National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

NOTICE

The quality of this microform is heavily dependent upon the quality of the original thesis submitted for microfilming. Every effort has been made to ensure the highest quality of reproduction possible.

If pages are missing, contact the university which granted the degree.

Some pages may have indistinct print especially if the original pages were typed with a poor typewriter ribbon or if the university sent us an inferior photocopy.

Reproduction in full or in part of this microform is governed by the Canadian Copyright Act, R.S.C. 1970, c. C-30, and subsequent amendments.

AVIS

La qualité de cette microforme dépend grandement de la qualité de la thèse soumise au microfilmage. Nous avons tout fait pour assurer une qualité supérieure de reproduction.

S'il manque des pages, veuillez communiquer avec l'université qui a conféré le grade.

La qualité d'impression de certaines pages peut laisser à désirer, surtout si les pages originales ont été dactylographiées à l'aide d'un ruban usé ou si l'université nous a fait parvenir une photocopie de qualité inférieure.

La reproduction, même partielle, de cette microforme est soumise à la Loi canadienne sur le droit d'auteur, SRC 1970, c. C-30, et ses amendements subséquents.

Canada

A Management Planning Model
for the Senegal River Basin

by

Henry David Venema

A thesis
submitted under the supervision of
Dr. Eric J. Schiller

in partial fulfilment of the
requirements for the degree of
Master of Applied Science
in
Civil Engineering

Department of Civil Engineering
University of Ottawa
Ottawa, Canada
K1N 6N5

July, 1993

The Master of Civil Engineering Program
is a joint program with Carleton University administered
by the Ottawa-Carleton Institute for Civil Engineering

National Library
of Canada

Acquisitions and
Bibliographic Services Branch

395 Wellington Street
Ottawa, Ontario
K1A 0N4

Bibliothèque nationale
du Canada

Direction des acquisitions et
des services bibliographiques

395, rue Wellington
Ottawa (Ontario)
K1A 0N4

Your file Votre référence

Our file Notre référence

The author has granted an irrevocable non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of his/her thesis by any means and in any form or format, making this thesis available to interested persons.

L'auteur a accordé une licence irrévocable et non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de sa thèse de quelque manière et sous quelque forme que ce soit pour mettre des exemplaires de cette thèse à la disposition des personnes intéressées.

The author retains ownership of the copyright in his/her thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without his/her permission.

L'auteur conserve la propriété du droit d'auteur qui protège sa thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

ISBN 0-315-89710-4

Canada

UNIVERSITÉ D'OTTAWA
UNIVERSITY OF OTTAWA

Dedication

To my Mom and Dad who taught me everything I know
about peace, justice, the good earth and hard work

Acknowledgements

The list of people who helped in some way is almost too lengthy to list but here is my attempt:

Dr. E. J. Schiller for the independence, confidence and trust to pursue this idea,

Dr. K. Adamowski for essential technical training in stochastic hydrology and general optimism,

Dr. J. M. Thizy, System Science Program, University of Ottawa for valuable guidance in optimization issues,

Jean-Claude Bader and Dr. J. Albergel, ORSTOM-Dakar, for a tremendous effort in acquiring and interpreting the basic hydrologic data,

Dr. Michael Bassey, IDRC-Dakar, for technical cooperation, conversation and insight,

Mousse Seck, ENDA-Syspro, Dakar, for his unceasing optimism, encouragement and field level insight,

Boubacar and Aissatou Barry and the entire Barry clan of Dakar, Senegal for unforgettable friendship and support,

Dr. D. P. Loucks, School of Civil and Environmental Engineering, Cornell University, for his interest and valued advice in applying **IRIS**,

Dr. D. H. Burn, Dr. S. Simonovic and Z. Zrinji, Department of Civil and Geological Engineering, University of Manitoba for their ongoing friendship and support of a former student and colleague,

Mr. A. and Mrs. K. Makomaski for their wonderful logistical support and good natured understanding,

Jim Mansfield, NRC-Winnipeg, for great technical help and strategic advice,

Geir, Todd, Larry, Leny, Chris, Al and Asia (especially Asia!) for patience and for humouring me when my rantings got to be too much,

Finally my family, Mom, Dad, Kathleen, Sandy, Gary and Gwyneth whose constant love and support make it all worthwhile.

The funding for this project was provided by the Natural Science and Engineering Research Council, The International Development Research Centre, and the Association des Universites Partiellement ou Entierement de la Langue Francaise.

ABSTRACT

The Senegal River Basin (SRB), located in the Sahel region of West Africa is undergoing fundamental environmental, hydrologic and socio-economic transitions simultaneously. The tri-nation (Senegal, Mauritania and Mali) river basin development authority, the Organisation pour la Mise en Valeur du Fleuve Senegal (OMVS) is attempting to execute a shift to irrigated rice production in the river basin for domestic consumption, to ease the severe foreign exchange shortfalls these riparian nations face. Year-round irrigated agriculture is now possible in the SRB is now possible with recent completion of the Manantali and Diama dams. The full agricultural development potential of the SRB is however constrained by the limited hydrologic budget of the basin.

A time series analysis of Senegal River streamflows from 1904-1990 revealed that a stationary ARMA(1,1) model could be fit to the time series only after removing a linear trend beginning in 1960. The time series analysis provided powerful evidence that the prolonged Sahelian drought may be of a permanent nature. The Senegal River hydrology has been described as one of the best indicators available of climate change effects in the Sahel.

Compounding the severe effects of the drought on the river basin ecology is the negative impact of the state imposed agricultural policy of rice production. Rice production in the arid river valley has been a financial and social failure. Irrigated rice projects suffer a high rate of abandonment and have hastened the process of desertification in the river valley. This study postulates an alternative utilization of the scarce water resources in the basin. The water demand pattern for an alternative natural resources management focused agricultural development policy is based on the irrigation water requirements of well-researched village-scale irrigation projects in the SRB, and intensive irrigated agro-forestry projects. Village-scale irrigation is dedicated to low water consumption cereal grain crops and is managed by traditional socio-political structures. The agro-forestry production system analyzed has the joint objectives of using irrigation to re-establish a protective, diverse and productive bio-mass cover in the desertifying river valley, and to reverse the tide of drought induced migration from rural to urban areas.

A comparative river system simulation study was conducted to analyze the effects of both the rice production development policy (policy RP) and the natural resources management policy (policy NRM), on the full agricultural development potential of the SRB. Alternative hydrologic scenarios were generated for the simulation study according to the Senegal River time series analysis, for the historical level, 1970s level drought and 1980s level drought. Principles of dynamic programming were applied to Manantali reservoir management to optimize the allocation of water for all hydrologic scenarios.

For all hydrologic scenarios the lower over-all demand pattern exerted by policy NRM allowed a higher full development potential than for policy RP. For the worst case hydrologic scenario (the 1980s level drought), the full agricultural development potential under policy NRM which maximized water availability to only village-scale irrigation projects and irrigated agro-forestry projects was twice the area which was possible under a development policy that focused on serving only urban interests through the simultaneous provision of rice production, urban water supply and hydro-power.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

GLOSSARY

A_{ijk}	net hectares of crop j, soil i, region k, [ha]
A_k	kth order Fourier coefficient, [0]
$A(s_t)$	reservoir surface area-volume function, [km^2]
a_t	white noise process, time t, [0]
A_{tz}	water allocation for period t, demand site z, [10^6 m^3]
B_k	kth order Fourier coefficient, [0]
B^p	pth order Backshift operator, [0]
C_{jt}	irrigation water requirement, crop j, period t, [m^3/ha]
Dem_{kt}	irrigation water demands, region k, period t, [10^6 m^3]
DEM_{zt}	water demand allocation target, demand site z, period t, [10^6 m^3]
DF	river basin irrigation development factor, [0]
e_a	irrigation application efficiency, [0]
e_d	irrigation distribution efficiency, [0]
E_{ij}	consumption efficiency factor for crop j on soil i, [0]
E_t	energy production in period t, [MWH]
f	gauge flow multiple, [0]
f_j	dynamic programming objective function value, stage j
G_a	unregulated gauge flow at node a, [10_6 m^3]
h_{ik}	potential irrigable area, soil i, region k, [ha]
H_n	average net turbine head, [m]
I_{ab}	incremental natural inflow on river reach ab, [10^6 m^3]
IF	dry season "contre-saison" irrigation intensity factor, [0]
I_k	kth order periodogram ordinate, [0]
i_t	reservoir inflow, period t, [10^6 m^3]
K	reservoir capacity constraint, [10^6 m^3]
L_t	reservoir evaporation loss, period t, [10^6 m^3]
l_t	natural evaporation depth at reservoir surface, period t, [mm]
NQ_{tz}	natural incremental flow, period t, upstream node z, [10^6 m^3]
p_{ijk}	percentage of net hectares of soil i, in region k, in crop j, [0]

P_t	time series periodic component, [0]
Q_{tz}	flow volume, period t, site z, $[10^6 \text{ m}^3]$
r	percentage irrigation water return flow, [0]
r_t	reservoir release, period t, $[10^6 \text{ m}^3]$
R_t	time series stochastic component, [0]
s_t	reservoir storage, period t, $[10^6 \text{ m}^3]$
s_{inc}	storage state increment, $[10^6 \text{ m}^3]$
V_f	irrigation water volume delivered to field, $[\text{m}^3]$
V_p	irrigation water volume pumped into irrigation network, $[\text{m}^3]$
X_t	time series observation, [0]

Abbreviations

ACF	Autocorrelation Function
ARIMA	Autoregressive Integrated Moving Average
ARMA	Autoregressive Moving Average
CIDA	Canadian International Development Agency
DDP	Deterministic Dynamic Programming
DP	Dynamic Programming
ENDA	Environnement et Developpement Action - Tiers Monde
FAO	Food and Agricultural Organization
GIE	Groupement d'Interet Economique
GUI	Graphical User Interface
IIASA	International Institute for Applied Systems Analysis
IRIS	An Interactive River Simulation Program
IT	Intermediate Scale Rice Irrigation Project
LP	Linear Programming
NGO	Non-governmental Organization
NRM	Natural Resources Management
OMVS	Organisation Pour la Mise en Valeur du Fleuve Senegal
ORSTOM	Office de la Recherche Scientifique et Technique Outre-Mer

PACF	Partial Autocorrelation Function
PIV	Perimetre Irriguee Villageois
RACF	Residual Autocorrelation Function
RP	Rice Production
SAED	Societe des Ammenagements et Etudes de la Delta
SDP	Stochastic Dynamic Programming
SRB	Senegal River Basin
SYSPRO	Systemes et Prospectives
USAID	United States Agency for International Development

CHAPTER 1

INTRODUCTION

The Problem:

> *Development in many countries of sub-saharan Africa went into reverse gear during the 1980s. Rates of economic and social advance were outstripped by the most menacing land degradation and the highest rates of population growth in the world.*
>
> *Agriculture in the region is dominated by technologically resource poor farmers and pastoralists. The soils are fragile, the water scarce and the climate variable. In the 1950s and 1960s the region was marked by increasing agricultural productivity, including food. Since the 70s average food production per capita has been falling by about 1% per year, the capacity of the region to feed itself is declining. Inadequate production of staple foods and growing urban tastes for non-traditional foods are creating a growing dependence on imported foods. The region is experiencing high rates of rural-urban migration. Many join the throng of urban poor who are unable to create sufficient income to enable them to gain economic access to food.* [Food 2000, 1987]

The (Potential) Solution:

> *We believe that Africa's limitations can be overcome through spreading and developing new technologies to all farmers, with the focus on the majority who are small farmers, by exploiting to the full the natural and human resource potential; and by promoting production by sustainable land use and farm management patterns. To effect this would require the strengthening of natural agricultural systems in order to develop, with the farmers, the necessary locality specific research technologies.* [Food 2000, 1987]

The quote from the report to the World Comission on Environment and Development above describes the status of sub-Saharan Africa in general. Perhaps one of the best examples of the confluence of the environmental and economic obstacles to development in Africa is the case of the development of the Senegal River basin.

1.1 The Problem Context: Development of the Senegal River Basin

The Senegal River basin (SRB) is shared by the nations of Guinea. Mali. Senegal and Mauritania in the Sahelian and sub-tropical climate zones of West Africa as seen in Figure 1.1.

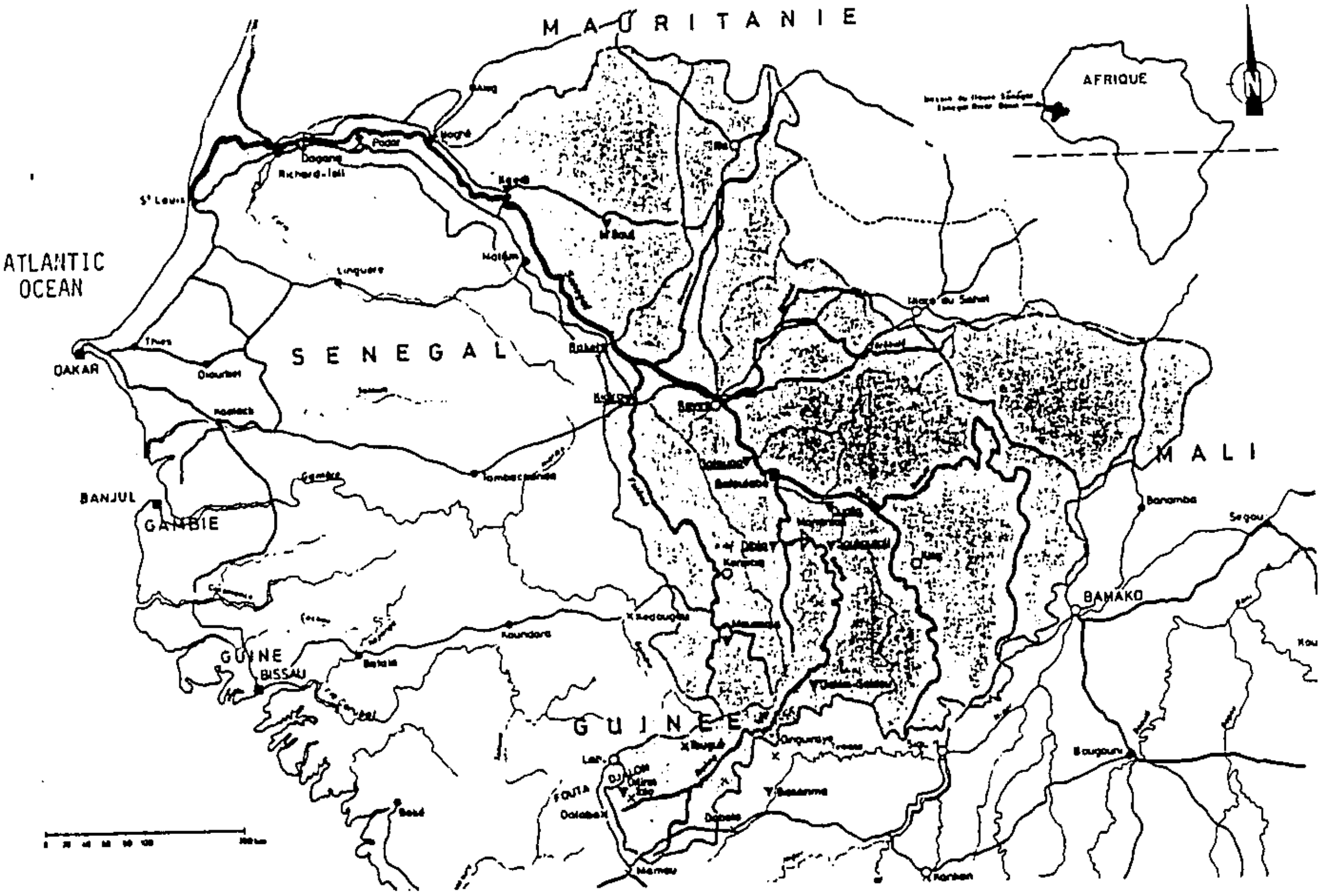


Fig. 1.1 The Senegal River Basin [Source: ORSTOM, 1992]

