a physically based model of flooding but two years of new field data are needed for testing and verification.

1.0 Introduction

This is the third hydrological report for the Senegal River Basin Monitoring Activity of IDA. The first report (Morel-Seytoux 1988) examined the management of Manantali, the development of the ORSTOM real time forecasting model. the lessons to be learned from tne non-release of an artificial flood in 1987, and the implications of these issues for the IDA project. The second report (Hollis, 1990):

- reviewed the status of the hydrological documentation at IDA,
- discussed the issues which seem to be generally agreed in the literature,
- detailed the issues that remain unresolved, and
- set out an agenda for the visit to Senegal.

The unresolved issues identified by Hollis (1990) form linking themes through this second report. The relationship between the water level in the river and that in the cuvettes is of major importance because it leads to the relationship between the flood hydrograph and the area flooded. The ensuing relationship between the area flooded and the area cultivated is both central and undetermined in a systematic fashion. The impact of Manantali and the cessation of the artificial flood on groundwater levels is unknown for the middle valley at least. Similarly the hydrology of the waalo lands has not been studied but it has been the subject of many assumptions in models. A very major issue was the interpretation of the results of the Gibb (1987) study of the management of the OMVS Common Works because they indicated a conflict between the artificial flood and the potential of Manantali to generate electricity. The role of groundwater in water resources management in the Valley, means of enhancing production in the waalo system, the flood dependence of the gonakier woodland and the optimization of the whole water resource system were discussed briefly. A final, major and unresolved issue was the feasibility of generating and managing an artificial flood. These unresolved issues are woven into this text rather than being reconsidered in the light of the further information gathered. The proposed programme of future hydrological studies incorporates fully the unresolved issues identified in Hollis (1990).

The mission to Senegal in August and September 1990 achieved all of the targets established in Hollis (1990). Almost all of the reports identified in the review at IDA were collected, numerous other hydrological treatises were obtained and all the necessary organizations were visited. The timing of the mission during the lengthy holiday period in Senegal meant that several key people were not available but this did not impair the mission critically.

This report is structured strictly around the lengthy list of questions posed in the scope of work (Appendix A). Part I focuses on the three study cuvettes of Thiemping, Boyenadji and Doumga Rindiaw. Their hydrology and flooding mechanisms are examined together with possible means of enhancing the utility of the flood. Part II examines the hydrology of the Middle Valley and the hydrology of the upper basin and Manantali as these affect the river below Bakel.

The mission was warmly received everywhere and assistance was given in almost all offices. However, the experience of the mission suggests that there are blockages in the flow of information in the system responsible for the management of water in the Senegal Valley. Moreover, the complexity of the organizations operating in the Valley, their interlinkages and the relative isolation of the local population from the decision making process suggests that it will be extremely difficult to implement truly integrated management of the system. The concluding section of this report treats this subject briefly.

Part I: The Cuvettes at Thiemping, Boyenadji and Doumga Rindiaw

2.0 Recent Inundations and Flood Characteristics at Bakel

The management of the artificial flood requires that the area that will be inundated by various levels of discharge be known. The first report (Hollis, 1990) dwelt at length on the possible relationships between flows at Bakel, the area inundated and the area cultivated under flood recession crops. That analysis revealed the very limited and poor data available, and the weak analysis undertaken to date.

OMVS has a project to map flood extent in September and flood recession cultivation in February from SPOT satellite imagery. This has produced, probably for the first time, reliable maps of the maximum extent of flooding for the whole valley. The mapping, to date, has been undertaken by the photo-interpretation of colour prints of the SPOT imagery enlarged to exactly 1:50,000 scale. Imagery has been obtained for September 1986, 1987 and 1988 and for February 1987. A SPOT image for September 1989 was not commissioned but an image may have been taken. An image for September 1990 has been commissioned.

Copies of the cuvette maps for flood extent were obtained for 1986 and 1988 for Thiemping and Boyenadji and for 1988 for Doumga Rindiaw. The missing map (1986 Doumga) resulted from CAB's copies being used away from the office by a staff member and OMVS being unable to supply a duplicate copy.

The imagery for 1987 has not been mapped since there was essentially no flood in that year.

The flood hydrographs for Bakel during the 1986 and 1988 floods (Figure 2.1) show that the flood in 1988 had a much higher peak and a far longer duration than that in 1986. The flood of 1986 had a higher peak, a longer duration especially at low flood levels, and a greater volume (8819 10^6 m^3) than the planned artificial flood (7500 10^6 m^3).

At Matam (Figure 2.2) the 1988 flood had a higher peak (14.32m IGN) than the 1986 flood (13.02m IGN), a particularly rounded peak with 25 days of flow over 13.0m IGN, and a greater volume of flow. The expected level of the artificial flood A at Matam can be estimated from Lamagat (1989 and 1990). The first report gives 2,500m^3/sec in terms of the stage board height at Bakel. Lamagat (1990) then allows this to be transformed into a stage board height at Matam using a revised curve with data from 1980 to 1986. Since Lamagat (1989) gives the zero value for the Matam stage board in m(IGN), the net result is the flood A level at Matam. This is calculated as 13.12m IGN which is a little higher than 1986 but much lower than 1988. Gersar et al (1990) give the level of the artificial flood at Matam as 13.15m.

The photocopies of the flood maps were shaded to show clearly the extent of flooding. The Thiemping cuvette was delimited essentially as for UNE MK2 with the limits being the

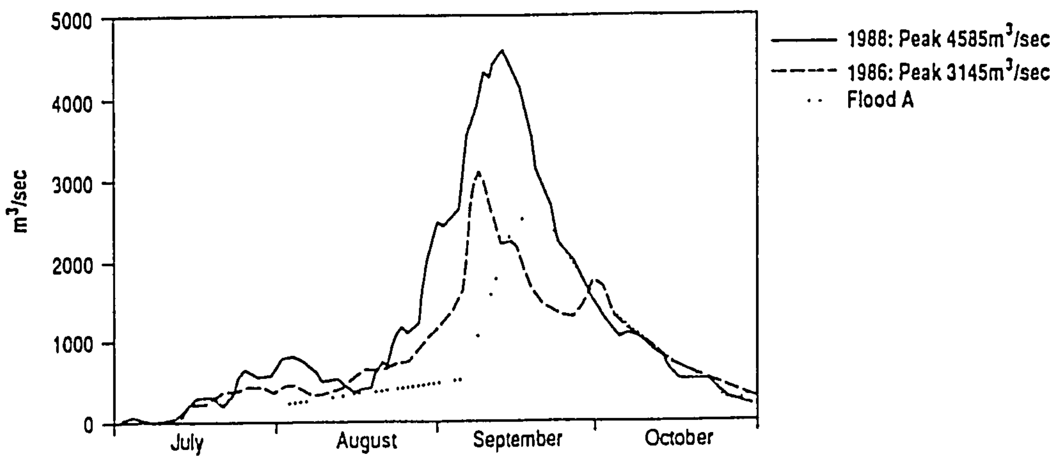


Figure 2.1 The flood flows at Bakel in 1986 and 1988

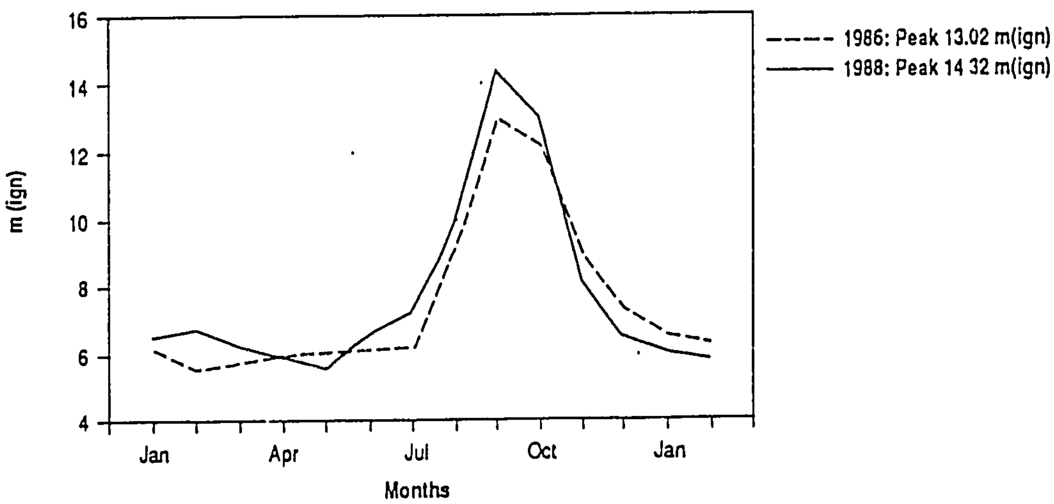


Figure 2.2 The Senegal River level at Matam during the 1986 and 1988 floods

Kanel-Tiali track in the east and end of the extensive cuvette west of Bidal in the west. The Boyenadji cuvette, parallelling UNE DI1, is a distinct unit west of the Ourosogui road and extending to a series of links to the
Diamel, the last being north of Moguo Aere. The Doumga Rindiaw cuvette is a very distinct entity between the village and Mbacha. This cuvette is only a part of the UNE DI4. The area of inundation was determined with graph tracing paper.

The results of the analysis (Table 2.1) are linked to the peak river level at Matam, the flood peak at Bakel and the area of inundation that can be calculated from the hypsometric data provided by the UNE analysis of Chaumeny (1973). The areas of inundation shown for the UNE model were calculated by reference to the peak water level at Matam. This is not strictly the UNE model which requires the flooding of the UNE to be at the same level as the adjacent river. The river levels are interpolated linearly between measurement stations. The full UNE model could not be applied in this case because recent water level data for the stations upstream and downstream of Matam was not available.

Table 2.1 Flood extent and explanatory variables for the study cuvettes

Year	Area Inundated km^2			Peak River Level	Bakel Peak	Flood Volume	Flood Extent		
	Thiemp	Boyen	Doumga	Matam mIGN	m^3/s	mill m^3	UNE MK2	Model DI1	km^2 DI4
1986	58.3	12.3	-	13.02	3145	8819	45	19	30
1987	(0)	(0)	(0)	10.97	1325	5448	8	0	2
1988	71.9	28.9	5.2	14.32	4585	12504	77	57	54

Table 2.1 shows that the varying morphology of the cuvettes together with the variety of flood water inflow and outflow arrangements makes for considerable variability between cuvettes. The larger 1988 flood increased the area of flooding at Thiemping compared to 1986 by 13.6km^2 (+23%) whilst at Boyenadji the flood extent rose by 16.6km^2 (+135%). The area of inundation at Doumga Rindiaw, at 5.2km^2, is minimal compared to the other cuvettes.

Comparison of the actual areas flooded with the areas estimated from the UNE model, based on levels at Matam, shows that the model is only of limited value in calculating flood extents. For 1986 the model underestimated by 23% at Thiemping and over estimated by 55.3% at Boyenadji. In 1988 the UNE model over estimated at both cuvettes, by 7% at Thiemping and 97.2% at Boyenadji. This confirms Morel-Seytoux's (1988) observation that the UNE model is very coarse.

The very small extent of the flood at Doumga Rindiaw, 5.4km^2, is remarkable compared to the hopeless estimate of 54km^2 made by the UNE model using water levels at Matam. Whilst the water level in the Diamel where it feeds the cuvette will certainly be less than that recorded at Matam, it is clear that the area of inundation at Doumga Rindiaw is much less than its topographic elevation would suggest. This view was confirmed by a field visit to the restricted and high level channel linking the cuvette to the Diamel. This issue is discussed more fully in Section 5.1.

The data from Table 2.1 has been plotted to show relationships between the area in each cuvette inundated and river level at Matam (Figure 2.3), peak flood flow at Bakel (Figure 2.4) and August to October flood volume at Bakel (Figure 2.5). The relationships suggested on the graphs are extremely tentative. The flood extent data for 1987 (0 km^2) has not been measured and Doumga Rindiaw lacks data, at this stage, for 1986. Straight lines have been used as the simplest alternative until further data define the form of the relationship more clearly. It is essential that a larger database be gathered, from past and future satellite images of flood extent, so that these relationships can be more properly defined.

The preliminary and tentative conclusion from this very limited analysis is that the artificial flood A is likely to inundate between 35 and 40km^2 at the Thiemping cuvette and 8 to 10km^2 at the Boyenadji cuvette. The latter figure, of course, will be completely invalidated if ITALTEKNA complete their embankments.

Taking the level of flood A at Matam to be 13.12m ign, the UNE model gives rather bigger areas of inundation, 47.95km^2 at Thiemping and 22.63km^2 at Boyenadji. The respective figures given in Gersar (1990, p 161 Annexes) for the area flooded for 15 days are 51.2km^2 for Thiemping and 8.79km^2 at Boyenadji.

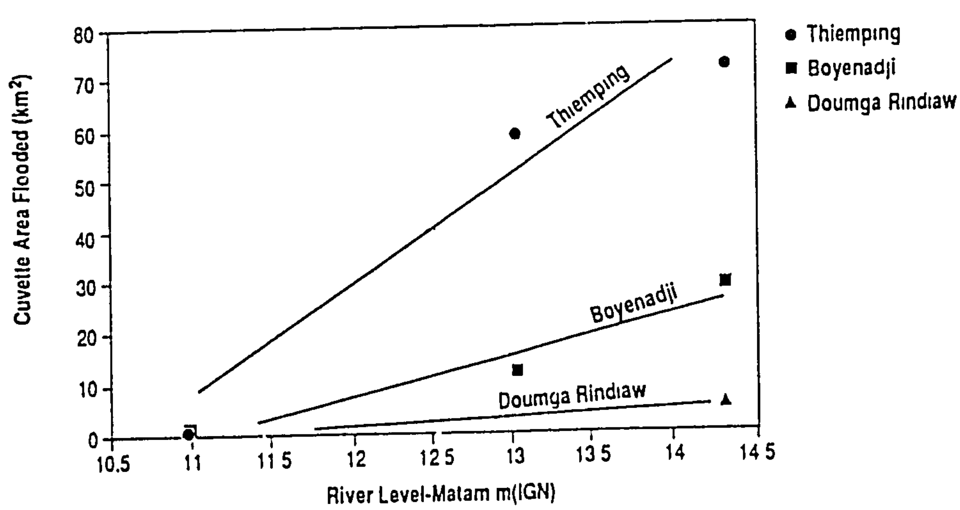


Figure 2.3 Tentative relationships between area of inundation and peak river level at Matam for three study cuvettes

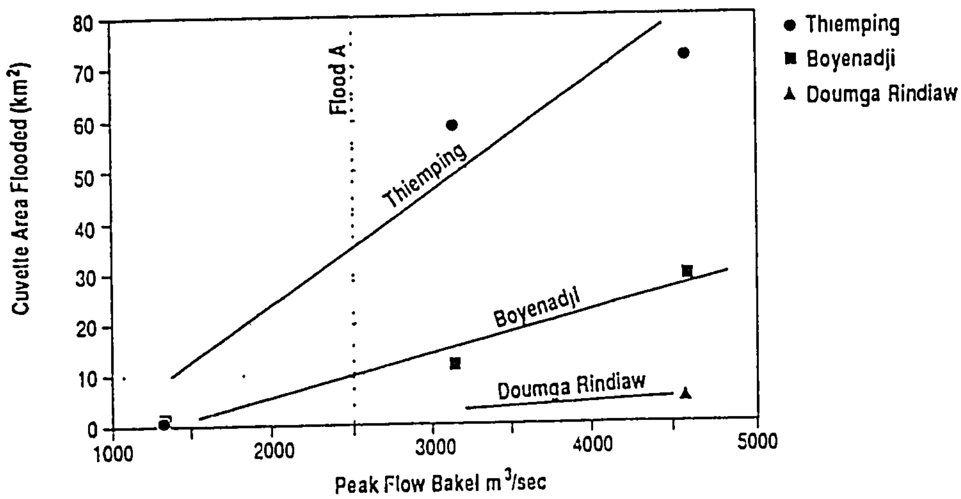


Figure 2.4 Tentative relationships between area of inundation and peak flow at Bakel for three study cuvettes

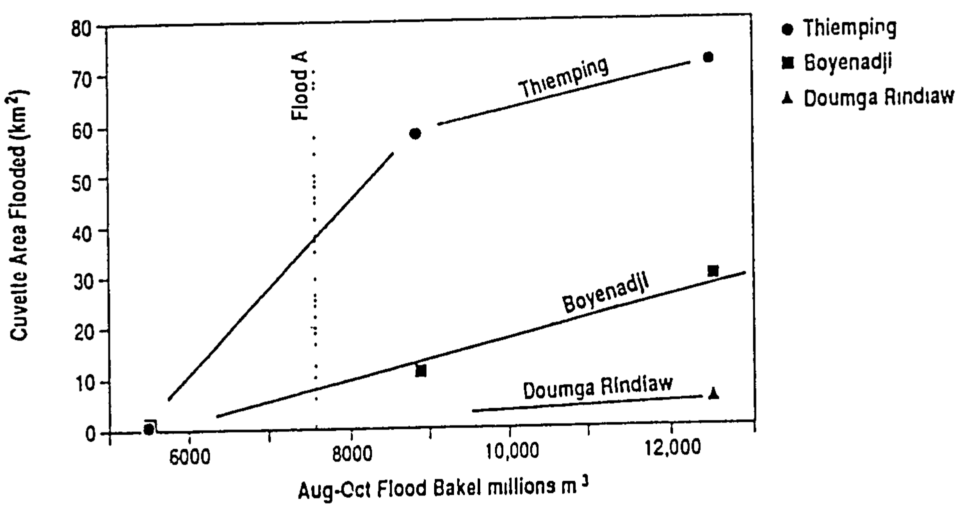


Figure 2.5 Tentative relationships between area of inundation and flood volume at Bakel for three study cuvettes

At Doumga Rindiaw it is not possible to estimate a flood extent with Flood A using the analysis of flood extent from satellite imagery. The present indications are that little, if any, of that cuvette will be flooded by the projected artificial flood. The UNE model suggests that up to 32.41km^2 will be flooded in UNE DI4, including Doumga Rindiaw, if the flood level of 13.12m IGN at Matam is used for the calculation. Gersar et al (1990) calculate that 4.36km^2 of Cuvette DI4 will be flooded for 15 days with artificial flood A.

There is an over estimation of the area flooded using the UNE model compared to the tentative results of synthesizing the results of the remote sensing analysis. This emphasises the great need for a more extensive analysis to satellite images to determine the true relationship between flood height and flood extent in the cuvettes.

3.0 River-Groundwater Relationships

The initial review (Hollis, 1990) utilized the work of Long, Dudley and Babcock (1976), Gersar (1988) and BRGM (1982). It was concluded that there were three aquifers in the middle valley, the surface alluvial aquifer, the Continental Terminal Aquifer and the deeper Maestrichtienne aquifer. Knowledge of the hydrogeology of these aquifers was good qualitatively and all authorities agreed that the major source of recharge was river flooding. These points are developed below using material gathered in Senegal.

The Illy (1973) study is of central importance and its findings are supported by the work of Bechtel (1976). The published reports of the OMVS/USAID Groundwater Monitoring project are outlined but they are not yet useful in determining the hydrogeology of the Middle Valley. Finally, some preliminary water level data derived from the OMVS/USAID Groundwater Monitoring Project is analyzed for the three cuvettes of Thiemping, Boyenadji and Doumga Rindiaw.

3.1 Illy (1973)

The 1973 hydrogeological study by Illy is probably the most important document available on this subject. It is a pity that, perhaps because of its age, it seems to be relatively little known and its conclusions do not seem to have lead to action.

Illy (1973) studied an area up to 25km from the river. There were a dozen geophysical transects undertaken and a network of 138 piezometers was installed between June 1970 and July 1972. One of the main aims of the study was to investigate the relationship between groundwater, and water from the river and floods. The study provided a large number of detailed geological cross sections and determined that the surface aquifer was separate from, but linked to, the lower aquifer. The upper aquifer was found to have a lower permeability than the deeper aquifer. Twelve pumping tests were done. The surface aquifer was shown to have the following characteristics:

- Diffusivity = T/S = 300m^2/day
- Storage Coefficient = S = 0.1
- Transmissivity = T = 30 m^2/day.

Illy's geological cross sections describe the underlying deposits in the valley. Figure 3.1.1, for the valley near Kanel, shows an alluvial valley fill of up to 40m in thickness directly overlying the Maestrichtienne. This pattern of an alluvial aquifer directly overlying the Maestrichtienne is repeated in Figure 3.1.2 for Matam and Figure 3.1.3 for a transect between Matam and Ourosogui. In each case the alluvium is up to 40m thick. However, it is very important to note that Illy had very few borehole logs upon which to base these sections and it is obvious that the boundary between the alluvium and the underlying strata was not fully explored.

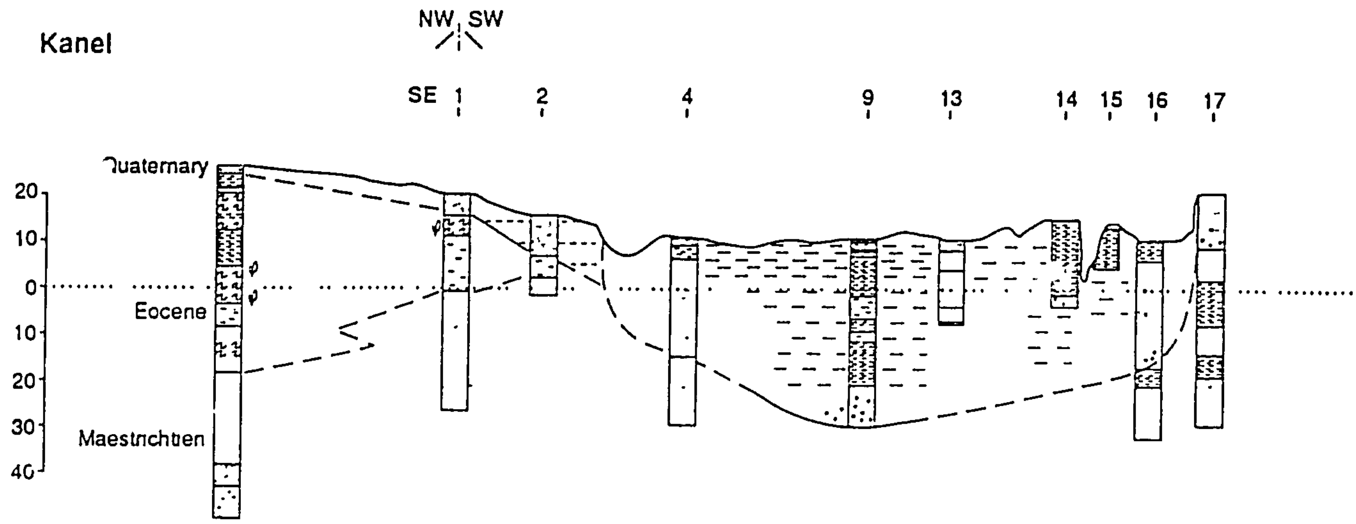


Figure 3.1.1 Geological cross section at Kanel (after Illy, 1973)

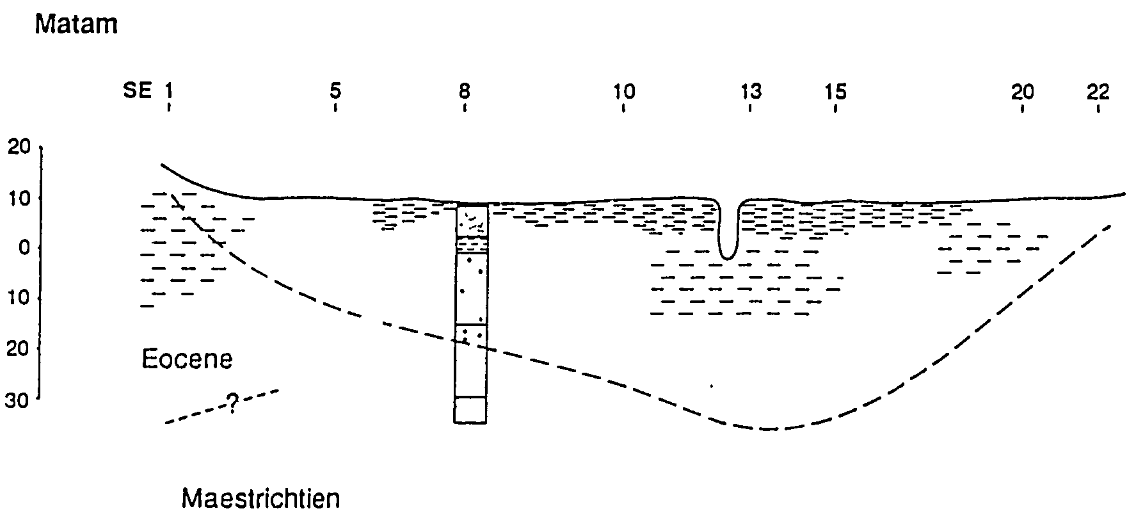


Figure 3.1.2 Geological cross section at Matam (after Illy, 1973)

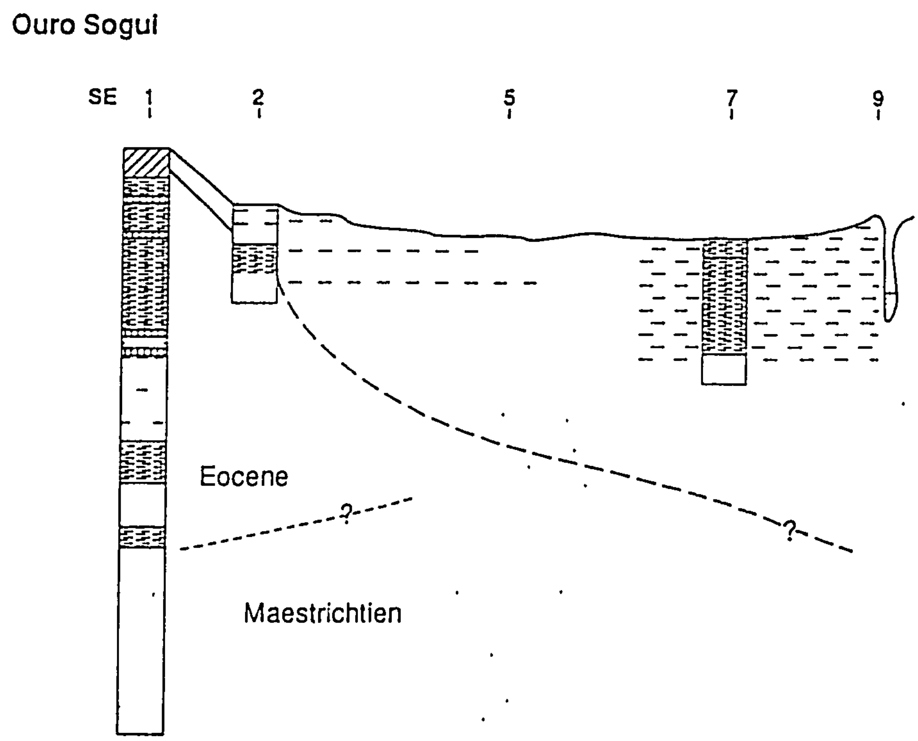


Figure 3.1.3 Geological cross section from Matam to Ourosogui (after Illy, 1973)

The piezometer data gathered by Illy covered the period from June 1971 to February 1973. The piezometers showed that the surface aquifer is alternatively recharged and drained by the river. Figure 3.1.4 shows the location of Illy's piezometers around Matam with the sites used in subsequent figures highlighted.

Figure 3.1.5 for the piezometers south of Matam shows that groundwater levels rose close to the river during the flood of 1971 but that the flood of 1972 really only affected the piezometers immediately adjacent to the river.

Figure 3.1.6 depicts data for sites between Matam and Ourosogui. It shows that whilst the 1971 flood raised groundwater levels by up to 3 metres, the flood of 1972 merely lead to the continued recession of groundwater levels.

In Figure 3.1.7, for the marigot south of the Diamel in Boyenadji Cuvette, there is a rise in groundwater level immediately adjacent to the Diamel (A1) in both 1971 and 1972 but very little impact of the flood on water levels further away from the Diamel.

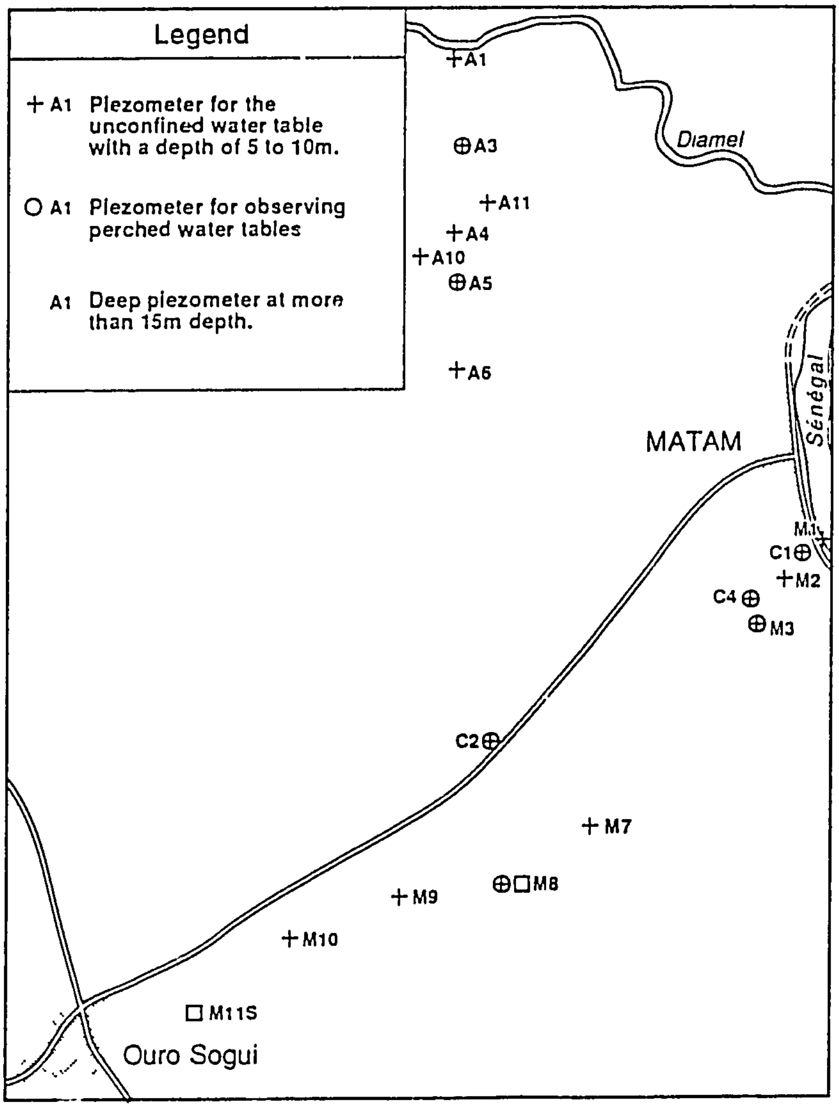


Figure 3.1.4 Piezometer sites around Matam investigated by Illy (1973)

Figure 3.1.5 Piezometer levels for sites close to the river south of Matam for 1971 - 1973 (after Illy 1973)

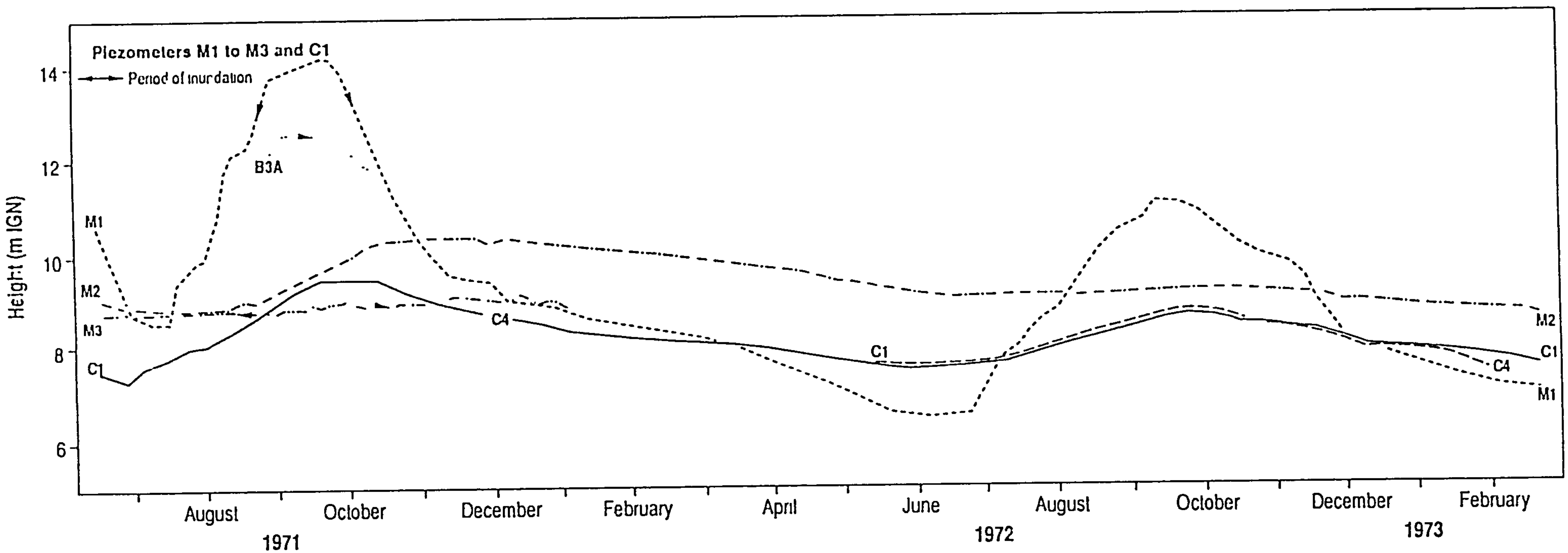


Figure 3.1.6 Piezometer levels for sites between Matam and Ourosogui for 1971 -1973 (after Illy 1973)

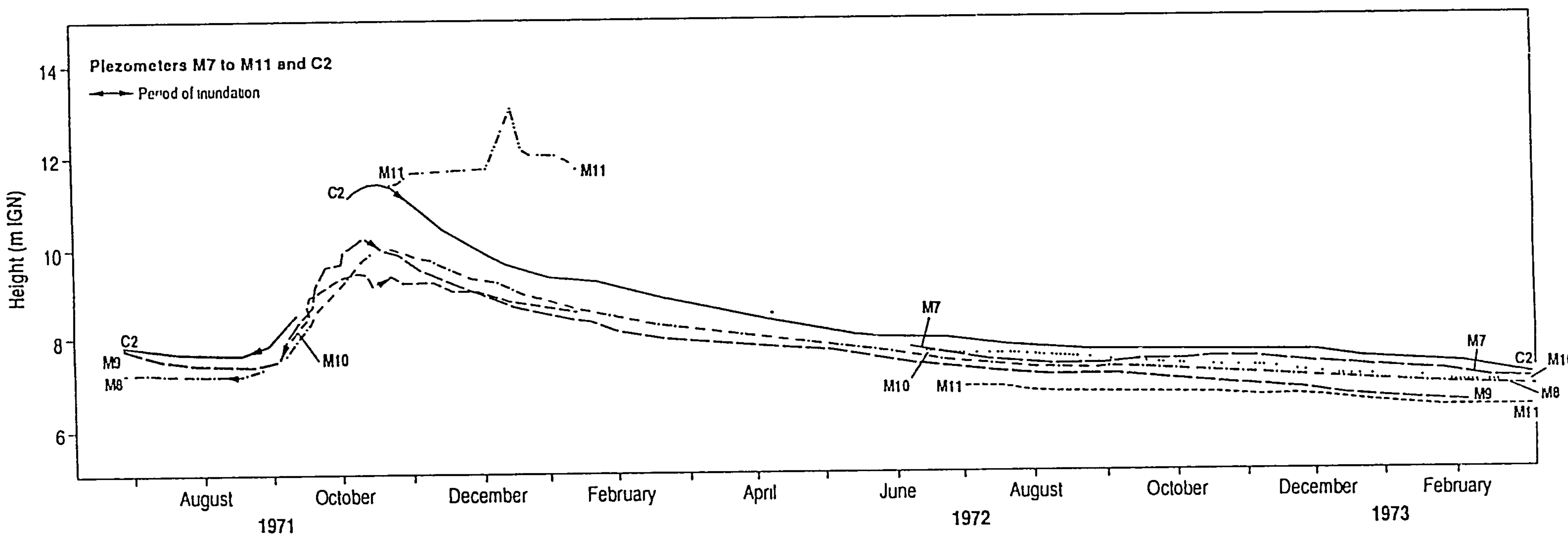


Figure 3.1.7 Piezometer levels for the marigot south of the Diamel in Boyenadji cuvette for 1971 - 1973 (after Illy 1973)

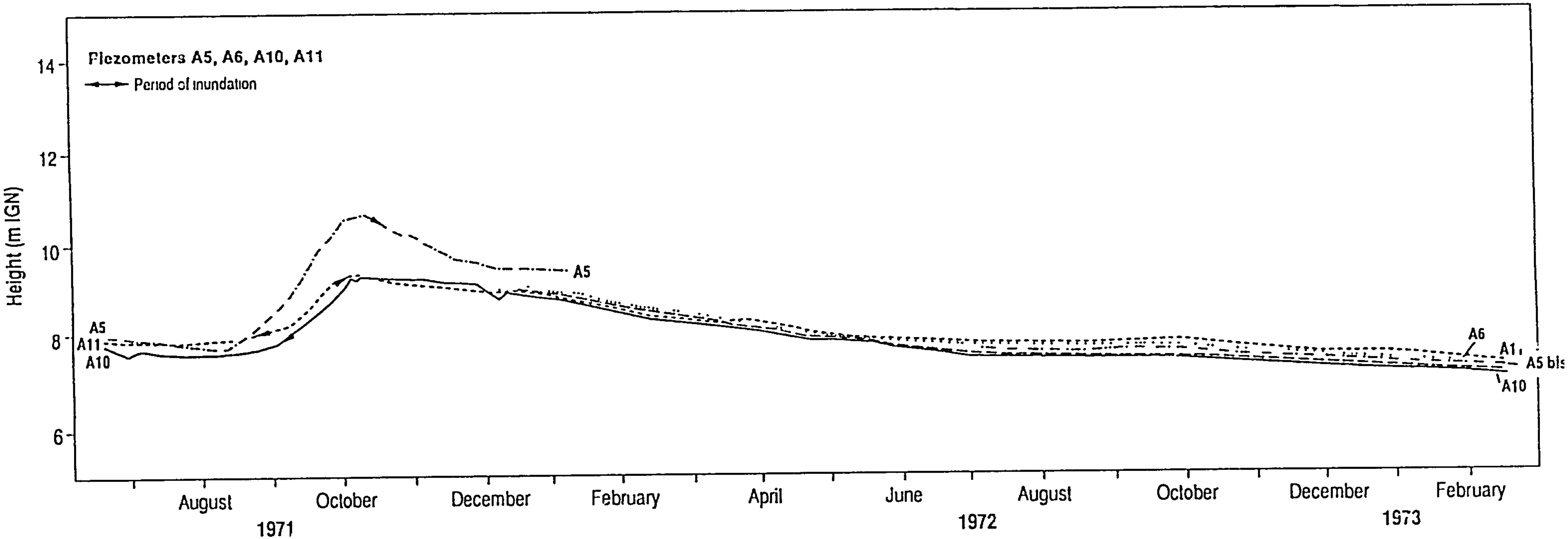
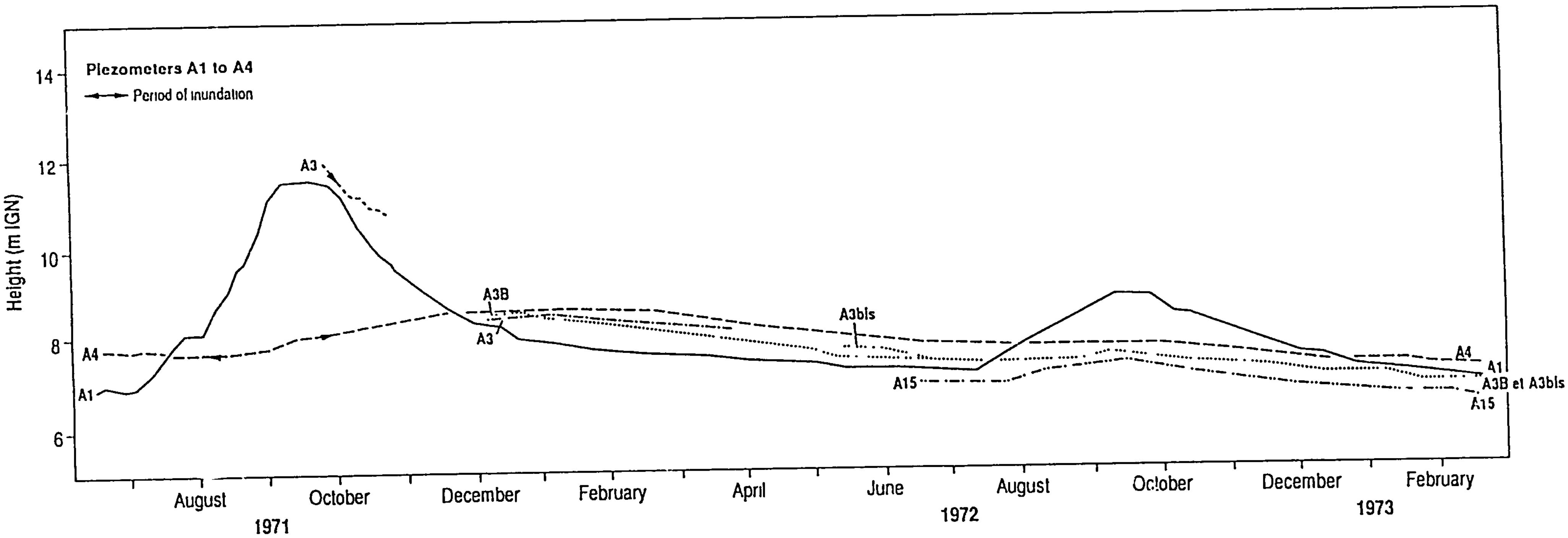


Figure 3.1.8 Piezometer levels for the centre of the Boyenadji Cuvette for 1971 1973 (after Illy 1973)



The groundwater beneath the centre of Boyenadji cuvette (Figure 3.1.8) rose by 2 to 3 metres during the passage of the 1971 flood but the recession of water levels continued throughout the flood of 1972.

It is very unfortunate that Illy's fieldwork covered two years with poor floods (Figures 3.1.9 and 3.1.10) that were less than the average for 1903 to 1984 and also below the volume and peak flow of artificial flood A.

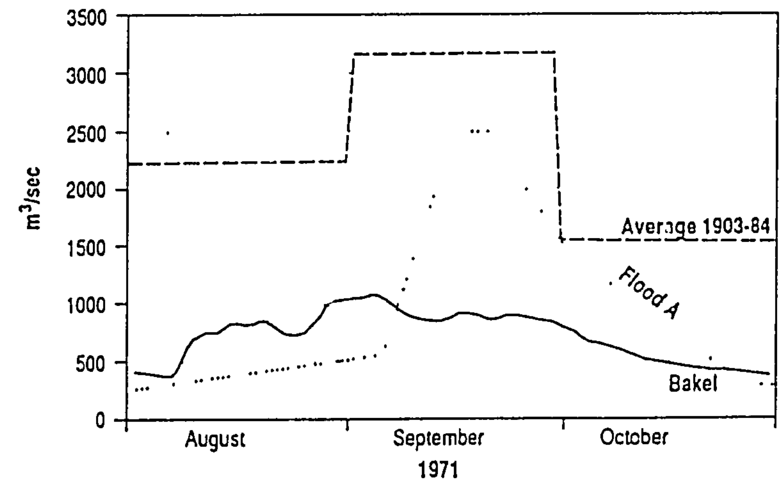


Figure 3.1.9 Discharge at Bakel during the flood of 1971 with the long term monthly average and artificial flood A for comparison.

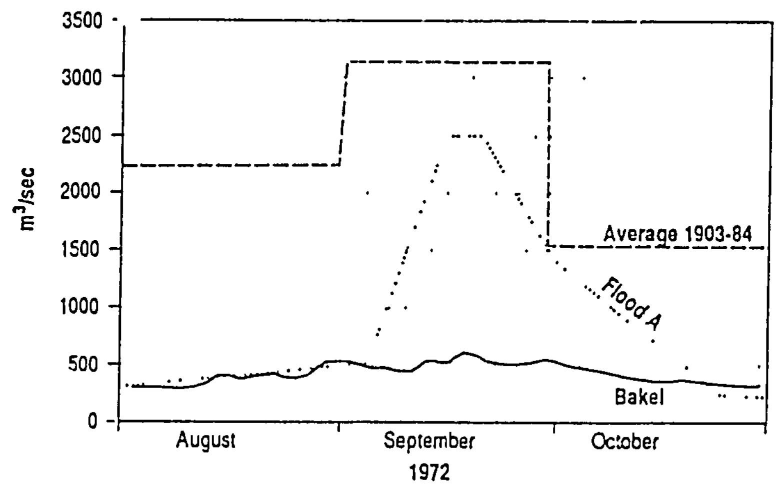


Figure 3.1.10 Discharge at Bakel during the flood of 1972 with the long term monthly average and artificial flood A for comparison.

As a result, it is difficult to utilize Illy's data alone to characterize the relationship between "normal" or artificial floods and the groundwater levels.

Illy (1973) showed evaporation and evapotranspiration to be important in draining the aquifer in low lying wetlands It was calculated that the seasonal exchanges of water were slightly greater in the upper aquifer than in the lower aquifer. The quality of the water in the upper aquifer was very fresh, usually being in the range 70 to 300 mg/l. Below Boghe the surface aquifer became rather saline. The deeper Maestrichtienne aquifer generally has a dissolved content of less than 300 mg/l but it is over 3,000 mg/l in the lower valley.

Isotopic studies were undertaken of 14 samples of groundwater and one sample of rainwater. These investigations showed that the surface aquifer is recharged by the vertical percolation of flood water. The infiltration of rainwater was of secondary importance. It was found that there was very little infiltration (<0.5 mm/day) in the flooded cuvettes where there is often 2.5m of clay. Infiltration on the faux hollalde soils was in the range 0 to 10 mm/day with an average of 2 mm/day. Overall infiltration of floodwater was estimated at 250 $10^6 m^3$ per year with rainfall adding a further 30 $10^6 m^3$. This represents 40mm of water on the surface and the figure was largely confirmed by the fall in water levels observed after the very poor flood of 1972.

The underground flow along the river was estimated at 300 $10^6 m^3$ per year with 270 $10^6 m^3$ of that coming from the inundation of the banks during floods. Evapotranspiration was calculated at 220 $10^6 m^3$ per year and it was found that the overall water balance for the area between Bakel and Richard Toll supported this figure.

However, it is important to emphasise that these values derive from data gathered during particularly poor floods. It is likely that they represent values that may be typical if Manantali ceases to contribute to the flood in the Senegal Valley. It is likely that in years of higher floods, when more of the faux hollalde and fonde soils are inundated, that recharge of groundwater will be more substantial.

Existing exploitation was estimated at 110 $10^6 m^3$ per year and it was argued that further exploitation could furnish irrigation water at the rate of 3.5 m^3 per sec. This latter development would however be at some cost to groundwater levels and the baseflow to the river. However the exploitation of the Maestrichtienne aquifer was little explored and it was thought that it was likely to be very variable from place to place. It was suggested that a double culture would increase infiltration and so recharge the aquifer to some extent.

Interestingly for the delta region, the Illy (1973) study drew almost exactly the same conclusions as the later $7 million USAID/OMVS Groundwater Monitoring Project (OMVS/ISTI, 1990, Volume 2). Illy reported that the river influences groundwater levels for only about 1km from the river and that drainage of the surface aquifer would need to be examined carefully especially if Diama maintained a water level above about 1.5m.

3.2 Bechtel (1976)

Bechtel (1976) examined 8 observation wells and did two pumping tests in the cuvette south east of Matam. They concluded (p 1.9 in French) that "the surface aquifer is more than 50m of sands and alluvial gravels. It is recharged directly from the river and has an estimated annual productivity of 30 $10^6 m^3$ per year. This may be greater if subsequent drilling shows that it extends further to the west." In the body of their report (p2.59) they go further and state that "the aquifer is recharged when the river is in flood". The exploratory borings done by Bechtel did not allow them to study the deeper Maestrichtienne aquifer in any detail but they repeated the earlier assertions of other experts that the recharge comes from the Senegal River. Bechtel suggested that the two aquifers could supply 80 $10^6 m^3$ reliably in the long term. They found (p2.63) that "the quality of the groundwater was satisfactory for irrigation and domestic supply".

Pumping tests were done by Bechtel in the surface and the deeper aquifer with the following results:

	Upper Aquifer		Lower Aquifer
	Bechtel	Illy(1973)	Bechtel
- Storage Coefficient = S =	0.001	0.1	0.0003
- Transmissivity = T =	1,800m^2/day	30 m^2/day	1,050m^2/day

It is clear that the properties of the surface aquifer are very variable from place to place because of the variability of the sediments.

Bechtel argued strongly for the use of groundwater for irrigation on five grounds:

a) minimal initial investment and easily phased investment as the perimeters are developed,
b) pumping from groundwater will assist in the control of waterlogging and salinization,
c) the deletion of long semi-stagnant canals will reduce the adverse health risks of the scheme,
d) wells will give considerable flexibility in the choice of the soil to be irrigated,
e) the use of groundwater offers a more secure source of supply during drought years than do surface water sources.

A final conclusion (p2.63) was that the combined use of surface and groundwater should be considered.

3.3 Diagana (1990)

The DEA thesis of Diagana (1990) examined the hydrodynamics of the aquifers in the lower Senegal Valley between St. Louis and Podor. The work was undertaken in the context of the OMVS/USAID Groundwater Monitoring Project. One of his major conclusions (p59) was that "there is annual recharge of the aquifers by flood water from the river inundating the waalo lands. Rainfall is removed by evapotranspiration and does not play a major role in the recharge of the aquifers". Diagana also showed that the closure of the Diama dam and the maintenance of high water levels in the river had tended to raise groundwater levels in the delta.

3.4 OMVS/USAID Groundwater Monitoring Project Data

The OMVS/USAID Groundwater Monitoring Project (OMVS/ISTI, 1990) covered the entire valley up to Manantali and aimed to:

a) develop a master plan for the management of surface and ground water

b) install an information management system for OMVS

c) implement a method of compiling and analyzing groundwater and related data

d) train OMVS personnel to implement and follow up the master plan for the management of surface and ground water

e) construct an OMVS piezometric network.

OMVS/ISTI (1990) conclude, following the Project review by Dendrou and Reeser, that points b), c) and e) were fully achieved. Point a) was replaced by the preparation of two synthesis reports for the hydrogeology of the Senegal Delta and for the area around Manantali. Since a Master Plan from Point a) was judged "ambitious and excessive", the training element in point d) was reoriented to the development and use of the data management system.

The piezometric network for the cuvettes around Matam are shown in Figures 3.5.1 to 3.5.3. The sites included in the computerized database have prefixes of GA or GB.

OMVS/ISTI (1990) recommended that the short term work programme should include the thematic mapping and interpretation of results for the upper middle valley and upper valley including the suspected Maestrichtienne recharge zone. Sadly, there has, as yet, been no detailed analysis of the data for the Middle Valley. The pumping test results have not been interpreted and there has been no systematic mapping or water level analysis. The Head of the Groundwater Monitoring Unit has not yet been able to examine the data for the Middle

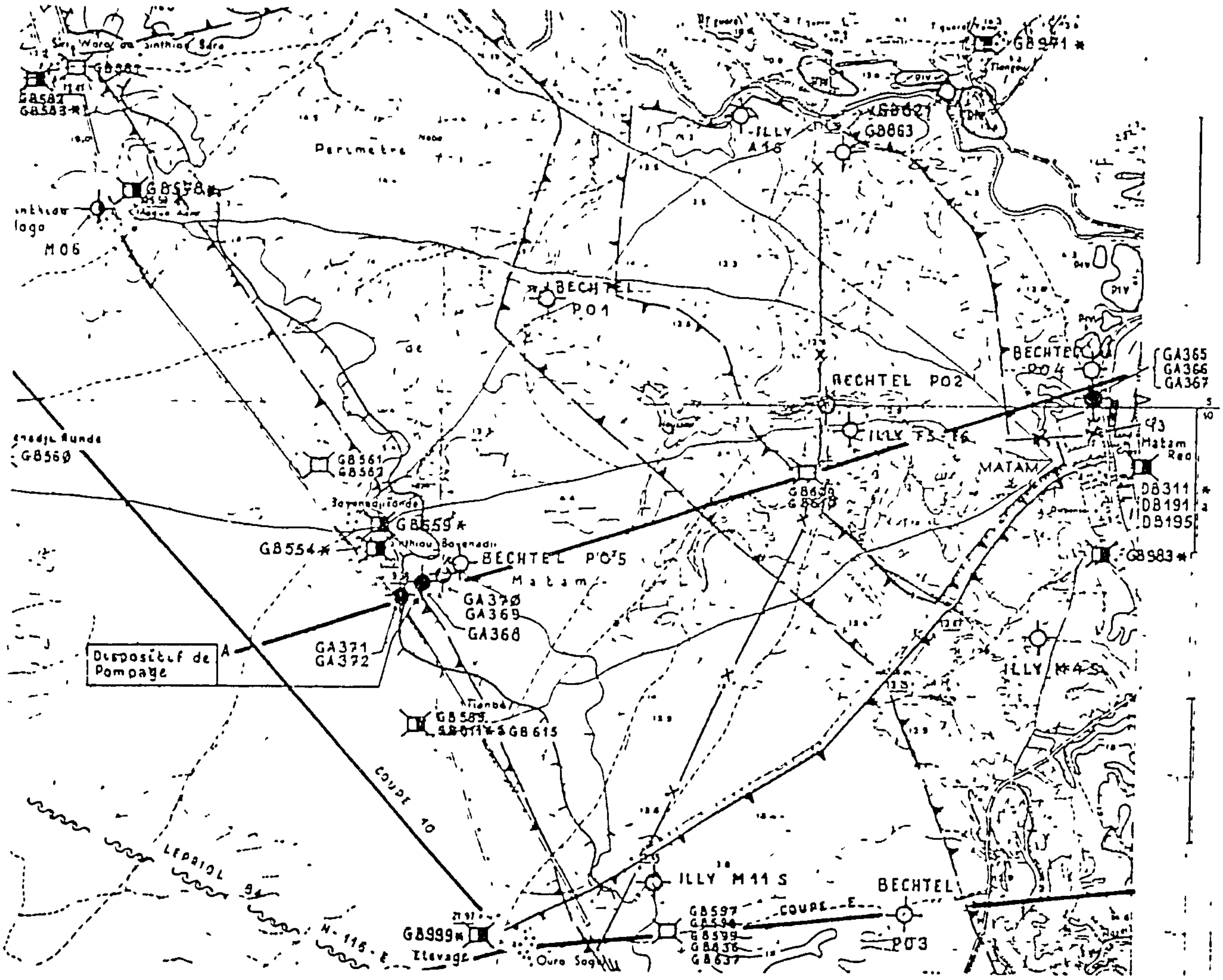


Figure 3.4.1 The OMVS/USAID Piezometric Network near Matam and in the Boyenadji Cuvette

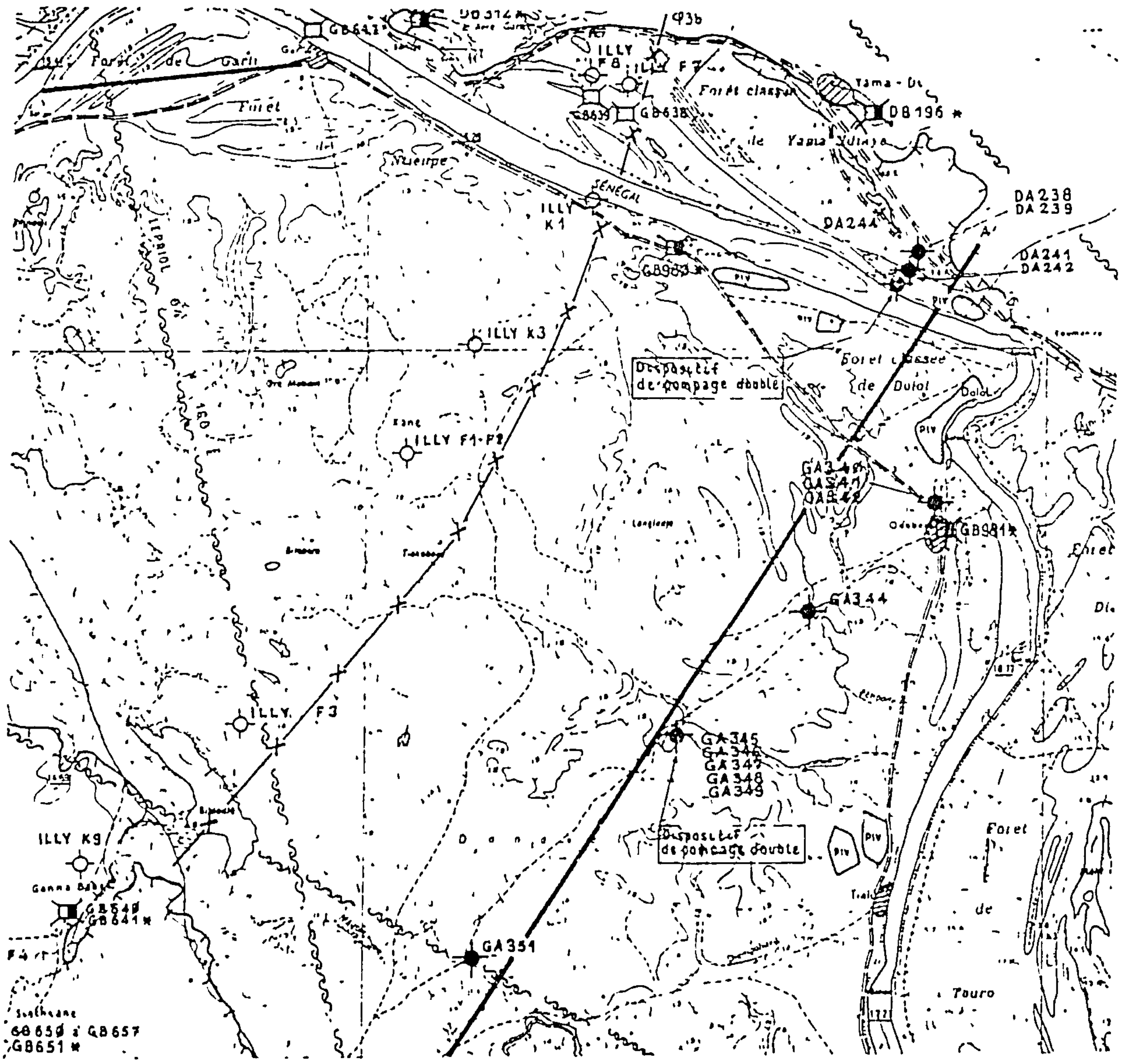


Figure 3.4.2 The OMVS/USAID Piezometric Network in the Thiemping Cuvette

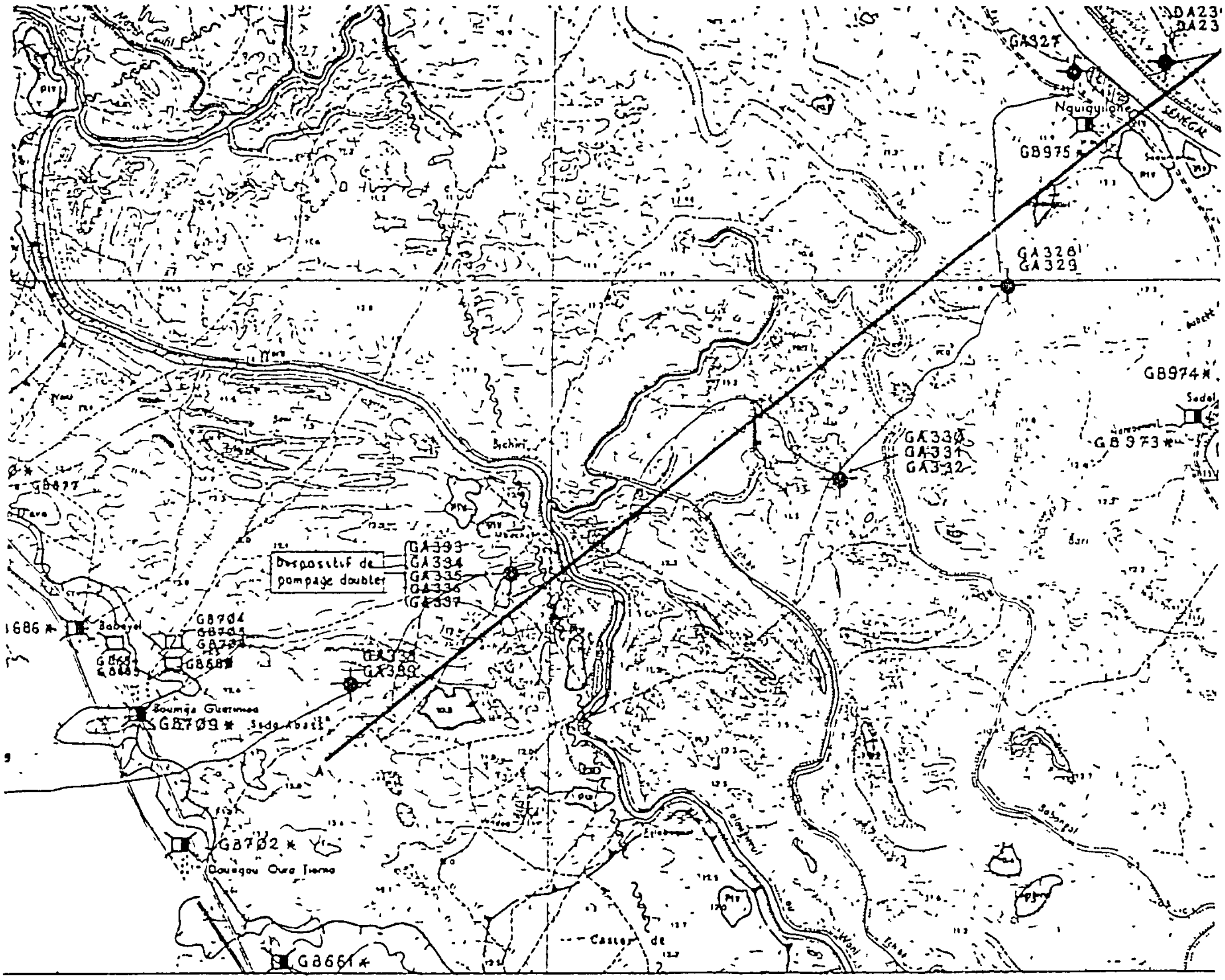


Figure 3.4.3 The OMVS/USAID Piezometric Network in the Doumga Rindiaw Cuvette

Valley and therefore cannot furnish even preliminary conclusions. It was reported that no programme has been set for the formulation of a report on the Middle Valley. However, monitoring of the piezometers is set to continue for at least some months in Senegal.

Whilst some of the computer equipment holding the Groundwater Database was operational it was not possible to make printed output or to plot maps or graphs. Consequently, the groundwater level data for a representative sample of piezometers in the three cuvettes of Thiemping, Boyenadji and Doumga Rindiaw was copied from the computer monitor and subsequently entered into the Quattro package for preliminary display. Data for the level of the river at Matam was also abstracted from the monitor.

3.5.1 Thiemping Cuvette

The water levels in piezometers in the riverside levees with fonde soils show (Figures 3.5.1 and 3.5.2) the classic pattern of recharge during the flood and discharge to the river during the low flow season. On the Mauritanian bank the recharge gives a change in level of over 2m whilst on the Senegal side, with limited data, the level fluctuation is of the order of 0.9m. In these riverside piezometers there does not seem to be any systematic variation in the water level measured in piezometers of different depth between 16 and 50m.

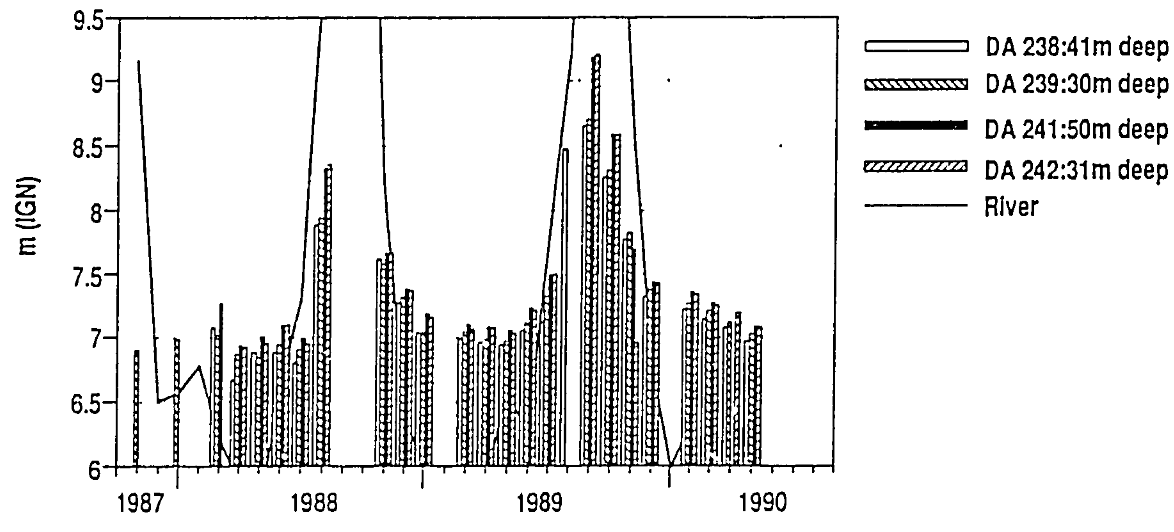


Figure 3.5.1 Piezometric levels for a site on the river levee almost opposite Thiemping (See Figure 3.5.2 for exact locations of coded piezometers)

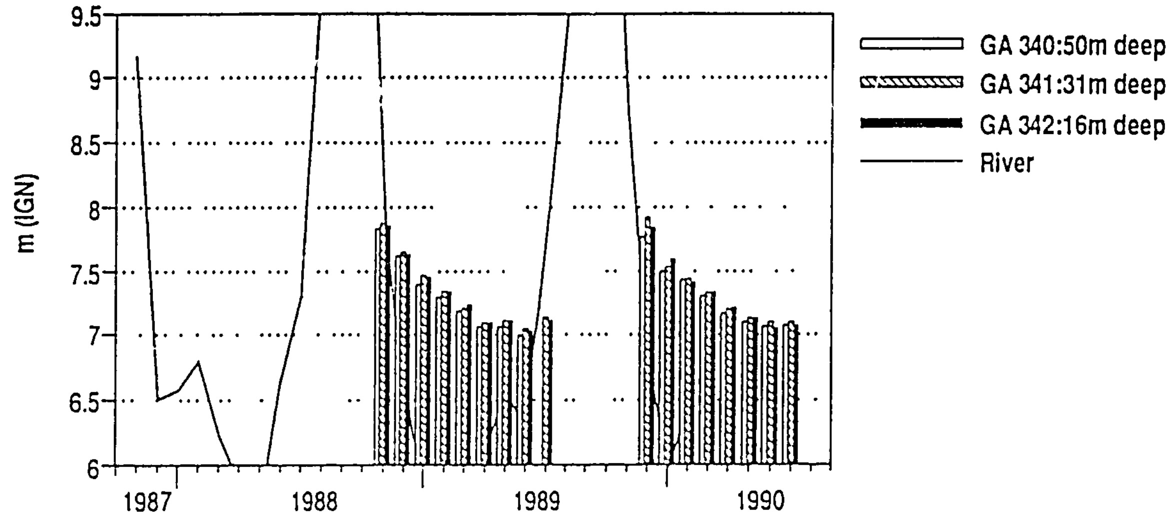


Figure 3.5.2 Piezometric levels for a site on the river levee upstream of Thiemping (See Figure 3.4.2 for exact locations of coded piezometers)

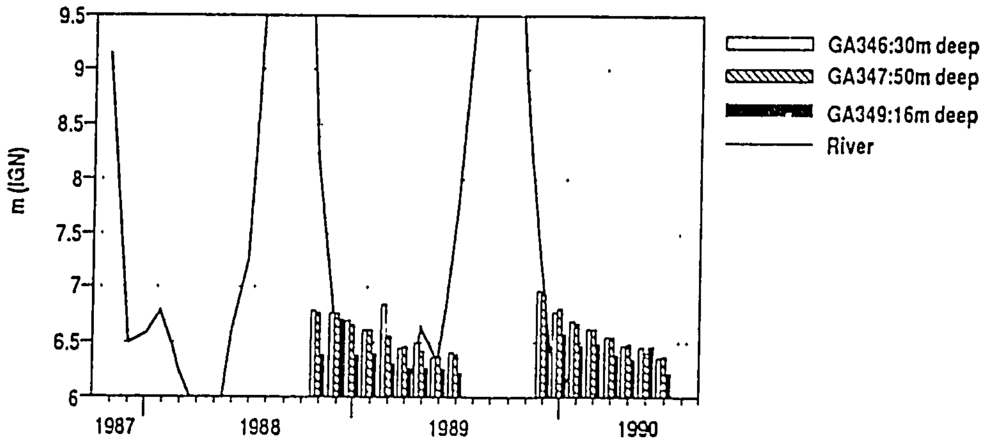


Figure 3.5.3 Piezometric levels for a site in the cuvette south of Thiemping (See Figure 3.4.2 for exact locations of coded piezometers)

Figure 3.5.3, for piezometers in the cuvette due south of Thiemping, again shows the classic pattern of recharge and discharge during and after the flood. At this site, some 3.5km from the river, the range of water level change is more muted with a normal range of under 80cm. The data for this site also suggests that the piezometers at 30 and 50m register water levels which are normally higher than the 16m deep piezometer. This suggests slightly confined conditions in the deeper parts of the aquifer.

Figure 3.5.4, 3.5.5 and 3.5.6 show the water level data for transects away from the river for shallow (14-17m), medium (30-31m) and deep (50m) piezometers. In each case there always is a strong slope of the groundwater surface away from the river. This confirms the findings of earlier studies that river flooding is the major source of recharge to the aquifers. In the case of shallow piezometer GA351, which is 5km from the river, the water level is almost always below that of the river. This suggests that the zone of active recharge and discharge is quite narrow and that for the parts of the aquifer remote from the river recharge is the main function of the river and its floods.