The social and ecological fabric of these nations, particularly Senegal and Mauritania in the semi-arid lower river basin, is highly stressed, a major cause of which is the drought that has continued largely unabated since its onset over two decades ago. Development of the SRB is continuously touted as a salvation for these poor and drought afflicted nations. Regulation of the river and associated agricultural development are believed to be capable of increasing regional prosperity and restoring the seriously degraded basin ecology to its former verdant status. [M'baye, 1966]

The dream of harnessing the highly irregular flows of the Senegal River and realizing the agricultural potential of the Senegal River Valley has been sought since the early French colonial period. Attempts to establish irrigated agriculture date from 1824 with the construction of rice perimeters at Richard Toll [Seck, S., 1991]. The origins of recent development plans for the basin date from the 1950s when the French colonial administration drew plans to exploit hydro-electric potential in the upper river reaches of Mali and the agricultural potential of mainly the middle and lower valley shared by Senegal and Mauritania. Development was seen primarily as a means to increase the wealth generating capacity of these colonies. The French shelved the plans however, as they appeared largely unprofitable at the time [Lemarquand, 1990].

Independence of the West African states in the early 1960s saw a revival of the SRB development plans. The project objectives shifted from serving the metropole (Paris), to meeting the expectations of rising prosperity that independence was supposed to bring. In addition to the explicit social welfare objectives of increasing productive employment in the valley, the basin states each pursued their own political agenda in seeking cooperative river basin development. Senegal, with its embryonic manufacturing sector, wanted to regain the economic lustre it lost with the balkanization of its markets in French West Africa; Mauritania wanted to carve out a distinct African identity, independent of its strong northern Arab-Berber orientation, and landlocked Mali sought a permanent navigable passage to lessen its dependence on its neighbours for trade routes. The post-independence fragmentation of Francophone West Africa compromised the ideal of Pan-African Nationalism. Co-operative river basin development promised to redress this as well, Lemarquand [1990] summarizes:

> *The Senegal River was a common link and in plans for its development the political leaders found something physical upon which to crystallize feelings about regional integration and satisfy some of the economic and political problems they faced. Not to be underestimated was the symbolic value of the actual projects. They would demonstrate physically the will of the states to work together and the dynamism of the leadership in working for economic development of their states.*

Thus in 1962, based only on the technical feasibility of the French engineering studies, the basin states of Mali, Mauritania and Senegal made the political decision to pursue river basin development with the concurrent construction of the Diama and Manantali dams. Simultaneous development intended to give each participating state something while making none completely vulnerable to the success or failure of the entire project. The decision was taken in the marked absence of any global study showing the overall feasibility of the project. LeMarquand maintains that all subsequent studies have largely intended to justify the original political decision and this "backwards planning approach" has plagued SRB development since the inception of the project.

The newly independent states of the early 1960s inherited the infrastructure component of the colonial development plans. Senegal, Mauritania and Mali jointly created the Organisation pour la Mise en Valeur du fleuve Senegal (OMVS), a supra-national river basin authority charged with the development of the river. The long-term development goals for the Senegal basin nations entrusted to the OMVS as formulated in 1974 are:

1. ensuring the reliability of incomes and to increase them for a maximum of the population.
2. to establish a more stable ecological equilibrium between man and the environment in the basin itself and as much of the three states in the Sahelian zone as possible
3. to reduce the economic vulnerability of the three states vis-a-vis climatic and external factors;
4. to accelerate economic development of the three countries and inter-state cooperation.

The OMVS plans called for the construction of the Manantali dam and storage reservoir complex (capacity: 7.9 billion m^3) on the Bafing tributary in Mali, capable of regulating 50% of the total flow in the basin. According to the design assumptions Manantali regulation could provide primarily for year-round irrigation of 376 000 hectares and would be capable as well of producing 200 megawatts of hydro-electric power. The Diama dam in the Delta region of the river comprised the second component of the project. Diama was designed primarily as a salt-barrage to prevent the intrusion of a saline wedge of seawater upstream into agricultural regions during periods of low flow. Diama also has secondary storage and navigation functions. Severe water deficits in the Cap Vert area (Dakar and environs) have recently forced the inclusion of a third infrastructure component to the global SRB development plan. [Potworowski, 1990] The scheme calls for the diversion of water from a natural surface recharge area of the river (Lac de Guiers) via the Canal du Cayor to the Dakar region for municipal consumption. Construction of the Canal du Cayor awaits the finalization of financing agreements with international donor agencies. Fig. 1.2 shows a schematic of the Senegal River system including the irrigation abstractions in the major agricultural development zones and the diversion at Richard Toll into Lac du Guiers to meet urban demands in the Cap Vert region via the proposed Canal du Cayor.

OMVS development objectives hinge on the infrastructural development (largely complete), a rapid transition to year-round irrigated agriculture, and increasingly tenuous assumptions regarding the basic hydrology of the SRB which will determine the global availability of water for all development purposes.

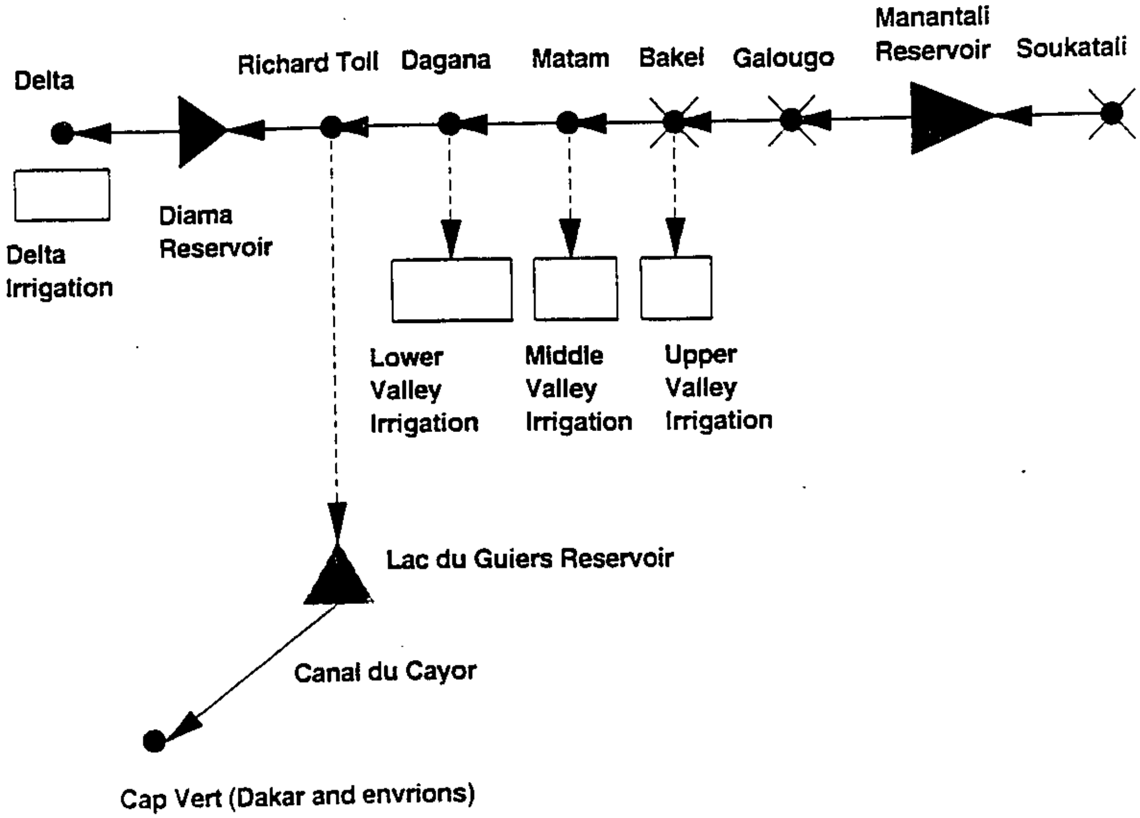


Fig 1.2 The Senegal River Basin Development: Schematic

1.2 Senegal River Basin Development: The Physical Context

1.2.1 Basic Hydrology of the Senegal River Basin

The Senegal River Basin has a total drainage area of 290 000 km^2 which is distributed among the riparian states as follows: Guinea: 31 000 km^2, Mali: 155 000 km^2, Mauritania: 76 000 km^2 and Senegal 28 000 km^2. The basin as shown in Fig. 1.3 is characterized by a steep rainfall gradient of approximately 1 mm/year/km from the headlands in the Fouta Djalon mountains of Guinea, to the lower valley shared by Senegal and Mauritania.

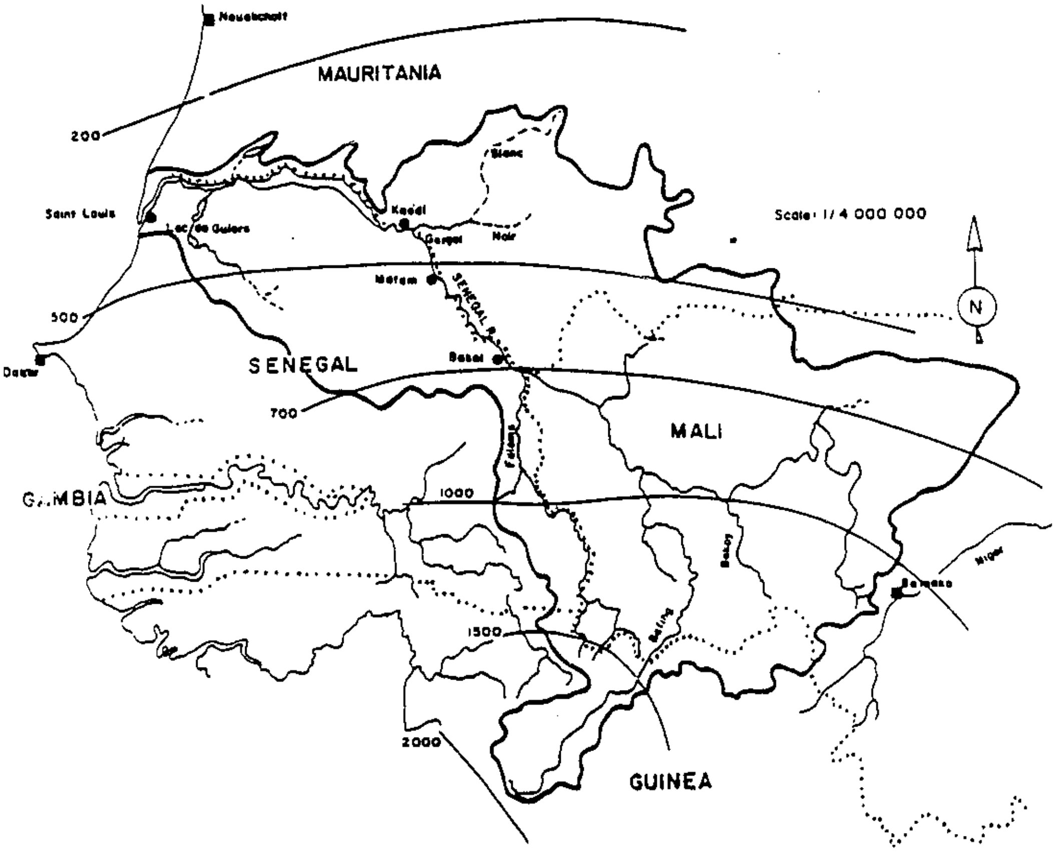


Fig 1.3 SRB Historical Rainfall Isohyets [Source: Riley et al, 1978]

Bakel, situated just downstream of the confluence of the two major tributaries, the Faleme and the Bakoye, is generally considered the point of division between the upper and lower basin. Bakel is also the point of maximum flow in the river. Humid hydrology dominates the upper basin with (historical) rainfall averaging between 2000 mm and 700 mm at Bakel. The magnitude and duration of the wet season (June to September) rains in the Fouta mountains determines the general flow regime of the river. The natural regime is thus extremely seasonal, in fact it is essentially characterized by a single flood event. High and low flow periods differ by about two and a half orders of magnitude. The average September flow at Bakel was 3590 m^3/s (1904-1969), decreasing to 1770 m^3/s (1970-1989) and the average May flow was 10 m^3/s (1904-1969), decreasing to 6 m^3/s (1970-1989). [Source: ORSTOM, 1992].

Downstream of Bakel arid zone hydrology dominates, as tributaries contribute negligible volumes. Evaporation, seepage and losses to flood plain storage dominate the natural regime. Between Matam and Dagana flood plain storage can be great depending on the magnitude of the flood. Downstream of Dagana the high season flows refill natural depressions in Mauritania at Lac R'Kiz and in Senegal at Lac de Guiers before entering the Delta region upstream of the port city of St. Louis.

1.2.2 Physical Features of the Senegal River Valley and Agricultural Potential

Irrigated agriculture is possible throughout the valley of the lower SRB [FAO, 1977]. Over 90% of the potentially irrigable area is in Senegal and Mauritania. Three main soil types differentiated mainly by clay content, dominate the valley and the delta. Their traditional names and principal characteristics are given in Table 1.1

Table 1.1 Soil Types in the SRB

soil	clay	silt	sand
fonde	25%	60%	15%
faux hollalde	40%	45%	15%
hollalde	50%	35%	10%

[Source: Frankenburger et al., 1987]

Fonde soils are loose and form the banks of the river, the hollalde soils are denser and more impermeable and are located in low lying areas of the flood plain where water settles. The faux hollalde is a transition soil of varying clay content.