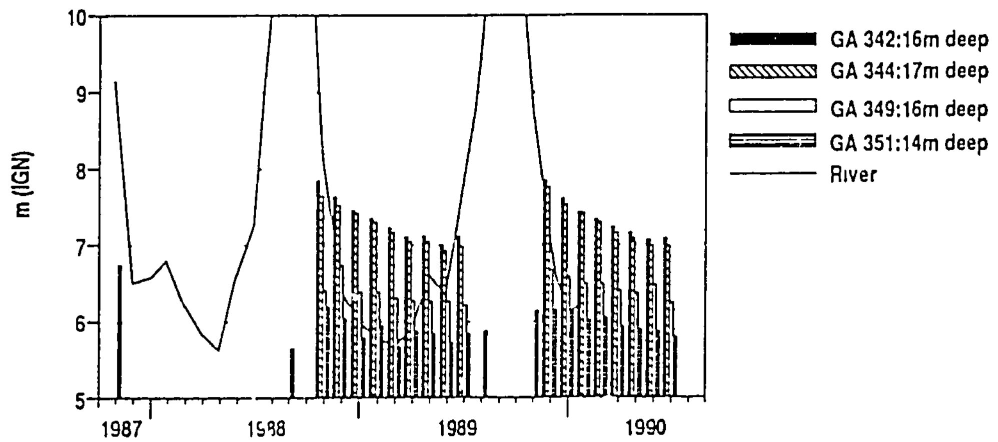


Figure 3.5.4 Water levels in shallow piezometers for a transect across the Thiemping cuvette (See Figure 3.4.2 for piezometer locations)

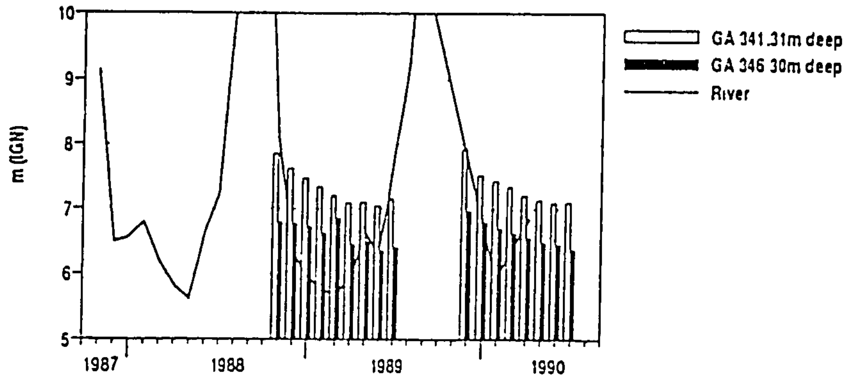


Figure 3.5.5 Water levels in medium deep piezometers for a transect across the Thiemping cuvette (See Figure 3.4.2 for exact locations of coded piezometers)

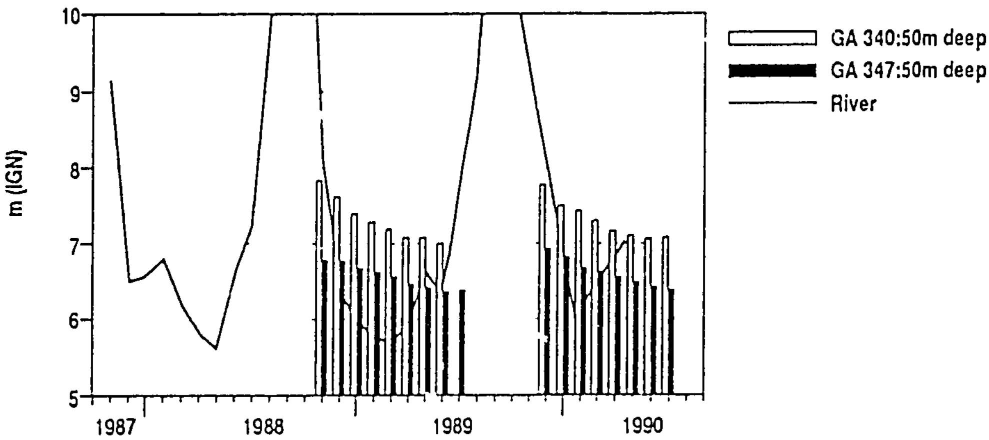


Figure 3.5.6 Water levels in deep piezometers for a transect across the Thiemping cuvette (See Figure 3.4.2 for exact locations of coded piezometers)

3.5.2 Boyenadji and Matam

The data for the three level nest of piezometers on the levee north of Matam (Figure 3.5.10) shows the classic recharge by the flood, including a level rise of over 3 metres, and a subsequent and small discharge to the river. Interestingly the deeper piezometers rise most rapidly and gain a higher level than the shallow 12m piezometers. Conversely, and strangely, during the discharge phase to the river the shallow piezometer has a higher level than the deeper ones.

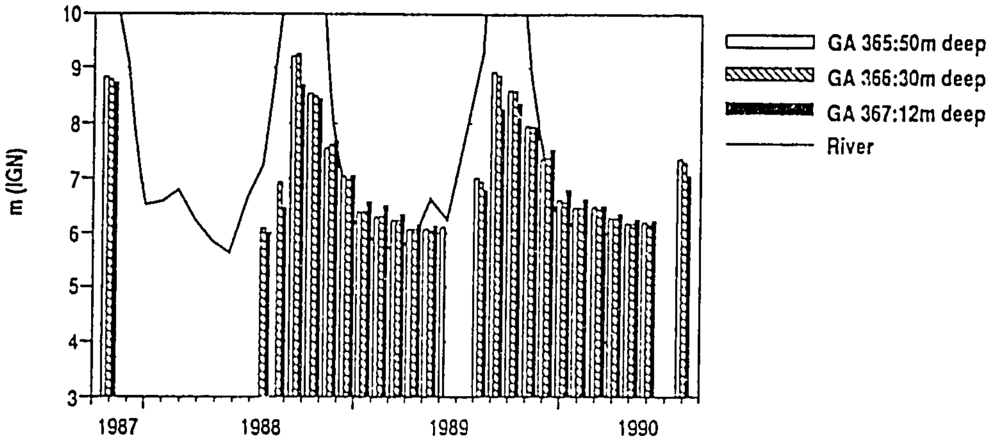


Figure 3.5.7 Water levels in a nest of piezometers on the levee north of Matam (See Figure 3.4.1 for exact locations of coded piezometers)

Figure 3.5.8 shows that for piezometers at 32 and 50m depth at Boyenadji village, some 9km from the river, the rise in level with the '89 flood was 60cm but that for the '90 flood was less than 10cm. Very significantly once again, piezometers relatively remote from the river have water levels which are constantly below the river level which indicates a continuous recharge of the aquifer by the river and its floods.

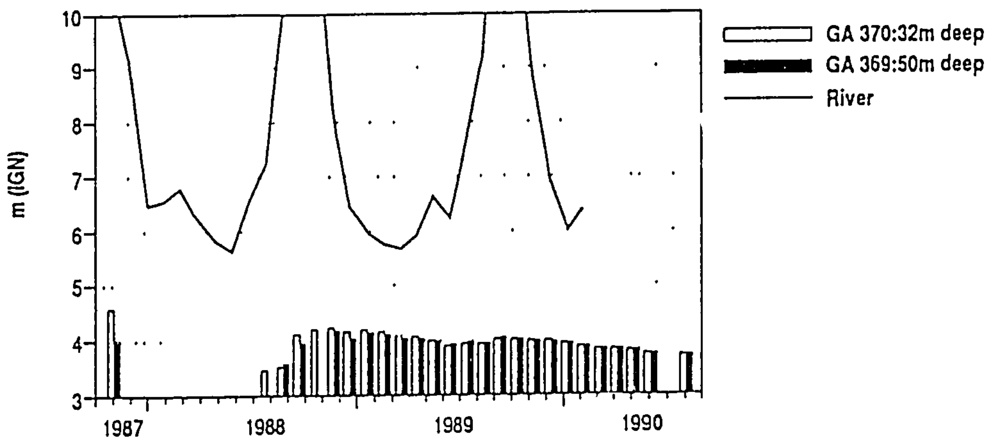


Figure 3.5.8 Water levels in a nest of piezometers at Boyenadji (See Figure 3.4.1 for exact locations of coded piezometers)

3.5.3 Doumga Rindiaw

The cuvettes at Doumga Rindiaw are fed by a small channel from the Diamel whilst to the east of the Diamel there are extensive cuvettes linked with both the Diamel and the Senegal

River. Whilst the river levels at Matam are a useful guide, they do not represent the actual level of water in the Diamel and Senegal River adjacent to the cuvette.

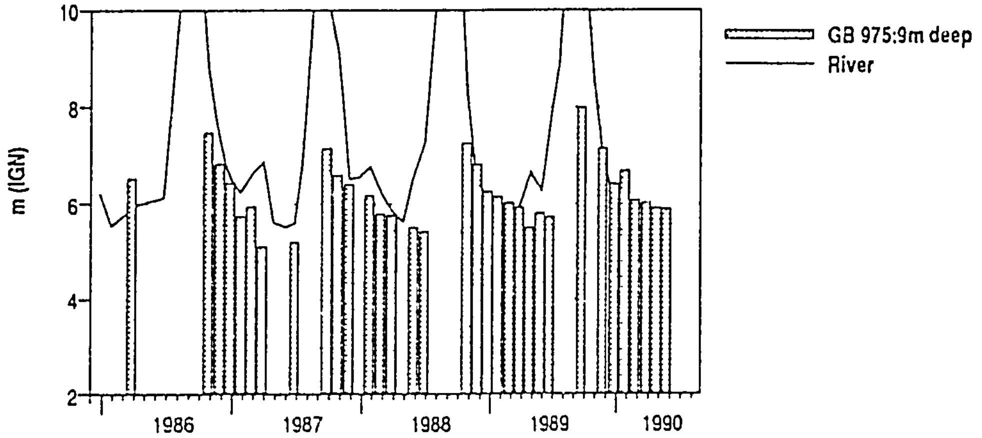


Figure 3.5.9 Water levels in a shallow well on the levee of the River near Nguiguilone (See Figure 3.4.3 for piezometer locations)

Figure 3.5.9 shows that the water level in a shallow well at Nguiguilone on the levee of the Senegal River follows the fluctuations in river level. Each flood, including the small peaks in 1986 and 1987, produce a rise in water level after which there is a fall. The nest of piezometers mid-way between the Senegal and the Diamel (Figure 3.5.10) has a limited amount of data but it shows some response to flood peaks and a general equality of water levels in piezometers at 16, 30 and 50m depth. The existence of water levels at least 2 metres below the river level at Matam would suggest a continuous recharge of the aquifer by the river.

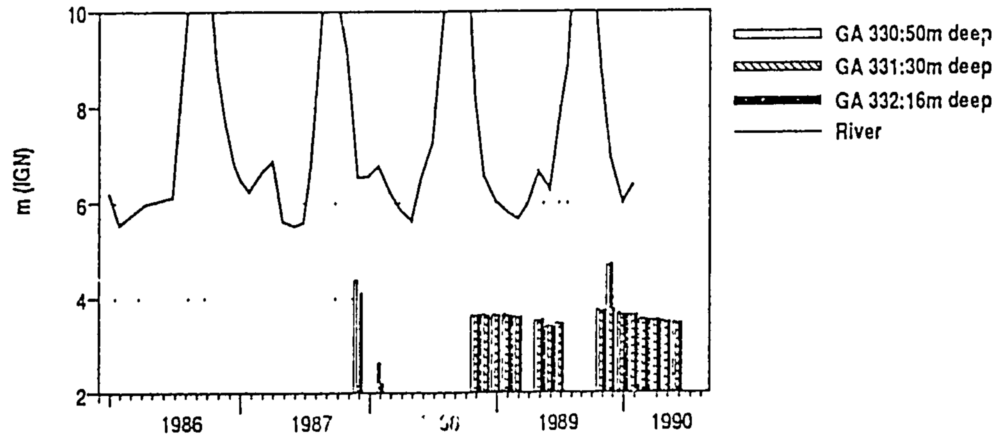


Figure 3.5.10 Water levels in a nest of piezometers mid-way between the Diamel and the Senegal east of Doumga Rindiaw (See Figure 3.4.3 for exact locations of coded piezometers)

Water levels in the shallow well at Doumga Rindiaw itself (Figure 3.5.11) are always more than 2 metres lower than the river at Matam. The water level shows a response of up to

80cm as a result of floods but the 1987 response of the well appears to have been similar to that in 1988 and 1989 after their much larger and longer floods. Figure 3.5.15 shows data for a transect of shallow wells from the banks of the Senegal at Nguiguilone to Doumga Rindiaw. Despite the existence of the Diamel channel between piezometers GA332 and GB709, there is a marked gradient of the watertable away from the river at all times. This, as with the other similar observations in the other cuvettes, suggests that the river and its floods are a source of recharge to the regional aquifer.

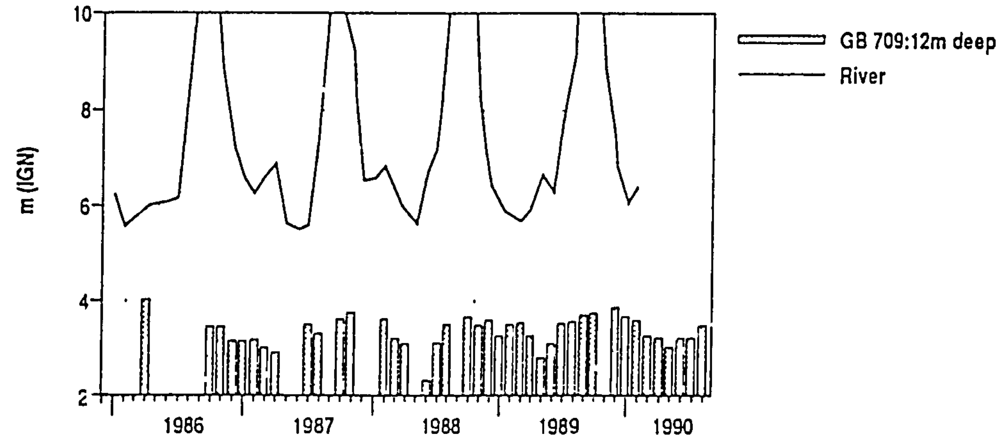


Figure 3.5.11 Water levels in a shallow well at Doumga Rindiaw (See Figure 3.4.3 for exact locations of coded piezometers)

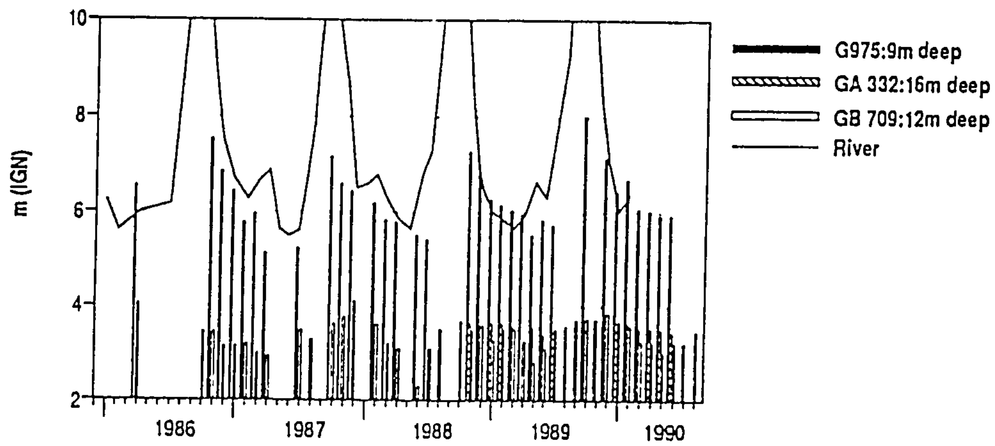


Figure 3.5.12 Water levels in a transect of shallow wells from the levee of the River near Nguiguilone to Doumga Rindiaw (See Figure 3.4.3 for exact locations of coded piezometers)

3.6 Usage of Groundwater

Every village visited in the entire area appears to use wells for its water supply. A few villages have pumped systems with water towers but open shallow wells are the norm. In many places the depth of the water was eight to ten metres. Clearly any diminution in water levels would have an adverse effect upon water supplies if only to involve extra costs involved in deepening wells and extra energy in withdrawing water.

CAB's view, which is strongly supported by OMVS, is that groundwater pumping is much too expensive for irrigation purposes. The cost of the wells is said to be prohibitative. An environmental economist would conduct a full costing of river water versus groundwater exploitation. However, since the investment has already been made in Manantali, it may presently be cheaper to exploit river water than groundwater.

3.7 Conclusions

The scope of work asked two questions:

i) Is the aquifer flood dependent?

ii) Based on rainfall, evapotranspiration rates, water table elevations in observation wells etc, what is the volume and duration of flood necessary to recharge aquifers in proximity to the villages of Thiemping, Boyenadji, and Doumga Rindiaw?

Aquifer recharge is certainly dependent upon flooding of the cuvettes and especially the inundation of the more permeable soils at higher elevations. This is the unanimous view of all of the published authorities. Moreover, the relationship between the occurrence of the flood and the rise in groundwater levels in the OMVS/USAID network has been clearly established. There will certainly be some recharge of groundwater from local rainfall but this was estimated by Illy to be only 11% of total recharge.

Groundwater levels, within 1 to 2 km of the river, suggest that there is recharge of the aquifer during the flood and then a discharge of groundwater to maintain the low flow of the river during the dry seasons. At distances greater than 2km from the river, it appears that groundwater levels are almost always below those in the river. Therefore, there is a regional flow of groundwater away from the recharge zone on the floodplain. The area of groundwater recharged by the river floods is not known precisely but it is likely to involve several thousands of square kilometers of the Ferlo lands of Senegal and similar areas in Mauritania. Interestingly, Sow (1984) reproduced Figure 3.7.1 from work dating back to 1959 to show that there are significant flows of groundwater recharge from the Senegal Valley into the Ferlo. The large arrows from Bakel, Matam and Boghe suggest that the Senegal Valley is the main source of recharge for the entire Ferlo area.

It is not possible to answer the second question in this brief study because the information on the extent and duration of flooding in the cuvettes is very limited and several months of work are needed to fully exploit and develop the data existing in the OMVS/USAID Groundwater Database.

Subsequent analysis of this question will have to pay close attention to rainfall and evaporation rates as well as river levels and groundwater levels. All of the floods for which there is some data, save that in 1972, appear to have recharged groundwater to some extent but it must be determined what proportion of that rise in water table levels can be attributed to rainfall infiltration. In addition, any future study of this question will have to assess in some detail the amount of enhanced recharge coming from percolation from the irrigated perimeters in the valley. The published studies suggest that this will be substantial and its significance will grow as further perimeters are commissioned.

This question will only be answerable if the monitoring of the OMVS/USAID network continues with more strenuous efforts being made to take readings during and immediately after the flood. At present, as is obvious from the diagrams already presented, there are usually a number of months without data during the flood season. Any study of floodwater infiltration will have to have groundwater levels during this critical period. Similarly, a full understanding of the relationships between groundwater recharge and flood volume and duration will require regular measurement of water levels in the cuvettes as detailed in the next section.

Finally, it is clear from the published work and from the variability in the apparent degree of confinement of the lower aquifer in the OMVS/USAID data that the hydrogeology of the Senegal Valley is complex at the local scale. The large differences between the pumping test results of Illy and Bechtel for the surface aquifer confirm the heterogeneity of this stratum. Consequently, before there is any extensive exploitation of the large reserves of groundwater that exist in the valley, it is essential that a detailed study be conducted using all of the data gathered to date in the OMVS/USAID project.

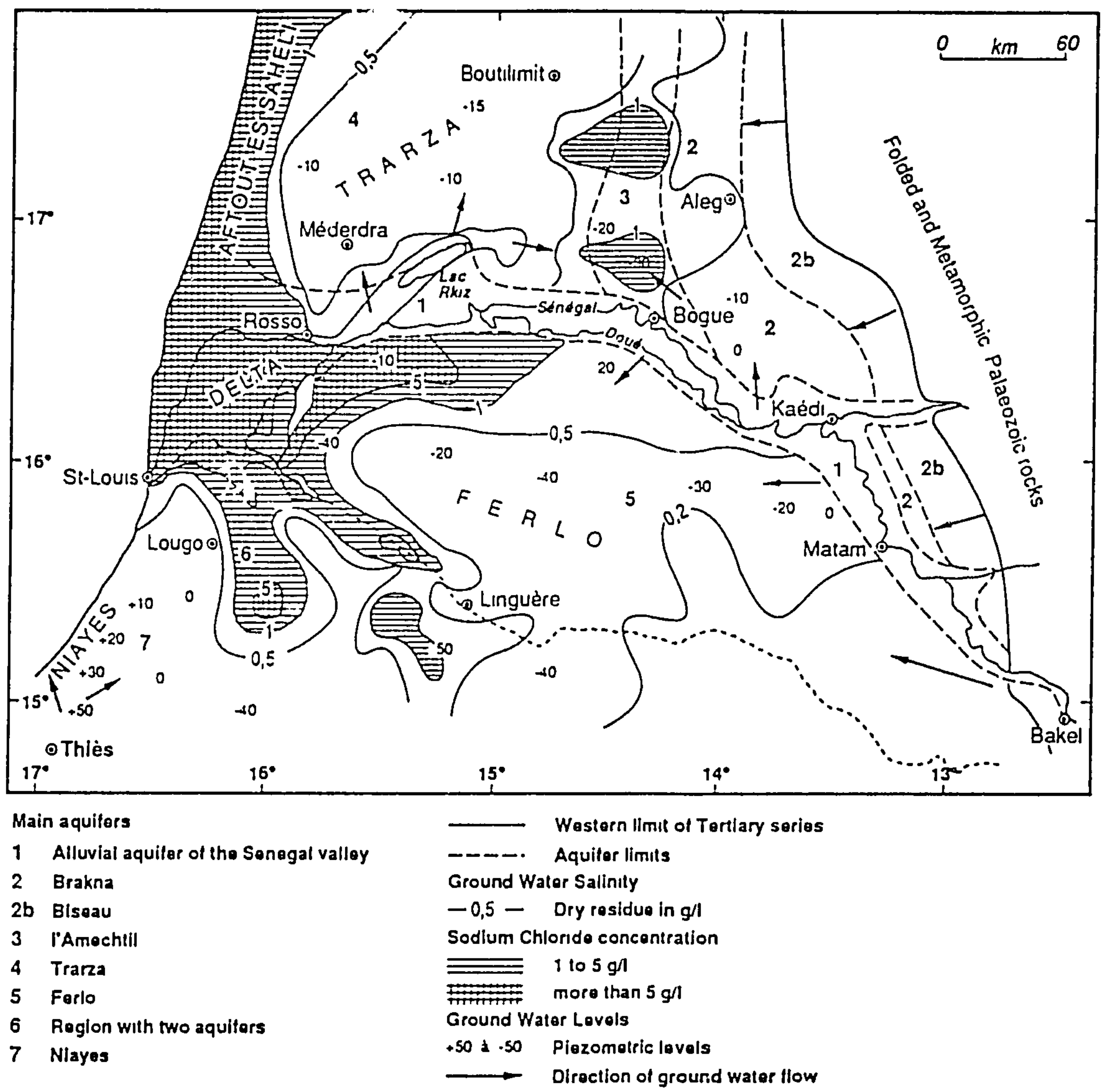


Figure 3.7.1 Groundwater levels in south west Mauritania and northern Senegal (after Sow, 1984, who took the diagram from other sources)

4.0 Methodology for Monitoring Flood Volume in Cuvettes

The monitoring of the volume of water in a cuvette requires a knowledge of the water level in the cuvette measured in m (IGN) and a knowledge of the hypsometric characteristics of the cuvette. The volume of water in the cuvette can then be easily calculated. The ensuing text is divided into two parts, the first dealing with the assessment of hypsometric data for cuvettes and the second discussing the measurement of water level in cuvettes.

4.1 Hypsometric Data for Cuvettes

The Senegal Valley has excellent IGN 1:50,000 topographic maps available with a 1 metre contour interval and 50cm form lines in some places. These maps have already been fully analyzed by Chaumeny (1973) who derived hypsometric data on the area of land between each pair of contour lines in each cuvette. He classified the cuvettes of the valley into 72 "Unites Naturelles d'Equipement" or UNEs. This data would appear to be satisfactory for all foreseeable research and modelling work. In some circumstances, such as when major natural or human-induced changes have taken place in the form of the cuvette or when especially precise data is needed on flood volumes, it may be necessary to undertake a detailed topographic survey of a cuvette. This, however, will be time consuming and very expensive.

The hypsometric characteristics of the three study cuvettes are given in Tables 4.1.1 and 4.1.2 (after Chaumeny, 1973). Whilst the Thiemping and Boyenadji cuvettes accord almost exactly with Chaumeny's MK2 and DI1 UNEs, the rather simplified map of UNEs suggests that the cuvette at Doumga Rindiaw is only a portion of the area covered by UNE DI4.

Table 4.1.1 The UNEs studied by IDA (after Chaumeny, 1973)

Village	UNE Region	UNE Code	Area ha	Flooded Area (ha) 1970	Recession Cultivat. (ha) 1970
Thiemping	Matam	MK2	12,385	8550	3780
Boyenadji	Diamel	DI1	7,310	2900	1865
Doumga Rindiaw	Diamel	DI4	5,810	905	440

Table 4.1.2 Hypsometric characteristics of the UNEs studied by IDA (after Chaumeny, 1973)

Sump	Height m IGN	Area (ha) within elevations (m) above the sump 0	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
MK2	10	130	640	1260	2440	2710	3120	2250	740	120
DI1	11	15	250	1655	2860	1910	740	300	170	-
DI4	9	25	25	110	770	2040	2260	770	190	10

Table 4.1.2 can easily be transformed into Table 4.1.3 which gives the volume of water necessary to achieve certain flood levels in each cuvette.

Table 4.1.3 Water volumes for certain flood levels in the UNEs studied by IDA (after Chaumeny, 1973)

	Volume of water ($10^6 m^3$) below elevations (m IGN) 9	10	11	12	13	14	15	16	17	18	
MK2		1	6	20	53	111	298	412	543	679	
DI1			1	2	13	45		102	171	246	323
DI4		1	2	7	27	67		123	184	245	

In any initial analysis of flood volumes in cuvettes the data in Chaumeny (1973) and its transformation as in Table 4.1.3 will be entirely adequate. However, in order to know flood volume it is essential to know the level of the flood water in m (IGN)

4.2 Water Level Measurement in the Cuvettes

The measurement of the water level in cuvettes demands attention to the height of water in various parts of the cuvette and to the installation of appropriate instrumentation. These will be discussed in turn.

In a thorough piece of hydrological research, it must not be assumed that large shallow areas of water have a surface which is level. Significant inflows or outflows will distort the water surface. Wind will blow the water towards the downwind end of the cuvette. When the wind stress ceases there may be a series of seiches as the water flows as a wave to the opposite side of the cuvette and then back again. The wind stress is, of course, greater with stronger winds and the effect of the wind decreases as water depth increases. However, in the case of the study cuvettes the flood water is always likely to be subject to wind set-up.

Therefore, whilst a single instrument will give an indication of water level, it is always best to use a number of water level recorders. They should be sited at the upwind and downwind sides of the cuvette according to the prevailing wind during the flood season. If resources permit, level recorders should also be sited at the points of major inflow and outflow from the cuvette.

A system of four or more level recorders (upwind, downwind, inflow, outflow) will give a good indication of the true water level, the direction of water flows into or out of the cuvette, and a means of checking the integrity of any one instrumental record. Where resources preclude this ideal arrangement priority should be accorded to a site in the middle of the cuvette. A second priority would be an instrument at the inflow point and thirdly at the outflow point. It is essential, when the stage boards are installed, that they be surveyed to a bench mark so that the true topographic elevation of the zero is known.

Water level can be recorded manually from direct observation of a stage board; recorded on paper/cassette tape/solid state memory by means of an instrument linked to a float or bubbler system in a stilling well; or transmitted in real time to a computer system via a radio/telephone/satellite link to a float or bubbler system. In the context of the Senegal Valley, there can be no doubt that the appropriate methodology is the manual recording of water level from a stage board by an educated member of a nearby village.

Such a system would be based upon local resources; provide opportunities to develop or link an awareness/sensitization programme to the measurements; function without mechanical breakdowns; be inexpensive requiring only infrequent visits from Headquarters; and be subject to data quality control if more than one village was involved.

4.3 Existing Installations

The ITALTEKNA project has installed stageboards at the confluence of the Diamel and Senegal, 23km down the Diamel at the end of the flood bank, and at the bridge on the Matam-Ourosogui road. These boards are read daily during the flood season and twice daily during periods of rapid water level change.

Close to the maree in the Thiemping cuvette there is a tall (4m) metal post with graduations each metre. Nearby, there are two smaller rusty metal poles. An informant reported that some years ago a man used to use a boat to visit the tall pole during floods. He apparently measured the length of pole above the flood water. No organization was found with knowledge of this system and no data was found which is directly attributable to this rudimentary stage board.

SAED are planning to install stage boards at the two pumping stations under construction along the Dioulol. It is planned to record water levels daily.

If it were decided to embark upon the routine measurement of water levels in a series of study cuvettes, the stage boards could be installed and surveyed during the dry season of 1991. It is highly likely that assistance with the task of surveying could be arranged with either ITALTEKNA or SAED, since they both have competent survey teams.

5.0 Flooding Mechanisms

There is no doubt from the literature that direct flooding from the river, via distinct breaks in the natural levees or by flooding from distributaries of the river, is the dominant process in inundating the floodplain cuvettes. There are modest stream channels originating on the djeri but these are ephemeral streams that dry up a few hours after heavy rainfall. Groundwater and underground water flows do not play a role since, at least in the area around Matam, the watertable is several metres below the surface at all times.

Rainfall directly into the cuvette is certainly a process that will add water to soil moisture and to any extant flooding. However, when daily evaporation is taken into account (Table 5.1), the amount of net rainfall reaching the cuvettes in the Matam area is probably quite modest.

The field evidence in August 1990, and the preliminary survey of the 1987 SPOT image by OMVS, suggests that some small cuvettes and small parts of larger cuvettes do get a thin skin of water over them after heavy rainfall. It will be useful for the September 1987 SPOT image to be mapped for flood extent so that the true extent of inundation by rainfall can be determined.

Table 5.1 Rainfall, Evaporation and Net Rainfall for Matam (mm) (after SATEC, 1980)

	Data	Jun	Jul	Aug	Sep	Oct
Mean Rainfall	1920-75	45.1	115.9	186.9	114.1	23.4
Evaporation[1]	1955-75	383	250	159	142	201
Pot. Evaptran[2]	1955-75	173	145	132	132	139
Net Rainfall[3]		-	-	54.9	-	-

1 Piche atmometer data
2 Potential Evapotranspiration by the Turc method
3 Rainfall minus potential evapotranspiration

So strong is the belief in the direct relationship between the level in the river and the water level in the cuvettes that most authorities have adopted the UNE model to estimate areas inundated from river level data. This model assumes an equality of level in the cuvette with the linearly interpolated level in the river adjacent. This issue is discussed in some detail in Hollis (1990). At the time of that literature review, comment was made on the appearance in Gersar et al (1988) of diagrams from SATEC (1980) showing water levels in the Senegal River, the Diamel and the Dioulol. The fact that these diagrams showed the fallibility of the UNE model was a source of comment since the diagrams had not featured in earlier studies, such as that by Gibb (1987).

In Senegal the SATEC (1980) report was found in full in only one location, the SAED Documentation Centre outside St. Louis. The Phase 1 study by SATEC contains a wealth of diagrammatic, tabular and raw data on flow patterns and levels in the floodplain between Waounde and Kaedi for the relatively feeble flood of 1978. This data is so important that the ensuing section is devoted to a summary of it. In addition there is a related diagram of floodplain water levels produced by Illy (1973) for 1971 and 1972 and ITALTEKNA have been collecting water level data for the surrounds of their perimeter since August 1989. Finally, but significantly, Rochette (1974) reports on ORSTOM's measurements of the flow of the 1964 flood under the Ourosogui to Matam road. The flow was moving from the Thiemping cuvette to that at Boyenadji and onwards to the Diamel.

5.1 The Studies by SATEC et al (1980)

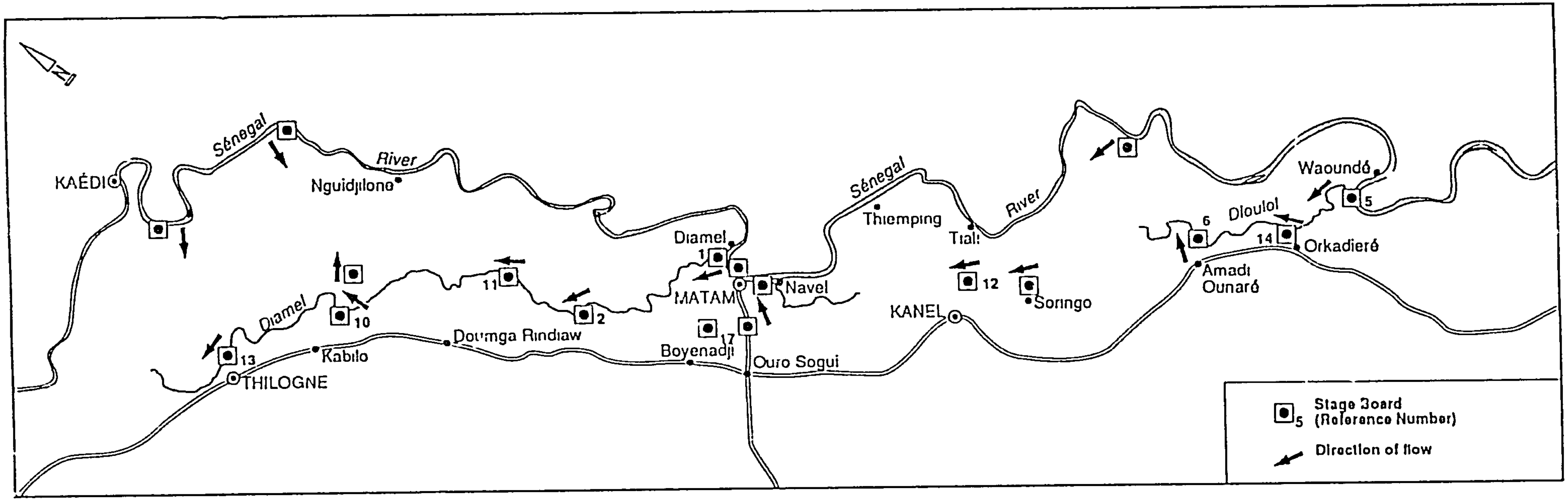
SATEC established seventeen stage boards in addition to the Matam stage board. They gathered water level data throughout the flood of 1978 (Figure 5.1). This was a relatively modest flood with a peak level at Matam of only 13.34m ign. This was 22cm higher than the expected level of artificial flood A at Matam and 32cm higher than the flood of 1986 which has already been discussed.

The pattern of peak levels and the date of attainment of the peak reveals the relative complexity of the floodplain flows around Matam (Table 5.1). In addition the table reveals the potentially dangerous simplicity of the UNE model.

ble 5.1 Peak water levels and dates for the SATEC (1980) stage boards around Matam in 1978

age Board	Water Body	Maximum level m IGN	Level on 15/11/78 m IGN	Date of the Peak
nfluence	Dioulol	17.45	12.33	28 Sep
kadiare	Dioulol	16.01	11.36	28 Sep
adiounare	Dioulol	15.66	11.41	29 Sep
ringo	Dioulol	15.66	-	1 Oct
nel	Dioulol	14.02	11.51	3 Oct
vel Conflu.	Navel	9.47	-	29 Sep
tam-OS Road	Waalo	13.39	12.47	4 Oct
ussoum	Waalo	12.76	11.56	4 Oct
nfluence	Diamel	13.36	9.36	30 Sep
badji	Diamel	12.32	9.36	1 Oct
ouloumadji	Diamel	12.23	9.21	1 Oct
kidiave	Diamel	11.95	9.37	2 Oct
ilogne	Diamel	10.77	8.78	3 Oct
tam	Senegal	13.34	9.42	29 Sep

Figure 5.1 The stage board network established by SATEC et al. (1980)



Satec et al (1980) converted their large data base of level records into a series of maps which graphically illustrate the pattern of flows during the 1978 flood (Figure 5.2 - 5.6. In the early stages of the flood up to 12 August (Figure 5.2) there is a strong flow of water into the Dioulol and onwards into the Thiemping cuvette. At this stage the Navel was also carrying water into the Thiemping cuvette. The Diamel carried water from the Senegal river directly to Thilogne.

During the middle of August (Figure 5.3) the strong flow down the Dioulol continued into the cuvette east of Kanel. Water from this cuvette spilled through the marigot directly north of Kanel and continued to fill the Thiemping cuvette. However, by this time the level of water in the Thiemping cuvette was higher than that in the Navel and water began to drain out of the Thiemping cuvette via the Navel. The flow in the Diamel had risen and this drove water eastwards into the marigots of the Boyenadji cuvette and deep into the complex of cuvettes north of Thilogne.

As the peak of the flood approached in mid September there was still a strong flow down the Dioulol and through the marigot north of Kanel into the Thiemping cuvette. Drainage via the Navel was still occurring, but the water level in the Thiemping cuvette had reached such a level that it began to flow across the Matam-Ourosogui road to continue the filling of the Boyenadji cuvette. This flow became the major source of water for that cuvette with the result that water simultaneously drained from the cuvette into the Diamel via the two main marigots (Figure 5.4).

At the peak of the flood the strong flow down the Dioulol continued through the Thiemping cuvette (Figure 5.5). This drained via the Navel to the Senegal and via the Matam-Ourosogui road to the Boyenadji cuvette and thence into the Diamel. Therefore at the peak of the flood there is a strong flow of floodwater down the floodplain from the confluence of the River with the Dioulol to Kanel to Boyenadji and thence to Thilogne via the Diamel.

Six weeks after the flood peak at Matam, the Dioulol was flowing back eastwards into the River. The marigot north of Kanel had stationary water, whilst the Thiemping cuvette continued to drain via the Navel. The Boyenadji cuvette was completely drained an, interestingly, the Diamel continued to flow gently away from the river towards Thilogne (Figure 5.6).

This dataset, which is published in full in SATEC (1980), is an excellent record of the 1978 flood. Gersar (1990) emphasise the relevance of this study by showing that the expected levels of the artificial flood A are similar to the river levels observed by SATEC (Figures 5.7 and 5.8).

The SATEC data will be invaluable to any future modelling of the floodplain hydrology. In addition, since SATEC did not map the extent of flooding in 1978, high priority should be

Figure 5.2 Patterns of flow on the floodplain around Matam 1 July 1978 to 12 August 1978 (after SATEC et al. [1989])

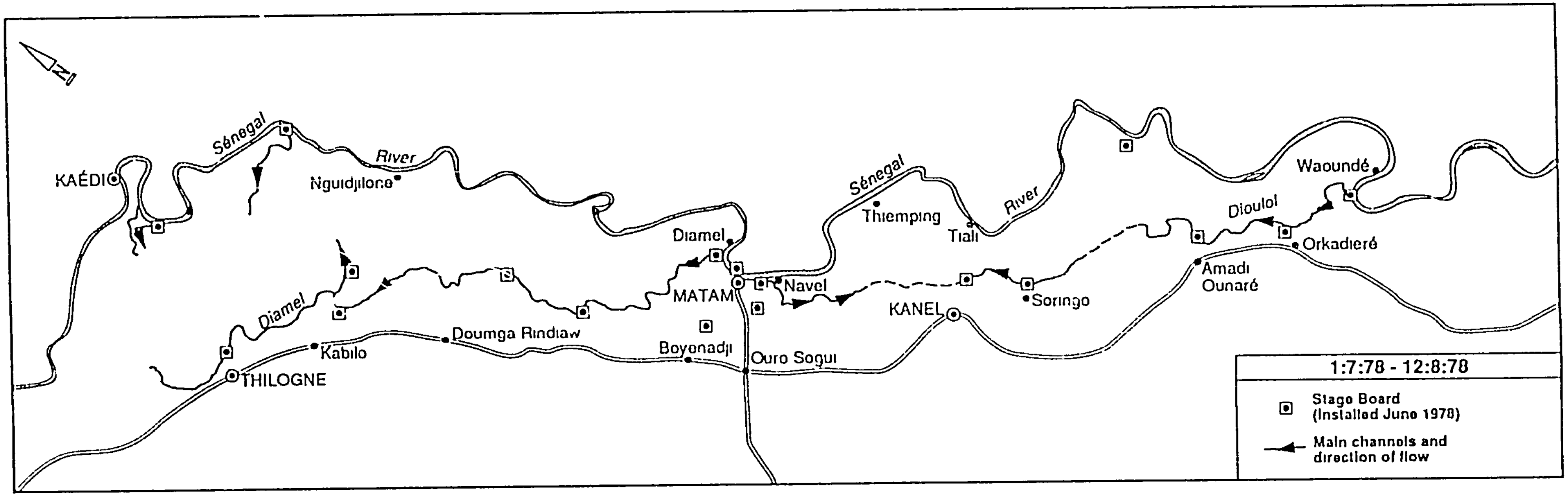


Figure 5.3 Patterns of flow on the floodplain around Matam 12 August 1978 to 21 August 1978 (after SATEC et al. [1980])

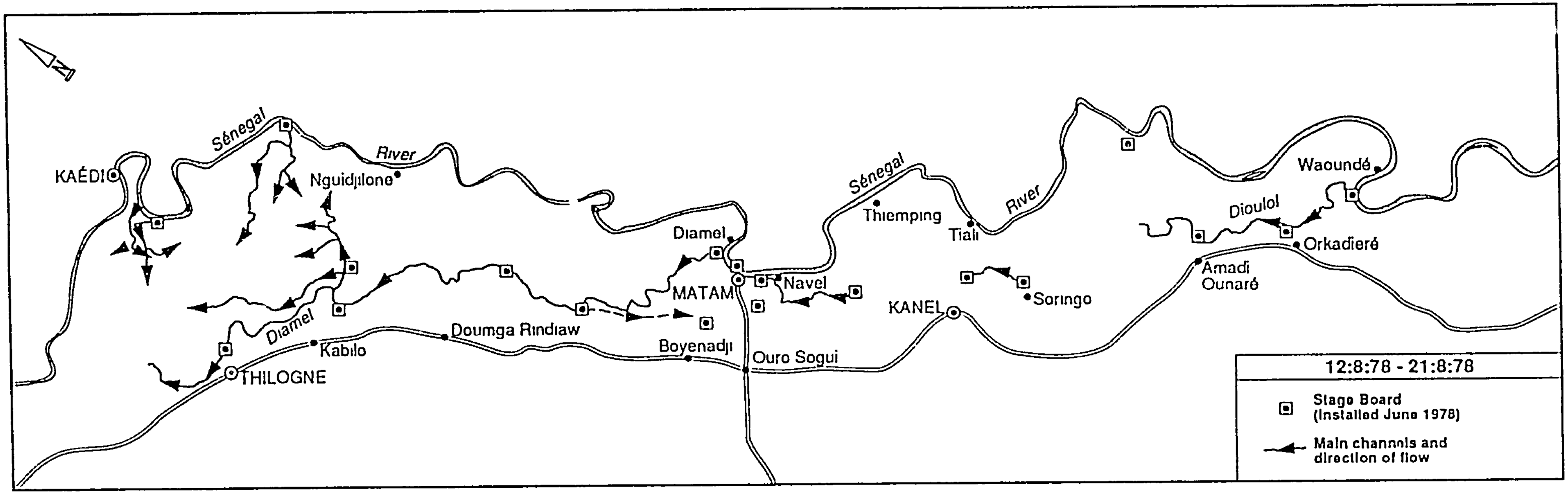


Figure 5.4 Patterns of flow on the floodplain around Matam 22 August 1978 to 16 September 1978 (after SATEC et al. [1980])

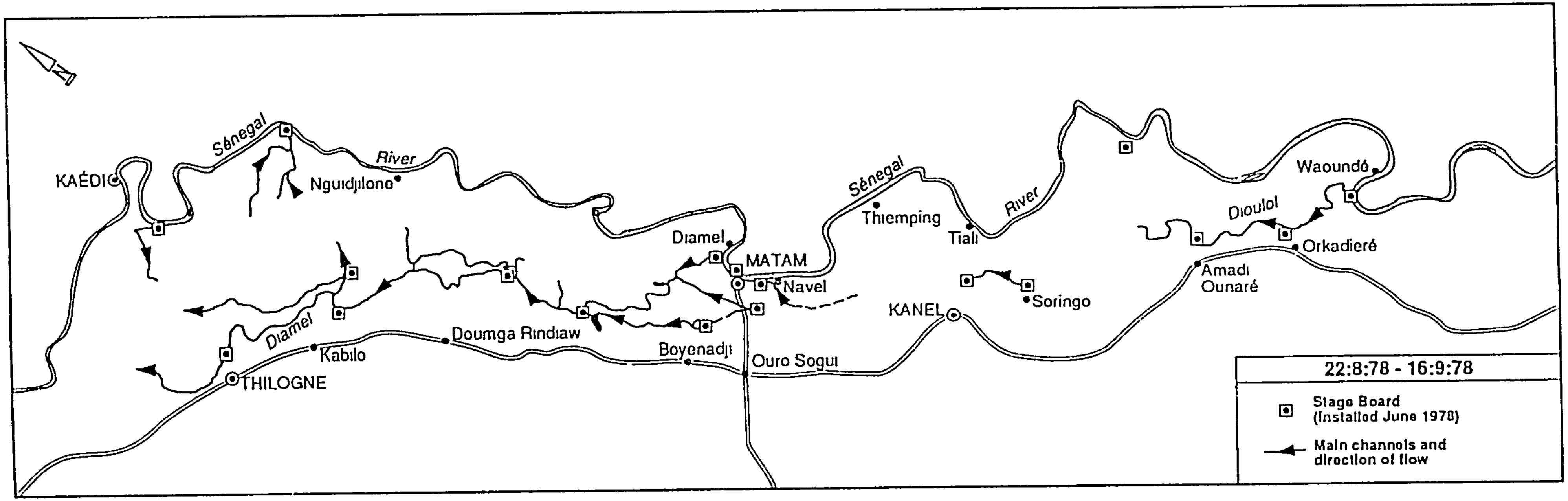


Figure 5.5 Patterns of flow on the floodplain around Matam at the peak of the flood at the end of September 1978 (after SATEC et al. [1980])

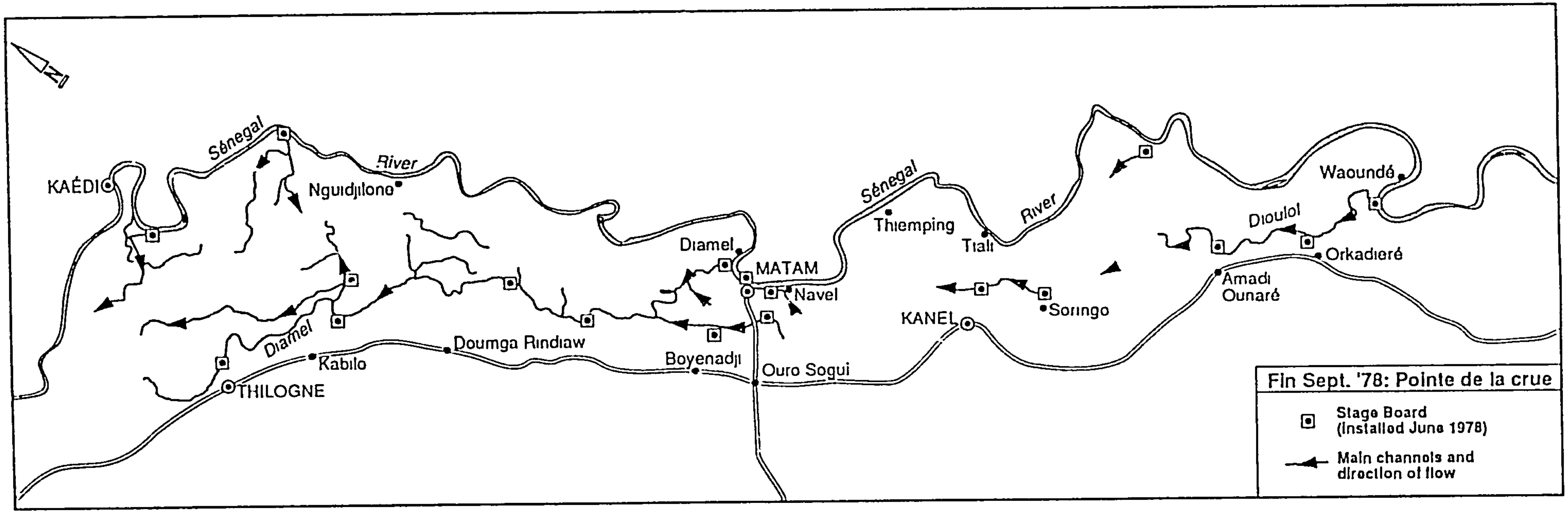
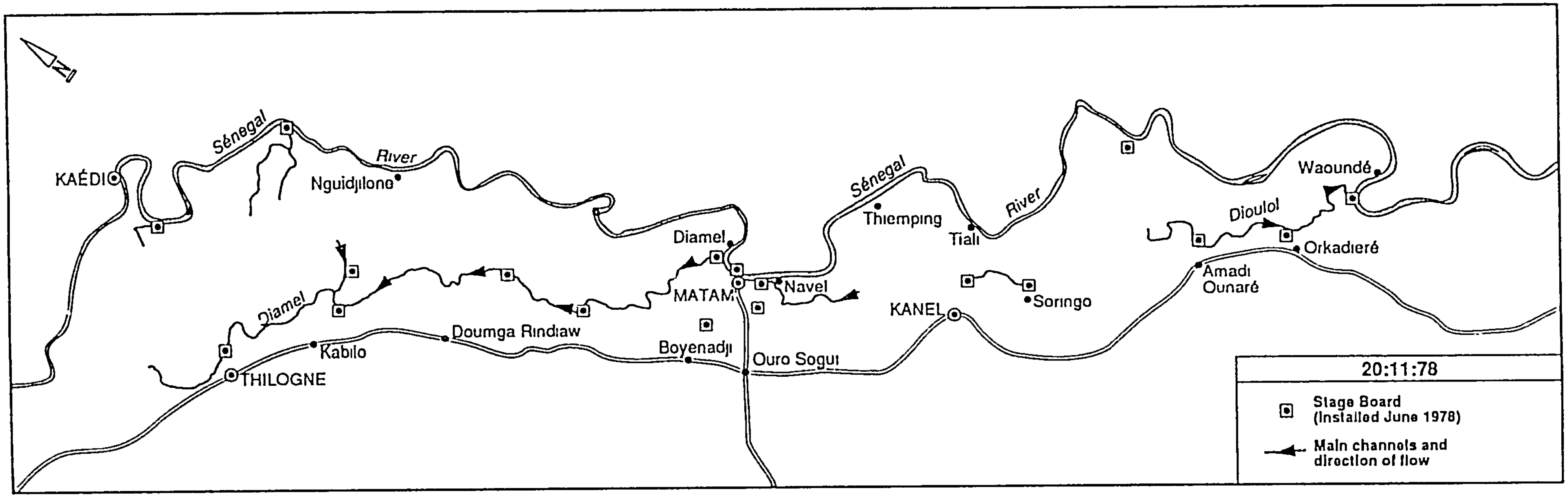


Figure 5.6 Patterns of flow on the floodplain around Matam 20 November 1978 (after SATEC et al. [1980])



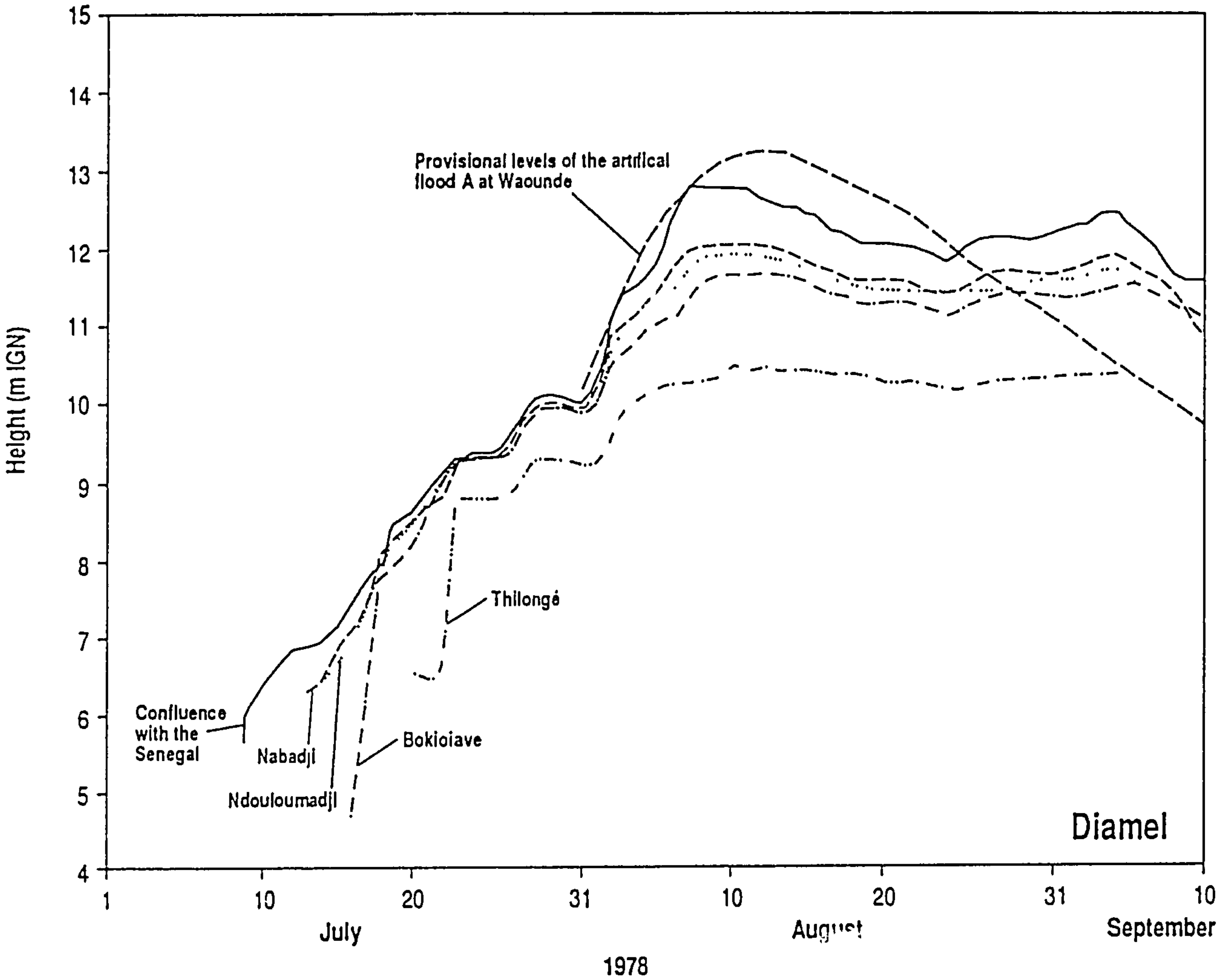


Figure 5.7 Water level data for 1978 in the Dioulol (after SATEC, 1980)

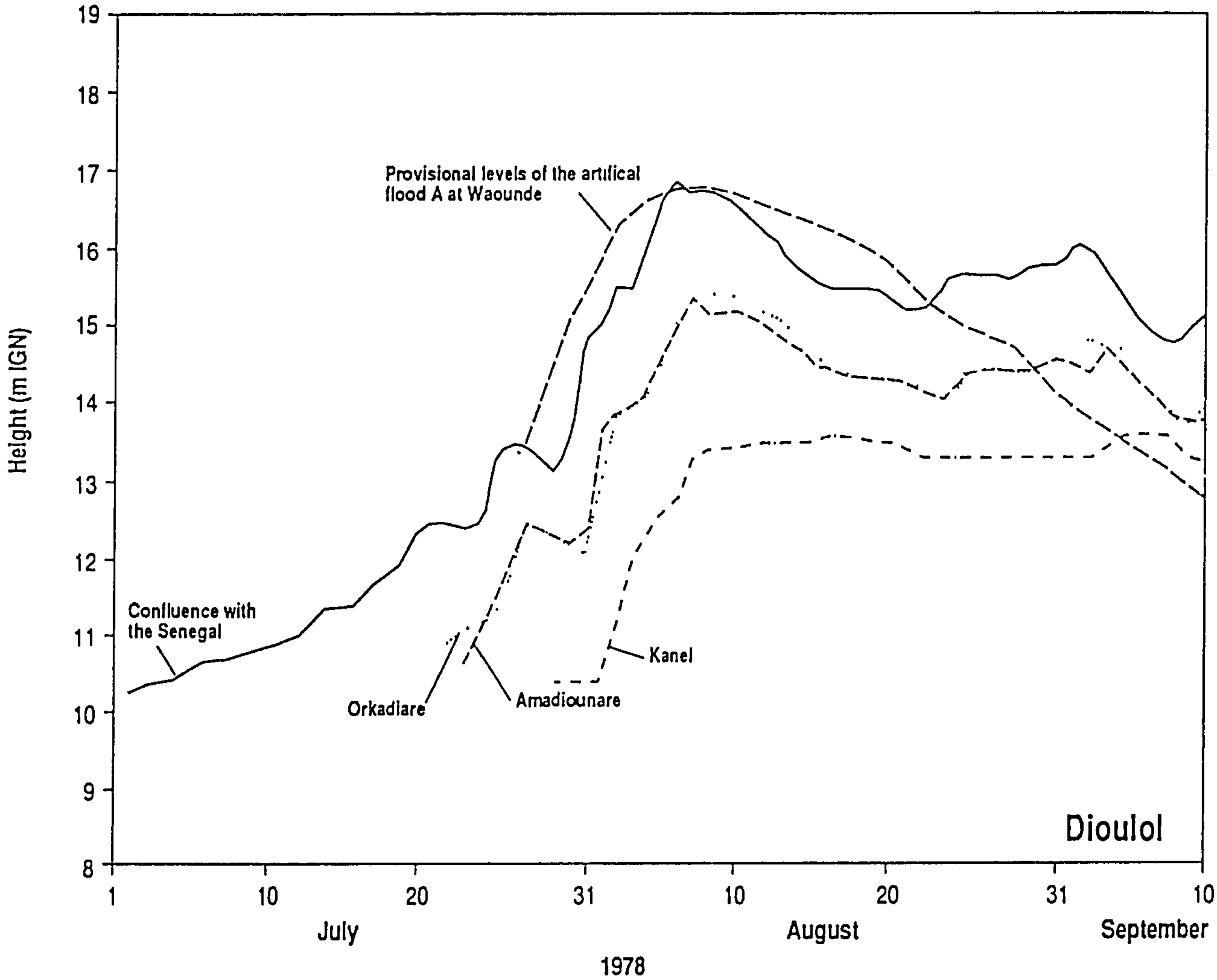


Figure 5.8 Water level data for 1978 in the Diamel (after SATEC, 1980)

given to the mapping of flood extents in late August, late September and mid November using LANDSAT MSS images.

Gersar et al (1990) implicitly recommend the same study. They demonstrated that the 1978 flood was close to the likely hydrograph of artificial flood A and they recommended (p173, Rapport) the mapping of the zones to be inundated by the artificial flood.

5.2 The Studies by Illy (1973) and ITALTEKNA

Illy presented data for water levels at Matam in the River and at Kanel in the Thiemping cuvette in 1971 and 1972 (Figure 5.9). The very feeble flood of 1972, with a peak level at Matam of only 12.1m IGN, had a peak water level at Kanel 45cm higher than at Matam and it occurred four days after the peak at Matam. This pattern of higher and later peak levels at Kanel is the same as was observed for the small flood of 1978 by SATEC (1980).

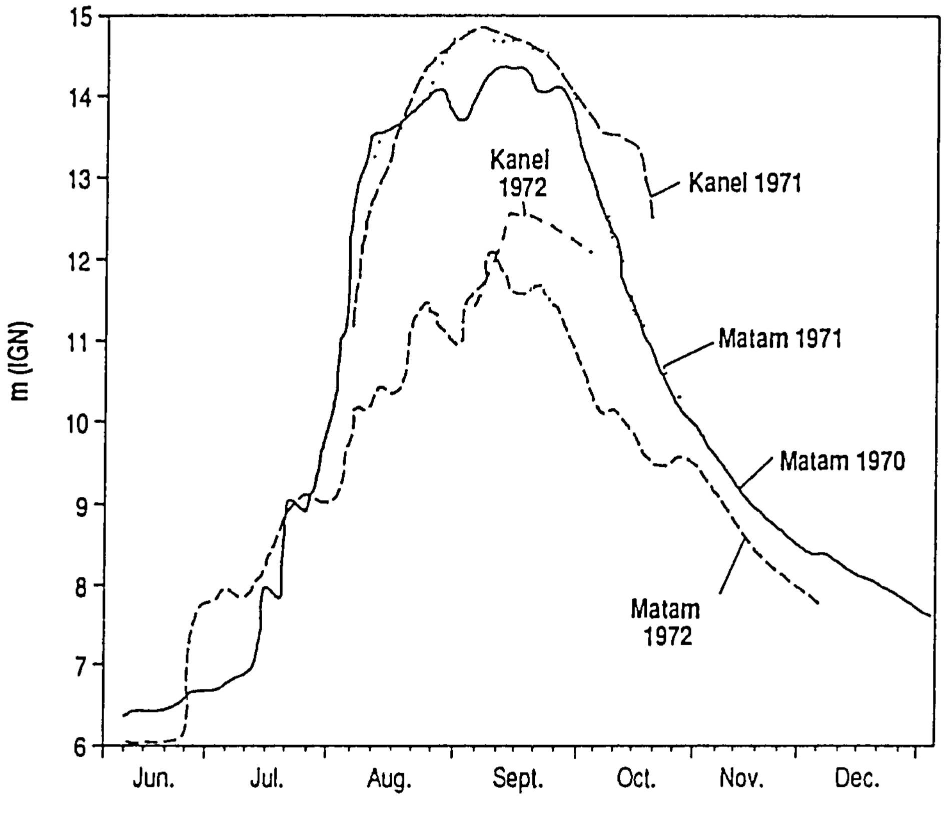


Figure 5.9 Water levels at Matam and Kanel during the floods of 1971 and 1972 (after Illy, 1973)

However, Illy's curves for the large flood of 1971 (14.6m at Matam) re·;al that there was an equality of peak levels at Kanel and Matam but a five day delay in the achievement of that peak at Kanel. This would suggest that the functioning of the Navel and the link to the Boyenadji cuvette may be rather different during large floods than in the smaller floods of 1972 and 1978.

The data gathered to date by the ITALTEKNA project tends to confirm the patterns of flow already established save for the fact that ITALTEKNA have found that the level at the road is higher than that in the river at Matam. The stageboards are located at Matam, the bridge on the Matam-Ourosogui road, 23 km down the Diamel at the end of the flood embankment and at the confluence of the Senegal and the Diamel.

Figure 5.10 shows that, during the 1989 flood, the level of water at the road bridge rose to a higher peak on both occasions than the river at Matam and that after the passage of the first peak at Matam the road bridge had a higher water level than the river well into November. This would suggest a steady flow of water through the road bridge and into Boyenadji cuvette. Rochette (1974) reported that during the large flood of 1964 the level at the Matam-Ourosogui road was always lower than that in the river.

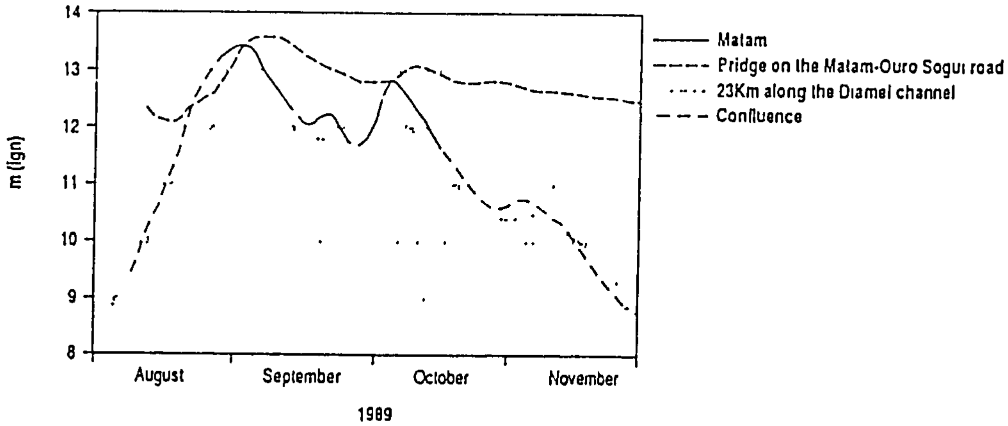


Figure 5.10 Water levels in the Matam area for the flood of 1989 (using data supplied by ITALTEKNA)

The level 23km down the Diamel was always below that at the confluence, therefore indicating flow away from the river, for the whole period save for a spell at the end of October when there was a very small gradient, and therefore flow, towards the river. It is not surprising that the level of the river at the confluence follows exactly the level of the river about 1km upstream at Matam.

5.3 The ORSTOM Current Meternng at the Ourosogui-Matam Road

Rochette (1974) reports that the first embankment between Ourosogui and Matam was constructed in 1950. The embankment was washed away in September 1954. On 17th September 1954, when the stage board at Matam read 9.37m (16.41m IGN), M.A.S.

estimated the flow through the break in the bank to be 1040 m^3/sec. Rochette reports that a stage board was established in 1963 on the major bridge on the reconstructed road with a zero at 12.18m IGN. There was a campaign of current metering at each of the bridges throughout 1964. On 16th September flows of 730m^3/sec and 148m^3/sec were measured at two of the bridges. The third bridge had a flow of 362m^3/sec on the 17th September Therefore, the flow on 16th September 1964 was in the region of 1242 m^3/sec. Since the peak flow at Bakel in 1964 was 7180m^3/sec on 9th September (Rochette, 1974), the floodplain at Matam conveyed 17% of the peak flow at Bakel. Rochette (1974) presents Figure 5.11 as the stage discharge relationship for the bridges over the Ourosogui-Matam road.

In presenting Figure 5.12 showing synchronous levels at the embankment and at Matam, Rochette (1974) comments that the level of water at the embankment is always less than that in the river. The difference is 60 cm at the beginning of flow across the floodplain and this falls to 10cm at the peak of the flood.

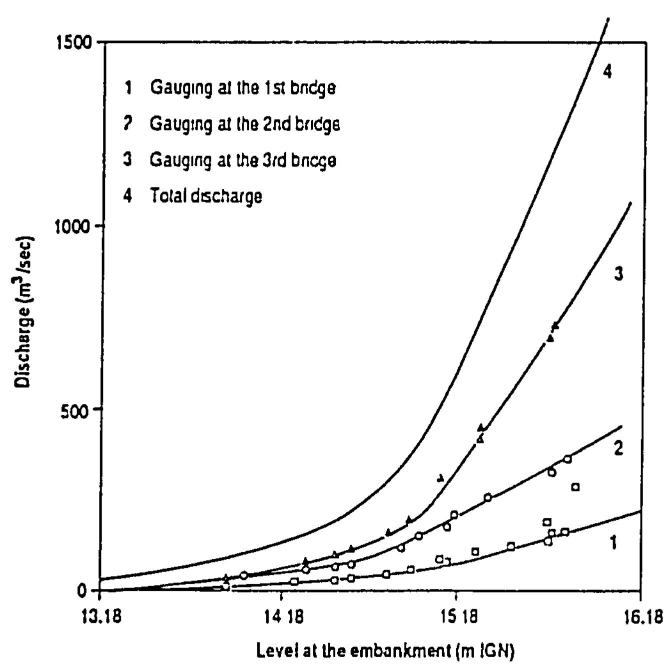


Figure 5.11 Stage discharge relationship for flows westwards through the Ourosogui - Matam road bridges in 1964 (after Rochette, 1974)

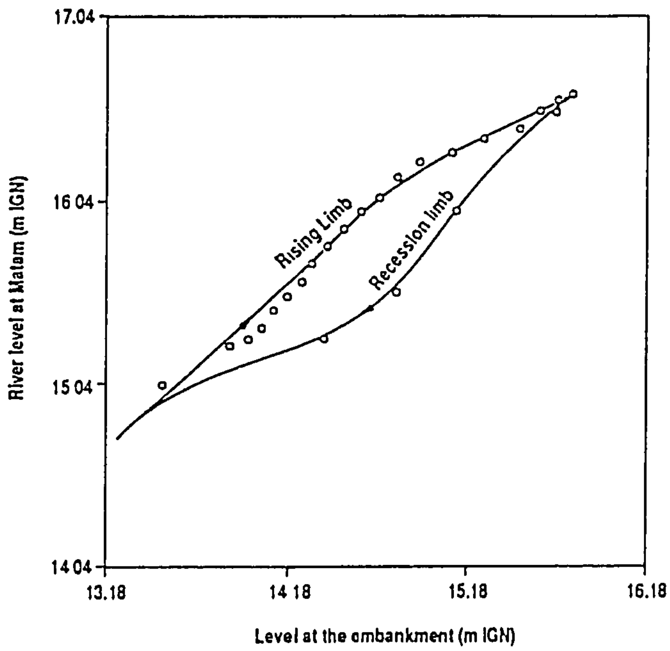


Figure 5.12 Relationship of water levels in the river at Matam and at the bridges over the Ourosogui road for the flood of 1964

5.4 Field Visit to Cuvette MK2: Thiemping

The Thiemping cuvette was visited with John Magistro's main informant as guide.

The area of the sorghum cultivation, in this most extensive cuvette, was remarkable. There had clearly been an enormous harvest in 1990.

The cuvette is very complex in form with a whole series of more or less inter-related cuvettes and intervening areas of fonde lands. Only one relatively small marigot was crossed quite near to Kanel and so most of the flooding must come as a sheet of water spreading over the hollalde soils. The "maree" area was visited since it was explained that this was the deepest part of the cuvette and it was here that the water remained for longest The area turned out to be rather extensive with a strong growth of Scirpus and fairly extensive tree stands. The edges of the "maree" were clearly undergoing conversion to flood recession sorghum cultivation in many places.

A tall metal post with graduations was found near to the deepest part of the cuvette. It was said that a man used to come in the flood season and take a boat to make readings at this post.

The mechanism of flooding for the Thiemping cuvette was explained by the informant and it accords exactly with the mapped data in SATEC (1980). There is a strong flow of flood water which comes quickly from the Dioulol with a secondary flow entering from the Navel. The complexity of the form of the cuvette suggests that there must be quite complex flow patterns. After the peak of the flood, whilst there is some flow back to the Dioulol, the major output of water is to the Navel. The informant also reported that there was an old marigot, the Diembahara, near to Tiali in the east of the cuvette. This once carried floodwater but it is now completely blocked with sediment.

On a second occasion, and after heavy overnight rain, the low lying hollalde clays between Kanel and Tiali were explored on foot. Runoff from the overnight rain was still pouring westwards across a wide and flat plain with a small channel, 3m wide and 40cm deep, in the middle. Whilst there was a little water to be seen in the cuvette to the west it cannot be said to be partially flooded. About 1km along the track there was a much larger marigot about 10m wide and 3m deep overall. A deeper section of this marigot had been filled with runoff and sediment from the rains but there was no flow in either direction.

Observation of the hollalde soils was instructive. In the large areas which had had no overland flow, most of the deep (10 to 40+cm) cracks remained open and the wetting front had moistened only about 2cm at the surface and about 4cm of the walls of the cracks. Below this wetting front the soils were still hard and completely dry despite the prolonged and heavy rainfall. It is clear that a large part of the rainfall had penetrated deep into the soil.

Between Kanel and Matam virtually all of the channels had held water during the rainfall, but only 6 hours after its termination, they were largely dry. Those that were flowing had only a few cm of water in them. It therefore appears that heavy rainfall in the Matam area plays a very modest role in flooding the major cuvettes.

There appear to be no problems with flows of water into or out of the Thiemping cuvette at present. An adequate flood in the river clearly gives excellent conditions for very extensive flood recession cultivation.

5.5 Field Visit to Cuvette DI1: Boyenadji

The field visit to the Boyenadji cuvette consisted of a visit to the offices of the ITALTEKNA project and then a field visit to the whole area of the scheme with the project manager. No specific investigations were made of flooding mechanisms because it is ITALTEKNA's intention to close the whole perimeter to floods and the nature of the flooding had been clearly established from the SATEC (1980) study.

The ITALTEKNA project is a 10,000ha scheme of which 2,000 ha are being prepared at present. The scheme covers almost all of the floodplain land west of the Matam-Ourosogui road embankment and south of a 23km long stretch of the Diamel.

A flood protection embankment has been constructed along the Senegal River, on the floodplain and along the Diamel for the whole scheme area. The flood bank has not been completed where it cuts the main marigots feeding and draining the cuvette. This has allowed the farmers to continue with their recession cultivation. It is, however, planned that the bridges on the Matam-Ourosogui road will be removed to be replaced by an embankment and a better road. The gaps in the embankment where the marigots link with the Diamel will be closed too. The dyke is a truly enormous construction being perhaps 7 metres high in places with enough space on the crest for two vehicles to pass. The embankment has been designed to give three metres freeboard above the level of the 100 year flood.

A pumping station, with sufficient capacity to irrigate the full 10,000ha, will be constructed on the banks of the Senegal river. A little of the primary, secondary and parts of the tertiary canal system is in place. A small number of parcels quite near to the planned pumping station are already being irrigated but this is an existing and rehabilitated PIV rather than the first parcels of the ITALTEKNA scheme.

The scheme has been under way for about five years and it was reported that it would be another three years before the parcels would be ready for cultivation. To date a dozen or so 1200m^2 parcels have been fully converted for eventual irrigation. Each parcel will be for one family and they will be able to decide the crops to be grown. There are plans for a training scheme for farmers but this part of the project is not yet under way.

It is planned to locate all of the parcels on the slightly higher land within the embankment. The marigots and their surrounding land will be left uncultivated. Drainage water will flow down the marigots to evaporate in the lowest parts of the cuvette.

The entire 2,000+ ha that will form the first element of the scheme has been entirely cleared of trees ready for the land conversion work. It presents a very desolate prospect at present.

At the junction of the Diamel and the River, ITALTEKNA had constructed a temporary road on an earth bank across the Diamel in the previous dry season to ease access across the river. Whilst part of the bank had been swept away by later high water, it was clear that this scheme was leading to a restriction in the inflow of water to the Diamel.

There are several remarkable features in the scheme's organization and planning:

i) all of the documentation for the scheme, save that immediately needed for construction work, is retained in Italy;

ii) there are no firm plans for cropping and ITALTEKNA will have nothing to do with the allocation of land to farmers. This latter activity will be left to the Senegalese Rural Cooperative Reform Organization.

iii) there is no total cost projection for the scheme. To date, 10,000 million FCFA have been expended but no irrigation is yet possible. A vague and tentative estimate of the final cost by the project manager was put at 25,000 million FCFA. If this latter figure is reached, the conversion cost for each hectare in the initial 2,000ha scheme will be 12.5 million FCFA (almost $50,000 per ha!!) even if the scheme's notional share of the cost of Manantali is neglected.

iv) whilst there is a notional SAED counterpart to the Italian project manager, he appears to be entirely marginalized. In addition there seems to be no contact at all between the ITALTEKNA scheme and SAED's local headquarters in Matam.