The upper valley contains a higher percentage of lighter soils while heavier soils dominate the lower valley and delta. Village scale irrigation projects are located primarily on the lighter soils of the fonde on higher ground where drainage is generally not required, although their command area frequently extends onto the heavier lower soils. The higher land is best suited to cultivation of grain crops. Rice perimeters are better suited to the heavier hollalde soils located on the lower flood plain, the low lying "cuvettes" typically require artificial drainage, particularly in the Delta region. Considerable flexibility in the crop mix is possible throughout the valley for example, cereals can be grown as a second season crop on hollalde and faux hollalde soil, and vegetables can be grown on any of the soils. Figures 1.4 and 1.5 illustrate typical valley cross sections and the relative occurence of soils at the incised high valley and in the middle valley where the floodplain begins.

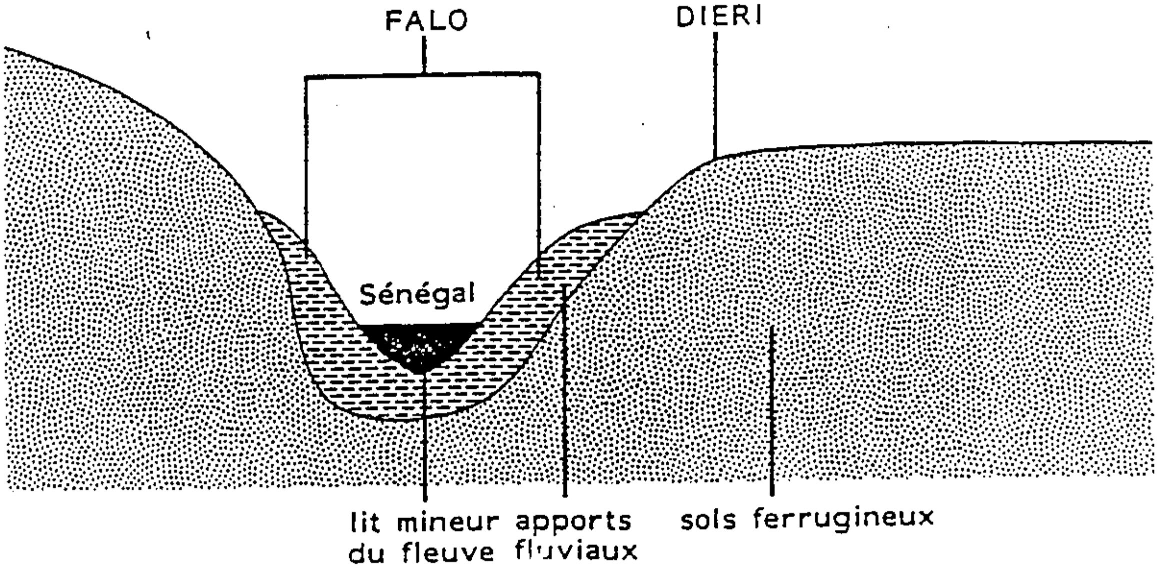


Fig 1.4 Senegal Valley Cross-Section (High Valley) [Source: Gersar, 1990]

Agriculture in the valley is currently still dominated by traditional flood recession practice in the flood plain and by extensive rainfed agriculture on the very light *dieri* soils that occur outside the floodplain. Both flood recession and rainfed agriculture have been drastically curtailed by the drought, which has decreased the area of inundated land during the flood and made rainfed agriculture much less viable. Some villages have adapted to the drought conditions by adopting irrigation techniques, however the drought has also displaced many traditional farming communities since traditional agriculture can no longer support the same population base as in previous decades [Frankenburger et al., 1987].

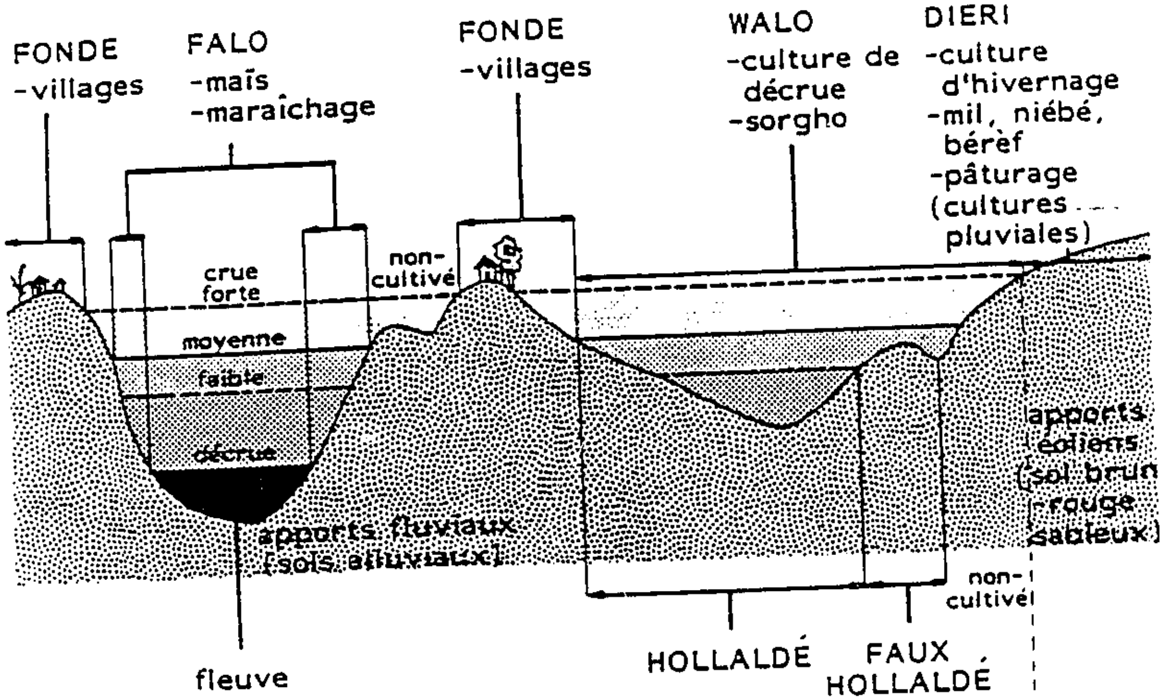


Fig. 1.5. Senegal Valley Cross-Section (Middle Valley) [Source: Gersar, 1990]

1.2.3 The Magnitude of the Environmental Crisis in the Senegal River Basin

Greatly compromising the development objectives of the OMVS is the environmental crisis brought on by the drought of recent decades, seemingly endemic to all of Sahelian Africa. The Senegal River basin as well as most of Senegal is in a state of severe environmental degradation. The last complete remotely sensed survey of Senegal was completed in 1985 under the auspices of La Direction de l'Ammenagement du Territoire, with administrative and technical assistance of the USAID and the Remote Sensing Institute at South Dakota State University (SDSU), U.S.A. The project produced many maps of the Natural Resources inventory in Senegal, (hydrological, mineral, soil resources etc.) including a map outlining the extent of vegetative cover degradation, reproduced in Appendix 1. Virtually the entire valley was classified as severely to very severely degraded, linked in all cases to the climate factor, (defined in this study as a 30% or more reduction in average annual rainfall between the periods 1930-1969, and 1970-1985) and to either anthropogenic pressure (deforestation, extension of cultivable land) or animal pressure (destruction of pasture by over-grazing) or a combination of both factors.

With the exception of the far south, the map depicts Senegal as more or less uniformly impacted by vegetation degradation. In the north, along the river valley, "normal" rainfall was the lowest to begin with, and the climate most arid and vulnerable to perturbation. The rapidity of valley degradation is perhaps the most startling phenomenon. Foret [1888] describes the environment between Dagana and Podor in the Lower and Middle Valley , as one "of forested hills without interruption as far as the eye can see composed of a variety of beautiful hardwood trees". Only a few decades ago M'baye [1966] described a flourishing Senegal River valley as: "The verdant valley of the river which has given its name to the country, interrupting the arid plains of Mauritanian desert and the wooded pastoral region of the Ferlo region". The photograph shown below, Fig. 1.6, was taken in late October 1992 in the middle Senegal River valley, revealing the massive deforestation and resulting land desiccation on what was (and officially still is) nationally protected forest inventory. The deforestation is largely an economic response on the part of Valley farmers to decreased yields caused by the drought. Unfortunately deforestation unleashes a cycle of ecological degradation which only exacerbates the worst effects of the drought.

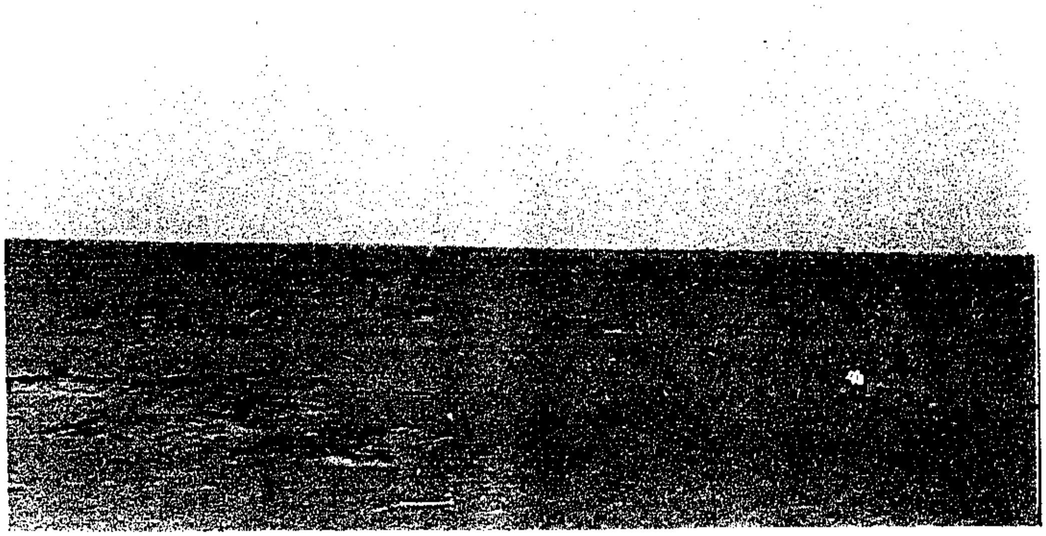


Fig. 1.6 Massive Deforestation in the Middle Valley

1.3 Criticism and Perspective of the SRB Development Plan

Despite widespread scepticism amongst international donors, the devastating drought that began in the early 1970s, the landscape degradation, the famine and the massive relief effort that followed stiffened donor resolve to attempt a permanent solution for the region. Senegal River development promised to increase reliable agricultural productivity in the river basin and thus most donor agencies were willing to accept the plan as a good investment compared with the cost of continued relief. The United Nations and its agencies, which at the time were actively promoting international river basin development as a basis for integrated development, supported the project as did the European Development Fund of the European Economic Community. Other donors, notably the World Bank and the United States Agency for International Development (USAID), remained doubtful that the plan could work. In 1977, facing continued donor scepticism, the OMVS commissioned a British engineering consultant, Sir Alexander Gibb and Partners (Gibb), to conduct the first independent global study of the SRB project. The sceptics seemed vindicated as Gibb's subsequent report contained two major critiques of the overall plan. Gibb's principal conclusions were the following:

> -Little complementarity existed between the Manantali and the Diama projects, i.e. the benefits attributable to each project were greater for each project separately than for the combined project.
>
> -There was a relative over-investment in physical infrastructure and under investment in the irrigation sector which provided the economic justification for the entire project. In Gibb's view, the plan called for a rate of development of irrigation perimeters that was beyond the capability of the basin states and the various aid agencies working in the basin.

The OMVS's response at the time (and at present) to economic criticism of the project, was that while the projects themselves may be uneconomical according to conventional calculations, the associated rural development that the projects would make possible would be profitable. As well, since financing for the project came on highly subsidized terms, 60-85%, typical for international development projects, infrastructure investment appeared more or less as a direct benefit from the OMVS's perspective.

The unorthodox economic reasoning the OMVS presents, may in fact have some merit. Their perspective reflects in part a development philosophy which stresses that sustainable development comes from the long-term evolution of agrarian economies and associated support industries. Scudder [1989] describes the "true engine of development" as being large numbers of small rural producers all able to market modest surplus and move ahead together. This line of reasoning finds empirical justification in the Ivory Coast example. Despite the collapse of tropical commodities prices in the 1980s, the relative affluence of the Coté d'Ivoire is routinely attributed to its agriculture sector having evolved in the hands of tens of thousands of small producers [Newton, 1988]. The long-term effect of this style of development is to diffuse capital locally rather than concentrate it. This philosophy however transcends normal analysis and involves payback periods, rates of return, and intangible socio-economic benefits largely incalculable with conventional engineering economic tools.

In retrospect the continued drought may have helped justify the construction of both dams. Diama's function as a salt barrage becomes extremely important during periods of very low flow. Without it, releases of water from Manantali are required just to prevent the intrusion of the salt wedge. Gibb's analysis was based on the historical hydrological record from 1904; if however the drought of the last two decades represents more realistically the prevailing hydrological regime, the availability of water from Manantali for any purpose would be more limited than their use of historical averages suggests. Diama's value would therefore have been under-estimated.

Gibb's second major critique, that there was a relative under-investment in the rural development to establish irrigated agriculture, was largely irrefutable. The irony is that the economic justification of the entire project depended heavily on exactly this, the rapid transition of the valley to irrigated agriculture. There was unfortunately very little the OMVS could do about it. Donor agencies typically favour capital infrastructure projects with high foreign exchange components and the promise of tangible results and the SRB project was no exception. The need for associated rural development is obvious and widely recognized. The daunting difficulty however, of executing a large scale shift from traditional to modern agricultural methods, with no promise of tangible results, is for most donor agencies not a preferred investment option. This task typically falls to chronically underfunded national agriculture development boards and non-governmental organizations. The last fifteen years of agricultural development in the SRB has proven that the shift from traditional flood recession to mechanized irrigated agriculture is in fact a disturbingly complex socio-economic problem which also risks further destabilizing an already highly stressed ecosystem.

1.4 Current Status of the SRB Development Program

November 1, 1992 saw the official opening of the Diama dam and with it the public re-affirmation of the basin states' commitment to co-operative river basin development as the key to a new era of collective security and prosperity [Diouff, A., 1992]. The public expression of optimism belies the huge obstacles the OMVS still faces:

-Senegal and Mauritania still have not restored normal relations after open hostilities in the river region in 1989. Unsettled land tenure issues regarding agriculture in the middle valley triggered the border conflict.

-The development of state managed irrigated rice perimeters in the valley has stagnated badly as they are plagued with a high level of social alienation, mediocre output, and rapid abandonment. The large perimeters have required huge state subsidies for their continued operation and have caused serious negative environmental impacts [Seck, S., 1991; Mbalo, 1993].