There are, in addition, two major hydrological problems with the scheme. First, it is intended that the ITALTEKNA scheme will become a "closed system". It is intended to close the dykes where the present marigots enter the scheme area and to prevent all flood water entering the scheme area. Much more seriously it is intended to use the existing slope of these marigots to drain water from the fields away from the River and Diamel and directly into the cuvettes that are within the protective banks. It is intended that the drainage from the irrigation scheme will evaporate from these sump areas. It is appreciated by the Italians that these cuvettes will become salt flats within a number of years. It is not envisaged that this salinization of cuvettes, and probably of the groundwater beneath, will produce any problems. It is known that it is possible to drain the water into the Diamel and the River. However, it is thought that the cost of reversing the slope in the marigots will be excessive. Second, the enclosure of the scheme by its protective embankment will include the removal of the present bridges between Matam and Ourosogui. Such a closure will halt the down valley flow of flood water across the floodplain and raise water levels significantly upstream of Matam. ORSTOM measured a flow of around 1242 m^3/sec (almost 17% of the peak at Bakel) under the Ourosogui road in the large flood of 1964. Therefore, it is highly likely that an exceptional flood would be forced to pass through Matam town when its way is blocked by the ITALTEKNA embankment in its final form. This embankment is noticeably higher than the land in Matam as one descends from the embankment into the town!

This final problem of exacerbated flooding is especially regrettable because it is cited by SATEC (1980) as one of the main reasons why a large irrigated perimeter at Matam should be abandoned (p 11, Phase II Avant Projets et Factabilite Economique). SATEC state that the complete blockage of the floodplain will provoke an elevation of maximum flood levels by 0.85m which will cause adverse effects on the right bank and lead to claims for compensation. It appears that the Italians have not seen, or not heeded, the advice of the SATEC (1980) report.

5.6 Field Visit to Cuvette DI4: Doumga Rindiaw

The Doumga Rindiaw cuvette was visited with the village head and his colleague. The visit centred on the small marigot that is the only inlet to the cuvette.

The three hundred metres of marigot adjoining the Diamel was about four metres wide at the top, three metres deep and semi-circular in cross section. The bed of the channel had a covering of long grass but the banks were generally bare. There were many threes and shrubs along the top of the banks but none of them would be likely to impede flow in the channel. The last 30 metres of channel had recently been excavated by the villagers and this was about 4.5m deep and was filled with water from the Diamel during our visit.

It was reported that even when the Diamel is very high there is often little or no flow into the cuvette. The reason given was the heavy sedimentation in the channel near to the Diamel. Several efforts have been made by the villagers to dig out the channel but the scale of the work has generally been beyond their capability. There is also reported to be a major problem with the drainage of the cuvette when sufficient water does manage to enter. The drainage is generally very slow and much of the cuvette is flooded for too long.

The analysis reported in Section 2.0 showed that for the 1988 flood the UNE model would suggest an area of inundation of $54km^2$ in cuvette DI4 which includes Doumga Rindiaw. It seems certain that the Doumga Rindiaw cuvette is not the entirety of DI4 but the actual area flooded in 1988, $5.2km^2$, is dramatically less than the topography would indicate. This therefore is circumstantial evidence to support the view of the local people that inflows to the cuvette are seriously restricted. The fact that the cuvette, when full, is slow to drain is further evidence of the inadequacy of the marigot linking the cuvette with the Diamel.

An obvious solution to this problem is for hydraulic machinery to be used to dig out about 300 metres of channel. There are large amounts of SAED machinery on the fringes of the cuvette but the village head had no mechanism for conveying his village's need to SAED. In addition, it was his view that such a request would be fruitless because SAED's function was only to install irrigation systems. Clearly there needs to be a better mechanism for the local people to make their needs known. Thought must also be given to the most cost effective means of increasing agricultural production rather than the single minded pursuit of the single option of irrigation.

There was an earth bank blocking about 40% of the width of the Diamel just downstream of the point where the Doumga Rindiaw marigot joined the channel. It was said that this bank had been constructed by SAED during the previous dry season as a means of taking machinery to the opposite bank. The remains of the bank were clearly leading to a water level reduction of over 20cm in the direction of flow. This type of scheme will severely restrict the flow of water into the Diamel in the future.

A meeting was held with the senior village elders at Mbakhna Less, a "Fishermans' Village" on the levee of the Diamel near to Doumga Rindiaw. The conversation turned on the nature of the problems that they faced and the water management measures that they believe are necessary.

The village cultivates some small flood recession areas, mainly as sharecroppers and they have a successful and well sustained PIV for the village. The fishing is done in the River (not at present, of course), in the Diamel and in the cuvettes when they are flooded. Many of the best and most valued fish species are said to have disappeared in recent years because of the drought and poor floods. The size of the fish has also fallen and so smaller mesh sizes are now in use.

The flood of 1988 had been excellent for the fishermen and that of 1989 was quite good for the fishing too. Despite the difficult drought years, the fishery had bounced back as soon as a good flood had occurred.

The main water management point was the necessity of a good and long duration flood. Ideally, the flood should inundate the cuvettes for up to three months. However, if the large floods of the 1960s returned, then relatively new houses would be inundated.

The most useful management action would be the dredging of the Diamel to increase its depth and to ease the flow of water along it. The excavation of the marigots to allow water onto the cuvettes was favoured but rapid drainage of the cuvettes was shunned. There was some support for the idea of a sluice at the mouth of the Diamel to retain water after the passage of the flood peak but there was no real interest in the establishment of 1 ha ponds within the irrigated perimeters.

There appears to be no mechanism for the fishermen to express their views or to make an input to the resource management system. Whilst a newly established system of Councils exists on paper, the Councils are inactive and the villagers were left very much to their own devices.

6.0 The Management of Flooding Mechanisms and Floodwater

To date there seem to have been virtually no efforts to improve the natural mechanisms by which the cuvettes receive or disperse floodwater. This seems to be true of national organizations such as SAED, regional groupings of villages, or individual villages. Doumga Rindiaw is reported to have endeavoured to dig out the channel linking their cuvette to the Diamel, but the field evidence is that the effort was very limited.

At the same time there seems to be a growing tendency on the part of organizations with large earth moving machines to construct temporary roads on earth banks across the Diamel, and perhaps other distributaries. These roads are washed away during the subsequent flood. However, the old ITALTEKNA road at the Senegal and Diamel confluence and the SAED road near the inlet to the Doumga Rindiaw cuvette inhibited flow into and along the Diamel. The result of these temporary constructions will be that the Diamel, and perhaps other distributaries, will rise to a lower level for a shorter time during the flood.

The situation in the middle valley of the Senegal differs significantly from that existing on another Sahelian floodplain between Hadejia and Gashua on the Yobe system of north east Nigeria (Hollis and Adams, in press) Here individual farmers and villages dig channels and construct banks to management the inflow and outflow of floodwater. The excavation of flowing channels is undertaken by individual villages. There is a great tradition of work gangs from up to half a dozen downstream villages travelling up the valley to spend up to a week encamped near a channel which is restricting flow to their area. During this time the whole gang work communally to remove the restriction to flow. In recent years KNARDA, a Kano based quasi-governmental agricultural development agency which was originally World Bank funded, has contributed substantially to the flood management programme at the local scale. In some places, such as the Keffin Hausa confluence with the Hadejia river, KNARDA have used their excavators to dig out about three kilometers of channel to increase the flow of flood water to one part of the floodplain. This was done in collaboration and in conjunction with the villagers' efforts to enlarge the channel. One of KNARDA's main programmes has been fadama (cuvette in Hausa) rehabilitation. This involves excavating the channel linking the fadama to the main water course and then installing a simple sluice with baulks of wood which drop into slotted concrete foundations. The sluice is operated to allow a free flow of floodwater into the fadama and then it is closed to retain the water for the benefit of the rice crop and the related fish. In the dry season the sluice is open and allows irrigation by small pumps from the over deepened channel dug into the fadama The sluice is also used on some occasions to exclude early flood peaks which would drown the rice before the arrival of the main flood. Whilst this scheme is very effective hydrologically, and financially, it has caused some severe social problems. These problems relate to the farmers desire to exclude semi-nomadic pastoralists from the fadamas once the small pump irrigation schemes are operating in the dry season. The pastoralists have reacted angrily and there have been many fatalities.

6.1 The Essential Elements

1. Undoubtedly the most effective means of improving the natural mechanism by which basins receive flood water will be to augment the natural flood emanating from the Faleme and Bakoye with a substantial slug of water from Manantali. The maintenance of a substantial artificial/augmented flood in the Senegal is essential to the maintenance of flood recession cultivation and the other benefits that follow from the flood.

Hollis (1990) commented at length on the very restricted view of the functioning of Manantali that had been taken by Gibb (1987) and Gersar el al (1988). In particular those reports tended to point to a fundamental conflict between the generation of the artificial flood and the potential of Manantali to generate hydro-power and to furnish a sustained dry season flow.

Gersar, Gibb et al (1990) have found that (p57) "The artificial flood reduces Manantali's hydro-power potential with a 95% guarantee by 10%. It is possible to furnish a regulated average discharge, 95% of the time, of 150 to 200m^3/sec with artificial floods A and B. These flows are sufficient to cover the aggregate irrigation demands of the valley up to 100,000ha".

2. The organizations responsible for water management in the valley, eg OMVS, and those responsible for hydraulic works, such as SAED, must be better informed about the local people's aspirations, more responsive to the villagers' demands, and increasingly integrated with the local people.

It is clear from the conversations in Thiemping, Doumga Rindiaw and Mbakhna Less that the local people have an intimate knowledge of the hydrology of their local area. They have detailed information on the relationship between changes in the hydrology of their cuvettes and their agricultural and fisheries productivity. Clearly this information must be tapped and utilized for effective water management in the valley.

3. It is important to emphasise at the outset the wholeness of the river and its valley. Schemes that put more floodwater into certain cuvettes will undoubtedly leave less water for other users downstream. Dredging of the main channel may become essential for navigation but it will inevitably lower flood levels. The embanking of irrigated perimeters to prevent their flooding will reduce flood plain storage and cause floods to rise higher and to flow faster in other parts of the floodplain.

It is essential that the planning of the water management of the valley be done in a holistic fashion. This will take into account the complex interplay of the various hydrological, social and economic factors for the whole valley.

Integrated management involves more than one organization being responsible for the operation of dams and a series of others being independently responsible for hydraulic works related to agriculture.

6.2 The Water Management Options

Gersar et al (1990) briefly discuss measures to improve flood recession cultivation. They propose four systems but they are all variations on the theme of establishing embankments with sluices across the entrance to cuvettes. They do not propose any excavation of marigots to individual cuvettes. They note two constraints on the application of their ideas. First, there will have to be a perfect knowledge of the topography linked with a knowledge of how each cuvette actually floods. Second, they suggest that the cost of such schemes will be high except in sites where natural conditions are favourable and it is possible to quantify an augmentation of production.

There seem to be three options for improved water management in the cuvettes.

1. SATEC (1980) demonstrate that flow along the distributaries, the Diamel and the Dioulol, is restricted by a series of sills. The dredging away of these sills would allow a more rapid, steadier and increased flow of floodwater into the distributaries. This would have the benefit of bringing flooding to the cuvettes earlier and in greater volumes.

Gersar et al (1990) report that a part of the Dioulol around Amadi Ounare, to the east of Kanel, was dredged in 1988. It is reported that this has allowed the flood to arrive more quickly but the size of the floods has not been increased.

However, the increased hydraulic efficiency of the distributaries will also increase the speed of the flood recession but the data available in Sections 5.1 and 5.2 suggests that only a modest amount of water flows back into the Senegal river and that that only occurs for a short period at the very end of the flood.

2. The small marigots which link individual cuvettes to the river of the major distributaries could be dredged and enlarged. Some which still carry flow would have their discharge into the cuvette increased. The opening of those that have not carried water for many years would bring addition sources of water for the inundation of the cuvettes.

A corollary of the enlargement of these marigots will, or course, be that the floodwater will drain away speedily from the cuvettes after the flood has past. These aspects of flooding and drainage will need careful study at each site.

3. Gates or sluices could be installed where the distributaries leave the river or where marigots feed individual cuvettes. These structures would allow an entirely free flow of flood water as the flood rose. They could then retain water in the system for as long as necessary. In addition the sluices would provide the possibility of excluding secondary peaks from the cuvettes if they arrived at a hazardous time.

Gates on the major distributaries, which have been mooted in earlier planning studies, will need careful investigation of their hydraulic, agricultural and management aspects. However, sluices on small channels feeding individual cuvettes could be constructed with a few m^3 of concrete and some timber within a week or two. They could easily be done using collaboration between the local villagers and the agency responsible.

These locally controlled sluices could yield substantial benefits in terms of water control. They are likely to be essential if significant excavation of channels takes place.

The only disadvantage of gates at the entrance to the main distributaries is that they would have to be operated in a manner that satisfied the varied demands of the local people. It could be unfortunate if such gates were constructed simply to hold water at a high level for irrigation. Such a scheme could prolong flooding in certain cuvettes and reduce their value for recession agriculture.

6.3 Doumga Rindiaw

The solution to the problem of poor flooding and slow drainage is to use a mechanical excavator to clear and deepen about 1 km of the channel linking the cuvette to the Diamel. There would need to be periodic maintenance to clear any accumulated sediments.

It may be necessary, following a couple of years experience, to install in the channel a small sluice. This would consist of slotted concrete abutments and baulks of timber to drop into or withdraw from the vertical slots in the concrete.

During the field visit large amounts of SAED earth moving machinery was being used to construct a third PIV for the village about 500 metres from the channel.

The lack of a mechanism whereby SAED can receive and respond to the villagers' very sensible and minimal requests seems to be as serious a problem as the actual sedimentation of the channel itself.

6.4 Boyenadji

This cuvette is set to become completely isolated from the river and the Diamel because of the ITALTEKNA embankments. It is destined to be the drainage sump for all of the brackish drainage from the whole ITALTEKNA scheme. As a result it will become highly salinated in the near future.

Since, in addition, the embankment scheme is likely to produce serious flooding problems in other areas of the floodplain, it is essential that the planning of the scheme be modified.

The ITALTEKNA scheme should:

a) dredge the marigots so that drainage water can discharge via non-return flaps into the Diamel,

b) leave an extensive floodway through their perimeter so that floodwater from the Dioulol, Navel and Thiemping cuvette can pass through to the Diamel and beyond.

6.5 Thiemping

There do not appear to be any major problems with the flooding or drainage of this cuvette at present. Therefore hydraulic management action is not a high priority as regards the functioning of the natural hydrological system or the traditional agricultural system.

The dredging of the Dioulol that has already taken place will certainly assist in flooding the cuvette.

The local informant believed that the single biggest improvement would come from the excavation of the largely blocked Diembahara marigot south of Tiali. The map shows that there is a very clear deep channel on the floodplain side of the levee but the actual entrance from the river appears to have become completely silted up. The informant reported that the river hardly ever enters the cuvette by that route any longer. The site could not be visited in the field because rainfall had made the track to Tiali impassable even on foot.

Gersar et al (1990) also favour the opening of the Diembahara channel with an excavation to a level of 11m IGN. They state (p414 Rapport) that the canal would carry water to three of their proposed irrigation perimeters to be located on the fonde soils and that it would assist in the flooding of the cuvette during high river flows. Gersar et al (1990) propose that a pumping station maintain water levels in the canal in periods of low flow whilst the works would be opened to allow a free inflow of flood waters to the cuvette.

7.0 Downstream Consequences of Pumping Stations

The question posed in the scope of work "What are the consequences for downstream flows of large pumping stations drawing water from the river" has a simple answer. The pumping stations will lower the flow downstream because they take water directly from the river. The drainage water from the irrigated perimeters will be brackish. The net effect of the pumping stations will be a river with relatively lower and saltier water.

The planning of the future water management of the valley has advanced significantly with the publication of Gersar et al (1990). This report develops the water resource allocation model used earlier by Gibb (1987). The Gersar et al (1990) study has adopted much more severe assumptions about the water requirements of irrigation and the likely losses in the system as water flows down the valley. Evaporation is now counted for the river, the Doue distributary, Lac de Guiers and the reservoir behind Diama. The efficiency of the distributaries is set at 65% which reflects to some extent the non return of water from these channels to the river. The evidence of the foregoing discussion is that 65% may be shown by subsequent studies to be a little over optimistic. Finally, a fourth loss parameter was introduced at a value of 90%. This coefficient, to cover losses in transport, simulated the inertia of the system in that releases from Manantali take many days to reach the lower parts of the valley and illegal pumping of water from the river by "pirates".

This Gersar et al (1990) simulation of the downstream movement of water under different development strategies has adopted more realistic assumptions than earlier versions of the model but there is further to go yet. The recharge and discharge of groundwater is an important process in the valley. The effect of the slow discharge of groundwater from the alluvium near to the river is to maintain dry weather flows in the river. This process is not included in the existing model and it is possible that baseflows in the river will change as the modified flood regime alters groundwater-surface water relationships. A further element which appears to be missing from the existing modelling effort for the river is the testing of the model against historical data. Nowhere in the reports to date does there appear to be a comparison of the performance of the model against a representative selection of past years.

Gersar et al (1990) were correct to conclude (p173, Rapport) that a first priority for subsequent studies was the modelling of the Senegal River taking into account the withdrawals of water, including irrigation, that are foreseen and the determination of the water levels which will be attained in the dry season under different development scenarios. With regard to the adverse effects of irrigation pumping on downstream water quality, Gersar et al (1990) also give as a priority a detailed study of the quality of drainage water and their effect on the environment.

Sadly, it is not possible to illustrate the likely impact on the Senegal River of the substantial ITALTEKNA pumping station at Matam. Since all of the technical documents are held in Italy, it was not possible to discover the likely pumping rate on site. However, some simplistic assumptions will permit a preliminary estimate. The mean potential evapotranspiration rate for Matam is 2183mm/year (Gersar et al (1990) and the mean open water evaporation is 2711mm/year. Given that Gersar et al assume global losses from their irrigation calculations of 23% it is not unreasonable to assume that ITALTEKNA will require up to 2500mm of irrigation water per year over their scheme area. The initial 2,000ha will deplete the river by 1.6 m^3/sec. The full scheme of 10,000ha may have to take almost 8m^3/sec from the river. This is likely to be around 4% of the flow maintained by Manantali in the medium term.

8.0 Recent Hydrological Studies Related to the Artificial Flood

There have been three significant developments in hydrological studies in relation to the artificial flood since Morel-Seytoux's report in 1988. First Gersar, Euroconsult, Gibb and SONED (1990, p 23 Annexes) have recognized that it is possible to maintain a balanced strategy in water management so long as planning is based on a 95% certainty of success rather than 100%. Second, ORSTOM have commissioned the telemetering system for river level recorders in the upper valley of the Senegal above Bakel. The data is routinely used to forecast flows at Bakel and to decide upon releases from Manantali. Finally, the ORSTOM real time forecasting model for the Senegal River (Lamagat, 1990) has been published and implemented in Dakar, Senegal.

8.1 Feasibility of the Artificial Flood

Hollis (1990) commented upon the narrow perspective taken by the Gibb (1987) studies, their focus upon hydro-power generation and their insistence upon the calculation of power and regulated flow levels with a 100% guarantee of achievement. It was argued that the inclusion of the driest years in the 1980s in this analysis distorted the results to the detriment of the many products and services flowing from the artificial flood. Hollis (1990) recommended that further work was undertaken examining the balance of demands upon Manantali if 95% or 90% guarantees of achievement were used.

Gersar et al (1990) have reexamined their simulations of water management strategies. Their finding (p23 Annexes) is that for 95% of the time, a flood of 7.5 $10^6 m^3$ can be released whilst maintaining a year round regulated discharge of 150 to $200 m^3/sec$ in the river and hydro-power of 70MW which is equivalent to 912GWh of energy. They conclude (p174 Rapport) that "it is possible to envisage the extension of double crop irrigation, equivalent to an intensity of cultivation of 160%, on the left bank in an area of 98,500ha, which has 88,000ha of growing crops, whilst at the same time generating artificial flood A with a volume at Bakel of 7.5 $10^6 m^3$". Clearly. there has been a major advance in thinking since the major consulting firms no longer see a conflict between irrigation, the artificial flood and hydro-power generation.

8.2 Telemetering of Hydrometeorological Data

Each of the major gauging stations in the Senegal Valley above Bakel have been equipped with telemetering water level recorders. The data is transmitted every three hours to OMVS Headquarters in Dakar by radio. The ORSTOM system, via the ARGOS satellite to the ORSTOM offices in Dakar, gives half hourly levels throughout almost the whole of each day. This system is operating without problems.

At the ORSTOM offices, the data is received by a desk top computer which automatically updates the data base and provides alarm signals at certain levels of flow. The system became operational for the flood of 1988 (Lamagat, 1990). Whilst there is no documentation available on the system, it was observed in operation during the visit to ORSTOM.

The visit to the meteorological station at Matam revealed that it transmits its observations every three hours to METEOSAT. After data quality control in West Germany, METEOSAT is able to transmit the data to all of the receiving stations within its range. ASECNA report that at present Matam is the only station to be equipped with this experimental facility. However it is planned to extend the facility to St. Louis and Bamako in the near future and to other stations eventually.

These two important developments show that the receipt of real time hydro-meteorological data is both practical and economic. This is important since subsequent sections of this report elaborate on ways in which Manantali could be better managed if there were improved real time forecasts of flow in the rivers.

8.3 Real Time Flow Forecasting Model

The details of the forecasting model were published by ORSTOM and OMVS as Lamagat (1990). The model is operational on desk top computers at both OMVS headquarters and the ORSTOM offices.

The model predicts downstream flows or water levels from a knowledge of upstream flows or water levels. It is based upon the twin premises that:

i) the speed of a flood wave down the valley is constant for a given upstream water level,

ii) there is a quasi-linear relationship between upstream flow or water level and downstream flow or water level.

Both of these major simplifications are defensible and they are certainly long established and traditional assumptions in hydrology. Indeed, a forecasting procedure for the Senegal River, essentially the same as that developed by ORSTOM, is set out in the report by the Service des Travaux Publics (1951).

The model is composed of sections representing the upper valley above Bakel and the lower reaches from Bakel to Boghe. The model for the upper valley consists of two sub-models. The first predicts conditions at Kayes (Senegal) from those at Oualia (Bakoye) and Manantali (Bafing). The second predicts conditions at Bakel from those at Kayes and Gourbassy (Faleme). Both of these sub-models for the upper basin operate on the basis of river discharge data. The model below Bakel operates only on water level in the river as measured at the stage board. It predicts sequentially down the river through Bakel, Matam, Kaedi, Salde and Boghe.

The upper valley model was calibrated with data from 1967 to 1971. The lower valley model used different periods for calibration. Bakel-Matam used 1961-65 and 1980-86. The latter period demonstrated lower water levels at Matam and faster transmission times for a given level at Bakel. Matam-Kaedi used 1980-86 data whilst Kaedi-Salde employed 1973-1977 and 1980-86 data for calibration. The Salde Boghe reach was calibrated on floods during 1968-72 and 1982-86. The reasons for these varied calibration periods is given. Usually over 80 data points are used in the calibration but it is not clear how these data points relate to individual floods during the years utilized. Save for the Bakel-Matam reach, shifts in the parameter values are not apparent in the calibration data used.

The calibration is undertaken in two steps. First, the flood wave propagation time is calculated by Lamagat's (1989) procedure to relate inflows-outflows and storage in reaches, and this is tabulated and graphed against flow or water level at the upstream station. Subsequently, an operational relationship is derived by a method which is not described. The method does not appear to be rigorous but sensible operational values are selected. Second, the upstream flow or aggregate of two tributary flows or water level is plotted against downstream flow or water level. A line is then fitted through the points again using an undisclosed and probably non-rigorous procedure.

The model is shown to operate successfully by the presentation of an observed and predicted hydrograph for each river reach. A different year's flood is used for almost every reach. The floods illustrated are taken from 1966, 77, 79, 80, 85, 86, and 88

The model provides a forecast period of from 1 to about 9 days depending upon the flow in the river, high flows giving shorter forecasts than low flows. Table 8.3.1 shows the forecasting horizons for a flow of 2,500 m^3/sec at Bakel. This level of flow was chosen because it is the peak flow for artificial flood A. The value of the stage board level at Bakel was taken from the graphical representation of the stage discharge relationship for Bakel for 1973-86 on page 43 of Lamagat (1989). This was necessary because the tabulation of the rating curve on pages 35 and 36 misses out stages between 659 and 800cm which accords to flows between 2001 and 2825 m^3/sec.

The model reproduces the test hydrographs very successfully. The discussion in Section 9 below suggests that it has been used successfully to achieve a flow at Bakel appropriate to the Artificial Flood A for certain periods of time. As such it is suitable for the purposes of OMVS whose policy is to endeavour to achieve Artificial Flood A for a transition period whilst irrigation is developed in the valley.

The OMVS contingent at the technical discussions in Dakar strongly supported the idea of an "augmented" flood rather than an "artificial" flood. This was because timing releases from Manantali to coincide with the peak of the natural flood from the uncontrolled part of the basin would economise on water from Manantali. It would also achieve a hydrograph similar to Flood A but at a time determined by nature. Gersar (1990 p16 Annexes) say that "the aim is to make the peak of the artificial flood coincide with the peak of the natural flood from the uncontrolled tributaries". Sadly, they do not follow this with any effort to examine an augmented flood. Instead they merely restate the reasons used to select the artificial floods A, B and C.

Table 8.3.1 Forecasting horizons for a flow of 2,500m^3/sec at Bakel using the ORSTOM model (Lamagat, 1990).

Station	Days	Flow m^3/sec	Level cm Stage Board
Soukoutali and Oualia	-2.5	1,600	
Kayes and Gourbassy	-1	2,150	
Bakel	0	2,500	755
Matam	+3.0		775
Kaedi	+6.75		700
Salde	+9.75		800
Boghe	+14.25		740

Morel-Seytoux (1988) comments on the advantages of such an augmentation of the natural flood. He notes, however, that such a regime will require the political will to allow the level of the reservoir to be drawn down before subsequently rising after the releases have finished.

The ORSTOM model is not capable of providing a sufficiently long forecast horizon to permit the operation of an "augmented" flood strategy because:

a) the model gives a forecast 1 day ahead for the Faleme and 2.5 days ahead for the Bakoye. This is not sufficiently long to demonstrate if a significant natural flood is about to occur and therefore to show that the releases should be made from Manantali. The model cannot forecast the uncontrolled tributaries likely contribution to the augmented flood. An "augmented" flood A would have a duration of around 30 days at 50% of peak discharge.

b) the model cannot forecast the need to make the releases that are necessary from time to time for the safe operation of Manantali. This is because the model has no facility to forecast levels in Manantali. The Makana gauging station is said to be used to give a few hours warning of forthcoming high discharges into Manantali.

   Therefore, the model does not permit decisions on "artificial" or "augmented" releases to be made on the basis of any knowledge of future "essential" releases.

There was complete unanimity in the technical discussions with OMVS that the existing ORSTOM model was not suitable for the management of an "augmented" flood.

A further difficulty with the ORSTOM model is that it can only be used in the valley below Bakel whilst irrigation perimeters cover a tiny fraction of the floodplain. As elaborated in Hollis (1990) and Gersar et al (1990, p33 Annexes) the creation of 130,000ha of irrigated area behind flood protection embankments will raise water levels at Matam by 0.73m and by up to 0.82m in the lower valley. The reason for this is that the removal of floodplain storage for water by embankments merely forces the water to be stored at a greater depth on those parts of the floodplain without banks.

Therefore, the calibration of the ORSTOM model will quickly become outdated as perimeters are commissioned. It will require recalibration in the lower reaches below Bakel as embanked perimeters, water control structures and pumping alter the nature of the downstream hydrology. However, such recalibration is not possible on a year to year basis since a wide range of flows are needed to ensure the model's applicability over all likely flows.

Finally the model has been used, eg Gersar et al (1990, p27 Annexes), to calculate water levels along the river for certain dry season releases from Manantali. It is very dangerous indeed to use the model for this purpose because it has been calibrated against flood discharges in the wet season and it does not model any of the physical processes involved. The relationship of the river to the alluvial and deeper aquifers is different in the dry season from that in floods; the evaporation rate peaks in the spring and is at its lowest during floods; and the relationships between the distributaries and the main river may be different during the dry season than during the rise and fall of floods.

Therefore, whilst presently a usable tool given current policies for the management of Manantali, the ORSTOM flood forecasting model is entirely inappropriate for use in the medium term for the creation of an "augmented" flood in the Senegal River. It is also dangerous to derive contra-saison water levels from the model for the time when Manantali is making baseflow releases.

It is reasonable to suppose that, despite the desires of OMVS and the stated aim of Gersar in matching the timing of the artificial and natural floods, the actual management of Manantali is restricted to the things which are operational at the time. Therefore, the poor forecast horizon of the ORSTOM model is a positive bar to the achievement of an augmented flood with its concomitant benefits to the people of valley and the conservation of water stored in the reservoir. As Morel-Seytoux (1988) observed, "long-term forecasting has received little attention despite its importance for reservoir management."

9.0 Operation of the Artificial Flood

A written statement of the precise operating rules for Manantali was not obtained but they were outlined in conversation. A vital element in the current management of Manantali is that the dam must be filled in 1991. This will enable the consulting engineers to undertake tests of overflows down the spillway whilst they retain responsibility. However, the dam must not be allowed to fill at too great a rate since the earth part of the dam needs to saturate with water at a controlled rate. The maximum allowable rate of rise of the reservoir is around 10cm per day. During the hivernage, an effort is made to ensure that the flow at Bakel follows the artificial flood hydrograph A. In the contra-saison releases are made for the benefit of the river and river users downstream.

Morel-Seytoux (1988) wisely observed that three things were necessary for the achievement of the artifial flood:

- sufficient water in the reservoir,
- enough political will to ensure an artificial flood, and
- respect for decisions to release a flood by the actual operators in charge of Manantali.

At present, there is no attempt whatsoever to top up a natural flood generated in the uncontrolled tributaries before the dates appointed by Gibb. It is fully appreciated that this is a sub-optimal procedure which uses more water that would otherwise be necessary.

The discharge hydrographs for Bakel and Manantali for the years 1986 to 1989 are shown in Figures 9.1, 9.2, 9.4 and 9.6 with the artificial flood hydrograph superimposed. The inflow to Manantali at Makana and the outflow from Manantali for 1987 to 1989 is shown in Figures 9.3, 9.5 and 9.7. It is appropriate to discuss the operation of the artificial flood year by year.

9.1 Flood of 1986

This was the last year before the closure of Manantali and represents the last natural flood in the valley. As stated earlier in Section 2, the 1986 flood was broadly similar to Flood A but with a slightly higher and earlier peak. Figure 9,1 shows that only a modest portion of the Bakel flow came from the Bafing above Manantali.

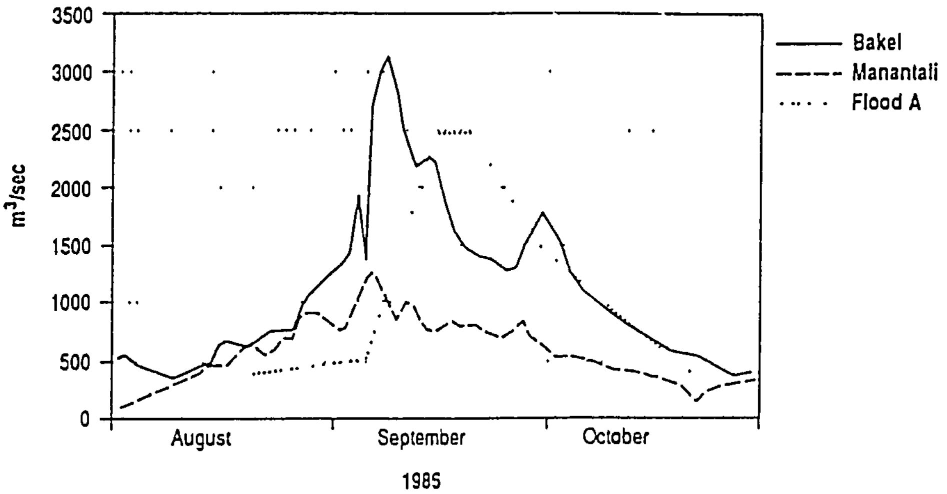


Figure 9.1 The hydrograph for 1st August to 31st October 1986 for Bakel and downstream of Manantali with Flood A superimposed.

9.2 Flood of 1987

The flood of 1987 at Bakel was particularly low with three insignificant peaks. The flood was much smaller in volume and peak flow than Flood A and therefore the artificial flood was not achieved during this year. There were, however, releases from Manantali of up to 1000 m^3/sec. It is important to appreciate that the telemetering of data and the real time ORSTOM forecasting model were not operational in 1987.

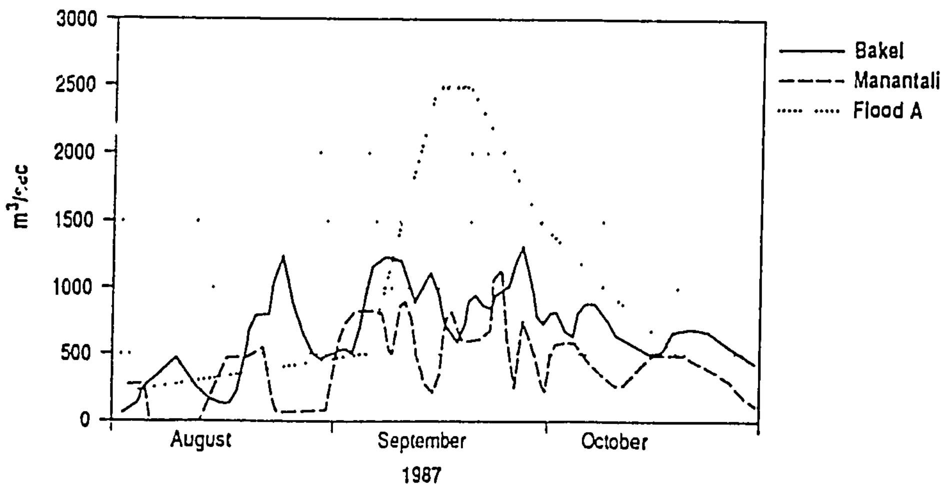


Figure 9.2 The hydrograph for 1st August to 31st October 1987 for Bakel and downstream of Manantali with Flood A superimposed.

During August 1987 (Figure 9.2) water was released from Manantali when the flow at Bakel was less than Flood A. When the flow at Bakel was above flood A then the releases promptly terminated. At the beginning of September there were big releases such that the flow at Bakel began to climb close to the rising limb of flood A. However after 7th September the releases were terminated and there followed two months of irregular releases with the flow at Bakel never approaching flood A until the very end of October. Figure 9.3 suggests an explanation for the large and rapid changes in the releases from Manantali. When the releases from Manantali exceeded the inflow at Makana, i.e. water level in the reservoir began to fall, the releases were terminated.

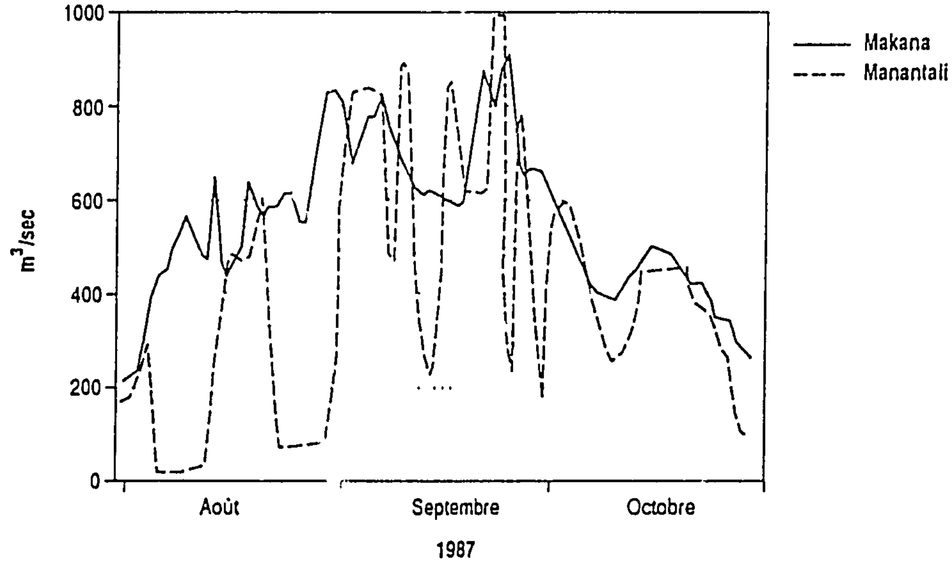


Figure 9.3 The inflow to Manantali (Makana) and the releases from Manantali (Manantali) for 1st August to 31st October 1987

In conclusion, it was not possible to achieve the artificial flood A in 1987 and the technical means to link releases to target flows at Bakel was apparently lacking. Morel-Seytoux (1988) comments that the dam was still under the control of the consuolting engineers in 1987. He adds, ominously, that the failure to respect the operating rules set out by Gibb bodes ill for the artificial floods in future years.

9.3 Flood of 1988

The flood peak in 1988 at Bakel was much higher than flood A and it occurred several days before the peak of flood A (Figure 9.4). The recession limb of the actual flood followed the recession limb of flood A very closely from September 22nd onwards. About one third of the peak flow at Bakel came as result of a large release from Manantali which began very suddenly at the beginning of September. Figure 9.4 suggests that, with the aid of the

ORSTOM model, it was possible to fine tune releases from Manantali after 22nd September so that the recession limb of flood A was followed faithfully.

Figure 9.5 shows that the rapid rise of flow at the beginning of the release and the peak rate of release were closely related to times of rapid rise in the level of Manantali. It is likely that the releases were made in order to respect the rule relating to the permissable rate of rise of the reservoir rather than to create a large flood in excess of flood A. The fine tuning of the recession limb of the Bakel hydrograph was done with allowing releases to exceed the inflow from Makana for more than a couple of days.

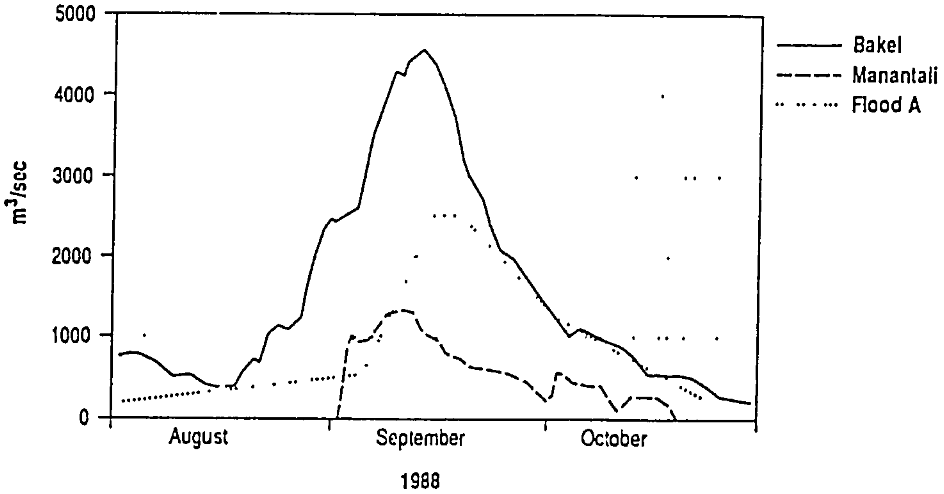


Figure 9.4 The hydrograph for 1st August to 31st October 1988 for Bakel and downstream of Manantali with Flood A superimposed.

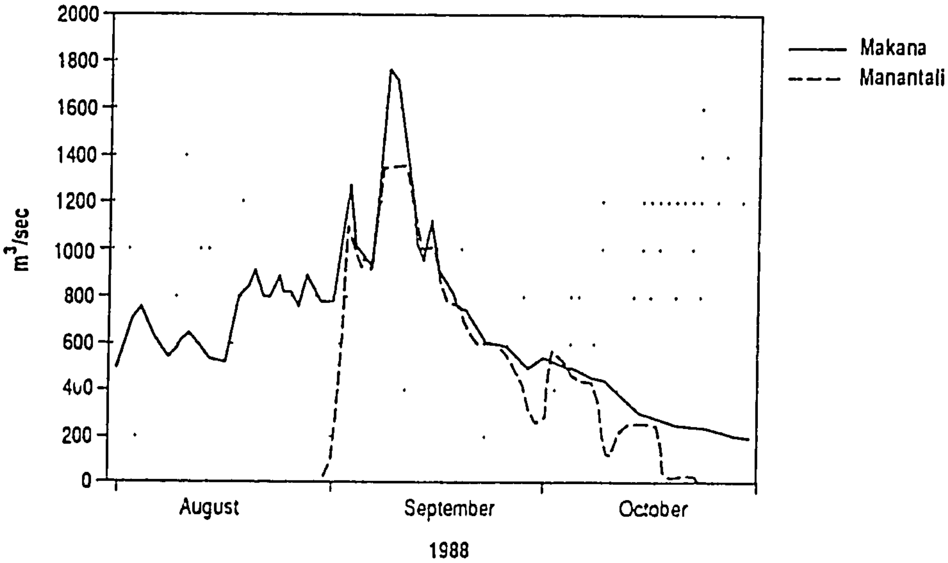


Figure 9.5 The inflow to Manantali (Makana) and the releases from Manantali (Manantali) for 1st August to 31st October 1988

The experience of the flood of 1988 shows that it is technically possible to achieve a good reproduction of the recession limb of the artificial flood hydrograph. However, the synchroneity of the peak releases with the flood peak at Bakel probably owes more to the timing of flood inflows at Makana than to a conscious management decision to maximize the downstream flood.

9.4 Flood of 1989

The substantial flood peak at the end of August 1989 was achieved with only a brief and small release from Manantali (Figure 9.6). On about 8th September the recession limb of the largely natural hydrograph was falling below the rising limb of flood A. Manantali released a large slug of water and the hydrograph began to rise in very close accord with flood A. However the releases from Manantali soon exceeded the inflow at Makana (Figure 9.7) and the release of water promptly stopped. On the 18th October, when there was a sudden rise in the already high inflows to Manantali, a large release was made which equalled the rate of inflow for a few days. This second large release of almost 850 m^3/sec elevated the second peak at Bakel from just over 2,000 m^3/sec to almost 3000 m^3/sec. The flow at Bakel did not follow the recession limb of flood A very closely (Figure 9.6) because whenever the releases exceeded the inflow at Makana (Figure 9.7) they were reduced substantially.

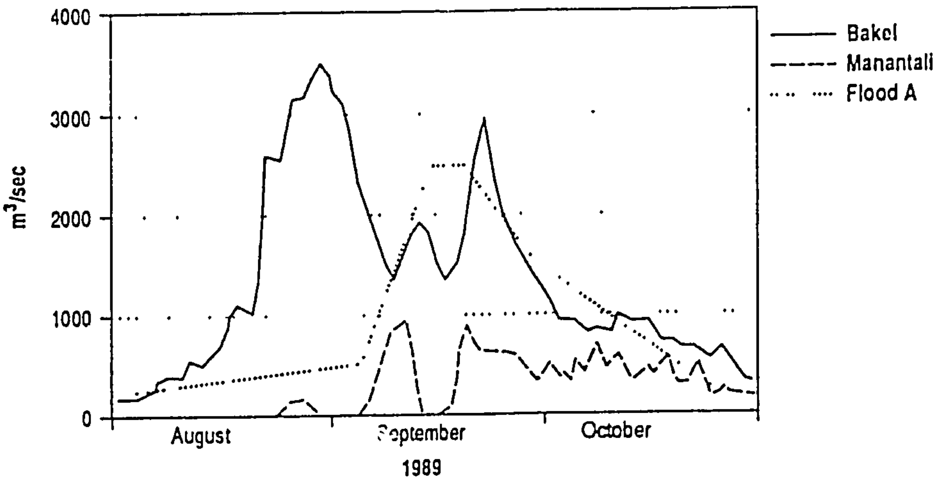


Figure 9.6 The hydrograph for 1st August to 31st October 1989 for Bakel and downstream of Manantali with Flood A superimposed.

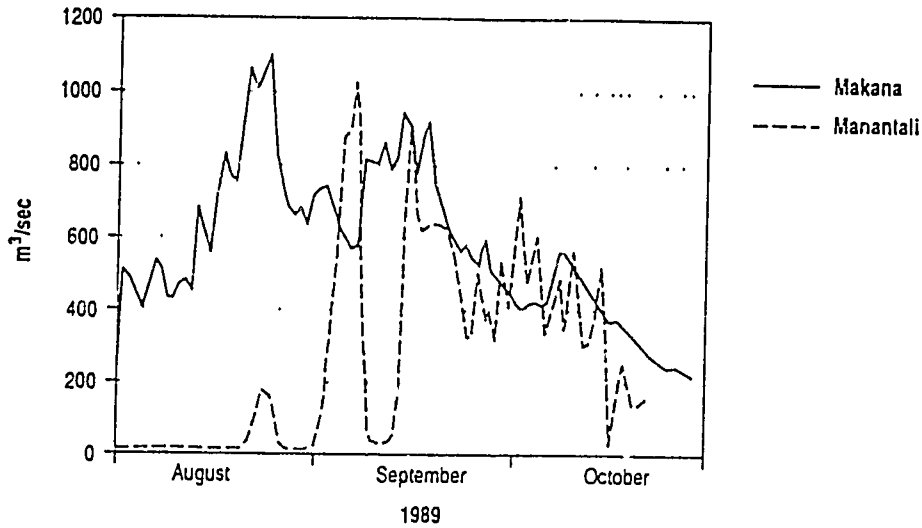


Figure 9.7 The inflow to Manantali (Makana) and the releases from Manantali (Manantali) for 1st August to 31st October 1989

Clearly the experience of the first two years of operations has been valuable for the operators of Manantali because they were able to recreate a part of the rising limb of flood A. Their manipulation of the recession limb was much poorer than in 1988, probably because of the apparent need to keep releases below the level of inflows.

The experience of 1989 suggests that there is a need to forecast the inflows to Manantali to facilitate a more measured control of its water level and the reservoir releases. In addition, a strategy which aimed to optimise the flood conditions downstream, rather than following slavishly a pre-ordained hydrograph, could in 1989 have avoided a double peaked hydrograph and produced a longer and more sustained flood with smaller releases from the dam.

There was some comment in Dakar on the reasons for the double peaked hydrograph and the release strategy for Manantali in 1989. Some people asserted that the problem was late rains in the uncontrolled part of the basin. Others suggested mis-management by OMVS staff at Manantali who delayed opening the sluices despite instructions from Dakar. Apparently, whilst the telemetered data arrives at OMVS in Dakar where it is input to the model for forecasting purposes, instructions issued can, from time to time, conflict with the somewhat independent position taken at Manantali itself.

9.5 Conclusions

The implementation of the ORSTOM real time forecasting model enabled the management of releases from Manantali to follow both the rising and falling limbs of flood A at Bakel. Late September and October 1988 and 9th - 13th September 1989 are examples of where the recession limb and the rising limb respectively have been followed very closely.

The seemingly overriding importance attached to the need to fill Manantali as quickly as possible, and certainly by 1991, has apparently limited the achievement of the artificial flood to date. The whole of 1987 and October 1989 are examples of where releases appear to have been restricted to less than inflows at Makana even when flood A demanded greater releases.

The necessity to limit the rate of rise of the reservoir has necessitated large and sudden releases from Manantali. In 1988 the release aided the formation of the flood peak but in 1989 it enlarged a rather undesirable secondary peak.

There appears to have been no effort at all to produce an augmented flood by releasing water from Manantali to coincide with the peak of the natural flood from the uncontrolled part of the basin. In the view of OMVS staff in Dakar such a management regime is impossible with the limited forecast horizon of the ORSTOM real time forecasting model.

10.0 Availability and Use of Daily Hydrological Data

The Senegal River basin is unusually well provided with gauging stations, raingauges and meteorological stations all of which record data on a daily basis. In addition the length of record for some of these stations, from 1903 in some cases, is exceptional. The very substantial body of data available from the early 1950s is particularly important.

10.1 Rainfall

Rochette (1974) lists, for the upper basin, 16 raingauges in Mali, 2 in Senegal, 9 in Guinea and 5 in Mauritania. They had 844 stations years of data between them up to 1964. The number of station years of daily rainfall data for the upper basin is now likely to exceed 1,600. Rochette lists 10 Senegalese rain gauges for the lower basin and 5 Mauritanian ones. They had 530 station years of data in 1964 and this has probably grown now to around 800 station years of data. Rochette therefore utilized data from 47 rain gauges in the Senegal Valley. All of this data is published up to 1965 by ORSTOM (1974a) for Mali, ORSTOM (1974b) for Mauritania and ORSTOM (1974c) for Senegal. The daily rainfall data from 1966 to 1988 for Senegal is published in ORSTOM (1989) whilst that for Mali is said to be in press. It is believed that all of the rainfall data is held on computer files at ORSTOM Montpellier. At an initial technical meeting it was said that OMVS have a complete copy of the ORSTOM data archive but during a subsequent discussion it was said that OMVS hold no rainfall data.

Sow (1984) employed data from 49 raingauges for the period 1951 to 1980. The data for the gauges in Guinea was obtained through the Guinean Embassy in Dakar. Sow's analysis tackled only the monthly or annual totals of rainfall.

Lo (1984), in his analysis of the Gambia River Basin, names raingauges at Saraya and Nafadji in the headwaters of the Faleme, the latter station is in addition to those used by Sow. Lo also uses data from rain gauges at Fongolimby, Kedougou, Bransan, Boutougou Fara, Dalafi, Dianke Makan and Goudiry which are in the Gambia basin but close to the watershed with the Faleme basin.

10.2 Climatological Data

The Senegalese Meteorological Service have computerised all of their records. A series of floppy disks hold the data for each station. Daily data for mean temperature, minimum temperature, maximum temperature, relative humidity, vapour pressure (rarely available in fact), hours of bright sunshine and wind speed
was provided on floppy disk for Matam for 1950 to 1978 and for Bakel from 1968 to 1983.

In retrospect, the failure to penetrate deeper into ASECNA has left an incomplete knowledge of the availability of climatological data for the basin.

For the upper basin, Rochette (1974) reports wind speed and direction data for Kayes (14 years of data), Kenieba (14 years of data), Labe (Guinea with 7 years of data), Kita, Nioro, and Siguiri (Guinea). He presents mean temperature data for the same six stations plus Bafoulabe and Faladie. Insolation data is presented for Kayes, Kenieba and Labe in Rochette (1974).

For the lower basin, Rochette (1974) presents a basic range of climatological data for Matam, Rosso and St. Louis.

It is likely that the quality of climatological data collection has improved considerably in recent years in the valley. The ASECNA station at Matam, for example, was visited during the fieldwork. The station was exceptionally well equipped with a wide range of excellently maintained instruments and two highly experienced staff on site. The parameters measured are:

- rainfall
- rate of rainfall
- maximum and minimum temperature,
- wet and dry bulb temperature also with autographic thermograph and hygrograph
- Piche evaporation,
- wind speed and direction,
- sunshine and solar radiation,
- grass minimum, and soil temperature at four levels down to 1 metre,
- general meteorological observations,
- level of the river.

The data is recorded meticulously on a three hourly or daily basis as appropriate. A very significant recent development at the station has been the installation of an Epson computer, transmission equipment and an aerial to send Matam's meteorological observations to METEOSAT every three hours. It was reported that after data quality control in Darmstad, the data are rebroadcast to receiving stations over the whole area covered by METEOSAT.

At present Matam is the only station with this Meteosat link but ASECNA plan to extend the facility to Bamako and St. Louis in the near future and to other stations later.

10.3 Evaporation and Evapotranspiration

There appear to be far fewer stations measuring evaporation than there are rain gauges. In general Piche atmometers are much more common than evaporation pans.

The Senegalese Meteorological Service was able to furnish monthly Piche data for Matam for 1951 to December 1988. The data is, however, collected on a daily basis and the sheets completed at Matam include daily evaporation. The climatological data base utilized by the Senegalese Meteorological Service has the facility to calculate Penman's Potential

Evapotranspiration from the data recorded at each station but it was said that this was never undertaken.

Rochette (1974) presents summary data for Piche evaporation at Kayes, Kenieba, Labe, Matam, Rosso and St. Louis. The only evaporation pan data in Rochette is for Felou and Kenie which is outside the basin and near to Bamako but he names three other stations in Mauritania with evaporation pans.

10.4 River Flow Data

There is a particular wealth of river flow data for the Senegal Basin. All of the daily data up to, and including 1964, is published in Rochette (1974). The full dataset exists in computerized form at the ORSTOM archive in Montpellier and with OMVS.

Table 10.4.1 summarizes the data which has been collected and which may be obtained from ORSTOM, OMVS or the Ministere de l'Hydraulique for the those stations located in Senegal.

Table 10.4.1 River Flow Data for the Senegal Valley - Temporary Stations and those with only a small number of years of record are excluded. (after Rochette, 1974)

Station	River	Catchment Area km^2	Start of Records
Fadougou	Faleme	9,300	(1945) 1952
Gourbassy	Faleme	17,100	1954
Kidira	Faleme	28,900	(1903) 1951
Balabori	Bafing	11,600 (Guinea/Mali frontier)	1955-56 only
Dakka Saidou	Bafing	15,700	1952
Makana	Bafing	22,000	1955
Toukoto	Bakoye	16,500	(1903) 1958
Oualia	Bakoye	84,700	1954
Bafoulabe	Senegal	124,700	(1904) 1930
Kayes	Senegal	157,400	1904
Bakel	Senegal	218,000	1903
Matam	Senegal	230,000	1903
Kaedi	Senegal	253,000	1903
Salde	Senegal	259,500	1903
Podor	Senegal	266,000	1903
Dagana	Senegal	268,000	1903
Richard Toll	Senegal		1906
Rosso	Senegal		1951

10.5 Groundwater Level Data

The OMVS/USAID Groundwater Monitoring Project installed 569 piezometers in the Senegal Valley according to the following criteria (OMVS/ISTI, 1990):

1. one shallow piezometer/100ha within large irrigation perimeters,

2. 10 piezometric profile lines perpendicular to the River with shallow, medium and deep piezometers,

3. an overall density of one piezometer/100km^2,

4. detailed piezometric lines perpendicular to the river in the zone of influence of Diama Dam,

5. one piezometer per distinct geological target.

These piezometers, and a number of village wells, were observed monthly during the period from installation after 1986 to June 1990. In Senegal the observations are continuing at present but observations have apparently ceased in Mali and Mauritania.

There are in addition detailed well hydrographs for 138 piezometers studied by Illy from 1971 through to 1973.

10.6 Flood Level in Cuvettes and Distributary Channels

The data available for the actual level of flood water in cuvettes and distributary channels has only been investigated in detail for the three study cuvettes around Matam. The data, discussed and exemplified above in Section 5, consists of daily measurements of water level on 17 stage boards from the Dioulol to the lower reaches of the Diamel for the period 1st July 1978 to 20th November 1978.

Illy (1973) presented a diagram (Figure 5.9) giving daily values of water level at Kanel in the south east of the Thiemping cuvette.

10.7 The Responsible Agencies

The hydrometeorological network is operated by several organizations. The precise responsibilities of each organization were not researched in detail in Senegal but there is clearly duplication of effort and imprecise limits to responsibilities.

At Matam, for instance, the Meteorological Station is operated by ASECNA. However it is one of Senegal's main synoptic network of stations reporting to the National Meteorological Service. In addition, it is the ASECNA staff who record the level of the river. This latter data is essential for OMVS, the Senegalese Ministry of Hydraulics, CAB and Mauritania. In this instance, their appears to be an sensible, efficient and economical arrangement.

The network of piezometers in Senegal which form part of the OMVS/USAID Groundwater Monitoring Project are operated by OMVS. The data is gathered and centralised by OMVS but it is only available to agencies of the Senegalese Government by special arrangement.

The majority of meteorological stations in Senegal are operated by the National Meteorological Service, some are operated by ASECNA and others appear to be jointly operated under arrangements which are unclear.

The data from the river gauging stations is centralised by OMVS who cooperate with ORSTOM for the maintenance of a database of river flows. The Ministry of Hydraulic Works in Senegal receives copies of the river flow data. In the case of Matam, ASECNA is responsible for the actual recording of the data.

Hydrometeorological data for the other three countries sharing the Senegal River Basin is not readily available in Senegal. This is despite the existence of two international agencies who have a major role to play in centralising data from the whole region.

A very major gap in the hydrometeorological network is the apparent lack of any link whatsoever between Guinea and the international agencies, OMVS and ASECNA. It would appear that the only hydrometeorological data for Guinea that exists in Senegal is in the hands of M. Sow at the University of Dakar who obtained the information through personal initiative. Several international bodies do enjoy links with Guinea and a large body of monthly rainfall data for the headwaters of the Bafing, Bakoye and Faleme have been obtained through the good offices of the USAID mission in Conakry.

The model, established by ORSTOM in publishing the riverflow data in full up to 1964 in Rochette (1974), the rainfall data up to 1964 in ORSTOM (1974a,b &c) and the rainfall data up to 1988 for Senegal, should be continued. It will be important to establish publicly accessible sources of all of the hydrometeorological data for the Senegal Valley and data on rainfall, climatology and riverflow in Guinea should be included if at all possible.

10.8 The Application of Daily Data to Problem Solving

There has been very little detailed analysis of the hydrology of the Senegal River using the welter of daily data available. Rochette (1974) and Sow (1984) concentrated heavily on the use of monthly and annual data although Sow (1984) does examine peak daily flows in some detail. Gibb (1987) must have had access to the daily data in order to define the hydrographs of the artificial floods but the tabulations in their report employ monthly data. Even Gersar et al (1990), when looking at likely flows at Bakel under different development scenarios (Figure 2.5.4, p 21, Annexes) produce hydrographs with only one data point per month. Gersar et al (1990, p154 Rapport) state that it is impossible to calculate the areas likely to be flooded by the natural flows of the Faleme and Bakoye without a complex hydrological analysis. Their rapid termination of the issue with some qualitative generalizations suggest that they do not want to get involved in analysis of daily flow data.

ORSTOM have made use of their archive of daily data. The ORSTOM real time forecasting model (Lamagat, 1990) must have used daily data in the calibration of the model, although this is not clear from Lamagat (1990). The fact that the model has a time step of 6 hours suggests that, at least, daily data must have been used in the calibration. M. Bader of ORSTOM, who is undertaking the current investigation into the effect of different operating rules at Manantali on downstream flows, is certainly using the data bank of daily data.

11.0 Status of Hydrological Knowledge

The conduct of the mission during August and early September meant that several of the main actors in the water management scene were absent on holiday or left for a vacation very soon after a preliminary courtesy call had been made. This section is not, therefore, as informed or as informative as might have been the case if more people could have been contacted during the second part of the mission when the situation was more fully understood.

11.1 The Contractor's Views

M. Seguis (ORSTOM) identified the uncertainty about the area flooded and the area cultivated as one of the major problems. M. Seguis stated that there was to be a major new programme launched in October 1990 with studies using SPOT in October and March/April to determine the areas flooded and the area cultivated around their study area around Podor. In addition, M. Bader (ORSTOM) confirmed that his immediate research programme involved the study of the effect of different operating regimes for Manantali on the downstream flow. He is using daily data for all of the rivers in the upper catchment along with the ORSTOM flow forecasting model to translate flows at Manantali, and those in the Faleme and Bakoye into discharges and levels downstream. No report or documentation was available for this study, as had been the case for Morel-Seytoux in 1988. The latter had emphasized the importance of this study for the long-term management of the dam.

The two ORSTOM hydrologists appreciated the limited forecast horizon of the ORSTOM flow forecasting model and agreed that it could not be used when significant changes in flood plain storage had been caused by embanked perimeters. However, further work on flow forecasting in the upper valley is not a priority for ORSTOM.

M. NGom (OMVS Groundwater Monitoring Unit) noted that one of the problems was that his unit had only begun to collect groundwater data after the closure of Manantali. The fact that Illy's (1973) data also covers a period without significant floods because of the drought does not offset this difficulty.

For M. NGom, the two big priorities were the continuation of the field monitoring of groundwater level and the delta region where salinity is such a problem. He commented at some length on the way in which groundwater levels have risen under the irrigated perimeters in the delta with adverse effects on the soil salinity.

M. NGom accepted the recommendations of the final monitoring report that a comprehensive computer model of the whole valley and delta was not necessary. It was his belief that it would be better to develop a series of small local models at the level of individual PIVs or irrigated perimeters.

M. Sow (University of Dakar) believed that there was insufficient attention being given to the study of hydrological processes in natural catchments. His current research agenda is focussed on presently natural hydrology of the catchment of the Gambia basin. He was enthusiastic about the possibility of studies of the functioning of the Faleme and Bakoye catchments because, in this context, studies and modelling of a natural system would be useful for management work.

Gersar et al (1990) do not make many specific recommendations for further studies but it is possible to gleam a number of priority issues from their text.
In their overall conclusions from the discussion of the water resource management scheme (p174, Rapport) they say that the potential area of irrigated land depends on weather conditions in the future, the priority accorded to irrigation compared to other water uses, and "the real efficiency of releases of water from Manantali". This latter issue is very serious because there have been no studies of the fate of regular dry season releases from the dam. The Annexe dealing with water management (p27) states that the estimation of water levels down the river with various levels of release from Manantali have been estimated with the ORSTOM flow forecasting model. Gersar et al (1990) say that this takes account of evaporation and infiltration but <u>not withdrawals of water for irrigation</u> (their emphasis) nor the eventual creation of a navigable channel. It is therefore implicit that there needs to be a study, probably using test releases from Manantali, of the fate of water released.

Gersar et al (1990, p29 Annexes) say that there is insufficient data on areas inundated. They comment (p19) that only a series of systematic observations year by year of the area inundated and the area cultivated under recession agriculture will allow the refinement of estimates of these parameters for the artificial flood.
They note, (p7) that their new estimates of evapotranspiration by the Penman method are higher than the figures derived earlier by other methods. This suggests that evapotranspiration needs to be examined more closely in the valley.

11.2 The Client's Views

The conversations with OMVS staff were particularly fruitful in identifying research needs in hydrology.

Because it is hard to determine a simple relationship between area flooded and area cultivated there is a great need to continue the existing programme of mapping flood extent and flood recession cultivation from satellite imagery. In the ground truthing of this data, it will be important for IDA to compare their field data on cultivated area with the information gathered by OMVS. An ARC-INFO GIS has been installed and this will be ideal for the comparison of the various maps. The aim should be to develop a mutually acceptable procedure for continued monitoring.

Since the UNE model, with its simplifications and generalizations, can be criticized, hydrological studies in the cuvettes and distributaries are required. The appropriate technology is manually read stage boards.

Because of the variation in results between cuvettes, a study is needed to classify the cuvettes of the valley and to determine representative examples of each type.

The present ORSTOM forecasting model, which gives a forecast for only three days ahead, does not allow managers to top up a natural flood from the uncontrolled tributaries. It may be possible to produce an augmented flood by topping up uncontrolled flow if a forecasting procedure could be developed which allowed the prediction of the hydrograph for, at least, 14 days ahead. The development of such a real time flow forecasting system will have rainfall-runoff relationships at its core. In this context, data from Guinea will be essential for the model.

There is a need for a report for the Middle Valley from the Groundwater Monitoring Project. Such a report will be more definitive than earlier studies since it will be based upon many more boreholes.

SAED was contacted at the level of their senior engineers in Matam. Their strong view was that SAED was concerned with the implementation of irrigated perimeters and not with research. However, their concern to ensure an adequate supply of water to pumps feeding their perimeters has lead to a demand to understand rather better the hydrology and hydraulics of flows along the distributary channels and into and out of cuvettes.

ITALTEKNA are monitoring water levels at four points around their perimeter but no other research work is envisaged,nor is any apparently needed in their view, for the completion of their 10,000ha scheme.

12.0 Hydrological Analyses

12.1 The Probability of a Natural Flood of Type A

The scope of work asks about the probability of flooding more than 50,000ha. This is believed to reflect the misconception that Artificial Flood A would inundate 50,000ha and so make flood recession cultivation possible on that area. The question has been interpreted to seek the probability of a natural flood from the uncontrolled tributaries alone constituting a flood of Type A.

It is not possible to answer this question without the full data set of daily flow values from Oualia, Kidira (or Gourbassy) and Bakel. The data for Bakel is available at IDA but it was not possible to collect the Oualia and Kidira data in Senegal.

Rochette (1974) presents a flood frequency curve for annual maxima data for the Faleme at Kidira (Figure 111.33, p 299). This shows that 2,500 m^3/sec can be expected as the annual maximum flow at Kidira 15% of the time, i.e. one year in 6 or 7 years the flood peak will exceed 2,500 m^3/sec. A flow of 1,500 m^3/sec can be expected every 1.36 years.

Using the data for 13 years up to 1964 for Oualia th· published in Rochette (1974), a simple flood frequency curve has been prepared (Figu.. ..1). This curve suggests that 2,500 m^3/sec can be expected at Oualia about once every 15 years. 1000 m^3/sec can be expected almost every year.

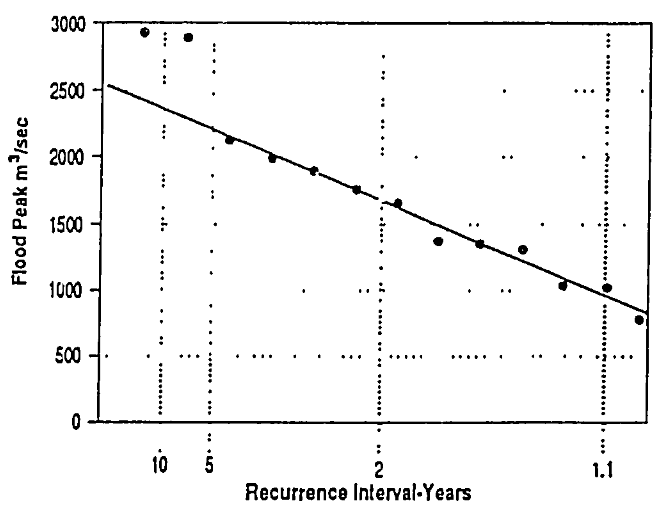


Figure 12.1 Flood frequency curve for the Bakoye at Oualia using data from 1952 to 1964

Sadly, it is not possible to combine these two pieces of analysis to calculate the probability of a flood of 2,500 m^3/sec at Bakel from just these two streams. This is because there are two independent probability distributions and they cannot be combined in any simple manner.

As an alternative, and primarily to illustrate the method rather than to derive a definitive answer, the peak of the aggregate flow at Kidira and Oualia for 1952 to 1964 and from 1986 to 1989 have been calculated from the data published in Rochette (1974) and from OMVS daily flow data available through CAB in Dakar. The aggregate of the daily flows at each station is only a preliminary estimate fo the actual flow at Bakel. A fuller analysis would allow for the slightly great time of travel for the flow from Oualia than from Kidira and there would be an additional element of flow calculated for the parts of the basins downstream of the gauging stations and downstream of the Manantali dam in the Bafing catchment.

Table 12.1 shows that it would be unproductive to attempt to plot a flood frequency curve because the two periods of data are so clearly different. If we use the 1954 to 1964 data, then we can conclude that a flood at Bakel of more the 2,500 m^3/sec would be likely almost every year. The data for 1986 to 1989 suggests that such a flood would be most unlikely ever to occur.

Table 12.1 The peak of the aggregate daily flows in the Faleme at Kidira and in the Bakoye at Oualia.

Year	Peak aggregate flow m^3/sec
1954	4202
1955	2496
1956	3651
1957	3250
1958	3587
1959	3044
1960	2569
1961	no data
1962	3115
1963	2069
1964	5115
..	..
1986	1255
1987	782
1988	1853
1989	1514

Gersar et al (1990) state that (p20, Annexes) that using data for 1903 to 1971, the largest of the artificial floods (Type C, Volume 10,000 10^6 m^3, Peak 3,000 m^3/sec) would have been exceeded in 52 out of the 68 years.

12.2 The Relationship between Flood Volume and Duration at Bakel

The peak flow and volume of the flood from August to October for the years 1930 to 1986 were taken from Gersar et al (1988). The duration of flows in excess of 2,500m^3/sec and in excess of 4,000m^3/sec were abstracted from a printout of daily flows at Bakel which is available at IDA.

Figure 12.2 shows that there is a poor relationship between the number of days that flow is over 2,500 m^3/sec and over 4,000 m^3/sec at Bakel. The reason for this is the wide variety of hydrograph shapes which occur at Bakel, some being relatively low and flat whilst others are relatively tall and narrow.

The strong relationship between the number of days over 2,500 m^3/sec and the volume of the flood is illustrated in Figure 12.3. The regression line that is plotted explains 87.5% of the variance in flood duration with a standard error in flood duration of 8 days.

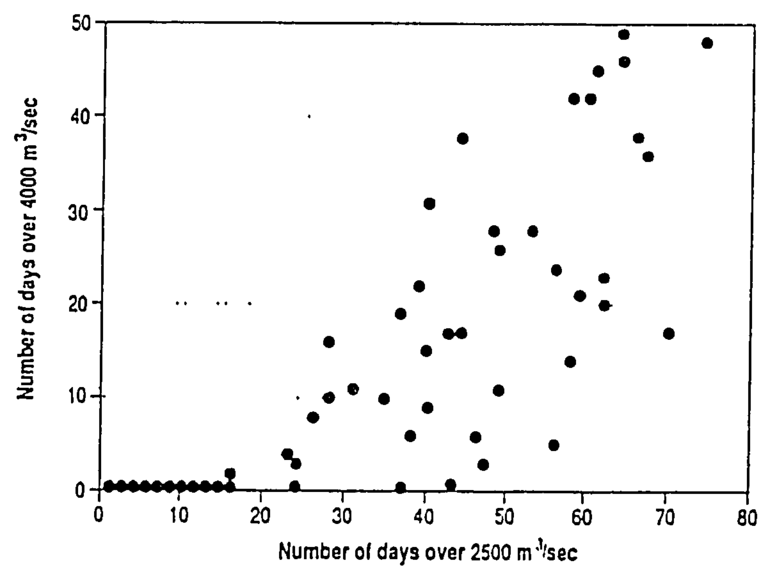


Figure 12.2 A plot of the duration of high flows against the duration of very high flows at Bakel 1930-1986

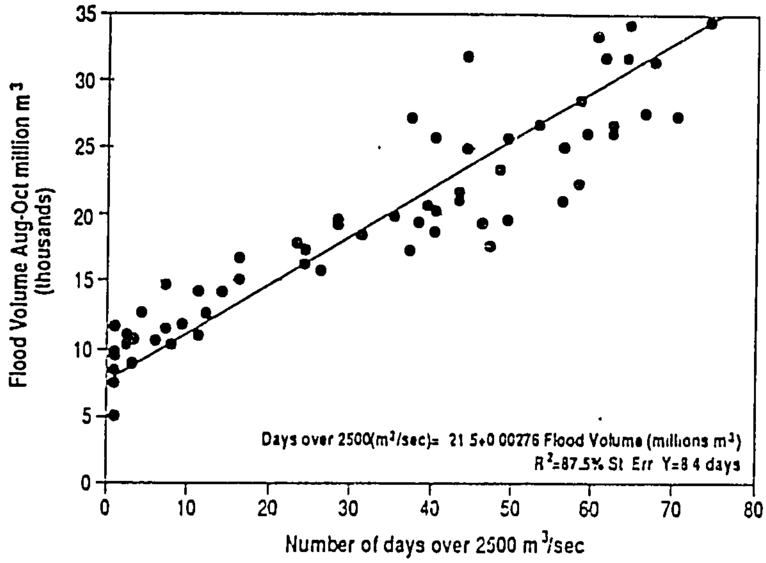


Figure 12.3 The relationship between the volume of the flood and the duration of the flood over 2,500 m³/sec at Bakel with data from 1930 to 1986.

For the largest floods with flows of over 4,000 m³/sec, there is an equally strong relationship between flood volume and duration of the flood over 4,000 m³/sec (Figure 12.4).

The strongest relationship, however, is between flood volume and the peak flow at Bakel (Figure 12.5). The regression equation explains 91% of the variance in flood volume with a standard error in flood volume estimation of only 2,000 10^6 m³.