-The annual artificial flood released by Manantali will continue indefinitely. The flood, which mimics the river's natural hydrology, was intended to be only a temporary practice to ease the transition from flood recession to irrigated agriculture. Using Manantali storage in this fashion significantly compromises the development objectives of river regulation for year round agriculture, eco-system stabilization, hydro-power generation and navigation that justified the Manantali's construction, while incurring all the direct costs and environmental impacts of the dam construction itself. Some observers speculate that given the poor development rate of irrigated perimeters, the artificial flood could continue until 2030 [Seck, S., 1991].

-The drought is entering its third decade, vast areas of the river valley are in advanced stages of desertification due to a variety of social and ecological pressures, and:

-An inter-related effect of drought, "l'exode rurale" has created massive urban poverty and swamped the infrastructure capacity of the Dakar region. To meet water demands driven by exponential population growth, Dakar plans to abstract water from the Senegal River through the Lac de Guiers-Canal du Cayor complex.

The incessant advance of the desert and the continued marginalization of land and people that it entails is the single biggest obstacle to development. The process of desertification is driven simulataneously by hydrological, social and economic factors. Falkenmark [1989] describes desertification processes as being catalyzed when poor rainfall is filtered through an environment whose land and water resources are already over-exploited. The conclusions drawn by a study of farming systems in the Senegal River Valley by The University of Arizona Department of Arid Land Studies [Frankenburger et al, 1987] paralleled Falkenmark's model: adequate rainfall of the 1950's and 1960's supported a population of pastoralists and livestock that was beyond the region's carrying capacity when the drought struck in 1970's. The ensuing overgrazing destabilized the fragile vegetative cover in the region and started the desertification process.

Other analysts have explored the macro-economic climate and the crushing indebtedness that Sahelian countries face as factors which hasten desertification:

> *The unfortunate terms of trade for primary production have reinforced government pressure for increasing cash crop production at any cost. Producers are expected to grow more cash crops and as they and their nations get poorer and fall deeper into debt, they over exploit the fragile ecological base to maximize their incomes and foreign exchange.* [Food 2000, 1987]

Short term economic objectives have effectively determined the course of SRB development until now, and have compromised other long-term objectives of the OMVS such as providing, "a more stable equilibrium between man and environment" [Lemarquand, 1990]. Senegal's decision to dedicate scarce extension resources to establish large rice perimeters was a direct attempt to ease foreign exchange shortfalls from ever increasing rice imports. Mbalo [1993] describes the negative environmental effects of large rice perimeter development orientation as having contributed significantly to hastened desertification in the valley.

1.5 Crisis Brings Opportunity: Options for Alternative Rural Development

The opportunity to re-integrate sustainable agricultural development philosophy into the SRB development plan arises in ironical fashion. Rather than easing foreign exchange shortfalls, attempts to establish large rice plantations have proven so costly and yielded such mediocre results, that the foreign debt crisis has forced Senegal to abandon or greatly reduce its subsidies to these projects. The Societe des Ammenagements et Etudes de la Delta (SAED), the national agency in Senegal responsible for irrigation development has in the last several years encouraged another form of irrigated agriculture development, the so-called Perimetres Irrigues Villageois (PIV's). Established with the aid of foreign non-governmental organizations, or often solely with the initiative of villagers themselves, the PIV's have been a relative success [Huibers and Speelman, 1991]. PIV's are characterized by their very simple hydraulic design and village-scale size and can be adapted for traditional village social organization. Most PIV's have been modestly profitable [Engelhard, 1991]. When designed with windbreak shelter-belts and managed for polyculture with crop rotation, PIV's can have a rehabilitative environmental effect. The PIV's are also generally significantly less water consumptive than the large mono-culture projects [Gibb, 1986a], an important issue in a water-scarce region such as the SRB.

Other innovative irrigated agricultural techniques integrating natural resources management methods have also proven workable in the SRB. ENDA-Systemes et Prospective (SYSPRO) has developed a "third generation integrated agriculture system" which stresses the ecological aspects of agro-forestry and associative cropping methods while maximizing water utilization. In one example SYSPRO has been productive on land which two years previous had been abandoned after rice cultivation left it salinized and desiccated. The SYSPRO development approach is also unique because of its innovative social organization which capitalizes on the human resources of a large, unemployed, motivated urban population willing to make the reverse migration back to the country.

1.6 The Challenge: Defining a Model for the Sustainable Development of the Senegal River Basin

Water is a limited resource in Sahelian Africa. Water resources and associated agricultural development hold the promise of contributing greatly to ecological and social stability. Exploitation of limited water resources for environmentally and socially maladapted projects can just as easily exacerbate the current process of desertification and with it the concurrent phenomenon of rural exodus and abject urban poverty. The challenge is first to meet the necessary condition of the fundamental hydrologic constraint, that the water demands exerted by the development program do not exceed the limited supply; and secondly to meet the sufficient condition: that the development has a positive environmental and social impact. These development objectives define the structure of the water resources systems analysis framework applied to the SRB.

1.7 Research Objectives and Methodology

The research objectives for the SRB study were **to establish the areal extent of irrigated agriculture which could be sustained for different assumptions regarding the prevailing hydrology in the SRB and basin-wide irrigation development policy.** The purpose of the study was essentially to establish the water resources management implications for two clearly delineated agricultural development policies, one stressing **rice production and strong centralized management** (effectively the status quo) and another hypothetical agricultural development policy stressing equally **small farmer priorities of cereal grain self-sufficiency and environmental rehabilitation through agro-forestry.**

1.7.1 The Water Resources Systems Analysis Framework

The general water resources analytical model is adapted from Loucks et al (1981) as depicted in Fig. 1.7.

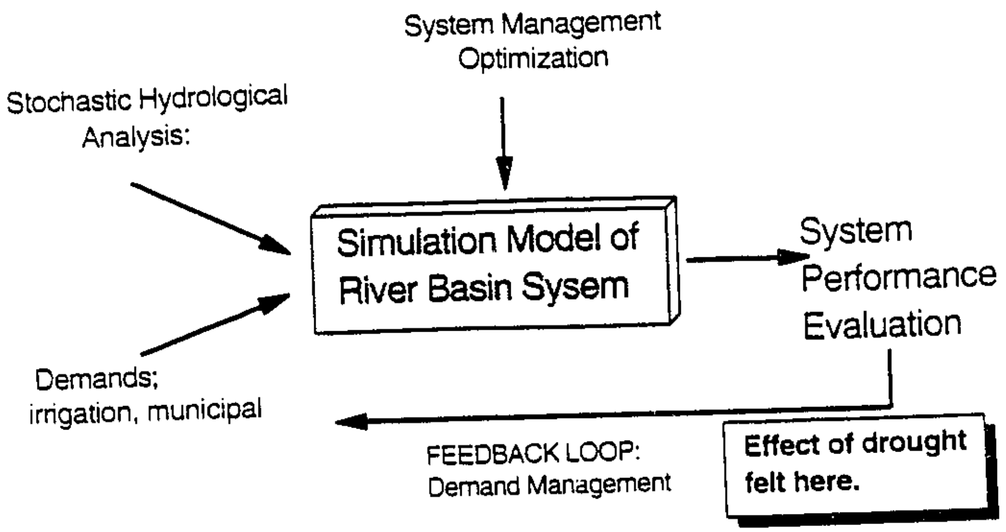


Fig. 1.7 SRB Analytical Framework [adapted from Loucks et al, 1981]

The feed-back loop represents a fundamental issue in the SRB study and departure from conventional supply side oriented engineering. In the case of the SRB, since infrastructure development can for all practical considerations be considered fixed, demand management offers the only feasible response to drought induced water scarcity which threatens all of Sahelian Africa. The elements of the model each formed a major component of the study. The specific research objectives pertaining to each element of the analytical framework shown in Fig. 1.7 were as follows:

A. STOCHASTIC HYDROLOGY

i. to use stochastic and spectral analysis techniques to perform a decomposition of the time series of Senegal River streamflows

ii. on the basis of the time series properties established above, to generate synthetic streamflow sequences for the SRB simulation studies, the structure and scale of which correspond to three different assumptions regarding drought conditions in the SRB.

B. DEMANDS

i. To establish on the basis of published field data and independant field study, representative crop consumption levels for different styles of irrigated agriculture development in the SRB.

ii. To delineate clearly between two different representative demand patterns on the basis of environmental and socio-economic impacts; one demand pattern representing government policy objectives of rice production, and the other, individual farmer self-sufficiency and environmental rehabilitation objectives.

C. RIVER SYSTEM SIMULATION

To construct a model for the computer simulation study of the water resources management aspects of the Senegal River system capable of simulating:

i. The operation of the Manantali and Diama dams

ii. The allocation of water to the major irrigation development regions in the Senegal river valley.

iii. The allocation of water to the Cap Vert (Dakar) region from the Senegal river through the Canal du Cayor complex.

D. SYSTEMS MANAGEMENT OPTIMIZATION

To apply dynamic programming methods and principles to establish operating parameters for the Manantali dam and irrigation allocations, for all assumed hydrologic and development policy scenarios.

E. SYSTEMS PERFORMANCE

i. To evaluate the sensitivity of the Senegal river system's performance in terms of reliability in meeting demand targets.

ii. To establish the maximum areal extent of irrigated agriculture development achievable under three different hydrological regimes.

iii. To estimate the impact of government irrigation development policy versus a "sustainable development" irrigation policy on the water resources management of the SRB.

1.7.2 Guiding Principles, Methodology and Organization

Although the Senegal river system analysis could be structured as a strictly water resources systems optimization and simulation study, doing so neglects the geophysical/environmental and socio-economimc context which wholly motivates the study. The chapter organization of the study reflects the "front-end" consideration of the intertwined socio-economic and environmental issues present in the SRB. Chapters 2 to 6 correspond to elements A to E in the analysis framework presented above.

Chapters 2 and 3 reflect the fundamental importance placed on the ecological and socio-economic crisis in the SRB. Addressing these issues initially defines the technical issues that must be considered.

Chapter 2, corresponding to element **A. Stochastic Hydrological Analysis** in the analysis framework, begins with a discussion of the continent wide drought in Sahelian Africa. The chapter continues with a discussion of the potential impact of possible climate change induced water scarcity and hence the constraints water scarcity places on development objectives in the SRB. A description of the mathematical methods used to analyze the time series properties of Senegal river streamflows follows. Chapter 2 concludes with a description of time series properties of Senegal river hydrology and how these properties were used to generate synthetic data for both the drought and non-drought hydrologic regimes postulated for the simulation study.

Chapter 3 is an extensive chapter that deals with managing water demand in the SRB through the choice of irrigation development policy, and the impact of different irrigation policies on natural resources management objectives in the SRB. Commencing with a qualitative description of the dynamics of desertification in a drought regime, the chapter continues with a description of irrigated agricultural alternatives in the SRB in terms of their physical and management features, socio-economic impacts, and their contribution (or lack thereof) to natural resources management objectives. The socio-economic performance of SRB irrigation development options is discussed extensively since this feature is crucially important is assuring the sustainability of a project and its potential contribution to SRB eco-system stabilization. The existing research on agricultural systems in the SRB consistently reports that the fundamental constraint on re-establishing vegetative cover in the region is the limited water resources availability. Chapter 3 thus provides the conceptual link between the ecosystem degradation and the water resources management issues in the SRB.

The last section of Chapter 3 defines the assumptions in delineating between a rice production irrigation development policy and a sustainable development/natural resources management policy. The chapter then concludes with a quantitative analysis of crop-water consumption characteristics, defining the demand pattern for the two different development policies, corresponding with element **B. Demands** in the water resources analysis framework of Section 1.7.1

Chapter 4 corresponds with element **C. River System Simulation** in the analysis framework of Section 1.7.1. The Chapter commences with a discussion of the modelling principles applied in the simulation study of the Senegal River System. The chapter then continues with a description of the physical and hydrological data used and the assumptions invoked in configuring the computer simulation model of the Senegal River.

Chapter 5 corresponds to element **D. Systems Management Optimization** in the analysis framework of Section 1.7.1. The chapter begins by introducing the use of optimization techniques in water resource system analysis. Chapter 5 then provides a conceptual overview of dynamic programming optimization principles and their application to reservoir management. Chapter 5 concludes with a thorough discussion of the novel decomposed space-time dynamic programming algorithm applied to Manantali reservoir operation.

Chapter 6 corresponds with element **E. Systems Performance Evaluation.** Key results from the simulation exercise are summarized and presented here, in primarily a graphical format, and their implications discussed. The key results presented include the irrigation development potential and hydro-power characteristics of the two development policies defined in Chapter 3 for the three hydrological scenarios postulated in Chapter 2. Chapter 6 also presents the simulation results for two more strongly opposed development policies; a strong natural resources management policy serving only rural development objectives, and a hydro-power optimized rice production policy designed to serve primarily urban interests.

Chapter 7 gives final conclusions and Chapter 8 offers key recommendations from both a strictly technical and an international development policy perspective.

It must be noted that due to the strong multi-disciplinary nature of the study, no single literature review chapter is included. Such a review would be both voluminous and highly fragmented. Instead, with the exception of Chapter 3, each chapter provides an introduction to the theme of the chapter and includes a description of the theoretical principles and cites pioneering research and fundamental developments extensively.

Chapter 3 instead focuses on the socio-economic and environmental factors that assure sustainable rural development in the SRB. Chapter 3 is therefore largely dedicated to a review of field experience with various rural development models and includes a case study of an alternative agro-forestry rural development model and its potential application for the social and environmental rehabilitation of the SRB.

CHAPTER 2

WATER SCARCITY IN SAHELIAN AFRICA

Applying Stochastic Analysis to Senegal River Basin Hydrology

Chapter 2 corresponds to element **A. Stochastic Hydrology** in the "Water Resources System Analytical Framework" discussed in Section 1.7.1 depicted in Fig. 1.7.

2.1 A Hydrological Regime in Transition

The last two decades have seen drought of previously unrecorded severity strike Sahelian Africa. Environmental and social effects of the drought have been catastrophic. The drought manifests itself as a southward shift in the rainfall isohyets. Data available in Figs. 2.1 and 2.2 for Senegal clearly illustrate this phenomenon.

The impact of the drought on water resources is shown clearly in Fig. 2.3 as the time series of annual flow volumes in the Senegal River at Bakel. The downward trend of the last twenty to thirty years reflects the onset of the drought. A simple statistical screen (the student's t-test) for time series non-homogeneity showed that the average annual flow at Bakel before and after 1960 differed at a 99.9% significance level. This preliminary result suggests the times series is not homogenous and that some intervening factor has altered the natural milieu. The obvious implication is that global climate change effects may be curtailing substantially the water resources availability and with it the prospects for basin wide development as originally envisioned.

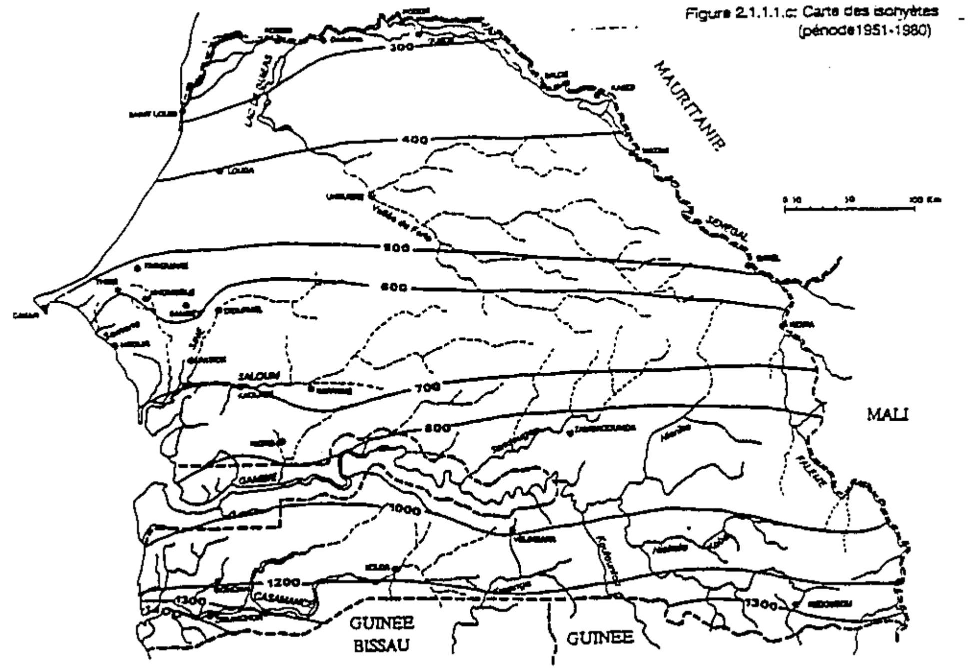


Fig. 2.1. Senegal Mean Annual Rainfall 1951-1980 (Source: ORSTOM)

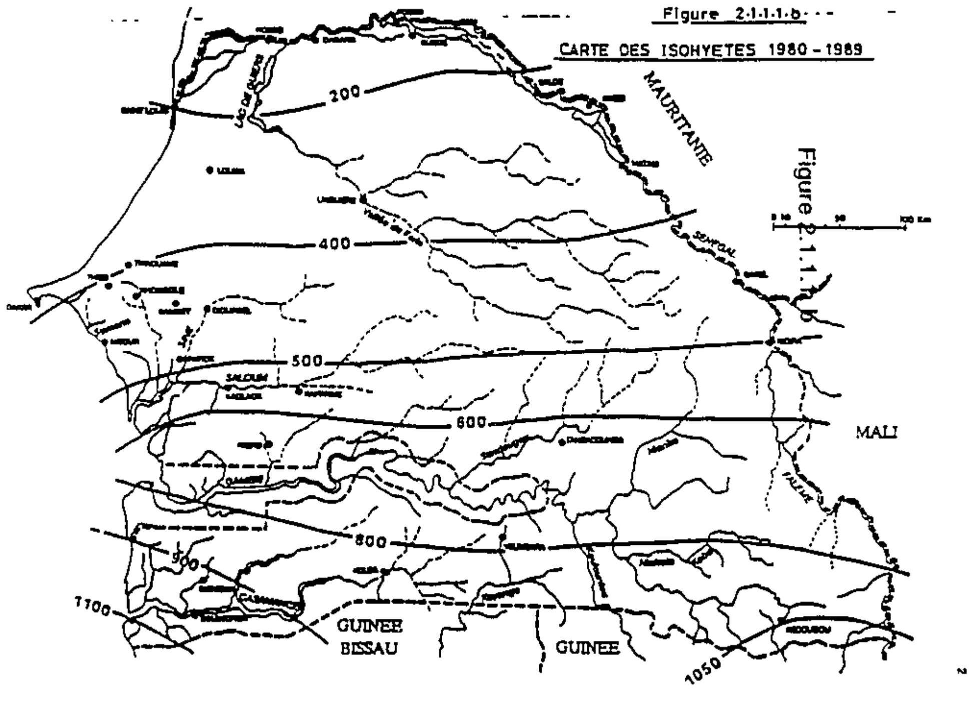


Fig. 2.2 Senegal Mean Annual Rainfall 1980-1989 (Source: ORSTOM)

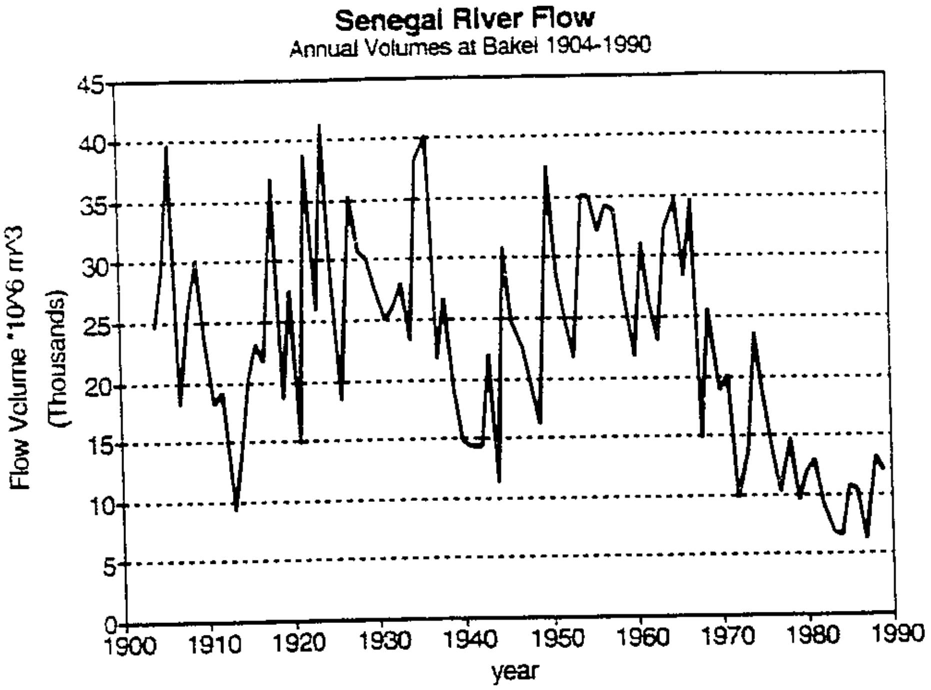


Fig. 2.3 Senegal River Annual Flow Volume 1904-1990

2.2 Climate Change, Water Scarcity and Water Resources Development

Gleick [1987], and Williams [1989] have speculated widely on global climate change and the potentially massive impacts on hydrologic and water resources systems. Climate change effects are difficult if not impossible to distinguish from long-term meteorologic periodicities [Hipel, 1985]. The advance of the desert is very likely part of a natural process that has been occurring for centuries. Historical records from the 17th century refer to southward migrations of people escaping the advancing desert [OMVS, 1980]. However it is the rate of advance, and the severity of the drought which suggests that permanent climate change and anthropogenic activity are aggravating and entrenching a coincident natural phenomenon.

Water resources development may be increasingly vital to provide water security in drought afflicted regions, particularly if the causal agent of the drought is non-transitory climate change. Conventional development models have traditionally included large scale water resources development. typically large dams. Water resources infrastructure offer the promise of launching developing countries into the industrial age by simultaneously providing control for domestic water supply, irrigation, flood control and hydropower. Water resources projects for international development have also been strongly criticized in environmental circles as some of the worst examples of unsustainable development:

> *The most striking failure of development aid are the many large dam projects whose environmental and social costs - the inundation of productive land, displacement of people, increased prevalence of diseases, and reduced downstream productivity resulting from salt intrusion, delta erosion, drying of downstream lakes, and channel deepening - sometimes far exceed the benefits of irrigation and hydro-electric power. In many cases, dams operate at only a fraction of the planned length of time because of the high rates of sedimentation that result from inadequate watershed management. Moreover, salinization of cropland following inappropriate irrigation often destroys the productive potential of land the dams brought under cultivation.* [Reid, 1989]

Reid's charges are a typical example of the criticism on environmental grounds of the Aswan High Dam in Egypt [Goldsmith and Hildyard, 1984] and more recently the Narmada Dam complex in Pakistan. However, Biswas [1992] has noted in retrospect that the ecological impacts of the Aswan Dam have stabilized at levels far less negatively impacting than predicted originally. Biswas claims that Aswan was crucial in saving the country first from the severe drought of 1979-1988, and then from the abnormally large flood later in 1988. Similarly Gleick [1987] maintains that over-riding concerns about the direct negative environmental impacts of dam construction, arid and semi-arid countries such as those of Sahelian Africa most vulnerable to climate change induced water scarcity are indeed *worse off* because they suffer a lack of water resources infrastructure which could attenuate the worst effects of water scarcity. In the case of the SRB the a posteori justification of Diama's construction as a salt barrage given the reduced available flows from Manantali is an example of this.

In a study of watersheds in Northern California, Williams [1989] describes the major first order climate change impacts on water resource systems including: altered run-off, increased run-off variability, altered geomorphic response of the watersheds and increased soil erosion. Williams concurs that arid and semi-arid climates and in particular Sahelian Africa are vulnerable to these hydro-geomorphic impacts and may be undergoing them already. William moves beyond the supply orientation of conventional water resources management in identifying key water resource management responses which are:

1. Changes in Agricultural Methods
2. Incentives of Watershed Management
3. Integration of eco-system needs in Water Resources Planning
4. Operating Policy redesign of existing Water Resources Systems

Significant in this is the call that water resources must move beyond its supply oriented/infrastructure design focus and recognize demand management and the integration of ecologically benign watershed management practice to cope with the worst effects of climate change and water scarcity.

2.3 Hydrology as the Fundamental Binding Constraint on Development in the Sahel

Lest the potential severity of the effects of an altered hydrologic regime on water resources development projects be minimized, one need only consider the recent case of irrigation development in Nigeria. Beginning in the 1970s Nigeria embarked on a large irrigation development project. The Nigerian project uses water from Lake Chad, a Sahelian lake on the Nigeria-Chad border which is in the same general pluviometric regime (the Sudano-Sahelian zone) as the Senegal River basin as illustrated in Fig. 2.4.

Kolawole [1989] reports that despite massive public investment only 5% of the land intended for cultivation is actually under irrigation command, the system is plagued with some of the lowest crop yields and irrigation efficiencies in the world. Many of the problems with the Nigerian project are due to technical and social obstacles such as poor land preparation, inadequate training and resistance of farmers to non-traditional cropping patterns. More fundamentally however the systems's under-performance was due to a simple lack of water. Lake Chad has been seriously affected by the Sahelian drought. the lake is constantly shrinking in response to the drought and the lake water level frequently dropped below the level of the intake structure for the irrigation projects.

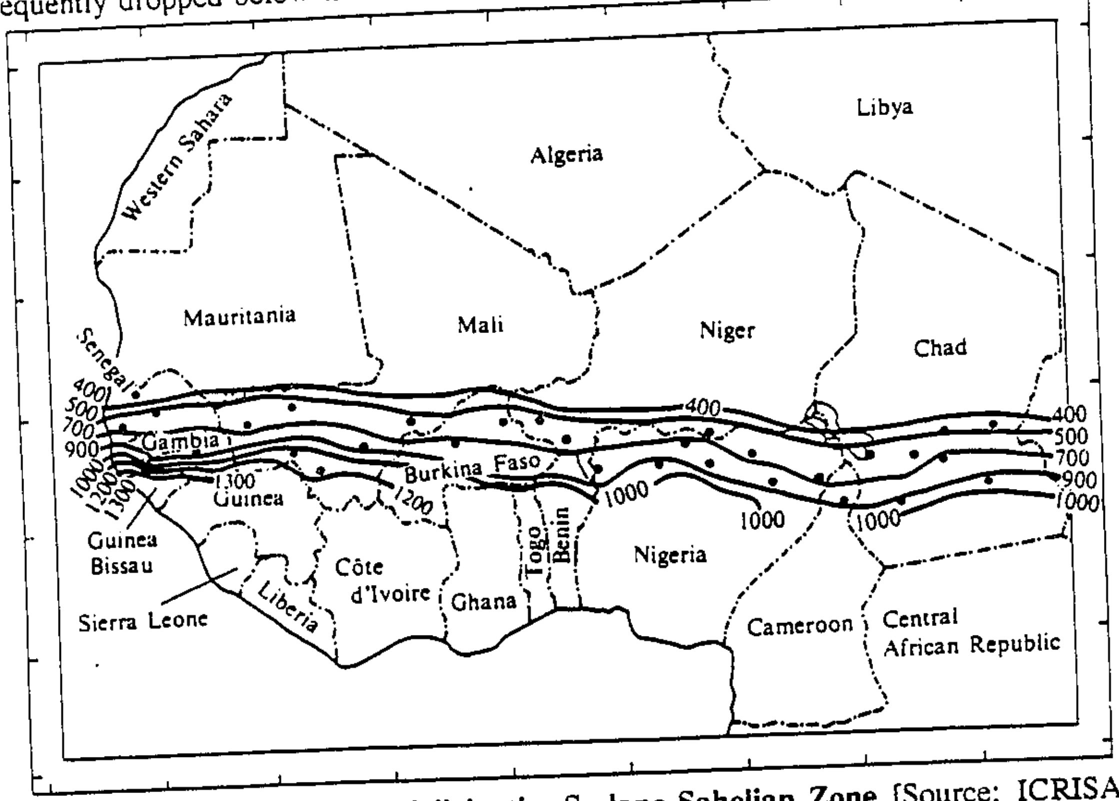


Fig. 2.4 Mean Annual Rainfall in the Sudano-Sahelian Zone [Source: ICRISAT. 1987]

A similar fate threatens irrigation development schemes in the Senegal River basin should the scale, severity and possibly permanent nature of the current drought not be adequately addressed. Kellor (1990) stresses the fundamental necessity of establishing the correct basic hydrology for any irrigation development program. and laments the tendency of planning authorities to assume the most optimistic scenarios to suit their economic analyses.

In 1977 an FAO study identified the amount of potentially irrigable land in the Senegal River Basin. Their study delineated irrigable lands according to region and soil type and concluded that a total of 376,000 ha of land could be irrigated throughout the Upper, Middle and Lower valley and in the Delta regions of the Lower Basin.

Since the FAO report, the 376,000 ha figure has remained the explicit development target of the OMVS. [Diouff A., 1992]. The OMVS stated that cultivating this quantity of land at 180% intensity (second crop annually on 80% of the land) was in fact a "perfectly reasonable" objective and may be exceeded in the foreseeable future [Platon, 1981].