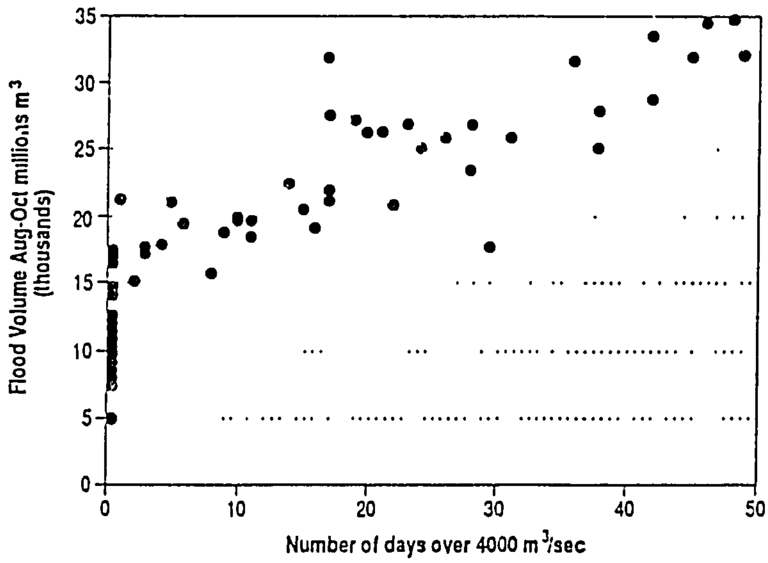


Figure 12.4 The relationship between the volume of the flood and the duration of the flood over 4,000 m³/sec at Bakel with data from 1930 to 1986.

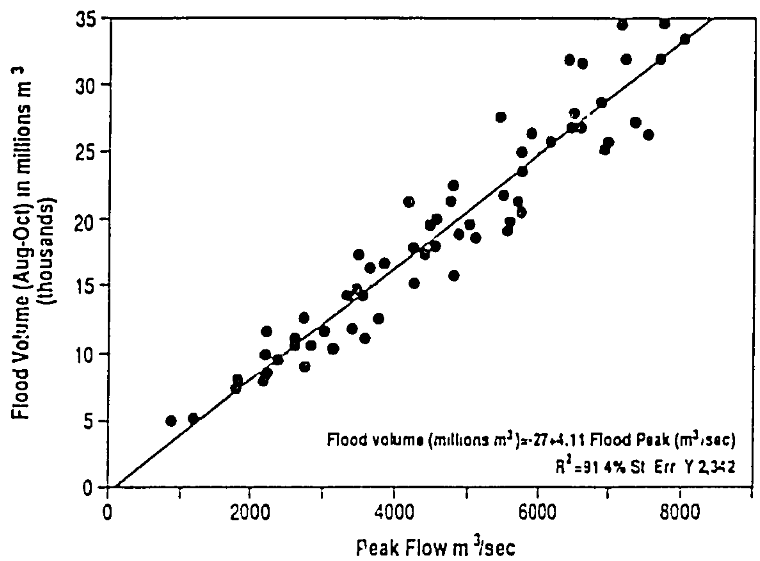


Figure 12.5 The relationship between the volume of the flood and the Peak flow at Bakel with data from 1930 to 1986.

12.3 The Contributions to Flow at Bakel from the Bafing, Faleme and Bakoye

Gibb (1987), Gersar et al (1988) and Gersar et al (1990) repeatedly report that the contribution of the Bafing to the flow at Bakel is 60% in dry years and only 40% in wet years. This section examines this finding in more detail.

Throughout this analysis the annual flows at Makana (Bafing), Oualia (Bakoye) and Kidira (Faleme) are expressed as a % the equivalent annual flow at Bakel. The data is taken from Table 2.6 on p15 of Gersar et al (1988, Schema Hydraulique) for 1952 to 1984. The data for 1986 to 1989 is derived from an analysis of the daily flow data furnished by CAB.

Figure 12.6 shows that the aggregate flows in the Bakoye and Faleme have constituted between about 54% and 17% of the flow at Bakel. Figure 12.6 suggests that the two uncontrolled tributaries contributed over 40% up to 1966, between about 30 and 40% between 1967 and 1982 and under 30% since 1982. The values for 1987 to 1989 ought to be excluded because these are the years during which Manantali has been filling. The apparent fall in the contribution of the uncontrolled tributaries appears, from Figure 12.6, to have resulted mainly from a fall in the contribution from the Bakoye.

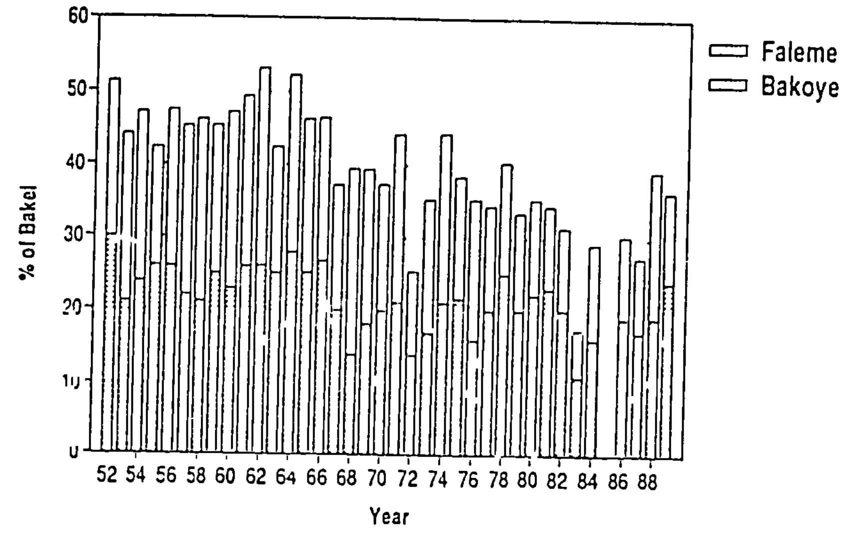


Figure 12.6 The % of the annual flow at Bakel originating from the Faleme and the Bakoye.

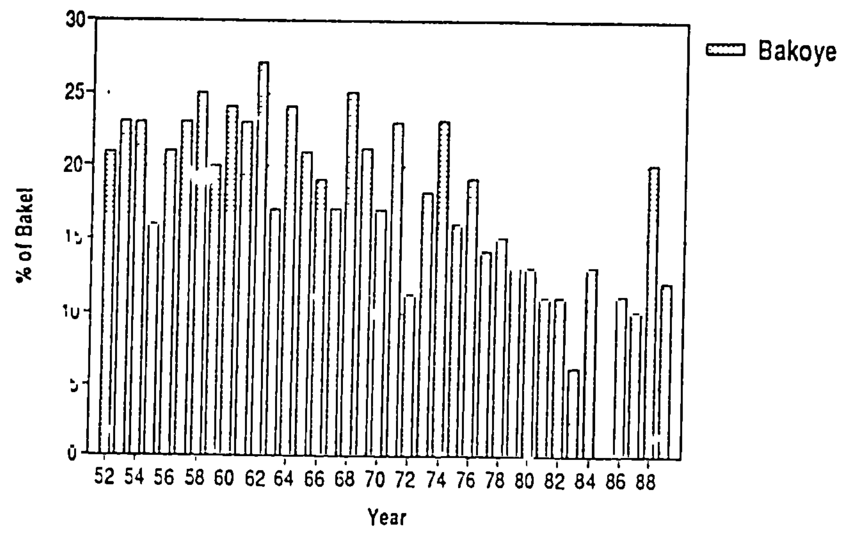


Figure 12.7 The % of the annual flow at Bakel originating from the Bakoye.

Figure 12.7 confirms that the contribution of the Bakoye to flows at Bakel has fallen from 15% to 25% from 1952 to 1976, to between 5% and 15% from 1977 to 1986. It would appear that the drought years have brought a change in the hydrology of the Bakoye. Figure 12.8 confirms that the upper part of the Bafing catchment does not appear to have had its relationship with Bakel altered by the drought. The flow at Makana has been between 35 and 50% of the flow at Bakel throughout the years before the closure of Manantali.

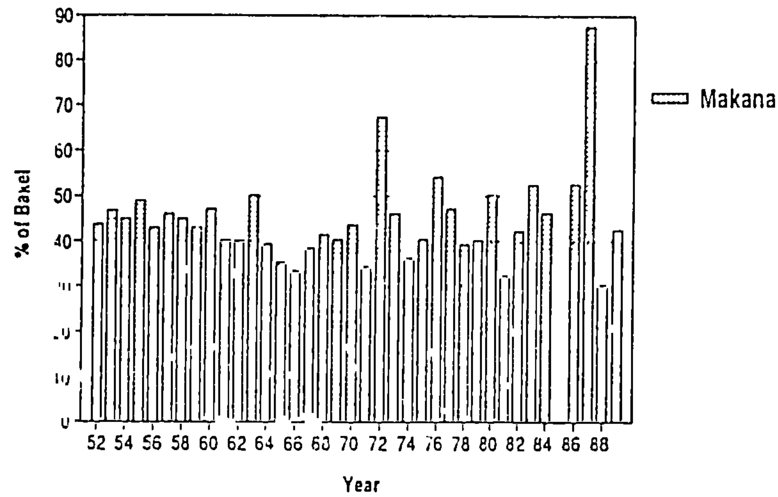


Figure 12.8 The % of the annual flow at Bakel originating from the Bafing at Makana.

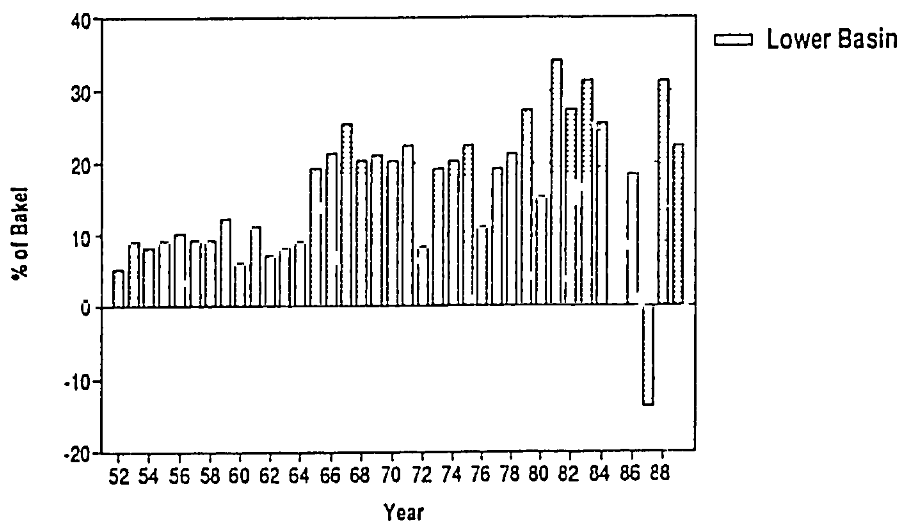


Figure 12.9 The % of the annual flow at Bakel originating from the lower part of the upper basin of the Senegal River.

With the proportion of flows from the uncontrolled tributaries apparently falling and the flow from the upper Bafing retaining its importance, Figure 12.9 demonstrates the significant rise in the importance of runoff from the lower part of the upper basin of the Senegal River. The area represents that part of the Bafing catchment below Makana including the ungauged tributary the Balinn, and the areas of the Faleme below Kidira and the Bakoye below Oualia. The runoff from this part of the basin has risen from under 10% of the flow in the 50s and early 60s to between 25 and 35% during the drought period of 1981 to 1984.

The declining contribution of aggregate flow from the Faleme and Bakoye compared to the Bafing at Makana (Figure 12.10) shows that during the 50s and 60s there was parity between these sources whilst during many years during the 70s and 80s the two tributaries have contributed only 40 to 80% of the flow in the Makana.

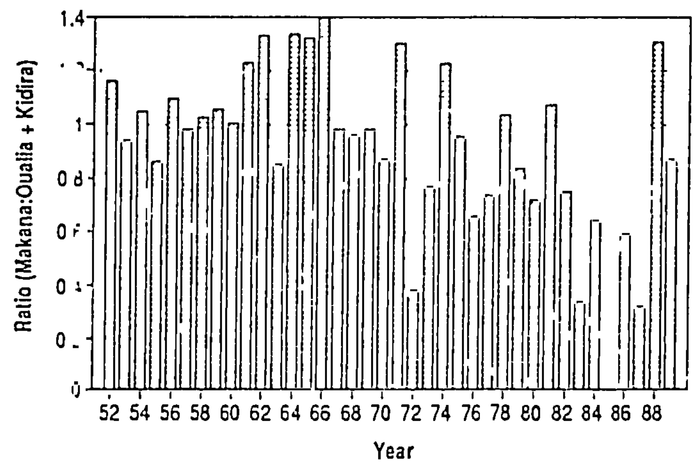


Figure 12.10 The ratio of the aggregate flow from the Bakoye and Faleme to that at Makana.

The declining contribution of the Faleme at Kidira and the Bakoye at Oualia, compared to the flow in the Bafing at Makana is succinctly summarised in the double mass plots (Figures 12.11 and 12.12). In both of these diagrams the slope of the cumulative total flow in the tributary flattens with the onset of the drought years, the effect being much more significant in the Bakoye than the Faleme.

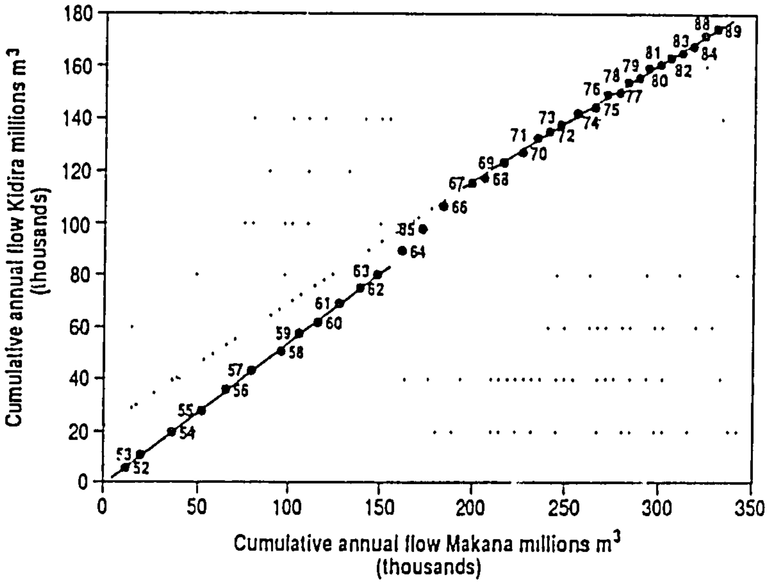


Figure 12.11 Cumulative total annual flow in the Bafing at Makana plotted against the cumulative annual total flow in the Faleme at Kidira

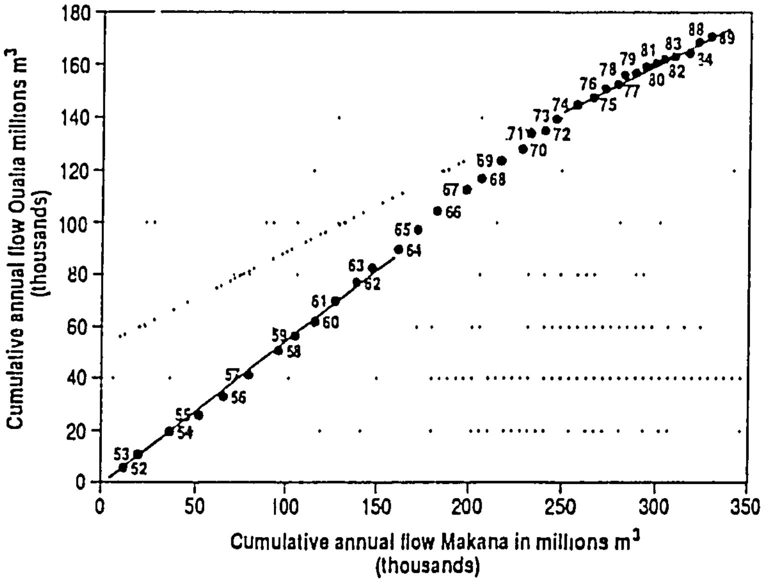


Figure 12.12 Cumulative total annual flow in the Bafing at Makana plotted against the cumulative annual total flow in the Bakoye at Oualia

In conclusion, Gersar et al's (1990) statement that Manantali controls 60 to 70% of flows in dry years and 30 to 40 % of flows in wet years is correct. A fuller analysis shows that the contribution from the Bakoye has fallen particularly dramatically during the drought years since 1972 and that from the Faleme has fallen to some extent. The importance of runoff from those parts of the upper basin between Bakel and Manantali, Oualia, and Kidira has grown in importance from around 5% in the 1950s and early 60s to 20 to 30% in the 80s before the closure of Manantali.

13.0 Spatial Distribution of Flooding During Artificial Flood "A"

The scope of work specifies "identify and collect the necessary data to assess specific areas affected if a 50K ha. flood is maintained". This repeats the misconception that the artificial flood will inundate 50,000ha because it is believed that the scope of work really seeks the areas that will be flooded by the artificial flood. Flood A has been calculated to inundate 144,000ha by Gersar et al (1990) using the UNE model (See Section 2 above). This will permit recession agriculture on 50,000ha in the whole valley and 33,000ha on the left bank (Gersar et al, 1990, p 154)

The identification of specific areas affected by flood A can be approached by three methods. First, via the flooded area in 1986 as mapped from the SPOT image. As argued above in Section 2, the 1986 flood hydrograph was close to that of flood A and therefore the areas flooded in 1986 are likely to be as good or better than the results from a modelling study. Second, the existing UNE model may be used, but as argued in Section 2 above this is a crude and imperfect method. Finally, the yet to be developed procedure that is outlined in Section 15 below could be used.

The Table on page 161 of Gersar et al (1990, Rapport) gives all of the essential elements of the UNE model under the influence of the artificial flood. the actual areas that will be flooded according to this model can be depicted on a topographic map by shading all of the areas below the level of the river adjacent to the UNE. This river level can be calculated be linear interpolation along the length of the river between an upstream and a downstream gauging station.

As has been argued above, and as has already been demonstrated with the limited available data, the UNE model is excessively simplistic and unrealistic for large parts of the Senegal Valley.

Consequently, in the absence of a model such as that outlined in Section 15, the best currently available estimate of the areas likely to be inundated by flood A is the OMVS map of the extent of flooding in 1986.

14.0 "Artificial" or "Augmented" Flood?

14.1 Floods from the Faleme and Bakoye

Gersar et al (1990) also tackled the question "During how many years would there have been a flood of Type A without a contribution from the Bafing?". Their answer was that this was outside the Plan Directeur and that it was impossible to answer without a complex hydrological analysis. Qualitatively, they suggested that in dry years there would be no inundation, in average years it would be very poor or negligible floods except if there was a coincidence of flows in the Bakoye and Faleme. In a wet year they suggested that the flood would approach the artificial flood. They calculated that, leaving aside the drought years from 1972 onwards, the artificial flood would have been equalled or exceeded in 52 out of the 68 years from 1903 to 1968.

Clearly, up to 1972 there were such large flows in the tributaries that minimal releases would have been necessary from Manantali. Since 1972, large releases would have been needed almost every year. This can be illustrated from the limited daily data that is presently available.

Figure 14.1, covering 1954 to 1964, and Figure 14.2, covering 1986 to 1989, depict the daily flow from 1st August to the 31st October for the Faleme at Kidira and for the Bakoye at Oualia. The graphs also show the aggregate of these two flows (Fal+Bak in the key) and the artificial flood A. There is a discussion of the line marked "Augmented" in the next section.

It is important to emphasise that this is a preliminary analysis with only a small quantity of the available data. When the analysis is repeated on the whole data set of daily flows it will be necessary to make a modification to the procedures. At present, for simplicity, it has been assumed tht if there are no releases from Manantali, the flow at Bakel will equal the sum of the flows at Kidira and Oualia. As has been shown in Figure 12.9, the significance of runoff from the lower part of the upper basin has been of increasing significance as the drought has continued. Any full analysis of this problem will have to add an estimate of the flows from the lower part of the upper basin to the aggregate of Kidira and Oualia to get a better estimate of the possible flow at Bakel.

A comparison of the aggregate hydrographs for the period 1954 to 1964 and those for 1986 to 1989 confirms the earlier finding that the drought has had such a profound effect on the upper basin that the whole nature of the hydrology of the area has been modified for the duration of the drought. Any analysis of the hydrographs has to treat the two periods separately.

With the data for 1954 to 1964 (there is no data for 1961), the aggregate flow peaked at over 2,500 m^3/sec every year save one and in every year the flow reached 2,000 m^3/sec. All of the peaks occurred before the planned peak of the artificial flood save for 1960 which was synchronous with the artificial flood. Six of the floods had single peaks, 3 had secondary

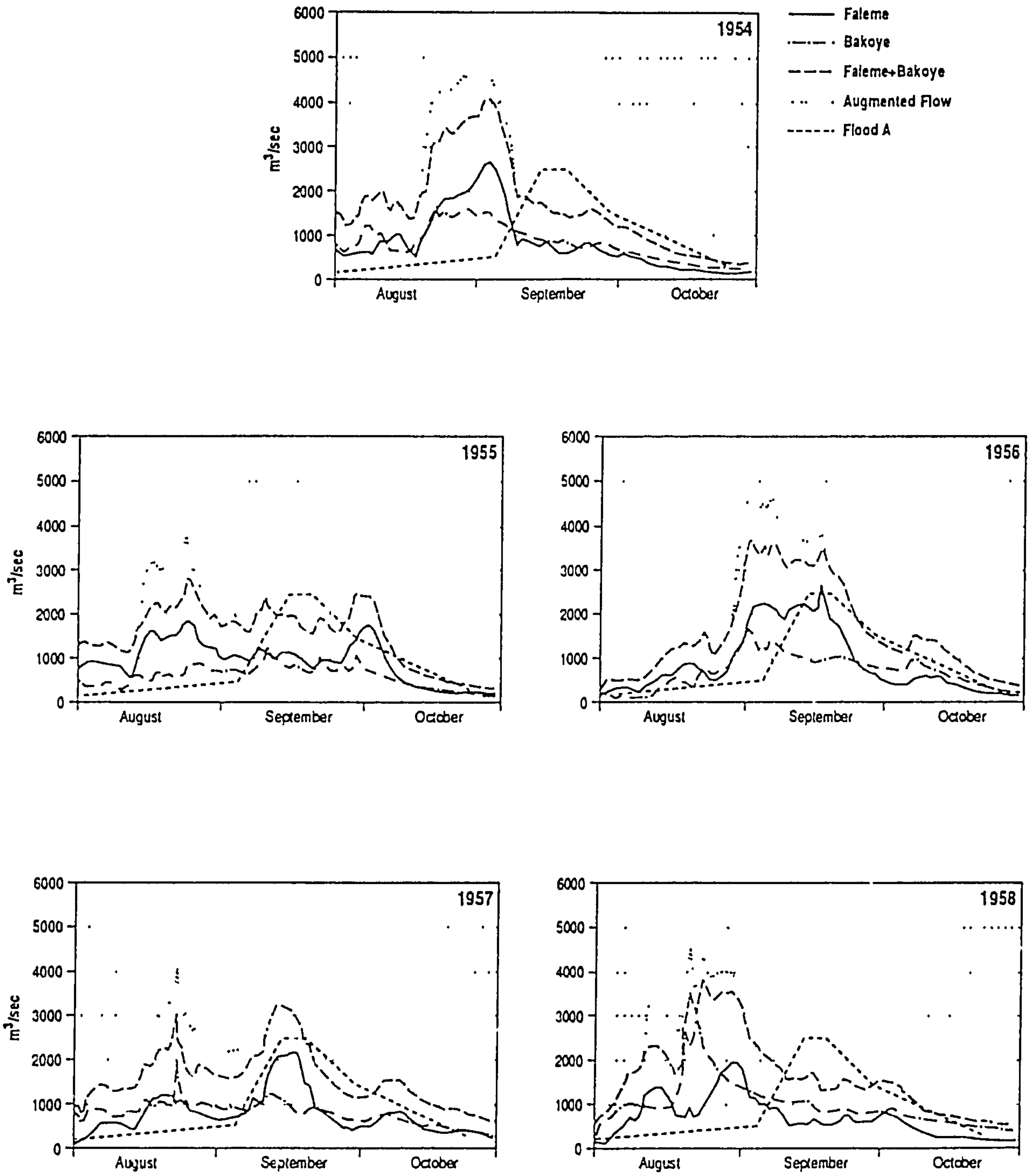


Figure 14.1 Daily flows, 1954 -1964, at Kidira (Faleme) and Oualia (Bakoye) from 1st August to 13st October with the aggregate of their flows (Fal+Bak) and the artificial flood A superimposed. The line marked "augmented" depicts the results of a certain set of release rules discussed in section 14.2.

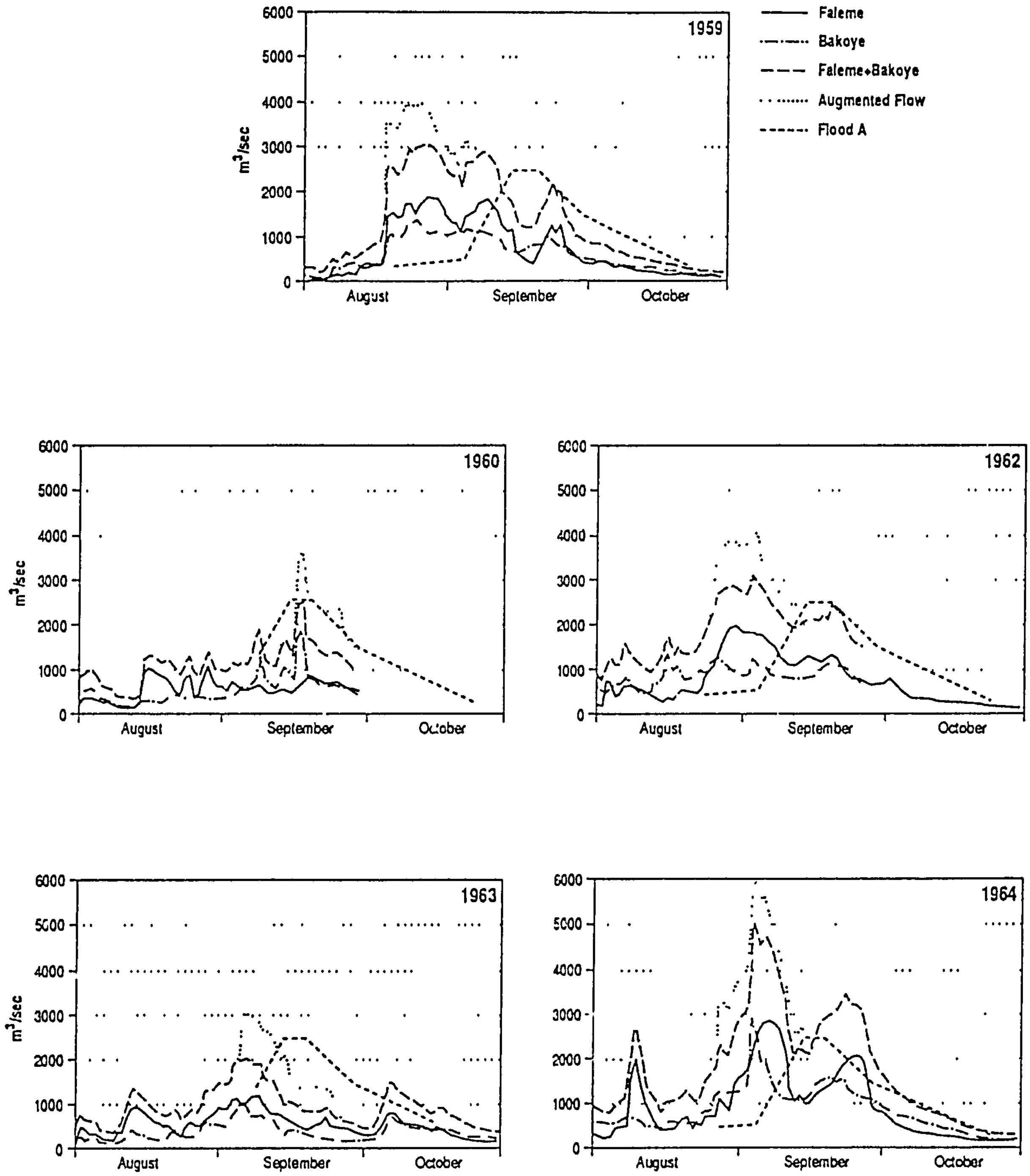


Figure 14.1a Daily flows, 1954 -1964, at Kidira (Faleme) and Oualia (Bakoye) from 1st August to 13st October with the aggregate of their flows (Fal+Bak) and the artificial flood A superimposed. The line marked "augmented" depicts the results of a certain set of release rules discussed in section 14.2.

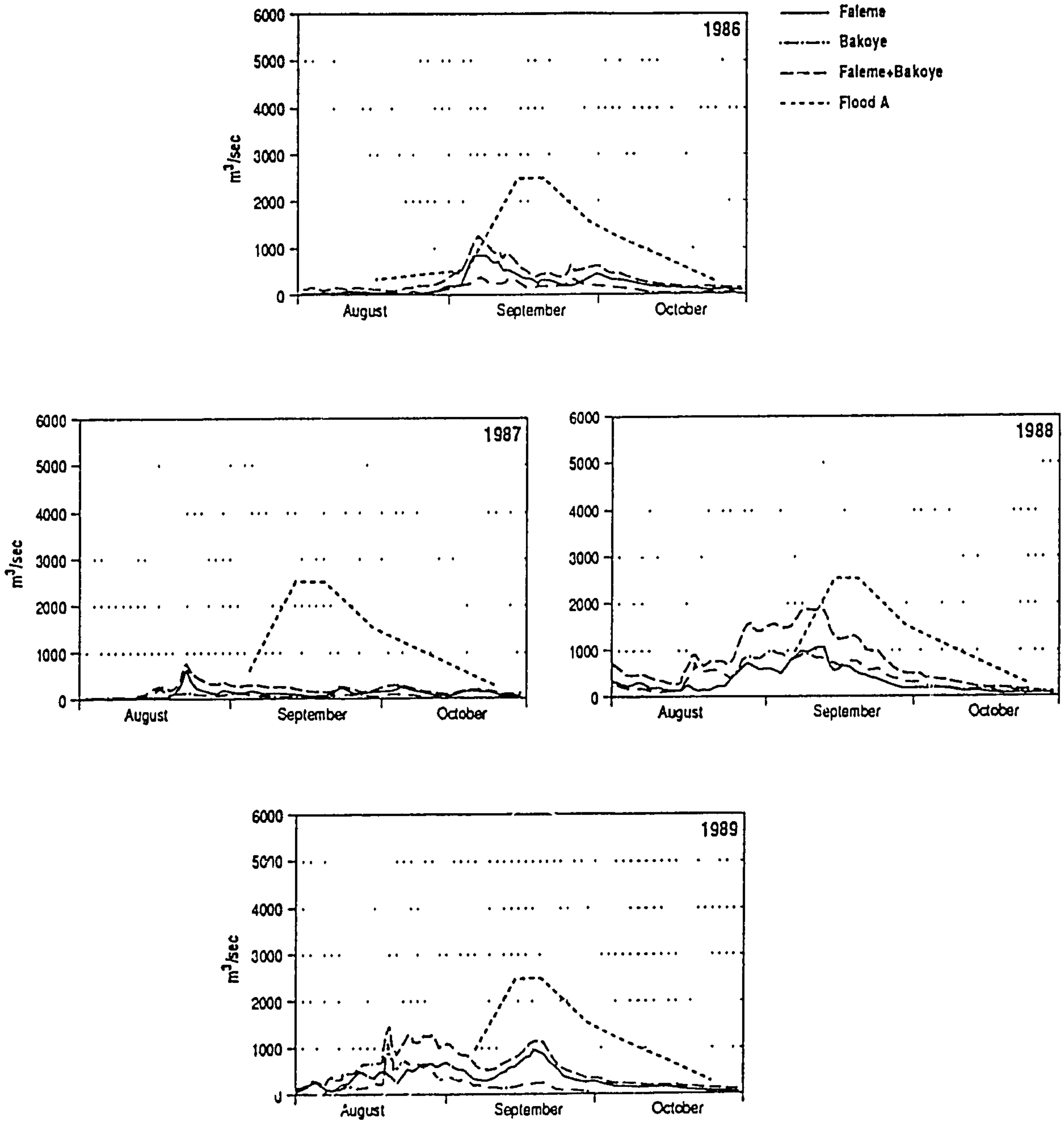


Figure 14.2 Daily flows, 1986 - 1989, at Kidira (Faleme) and Oualia (Bakoye) from 1st August to 13st October with the aggregate of their flows (Fal+Bak) and the artificial flood A superimposed.

peaks after the main flood and one flood had two main peaks. There were frequently small peaks of over 1500 m^3/sec that occurred before 16th August but in every case they were followed by a much larger peak after 16th August. In summary, there would have been a flood at least equal to the artificial flood in eight out of the 10 years of data for 1954 to 1964. In the other two years, 1960 and 1963, there would have been weak floods which would certainly have inundated some 10s of thousands of hectares.

From 1986 to 1989 the aggregate flow never exceeded 2,000 m^3/sec. All of the peaks occurred before the planned peak of the artificial flood. In summary, there would not have been any significant flooding in 1986, 87 and 89 whilst in 1988 there might have been some minor inundations.

14.2 The Releases Necessary to Guarantee a Flow Equivalent to Flood A

Table 14.1 shows the releases from Manantali that would have been necessary under three hypotheses. The first is that the artificial flood A would have been released as proposed by Gibb (1987). The second is that a hydrograph, equivalent to flood A, would have been released at the optimum time for it to augment the natural flood flows in the Faleme and Bakoye. The third hypothesis accords with a simple set of release rules formulated from the analysis of the floods from 1954 to 1964. The rules for this "augmented" flood are that, when the aggregate flow in the Faleme and Bakoye exceeds 2,000m^3/sec, there are 10 days with a release of 1,000m^3/sec followed by 10 days with a release of 500m^3/sec. This simple regime requires 1,300 10^6m^3 per year. The results of this regime, for 1954-64, are that the artificial flood A is exceeded every year and in many years there are spectacularly good floods.

The simple "augmented" operating rules for Manantali fails completely during the period 1986 to 1989. This suggests that simple operating rules for Manantali are not likely to suit conditions in both wet and dry years. It is likely that fairly sophisticated operating rules will be required to optimise water use.

The analysis in Table 14.1 shows that for 1954 to 1964, flood A would have required an average of around 953 10^6m^3 per year for its operation. With a flood forecasting system capable of allowing releases at the optimum time to generate an "augmented", rather than an "artificial", flood A, the average amount of water to be released would have fallen by 627 10^6m^3, or 66%, to only 326 10^6m^3 per year. During the years 1986 to 1989, artificial flood A would have required an average of 4545 10^6m^3 per year. Even in those relatively dry years, the release of water from Manantali as an "augmented" flood A would have saved 848 10^6m^3 per year since the average release for this hypothesis is down 19% to 3697 10^6m^3 per year.

Table 14.1 The required releases from Manantali under three hypotheses

Note 1: The flow at Bakel has been assumed to be the aggregate of that at Kidira and Oualia. No allowance has been made for the contribution from the uncontrolled part of the upper basin.

Note 2: 1960 and 1962 has complete data for only August and September

Releases ($10^6 m^3$) necessary to satisfy:

Year	Flood A	Flood A released at the optimum dates	Optimum date for the start of the rising limb	Augmented Flow (see text)
1954	1267	0	17 August	1300
1955	731	159	10 August	1300
1956	129	0	24 August	1300
1957	435	161	31 August	1300
1958	1156	0	10 August	1300
1959	1624	0	16 August	1300
1960	(1249)	(1249)	-	1300
1962	(369)	0	18 August	1300
1963	2450	1695	24 August	1300
1964	124	0	25 August	1300
Mean	(953)	(326)		1300
1986	4777	4611	2 September	-
1987	5842	5811	17 August	-
1988	3283	1588	17 August	-
1989	4280	2780	16 August	-
Mean	4545	3697		

14.3 Prefeasibility Study for a Forecasting Model with a Horizon of 2+ Weeks

The development of the real time model with a forecast horizon of two weeks or more will require a detailed analysis of the whole dataset available. It will be necessary to examine the relationships between rainfall, evapotranspiration, calculated soil moisture conditions, antecedent conditions and river flow at the station and at upstream stations for many of the gauging sites on the rivers of the upper Senegal Catchment.

Figure 14.3 shows the daily flow at Oualia and at Toukoto for the floods of 1954 (no data for Oualia), 1959 and 1963. The latter station is above Oualia and gauges the major tributary of the Bakoye at Oualia. Also shown on Figure 14.3 is the equivalent daily rainfall at Kita and Sirakoro. The graphical presentation makes it impossible to show other rainfall stations that exist in the catchment.