In 1985 a USAID-funded study on irrigation development in the SRB offered a somewhat different perspective on irrigation development in the SRB:

> *Ultimately, the limiting physical factor for irrigation development in Senegal Valley is water not land. The total quantity of water available for irrigation and in particular reliable minimum flows before and after Manantali is only approximately known. Irrigation along the Senegal River should aim at optimizing the use of water.* [TAMS, 1985]

The OMVS's consultant, a European consortium headed by Gibb tended to skirt the issue, though not entirely. More concretely, Gibb [1987] reports that their modelling of SRB showed that based on the historical hydrological record of 1904-1985, an irrigation development scenario of 300,000 ha at 180% cultivation intensity could be sustained at 89% reliability. What is not obvious however, is that the 11% failure rate is largely in the last 12-15 years of the historical record. The use of the entire historical record and the implicit assumption of statistical stationarity throughout the record obscures the fact that the incidence of failure is increasing rapidly towards the latter periods as flow volumes are declining significantly. Gibb is more succinct as to the dimensions of the crisis when referring to the current operation of Manantali in providing the artificial flood during the critical hydrologic period. Releases from Manantali for the smallest practical artificial flood (capable of inundating 50 000 ha) will result in serious conflict between irrigation and hydropower objectives. During the critical period downstream conflicts between domestic water requirements at the Canal du Cayor and the minimum flow requirements for navigation will also arise [Gibb, 1986b].

2.4 Stochastic Time Series Analysis of Annual Streamflows at Bakel

Even a cursory analysis of the OMVS SRB development program reveals the fundamental importance of assured water resources availability to meet the program development objectives. The experience of the last several decades has cast serious doubt on the assumptions regarding the base-line hydrology of the Senegal River which were made when the project began. In order to gain insight into the nature and severity of the SRB drought and to estimate the constraints which the continuance of the drought will have on SRB development, the time series of annual flow volumes at Bakel were analyzed using methods from the field of stochastic hydrology. Time series analysis provides techniques to isolate and remove trend, periodic and stochastic components inherent in any record of events measured at uniform time intervals. Time series decomposition can reveal the underlying characteristics of the system under study and can also be used for forecasting and generating synthetic sequences of events for simulation studies of the future management of the system [Hipel, 1985]. A description of the basic elements and methodology of the Bakel time series decomposition follows.

2.4.1 Fundamental Elements of Time Series Analysis

The methodology applied to the time series decomposition is similar to the procedure demonstrated by Kite and Adamowski [1973] and applied to climate change analysis of hydrological data by Kite [1989]. The time series of N annual flow volumes observations at time t, X_t is assumed to be represented by a linear additive model:

$$X_t = T_t + P_t + R_t \tag{2.1}$$

where:

P_t is a periodic component
T_t is a trend component
R_t is a stochastic component

The presence of the various components can be detected and the components subsequently removed by using spectral or periodogram analysis. The periodogram was first introduced to estimate the amplitude of a sinusoidal component of known frequency buried in noise. The theoretical development of the periodogram is most closely linked with the analysis of P_t, the periodic component.

Periodic Component

Analysis of the periodic component follows from the Fourier series representation of the periodogram and the assumption that any time series X_t actually contains N/2 superimposed sinusoidal signals (harmonics) such that:

$$X_t=A_o+\sum_{k=1}^{N/2}(A_k\cos\frac{2\pi k}{N}t+B_k\sin\frac{2\pi k}{N}t) \tag{3.2}$$

where:

t=1,2,...N.

A_o is the mean of the process

The coefficients A_k and B_k of the k th harmonic are given by:

$$A_k=\frac{2}{N}\sum_{t=1}^{N}X_t\cos(\frac{2\pi k}{N}t)$$

$$B_k=\frac{2}{N}\sum_{t=1}^{N}X_t\sin(\frac{2\pi k}{N}t) \tag{3.4}$$

where:

k=0,1,2,...N/2 is the index of the i th harmonic.

In general there are N/2 harmonics present at frequencies $f_k=k/N$

The periodogram is used to detect the relative intensity (amplitude) of harmonics, which can subsequently be removed. The periodogram ordinate, I_k, is proportional to the squared amplitude of the k th harmonic and is defined as:

$$I_k = \frac{N(A_k^2 + B_k^2)}{2s^2} \qquad (3.5)$$

By Khintchinine's theorem:

$$\frac{A_k^2 + B_k^2}{2s^2} = s_k^2 \qquad (3.6)$$

where:

s^2 is the total series variance, and
s_k^2 is the variance contribution of the k th harmonic.

A test of significance for the detection and removal of significant harmonics, suggested by Box and Jenkins [1970] and similar to that applied by Kite and Adamowski [1973] assumes a chi squared distribution of periodogram ordinates. The test is based on the null hypothesis, that if the series is truly a white noise process, no periodogram should differ significantly from the average variance contribution. Box and Jenkins suggest a 95% confidence level with two degrees of freedom.

Since the amplitude of the harmonic is directly proportional to its contribution to the total variance of the series. Using equations 3.5 and 3.6, the normalized variance spectrum is simply the scaled periodogram ordinates such that:

$$\sum_{k=1}^{N/2} \frac{I_k}{Ns^2} = 1 \qquad (3.7)$$

The cumulative normalized variance spectrum defined in equation 3.7 is also known as the integrated periodogram and is used as a diagnostic tool after time series decomposition. If the time series decomposition is adequate, there should be no significant variance contribution from any harmonic and the integrated periodogram should approach a straight line.

Trend Component

In general the trend component can be removed using polynomial regression of the form:

$$T_t = b_o + b_1 t + b_2 t^2 + \ldots b_p t^p \tag{3.8}$$

where:

b_o, b_1, b_2... b_p are constants.

The optimal polynomial order is established by comparing the residual variance between two successive polynomials.

The presence of a strong trend component manifests itself as a high amplitude harmonic at the fundamental frequency (1/N). Such a periodicity, with a period of N time intervals, is equivalent to a trend. Trend components should be detected and removed first since the removal of periodic and stochastic components is facilitated greatly if the time series process can be assumed to be stationary.

Stochastic Component

The stochastic component accounts for the internal correlation structure of the time series, as represented schematically by the linear-filter time series model shown in figure 2.5.

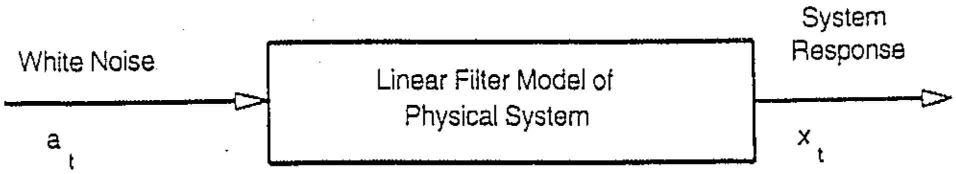


Fig. 2.5 Linear-filter time series model [adapted from Box and Jenkins, 1970]

The fundamental assumption in the Box-Jenkins linear filter time series model is that there is an underlying stationary, normally independently distributed random signal driving the process. However the system response is not serially independent. A simple example of this phenomenon is the first order auto-regressive (AR[1]) process where the system response at time x_t is a function of the process lagged one time step x_{t-1} and the current random shock to the system, at, where:

$$x_t = \phi_1 x_{t-1} + a_t \tag{3.9}$$

A physical example of a possible AR[1] process would be to represent annual precipitation as a random series. The system response - annual watershed outflow, for example may not respond purely linearly to the current years precipitation, but instead be damped by the storage in the system which is also a function of the previous years streamflow.

In general, by correlating previous time lags, time series models can be expressed as a combination of Autoregressive (AR) and Moving Average (MA) parameters. The AR process of order p, denoted as AR(p) is defined as follows:

$$x_t = \phi_1 x_{t-1} + \phi_2 x_{t-2} + \ldots \phi_p x_{t-p} + a_t \tag{3.10}$$

Physically, the AR(p) process represents the degree of correlation that the current observation, x_t has with previous observations up to a lag of p time steps. The presence of a strong AR(p) process is revealed in the periodogram by high amplitude harmonics at low frequencies.

The MA process of order q, denoted as MA(q) is defined as:

$$x_t = a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} - \ldots \theta_q a_{t-q} \tag{3.11}$$

Physically, the MA(q) process represents the degree of correlation that the current observation has with the random shocks driving the system, from the current time step, t up to a lag of q time steps. The presence of an MA(q) process is revealed in the periodogram by high amplitude high order harmonics, indicating that the high frequencies motion associated with the random shocks dominate the spectrum.

To simplify notation where one employs the back shift operator, B,

$$Bx_t = x_{t-1} \tag{3.12}$$

$$B^2 x_t = x_{t-2} \tag{3.13}$$

the AR(p) process can thus be represented as:

$$(1 - \phi_p B^p) x_t = a_t \tag{3.14}$$

while the MA(q) process can be represented as:

$$x_t = (1 - \theta_q B^q) a_t \tag{3.15}$$

The AR and MA processes are inversely related, consider for example the AR(1) process:

$$(1 - \phi_1 B) x_t = a_t \tag{3.16}$$

$$\therefore x_t = \frac{1}{(1 - \phi_1 B)} a_t \tag{3.17}$$

and by Taylor series expansion;

$$\frac{1}{1-x} = 1 + x + x^2 + x^3 \ldots \tag{3.18}$$

Thus an AR(1) process can be represented as an infinite series of exponentially decreasing significant series of MA terms and vice versa. For a parsimonious representation of the time series model, as few terms as possible should be represented. The generalized additive ARMA(p,q) model therefore allows inclusion of both AR and MA terms as follows:

$$\phi(B)^p x_t = \theta(B)^q a_t \tag{3.19}$$

Estimating the number of AR and MA parameters to include in the time series model is accomplished through simultaneous inspection of the Autocorrelation Function (ACF) and the Partial Autocorrelation Function (PACF).

The PACF controls the number of significant p terms; the PACF is not significantly different from zero at lag p+1 for a pure AR(p) process. Similarly the ACF controls the number of significant q terms; the ACF is not significantly different from zero at lag q+1 for a pure MA(q) process. For example if a PACF coeffecient is significant at lag 2, the AR(2) parameter should be included in the model, similarly if the ACF coefficient at lag 1 is significant, the MA(1) parameter should be included in model estimation. The theoretical development and conditions on the solution of the ACF and PACF is thoroughly discussed in Box and Jenkins [1970].

Commercial computer algorithms exist for the calculation and visual display of the ACF and PACF in order to facilitate estimation of the number of parameters to include in the model. The PACF and ACF coefficients should exceed an arbitrary confidence limit (typically 95%) for the corresponding AR and MA coeffecients to be included in the model. The confidence limits are plotted directly on the ACF and PACF. The model parameters themselves can then be readily be calculated with standard algorithms such as maximum likelihood estimation. Estimated model parameters are then checked for significance on the basis of a t-test. A parameter is generally accepted as significant if the t-ratio exceeds 2.

The final diagnostic check on model adequacy involves verifying the initial assumptions of the normal independent distribution of the residuals (the a_t's). The residuals should be a white noise series. Two simple diagnostic checks for residual whiteness are the Portmanteau statistic for the residual autocorrelation function and the residual integrated periodogram. [Hipel, 1977]

The basic ARMA model can be extended to the Auto-Regressive Integrated Moving Average (ARIMA), and Seasonal ARIMA cases which implicitly account for trend and periodic (seasonal) components of a time series, x_t by performing diferencing of the original series; i.e. $w_t=x_t-x_{t-d}$, and applying the ARMA model to the w_t series. The interested reader is referred to Hipel et al. [1977] and Mcleod et al. [1977] for a complete description of the application of ARMA[p,q], ARIMA[p,d,q] and Seasonal ARIMA[p,d,q]*[P,D,Q] models. The ARIMA and Seasonal ARIMA extensions were not appropriate for the Senegal River application.

2.4.2 Bakel Annual Volume Time Series Analysis (1904-1990)

ORSTOM [1992] has provided a complete data set of monthly streamflow volumes from 1904-1990 at Bakel. Bakel is situated just downstream of the point where all the major tributaries have contributed their volume and upstream of any major losses from the system by evaporation and seepage or by abstraction for agriculture. The Bakel time series is thus an accurate representation of the global hydrologic budget in the SRB.

The time series analysis was applied to the aggregated annual flow volumes rather than the disaggregated monthly flow series. This decision was taken because of the extreme peakedness of the Bakel annual hydrograph. Average high flow months are 300-400 times average low flow months and this extreme variation poses measurement and calibration difficulties. Many low flow months in the series could not be measured or were known to be in error. While ORSTOM has reduced the systematic error in the series through meteorologic correlation studies, there remains a higher than usual uncertainty associated with the low flow months. While Rao [1985] has shown in theory it is statistically more efficient to model monthly data and infer annual characteristics, this assumes a uniformly high level of fidelity in the monthly data. Klemes in Hipel [1985] notes that the decision to model a monthly or annual series must be made with an intuitive grasp of the physical system to understand where the better information lies. In the case of the SRB it is clearly more efficient to model annual flows since even gross measurement errors (>50%) in the low flow months would have negligible impact on the annual volume.

Spectral Analysis was used to detect and remove various time series components. Figure 2.6 depicts the periodogram of the historical series (Fig. 2.3).

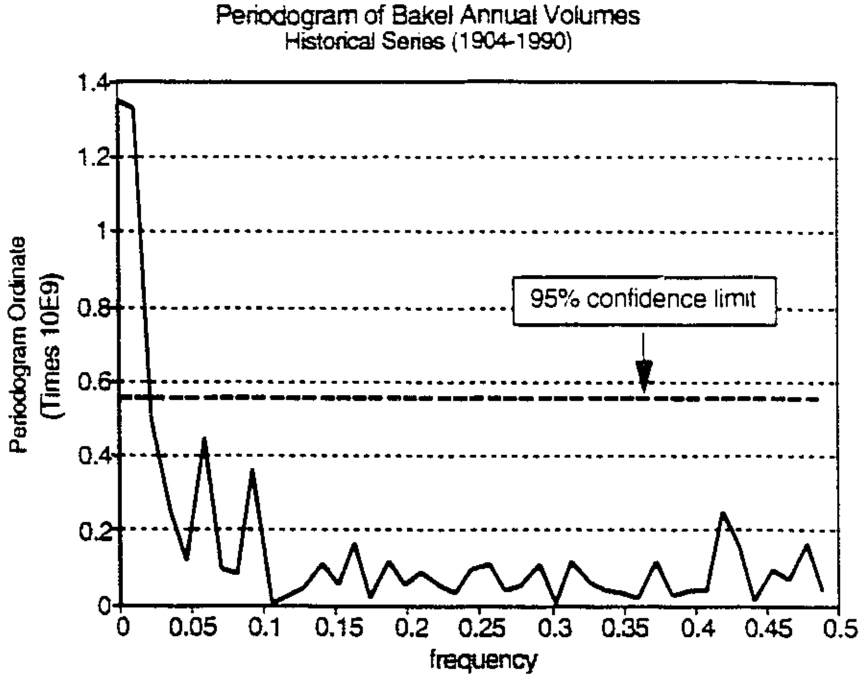


Fig. 2.6 Periodogram of Historical Bakel Flows

Of obvious note is the very strong lowest order harmonic which is indicative of a trend component. Visual inspection of the time series reveals an obvious downward trend in recent decades, it however is not present throughout the series. Several non-stationary ARIMA(p,d,q) models were applied unsuccessfully, supporting the assumption that the trend is not homogenously present throughout the series.

A first order linear trend component was removed after 1960. A comparison of the historic with the detrended series is shown in Fig. 2.7. The periodogram of the detrended series is shown in Fig. 2.8.

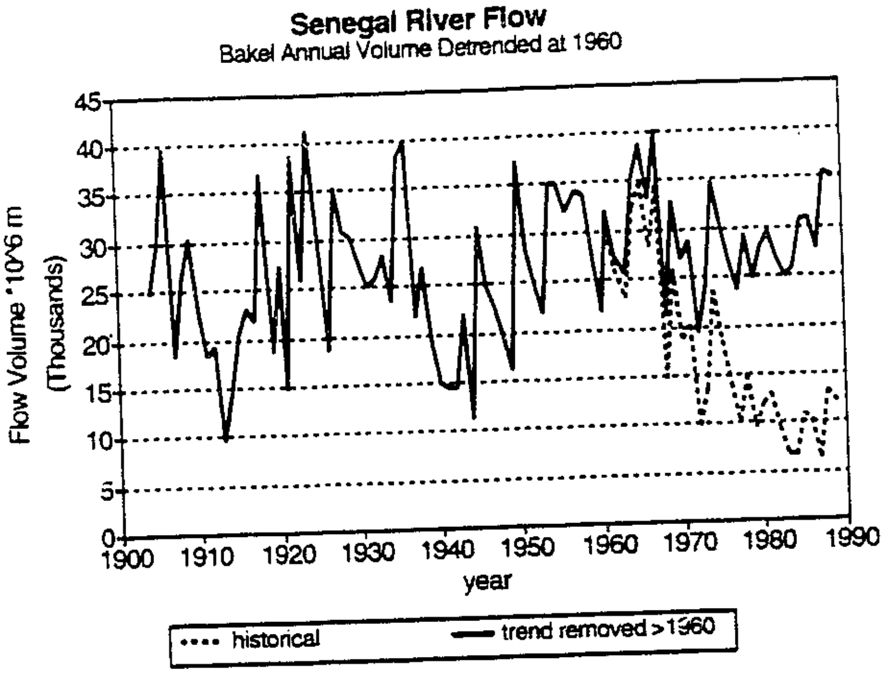


Fig. 2.7 Historic and Detrended (> 1960) Bakel Flows

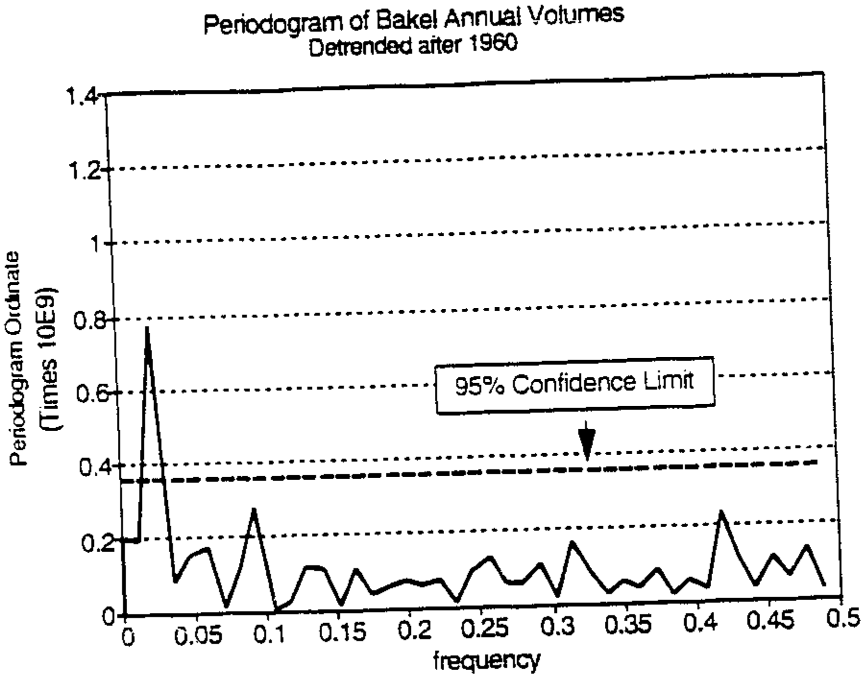


Fig. 2.8 Periodogram of Bakel Flows (Trend Removed > 1960)

Linearly detrending after 1960 has clearly removed the trend component from the periodogram. The spectrum is now dominated by a low order harmonic at a frequency of 0.0338 cycles/year corresponding to a period of about 29 years. The Fourier coefficients at this frequency were calculated and the periodic component removed. Figure 2.9 shows the overlay of the periodic component on the historical and detrended series.

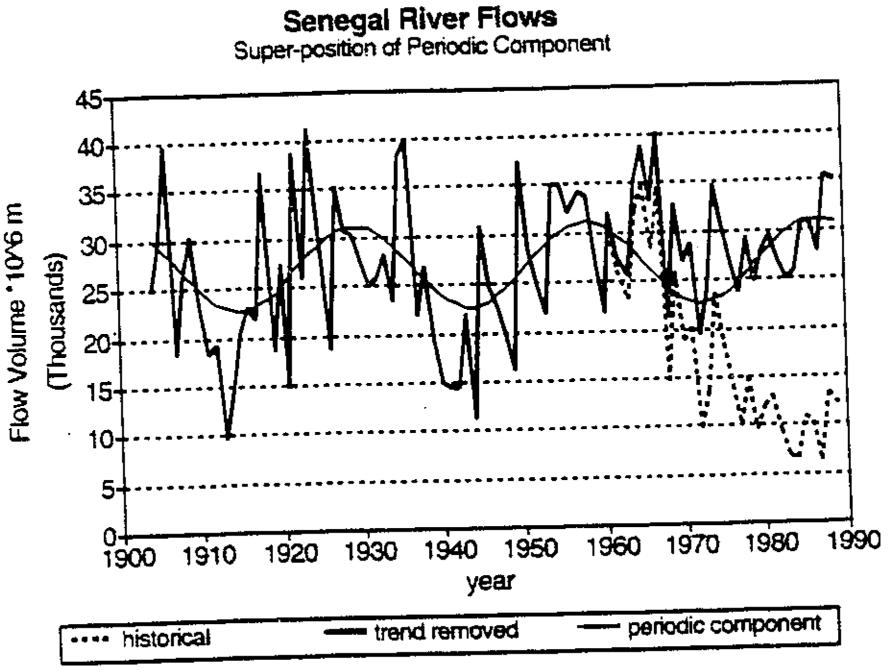


Fig. 2.9 Superposition of Periodic Component with Bakel Detrended Series.

The significant observation here is that this periodic component could plausibly partially account for the declining streamflows through the 1960's and worsening conditions in the 1970s, but it does not explain the most extreme conditions throughout the 1980's. This analysis gives credence to the proposition that the prevailing hydrological regime in the SRB and the Sahel in general has been fundamentally altered.

A primary objective of the over-all study is to establish the sensitivity of the Senegal River system management to different prevailing hydrologic regimes. The time series analysis conducted facilitates the delineation of two very distinct hydrological regimes. Case A postulates the most optimistic scenario as follows: The declining streamflows beginning in the 1960s and worsening through the 1970s and 1980s is an unusual aberration and the system is really in long-term equilibrium at the 1960s detrended level with the 29 year periodicity present. This scenario is roughly equivalent to modelling studies of the SRB which have been confined to the use of historical data. Case B postulates a more pessimistic scenario and represents the situation of a fundamentally altered hydrologic regime which is stationary at a much lower level and likely not influenced by the 29 year periodicity. Case B can be divided into 2 sub-cases of moderate and greater severity by postulating that the system is stationary at the 1970s average level or the 1980s average level.

For all the postulated scenarios the objective is to use the time series properties to generate multiple sequences of synthetic data. The rationale for using synthetic data is that the historical sequence provided only one realization of a random process. Long range planning studies must evaluate system performance against a range of possible input sequences to better establish system reliability.

Case A - No Drought

Fig. 2.10 depicts the Bakel time series, detrended after 1960 and with the periodic component removed. Fig. 2.11 shows the periodogram corresponding to this series. One low order harmonic appears very near the 95% confidence limit. More sophisticated series smoothing and spectra filtering methods may be justified to establish if in fact other significant harmonics are present in the low frequency range. Several ARMA models were fit to the remaining series, a strong AR component could potentially account for the low frequency behaviour. The residual variance was approximately equal to the variance of series before the ARMA model fit attempt, and the thus the estimated model parameters were statistically insignificant. The detrended series with periodicity removed was thus essentially a white noise process. Inspection of the residual auto-correlation function and the integrated periodogram (Figs. 2.12 and 2.13) supported this conclusion. The integrated periodogram does reflect the variance contribution of several near significant harmonics in the low frequency range.

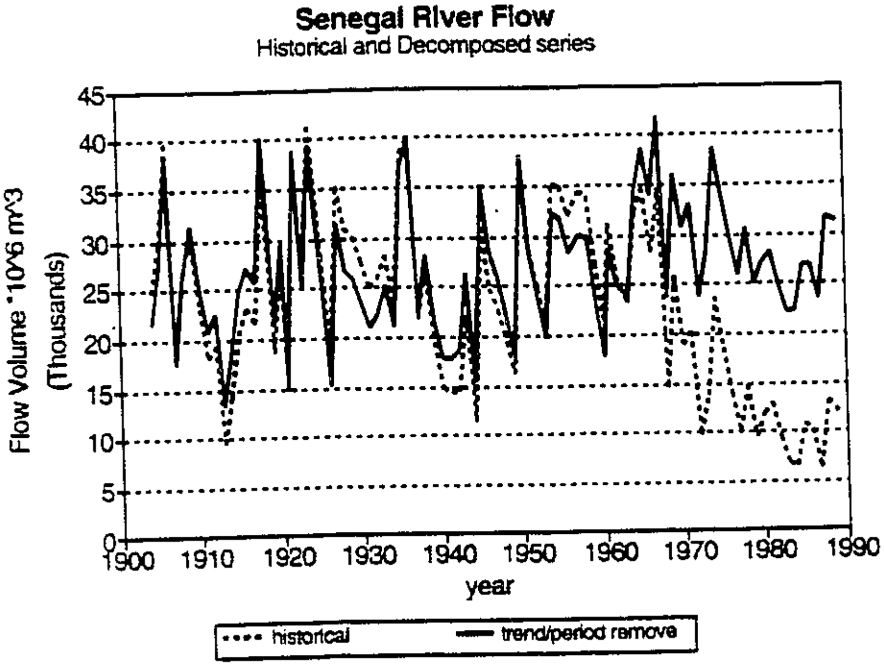


Fig. 2.10 Bakel Flows: Trend, Periodicity Removed (Case A)

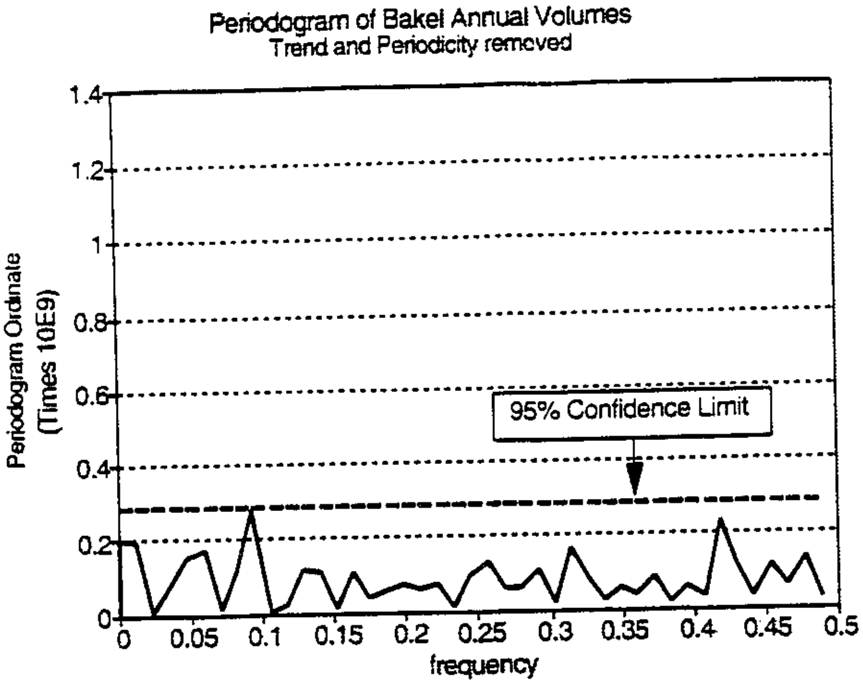


Fig. 2.11 Periodogram of Bakel Flows: Trend, Periodicity Removed (Case A)

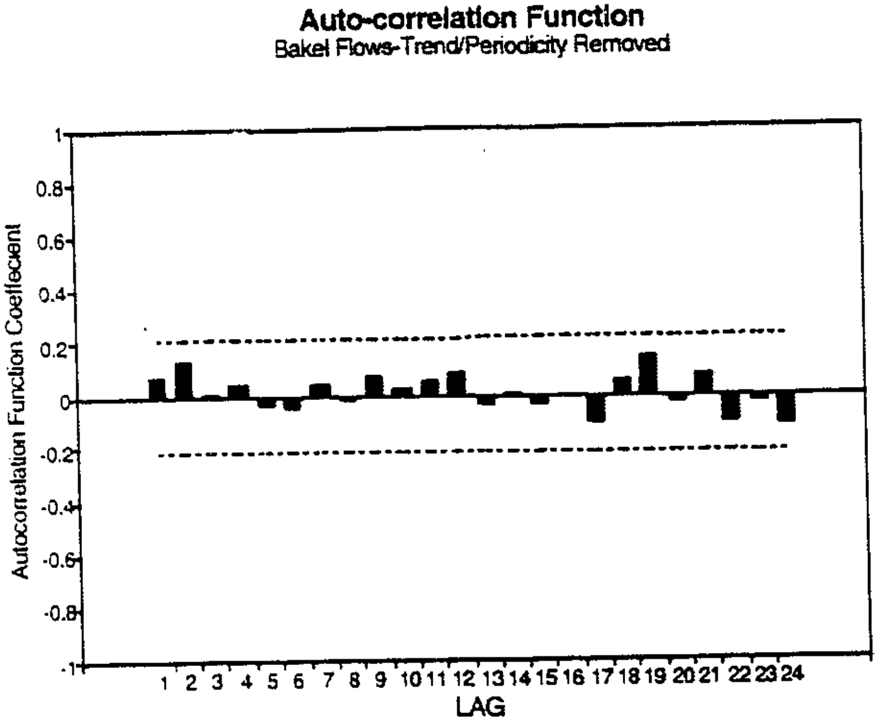


Fig. 2.12 Bakel Residual Auto-Correlation Function (Case A)