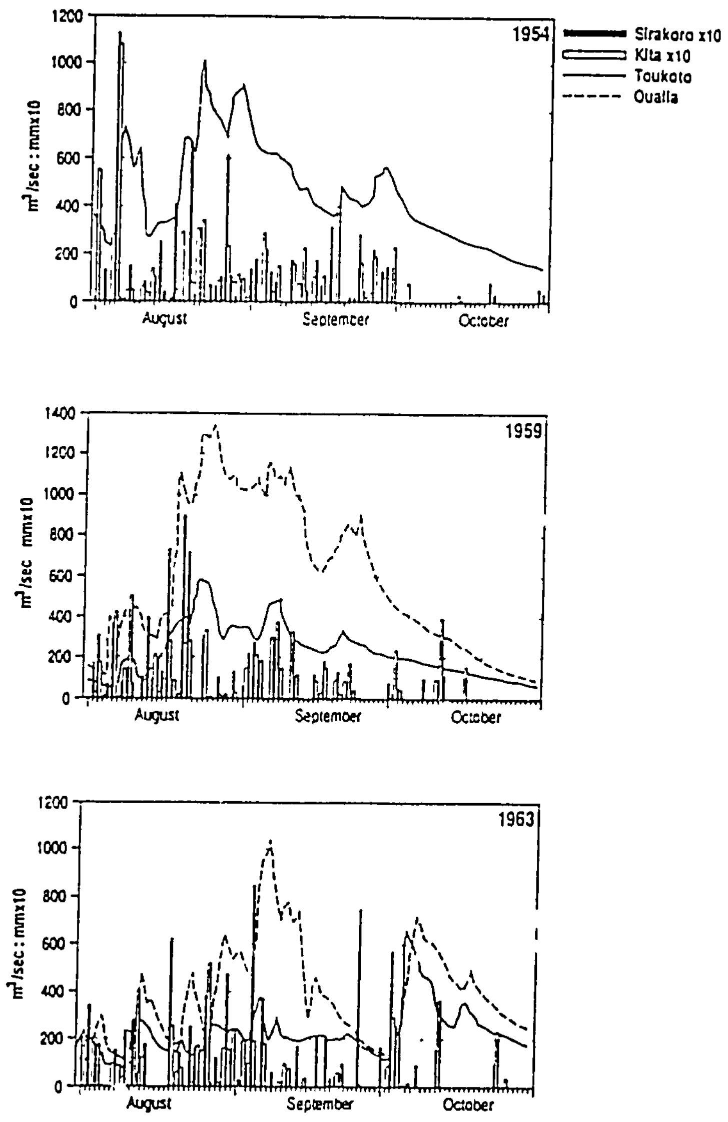


Figure 14.3 Daily rainfall and runoff in the Bakoye catchment for 1954, 1959 and 1963

Figure 14.4 shows the daily flow at Kidira and at Fadougou for the floods of 1954, 1958 and 1963. The latter station is above Kidira and gauges the Faleme soon after it leaves Guinea. Also shown on Figure 14.4 is the equivalent daily rainfall at Kenieba and Kedougou or Gourbassy. The graphical presentation makes it impossible to show more than two of the rainfall stations that exist in the catchment.

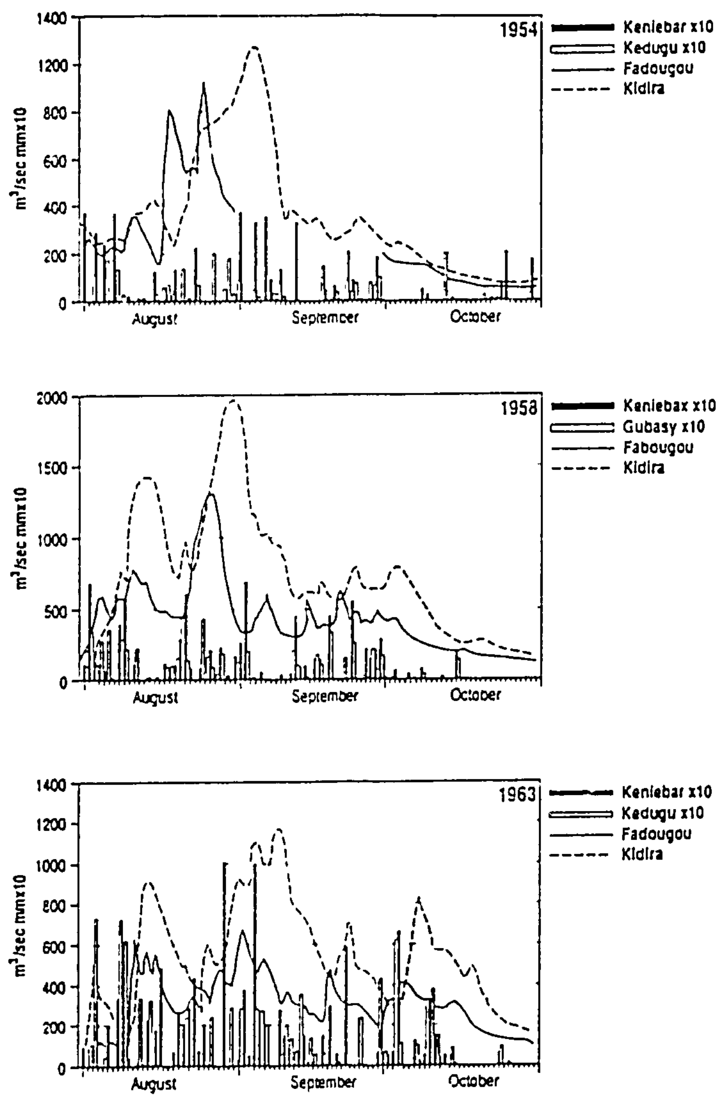


Figure 14.4 Daily rainfall and runoff in the Faleme catchment for 1954, 1958 and 1963

All of the hydrographs show that there is usually a strong relationship between upstream flow and downstream flow. In the case of each river there is a five to seven day delay between the upstream peaks and the downstream peaks. More significantly for the forecasting model, there is a clear association between high river flows downstream and heavy rainfall and/or persistent rainfall. In the case of rainfall there is often a delay of up to two weeks between the rain falling and the resulting flood arriving at the downstream gauging station. In general the effectiveness of rainfall in generating large flood peaks is smaller at the beginning of the wet season, when soils still have a soil moisture deficit, than later when a substantial amount of rain has already fallen. These qualitative observations will need to be turned into quantitative generalizations though a conventional analysis of the full dataset of rainfall, runoff and related variables.

The eventual real time forecasting model is likely to aim at the calculation of the flows at Makana, Gourbassy or Kidira, and Oualia. A forecast of the flow at Makana can be used to anticipate changes in water levels in Manantali. A forecast of the flow at Gourbassy and Oualia can be input to the existing ORSTOM model or the new model can be extended to include forecasts at Bakel.

The model is likely to work on a daily basis. It is likely that it will use rainfall data from Guinea to forecast flows in the highest gauging stations. The estimated flows at these stations will then be used with the local rainfall to estimate flows at downstream stations. For instance, rainfall at Tougue (Guinea), Mali (Guinea), Kenieba and perhaps other stations could be used to estimate the flow at Fadougou. This could then be used, with the further runoff expected from rainfall measured at Kenieba, Kedougou and Gourbassy to estimate flow at Gourbassy or Kidira. The model could be either deterministic, where an effort is made to simulate the real hydrological processes, or a stochastic model which employs statistical relationships to make forward estimates.

In this report it is not possible to make any firm propositions about the type of model that should be constructed. This will have to follow an analysis of the full dataset which presently exists.

However, less than half a man-day has been expended on two examples to illustrate that it will be neither difficult nor excessively time consuming to produce an adequate model with a two week forecast horizon. Very simple models were programmed into the spreadsheet program "Quattro" to estimate flows at Oualia and Kidira. The model for Oualia:

$$\text{Estimated flow at Oualia}_t = \text{Flow at Toukoto}_{t-7} + \left(\sum_{t-14}^{t-20} \text{Runoff from rainfall}\right)/7$$

$$\text{Runoff from rainfall}_t = \text{Mean catchment rainfall}_{t-14} \times \text{Runoff Coeff} \times \text{Conversion Factor}$$

This model calculated flow at Oualia from the flow seven days previously at Toukoto and rainfall in the catchment during the period fourteen to twenty days previously. The runoff coefficient used was set at 20% and the conversion factor transformed mm/day over the catchment between Toukoto and Oualia into m³/sec. Figure 14.5 shows the modelled hydrograph for 1959 which was used to develop the model. There is a fair accord between estimated and actual flows and it is important to note that the model is good at estimating the peak flow and the timing of the peak.

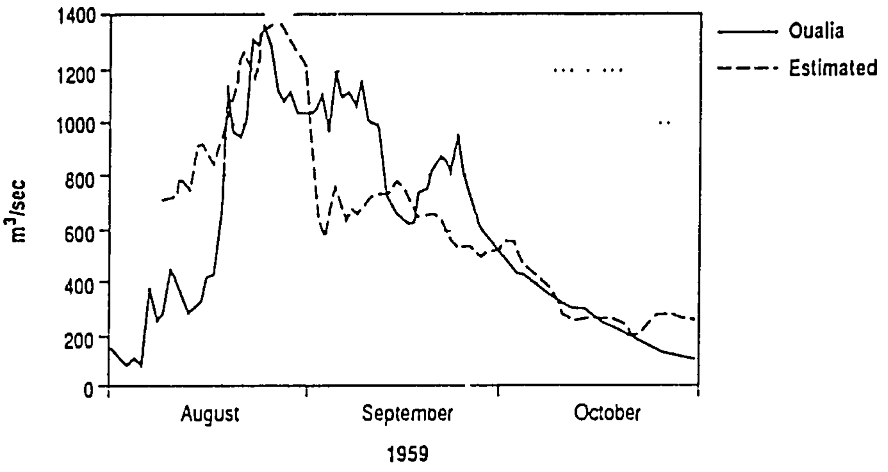


Figure 14.5 Actual and modelled flow at Oualia for the 1959 flood, which was used to develop the model

Figure 14.6 shows a test of the model for the flood of 1963. This hydrograph was calculated by substituting the 1963 data into the spreadsheet with the model and then simply printing the result. The fact that the model developed with 1959 data accurately calculates the size and timing of the major peak during the 1963 is remarkable. The simulation of the second peak in 1963 is very poor because the flow at Fadougou was exceptionally high and, in reality, there was little runoff from the catchment downstream of Fadougou. The model generates a significant runoff from rainfall in September and therefore gives an overestimate of the peak.

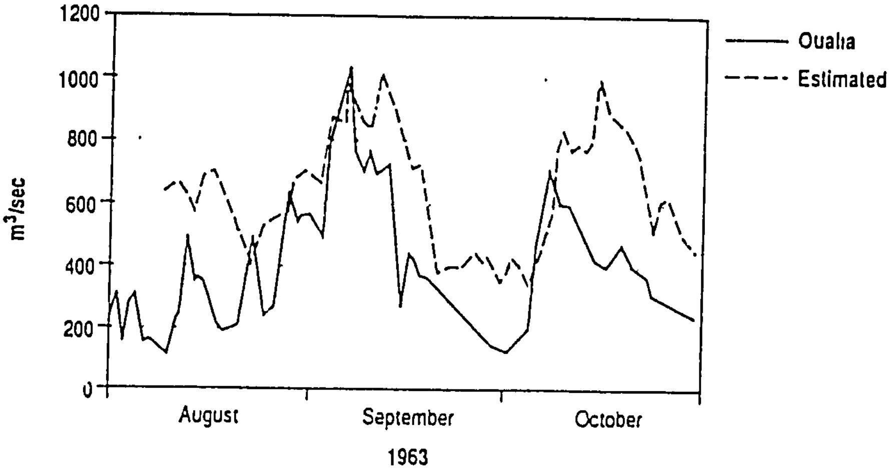


Figure 14.6 Actual and modelled flow for Oualia for the 1963 flood, which was used to test the model.

The model for Kidira:

$$\text{Estimated flow Kidira}_t = \text{Flow at Fadougou}_{t-5} + \left(\sum_{t-7}^{t-11} \text{Runoff from rainfall}\right)/5$$

$$\text{Runoff from rainfall}_t = \text{Mean catchment rainfall}_{t-7} \times \left(\sum_{t-7}^{t-11} \text{Antecedent rainfall}\right)/200 \times \text{Conversion factor}$$

This model estimates flow at Kidira from the flow five days previously at Fadougou and the rain that fell seven to eleven days previously. The conversion factor simply transforms mm per day over the catchment between Fadougou and Kidira into m³/sec. Figure 14.7 shows that with the 1958, flood the model gives a satisfactory representation of the actual flow. In the case of this model, developed on the flood of 1958, it did not give satisfactory results with other floods.

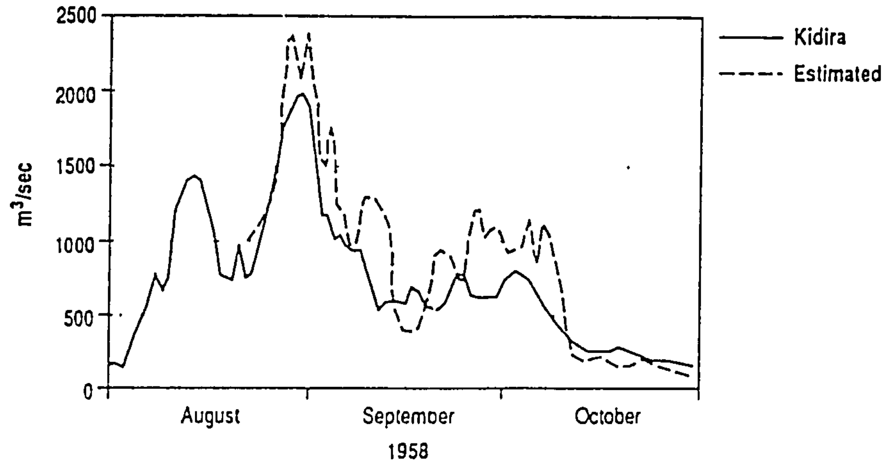


Figure 14.7 Actual and modelled flow for Kidira for the 1958 flood, which was used to test the model.

These very simple and hastily developed models are intended simply to indicate that it is possible to model riverflow in the upper Senegal Valley from daily rainfall data. At present the models have a forecast horizon of about one week because they are tied to an upstream gauging station. However, it will be easy to develop a subsidiary model to estimate the flow at this upstream gauging station from rainfall in the headwaters of the catchments in Guinea and Mali.

There may be a week's delay between rainfall in the headwaters and flow at the uppermost gauging station. There is up to a week's delay before that flow and its augmentation with local runoff reaches the downstream station. In the case of Oualia there is then a further few days before the flow reaches Bakel. If the models use forecasts of rainfall for two days ahead then the forecast horizon will lengthen accordingly. These timings suggest that a forecast horizon of at least two weeks will be achievable.

There is a need for an urgent feasibility study. If the initial promise is fulfilled, a model should then be developed. The whole process should take between 0.5 and 1 man-year. It is strongly recommended that such a real time forecasting approach be taken rather than the Groupement Manantali approach discussed by Morel-Seytoux (1988) as a means of establishing the nature of the season's hydrology. These authorities advocated decisions based on the cumulative amount of inflow to Mananatali by the end of July but such an approach will be less satisfactory and less sensitive to unusual weather conditions than one based on real time measurements of actual rainfall.

Data for monthly rainfall in Guinea has been received through the good offices of USAID in Conakry. It is likely that the model could be ready before funding agencies can assist in the development of the real time data collection by the extension of the existing METEOSAT network.

15.0 A Model for the Prediction of Flood Extent and Duration

There have been two modeling systems used to date in the simulation of flood extent from flows at Bakel. The SOGREAH model seems to be in a state of terminal decline since no copies of reports relating to it were located in Senegal and it does not seem to have been used in any of the recent studies of the valley. Morel-Seytoux (1988) favored the use of this model over the UNE model, but he did caution that the model might not be available. It is reported that the model was based on the Muskingum flood routing method. The second system utilises the ORSTOM (Lamagat, 1990) model for the calculation of flood levels downstream of Bakel and the UNE model for the estimation of the area inundated in each cuvette. These two models have been fully evaluated in earlier Sections and both models have been found to be inadequate to estimate flood extent in the Senegal valley during the forthcoming years.

A model which will calculate the depth, extent and duration of flooding in each of the cuvettes in the Senegal Valley will need to be a deterministic physical model which simulates the various flows and storages of water throughout the valley. It will be essential to treat each section of the model in a physically realistic fashion if the model is to cope with changes in the valley such as floodplain embankments, the removal of sills in distributaries and the dredging of a navigation channel in the main river. The increasing speed and capacity of computers should make such a model both feasible and inexpensive to install on a high specification PC.

A model which begins with a flow hydrograph at Bakel and ends at the head of the delta at Richard Toll will be much simpler and more realistic than a model which endeavours to simulate the hydrology of the upper valley and that of the delta at the same time. An approach to the modelling of the hydrology of the valley which accepts the need for a series of small models for parts of the valley has much to recommend it.

The model will have to simulate both the left and right bank of the valley as well as the main channel. This requirement is absolute for these three components act as a single system during high floods. However, this influences the decision about the requirement for further fieldwork before the commencement of the modelling since it would be essential for fieldwork to be synchronized in Senegal and Mauritania.

Whilst only the area around Matam has been investigated in detail, there is almost certainly sufficient data, already existing, for the Senegal side of the valley to begin the preparation of the model. However, there is not sufficient data for the calibration, testing and verification of the model. The collection of field data for two or three years during the 1990s is highly desirable as a means of testing and verifying the utility of the model developed.

If the existing data for the Mauritanian flood plain is equivalent to that for Senegal, a preliminary model could be prepared within one year of commencement. A fully verified model would take, at least, three years. One year would be required to establish the field installations and the equipping of the field teams. Subsequently, two years data, at least, would need to be collected.

The preparation of the model from existing data would require about three person-months to amass all of the existing data including that from Mauritania. There would be a need for considerable data entry work to be undertaken. The most daunting task, certainly taking person-years of work, would be the digitisation of the topographic maps of the floodplain. Once all of the data was organised into a suitable data base, the actual modelling work might take one to two person years to produce a user friendly and flexible system.

It would be essential that local staff be involved at every stage of the project and that the completion of the project would produce both a working team of local staff and a working model of flooding in the valley.

The existing data available for the model, with examples from the Matam area, are:

i) flood extent for the early 1970s. 1978, 1986 and 1988. It likely that the flood extent in 1987 will be mapped from an existing image and work is in hand to map flood extent in 1990.

ii) depth and duration of flooding as gathered for the Dioulol and Diamel for 1978 by SATEC (1980), for the Diamel and Matam area for 1989 by ITALTEKNA and for the Ourosogui-Matam road by ORSTOM in 1964.

iii) rates of flow across the floodplain as undertaken by ORSTOM at the Ourosogui-Matam road in 1964.

iv) river level, river flow, rainfall, evaporation, temperature, wind speed, humidity and sunshine. The dataset for this hydrometeorological data is particularly good and has been collected for many decades.

v) groundwater levels and rates of flow exist for 1971 to 1973 and from 1986 thanks to the work of Illy (1973) and the OMVS/USAID Groundwater Monitoring project.

v) topographic data for the floodplain exists as one metre contours and 50cm form lines in some places. More detailed topographic data, with contours at 50cm and a close matrix of spot heights at 10cm, exists for the ITALTEKNA perimeter. A major task of any modelling exercise will be the preparation of a digital terrain model of the entire floodplain in a GIS such as ARC-INFO.

vi) topographic data for the main river, marigots, distributaries and inlets to cuvettes such as those published by SATEC (1980) for the River, the Dioulol and the Diamel.

The new data which would be needed in an ideal world would include:

i) continuation of the existing hydrometeorological measurements, the monitoring of groundwater and the mapping of flood extent.

ii) further hydrological studies of the river and floodplain to determine

- the stage discharge relationships for various sites along the distributaries,
- river-groundwater relationships derived from a full analysis of the existing OMVS/USAID Groundwater Database
- infiltration characteristics of floodplain soils, although this may already exist in the pedological studies that have been undertaken,
- effect of antecedent precipitation on soil moisture and infiltration characteristics,
- the method of filling of each of the cuvettes and nature of their drainage including the levelling of the inflow and outflow channels,
- relationships between measured evaporation, potential evapotranspiration, actual evaporation and actual evapotranspiration,
- rate of pumping from the river and distributaries,

vii) information on recent artificial changes to the form of the river, distributaries, levees and embankments.

It is likely that the model will have to be specifically developed for the Senegal floodplain. However it may be possible for it to be based upon either an existing package such as FLOUT from Wallingford Hydraulics or the Dodo model used by the National Rivers Authority for the simulation of flood levels and extents in the large floodplain system of the River Severn in Britain. There are certainly major models that could be applied from the US such as HSP and the Corps of Engineers procedures for the Mississippi Valley.

The task could certainly be accomplished most quickly and expeditiously by the engagement of a major consultancy firm. Such a task would be straightforward for such an organization and would probably result in a procedure which could be operated with a PC. The cost is likely to be very high and it is doubtful if such a procedure would substantially enhance the ability of Senegal or Mauritania to sustain such work in the future. The dispatch of local staff or students for training overseas may not result in their involvement in the project or in further hydrological work in their home country.

A longer term approach to the development of the model could seek to develop indigenous expertise in Senegal (and Mauritania?) through the formation of a joint team involving perhaps OMVS, Dakar University, Senegalese Government Staff, External Consultants and an Overseas University. Elements in the programme could be visits to operational flood forecasting units in other countries, funding for enhanced equipment at the Dakar University and OMVS, joint training and supervision by Dakar and overseas academic staff of a large group of Senegalese post graduates working on aspects of the model, in-country training for groups of Senegalese students, administrators and officials, and limited overseas training for key staff already employed within the project. The model would be developed by the joint team with major inputs coming from the post-graduate research workers.

The longer term approach advocated will certainly produce a more sustainable model than a rapid and "efficient" consultancy exercise and the costs may be more modest if there is a significant input of staff time from the Senegalese side.

16.0 Organizational Aspects of Integrated Management

The integrated management of the Senegal Floodplain requires considerable attention to the human institutions involved in that management. Detailed research, engineering studies and integrated plans prepared by external consultants will not achieve integrated management if the organigramme for the management system militates against an integrated approach.

There appear to be major obstacles to the free circulation of information and reports. Basic hydrometeorological data for the valley is not freely available. Reports, often prepared with international funding, are not easily obtained in some cases. Whilst well organised documentation centres exist, they are rarely comprehensive in their coverage and are not easily accessed by some scholars because of their location. The University Library in Dakar is particularly poorly supplied with documentation on water related aspects of the Senegal Valley.

At the technical and personal level, relationships are good. The community of staff working on the integrated management of the valley is small. They all know one another well. They enjoy warm and friendly personal relationships.

There appears to be good cross sectoral integration at the national level, too, with a minimum of bureaucracy involved. However, the integration between the international and national levels is less well developed. The apparent lack of contact between SAED and ITALTEKNA, save SAED's titular assistant Project Manager, and the need for elaborate bureaucratic channels between CAB and OMVS are examples of this less than perfect integration at the management level.

A final, but perhaps the most important observation, is that the people of the valley do not seem to be involved in the planning of the integrated management of the valley. This appears to be true of both their relationships with national and international agencies.

The realization of truly integrated management in the Senegal Valley will require some structural changes to the organizations involved and a change of attitude in some quarters.

17.0 Conclusions

1. Artificial flood A is likely to inundate between 35 and 40km^2 at the Thiemping cuvette and 8 to 10km^2 at the Boyenadji cuvette. The latter figure depends entirely on ITALTEKNA's plans for their embankments. The UNE model gives rather bigger areas of inundation, 47.95km^2 at Thiemping and 22.63km^2 at Boyenadji. The respective figures given in Gersar (1990) for the area flooded for 15 days are 51.2km^2 for Thiemping and 8.79km^2 at Boyenadji.

   At Doumga Rindiaw the present indications are that little, if any, of that cuvette will be flooded by the projected artificial flood. Gersar et al (1990) calculate that 4.36km^2 of Cuvette DI4 will be flooded for 15 days with artificial flood A.

2. There is an over estimation of the area flooded using the UNE model compared to the tentative results of synthesizing the results of the remote sensing analysis. This emphasises the great need for a more extensive analysis of satellite images to determine the true relationship between flood height and flood extent in the cuvettes.

3. Aquifer recharge is certainly dependent upon flooding of the cuvettes and especially the inundation of the more permeable soils at higher elevations. This is the unanimous view of all of the published authorities. Moreover, the relationship between the occurrence of the flood and the rise in groundwater levels in the OMVS/USAID network has been clearly established. There will certainly be some recharge of groundwater from local rainfall but this was estimated by Illy to be only 11% of total recharge.

4. Groundwater levels, within 1 to 2 km of the river, suggest that there is recharge of the aquifer during the flood and then a discharge of groundwater to maintain the low flow of the river during the dry seasons. At distances greater than 2km from the river, it appears that groundwater levels are almost always below those in the river. Therefore, there is a regional flow of groundwater away from the recharge zone on the floodplain.

5. The quantification of the relationships between groundwater in each aquifer, the river, flooding, rainfall and evapotranspiration can only be found from a full analysis of the OMVS/USAID Groundwater Monitoring Database. This may require six person months or more of work. It is also important that monitoring of the OMVS/USAID network continues with more strenuous efforts being made to take readings during and immediately after the flood.

6. The monitoring of the volume of water in a cuvette requires a knowledge of the water level in the cuvette measured in m (IGN) and a knowledge of the hypsometric characteristics of the cuvette. The volume of water in the cuvette can then be easily

calculated. Water level is most appropriately measured by a series of two to four stage boards in each cuvette with the readings being taken manually by an educated member of a nearby village. Hypsometric data for all of the cuvettes has been published by Chaumeny (1973).

7. There have been measurements of water levels in cuvettes using stage boards during the floods of 1964, 1971, 1978 and 1989.

8. The Thiemping cuvette is filled mainly by flow from the Dioulol with a small additional inflow early in the flood from the Navel. Later in the flood, water drains continuously via the Navel. During large floods there is an outflow to the Boyenadji cuvette under the Matam-Ourosogui road. Current metering of this flow amounted to over 1,000m^3/sec in 1954 and 1964.

9. The Boyenadji cuvette is filled by flows eastwards into its marigots from the Diamel and, with large floods, by flows over the floodplain from the Thiemping cuvette.

10. The Doumga Rindiaw cuvette is filled and drained by a single small and high level channel from the Diamel. The Diamel has been partially blocked by the construction of temporary earth roads on banks across it.

11. The Boyenadji cuvette is being converted by the ITALTEKNA scheme. The plans for the ITALTEKNA Irrigation Perimeter at Matam must be changed because:

    a) the planned drainage of the parcels into the existing marigots and then into the cuvettes within the scheme's embankment will cause rapid salinization of the cuvette, groundwater and eventually of large parts of the perimeter,

    b) the replacement of the bridges on the Matam-Ourosogui road with a continuation of the embankment will seriously impede flood flows down the floodplain. During a large flood there is a danger of floodwater passing through Matam town which is lower than the crest of the embankment.

    The ITALTEKNA scheme should:

    a) dredge the marigots so that drainage water can discharge via non-return flaps into the Diamel,

    b) leave an extensive floodway through the perimeter so that floodwater from the Dioulol, Navel and Thiemping cuvette can pass through to the Diamel and beyond.

12. There are three essential measures which must be taken before steps are taken to improve the flooding of individual cuvettes. These are that the artificial or augmented flood must be guaranteed; the agencies responsible for hydraulic works must engage

in closer contact and collaboration with the local people; and it must be appreciated that the river system is a whole and that water taken from one place affects downstream sites.

13. Modest and relatively inexpensive excavations of the channel linking it with the Diamel and the installation of a simple sluice could enhance the extent of flooding in the Doumga Rindiaw cuvette and provide some control.

14. The Thiemping cuvette is flooded and drained very easily at present but the excavation of a blocked marigot to the south of Tiali could improve the flooding regime even further.

15. Pumping stations will lower the flow downstream because they take water directly from the river. The drainage water from the irrigated perimeters will be brackish. The net effect of the pumping stations will be a river with relatively lower and saltier water. These effects cannot be quantified at present.

16. There have been three significant developments in hydrological studies in relation to the artificial flood since early 1988. First, Gersar et al (1990) have recognized that it is possible to maintain a balanced strategy in water management so long as planning is based on a 95% certainty of success. Second, ORSTOM have commissioned the telemetering system for river level recorders in the upper valley of the Senegal above Bakel. Finally, the ORSTOM real time forecasting model for the Senegal River has been published and implemented in Dakar, Senegal.

17. The ORSTOM real time flood forecasting model is a useful and usable tool given current policies for the management of Manantali. However, it is entirely inappropriate for use in the medium term for the creation of an "augmented" flood in the Senegal River. It is also dangerous to derive contra-saison water levels from the model for the time when Manantali is making baseflow releases.

18. The limited forecast horizon of the ORSTOM model prevents the achievement of an augmented flood with its concomitant benefits to the people of valley and the conservation of water stored in the reservoir.

19. The implementation of the ORSTOM real time forecasting model has enabled the management of releases from Manantali to follow both the rising and falling limbs of flood A at Bakel.

20. The need to fill Manantali by 1991 appears to have limited the achievement of the artificial flood to date.

21. The necessity to limit the rate of rise of the reservoir has necessitated large and sudden releases from Manantali.

22. The Senegal River basin is unusually well provided with long established gauging stations, raingauges and meteorological stations all of which record data on a daily basis.

23. 1954 to 1964 data shows that a flood at Bakel of more the 2,500 m^3/sec would be likely almost every year. The data for 1986 to 1989 suggests that such a flood would be most unlikely ever to occur. Gersar et al (1990) state that using data for 1903 to 1971, the largest of the artificial floods (Type C, Volume 10,000 10^6 m^3, Peak 3,000 m^3/sec) would have been exceeded in 52 out of the 68 years.

24. Gersar et al's (1990) statement that Manantali controls 60 to 70% of flows in dry years and 30 to 40 % of flows in wet years is correct. A fuller analysis shows that the contribution from the Bakoye has fallen dramatically since 1972 and that from the Faleme has fallen to some extent. The importance of runoff from those parts of the upper basin between Bakel and Manantali, Oualia, and Kidira has grown in importance from around 5% in the 1950s and early 60s to 20 to 30% in the 80s before the closure of Manantali.

25. The areas likely to be flooded by Flood A can be mapped using the UNE model and data in the Table on page 161 of Gersar et al (1990). However, the UNE model is simplistic and unrealistic for large parts of the Senegal Valley.

26. The best currently available estimate of the area likely to be flooded by flood A is the OMVS map of the extent of flooding in 1986 when the flood was quite similar to flood A.

27. Data for 1954 to 1964 shows that the aggregate flow in the Faleme and Bakoye peaked at over 2,500 m^3/sec every year save one. In every year the flow reached 2,000 m^3/sec. All of the peaks occurred before the planned peak of the artificial flood save for 1960 which was synchronous with the artificial flood. From 1986 to 1989 the aggregate flow never exceeded 2,000 m^3/sec. All of the peaks occurred before the planned peak of the artificial flood. There would not have been any significant flooding in 1986, 87 and 89 whilst in 1988 there might have been some minor inundations.

28. For 1954 to 1964, flood A would have required an average of around 953 10^6m^3 per year for its operation. With a flood forecasting system capable of allowing releases at the optimum time to generate an "augmented", rather than an "artificial" flood A, the average amount of water to be released would have fallen by 627 10^6m^3, or 66%, to only 326 10^6m^3 per year. During the years 1986 to 1989, artificial flood A would have required an average of 4545 10^6m^3 per year. Even in those relatively dry years, the release of water from Manantali as an "augmented" flood A would have saved 848 10^6m^3 per year since the average release for this hypothesis is down 19% to 3697 10^6m^3 per year.

29. Analysis of rainfall and runoff in the Faleme and Bakoye shows that there is usually a strong relationship between upstream flow and downstream flow. In the case of each river there is a five to seven day delay between the upstream peaks and the downstream peaks. More significantly, there is a clear association between high river flows downstream and heavy rainfall and/or persistent rainfall. In the case of rainfall there is often a delay of up to two weeks between the rain falling and the resulting flood arriving at the downstream gauging station. In general the effectiveness of rainfall in generating large flood peaks is smaller at the beginning of the wet season, when soils still have a soil moisture deficit, than later when a substantial amount of rain has already fallen. These qualitative observations will need to be turned into quantitative generalizations though a conventional analysis of the full dataset of rainfall, runoff and related variables.

30. Simple rainfall-runoff models show that it is possible to model riverflow in the upper Senegal Valley from daily rainfall data. A forecast horizon of at least two weeks will be achievable.

31. A model which will calculate the depth, extent and duration of flooding in each of the cuvettes between Bakel and Richard Toll will need to be a deterministic physical model which simulates the various flows and storages of water throughout the valley. It will be essential to treat each section of the model in a physically realistic fashion if the model is to cope with changes in the valley such as floodplain embankments, the removal of sills in distributaries and the dredging of a navigation channel in the main river. The increasing speed and capacity of computers should make such a model both feasible and inexpensive to install on a high specification PC.

32. There is almost certainly sufficient data, already existing, to begin the preparation of the model for flood extent in the valley. However, the collection of field data for two or three years during the 1990s will be essential for testing and verifying the model.

33. The model could be developed most quickly by a consultancy firm. A longer term approach involving external organizations in partnership with local agencies and universities is recommended for a more sustainable modelling effort.

34. The realization of truly integrated management in the Senegal Valley will require some structural changes to the organizations involved and a change of attitude in some quarters.

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APPENDIX A

SCOPE OF WORK

George Edward Hollis

The work under this contract is to be accomplished in two phases:

(1) The first phase, involving travel to IDA in Binghamton, will be to review the relevant documentation and to discuss the hydrologic issues with IDA SRBMA staff. At the conclusion of this phase, you will prepare a paper summarizing the status of the hydrologic documentation, indicating what issues seem to be clearly resolved, where the documentation is incomplete, unconvincing, and/or contradictory, and how field and other research will lead to a resolution of these remaining issues. The report, in hardcopy and on diskette, is to arrive at IDA no later than 14 August 1990.

The dates for this phase of the work are 14 July 1990 through 10 August, including the period 14-22 July in Binghamton. Up to 15 days' work (on a 5-day/week basis) is authorized.

(2) The second phase, involving fieldwork in the Middle Senegal Valley near Matam, will focus on the hydrology of three basins in the floodplain: Thiemping, Boyenadji Roumde, and Doumga Rindiaw. At these sites, the following issues are to be examined:

(a) What is the relationship between actual areas inundated in recent years and the volume and duration of the flood as measured at Bakel?

(b) Based on rainfall, evapotranspiration rates, water table elevations in observation wells, etc., what is the volume and duration of flood necessary to recharge aquifers in proximity to the village? Is the aquifer flood-dependent?

(c) What is the appropriate methodology for evaluating the volume of water in a specific cuvette (a kollangal) at a specified time and during a specified period?

(d) What are the means/mechanisms of flooding/draining for each of the basins?

(e) What are the possibilities for improving the natural mechanisms by which basins receive and disperse water?

(f) What kinds of infrastructures might be introduced to enchance the productive contribution of floodwaters?

In addition to the above issues, focused on the SRBMA study cuvettes, you will respond to issues extended more generally to the Middle Valley:

(a) What are the consequences for downstream flows of large pumping stations drawing water from the river?

(b) Assess progress made in hydrological studies conducted since early 1988 relevant to the definition, accuracy, achievability, operational monitoring, and actual realization of an artificial flood for recession agriculture.

(c) Assess progress made in the development of operational rules for Manantali releases guaranteeing the highest probability of success in achieving a desired artificial flood hydrograph at Bakel in the downstream areas.

(d) Assess availability of hydrological data, especially daily ones, and their actual use in the previously conducted hydrological studies.

(e) Discuss the state of hydrological knowledge, and its utility for current development goals, with those who conducted the studies and with those who contracted for them.

(f) Perform basic statistical analyses to answer specific questions such as the probability of flooding more than 50,000 ha. in a given year, the correlation between annual flood volume and its duration, the contribution of the Bafing River to the annual flow at Bakel during the 20th century, etc.

(g) Identify and collect the necessary data to assess specific areas affected if a 50K ha. flood is maintained.

(h) During how many years would there have been a 50K ha. flood without the contribution of the Bafin? What release would have been necessary from Manantali to bring the flood to that level?

(i) Estimate the resource (flow data, aerial maps, etc.) availability and cost for eventual development of a model to predict downstream flooding extent and duration given a flood hydrograph at Bakel.

(j) Recommend to OMVS further work that may be necessary to provide a sound hydrological basis to development planning.

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