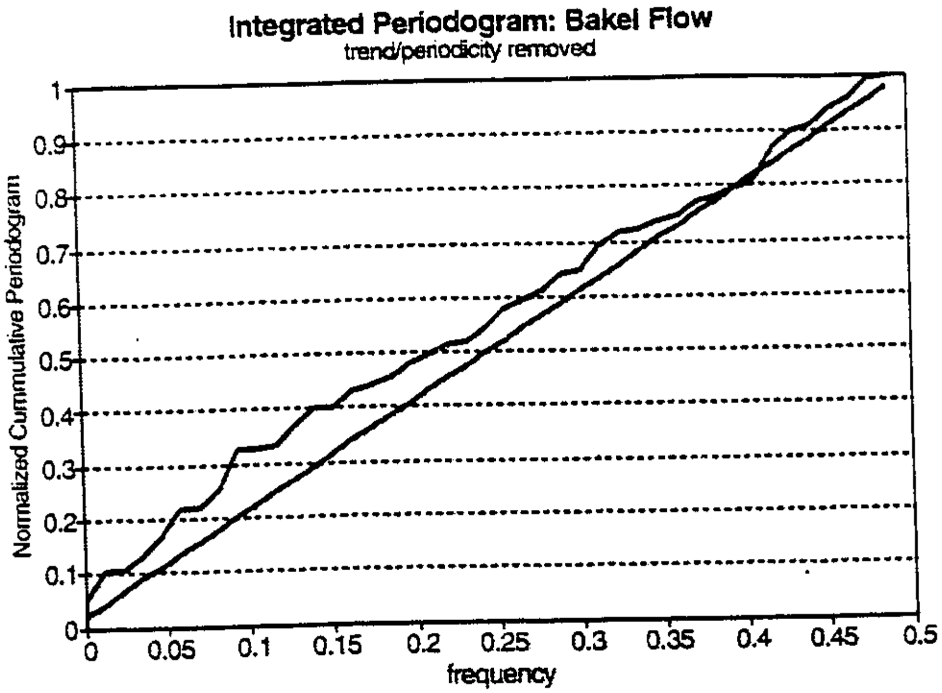


Fig 2.13 Bakel Residual Integrated Periodogram (Case A)

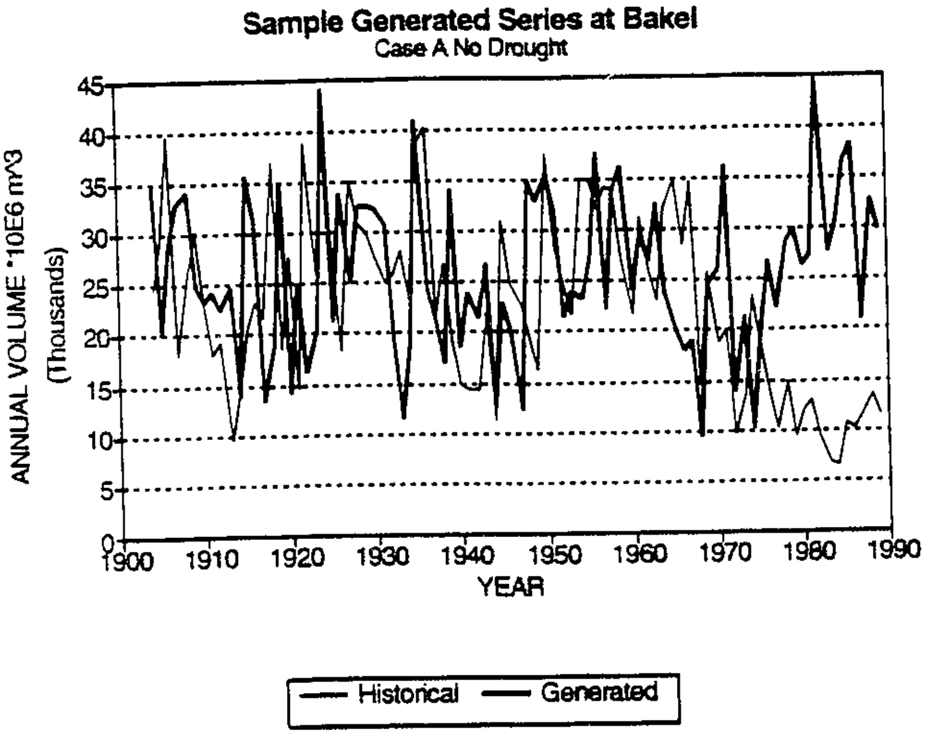


Fig. 2.14 Sample Bakel Synthetic Flows (Case A)

Thus to generate synthetic data for Case A, it was necessary only to generate a normally distributed random sequence at the appropriate level and variance and map the periodic component on to it. Figure 2.14 shows a Case A generated sequence plotted against the historical and detrended series.

Cases B1 and B2 - 1970s and 1980s level continued drought

The pessimistic, continued drought scenario postulates a different time series structure. The hydrologic regime has altered fundamentally: both the scale of the process, and the influence of the periodic component have diminished. For synthetic generation and simulation study the stochastic component should be preserved, as this is the essential remaining component of the time series. Inspection of the ACF and PACF of the 1960 detrended series, Figs. 2.15 and 2.16 indicated that 1 or 2 AR and MA terms should be included.

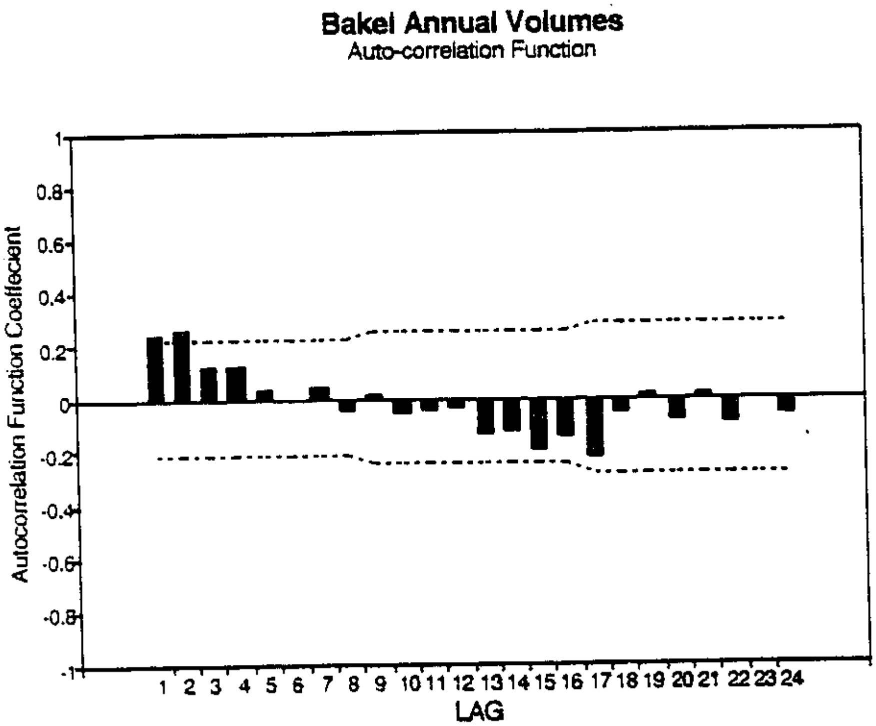


Fig. 2.15 Bakel ACF Detrended >1960 (Case B)

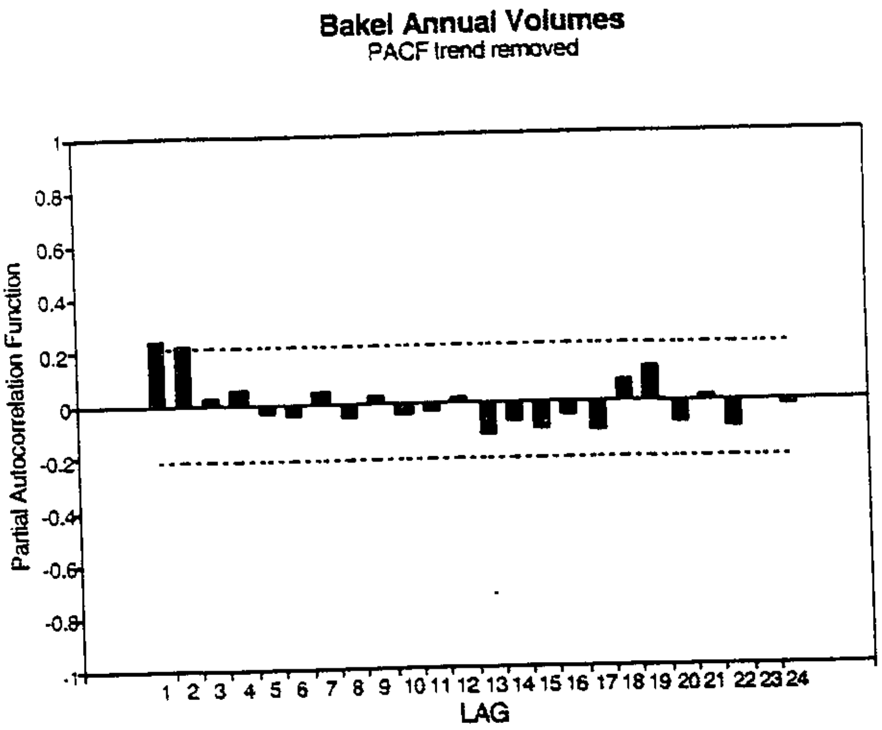


Fig. 2.16 Bakel PACF Detrended > 1960 (Case B)

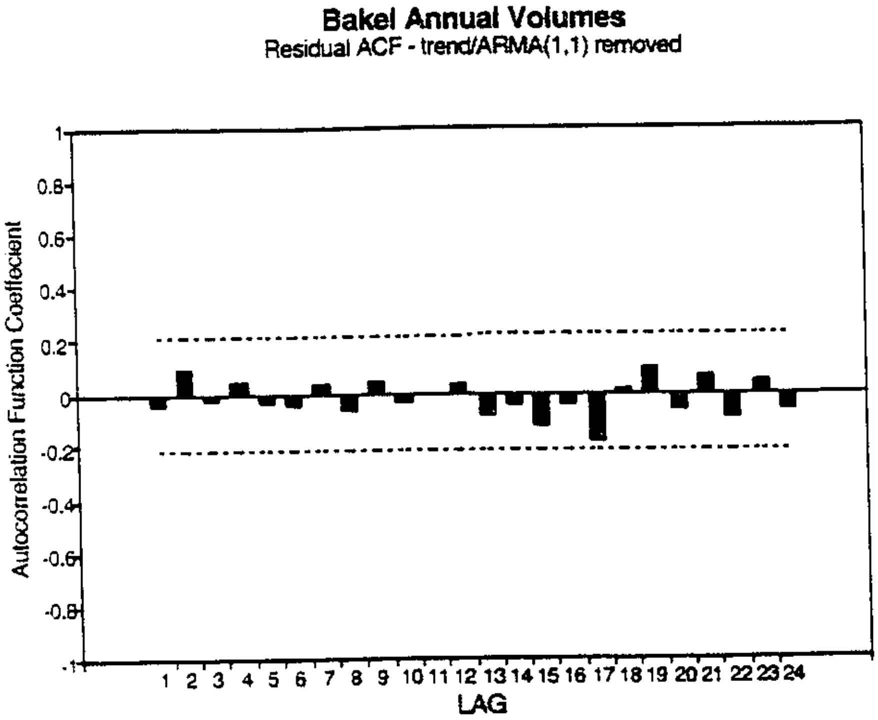


Fig. 2.17 Bakel Residual ACF (Case B)

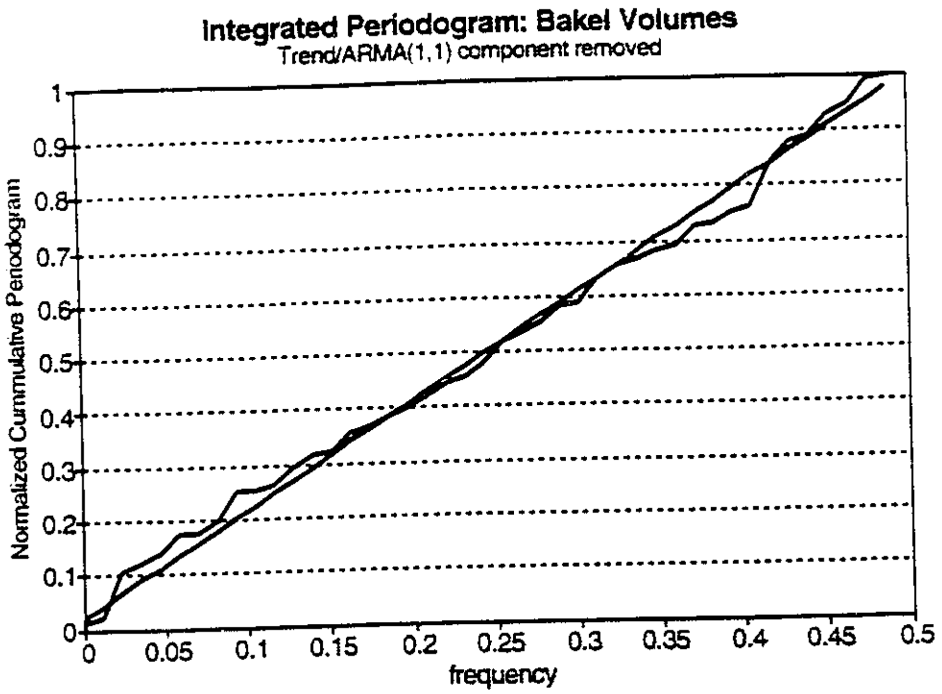


Fig 2.18 Bakel Residual Integrated Periodogram (Case B)

Application of diagnostic checking and standard model selection criteria [Akaike, 1974] showed that an ARMA(1,1) model provided the most efficient fit. The residual ACF (fig. 2.17) and integrated periodogram (fig. 2.18) confirmed the good model fit.

To facilitate the scaling of the stochastic process to drought levels, the same detrended series was normalized and the ARMA(1,1) model was fit to these standardized variates. Table 2.1 gives the ARMA(1,1) model summary. The estimated parameters were identical for the detrended historic, and the normalized detrended historic series, indicating that normalization had not altered the stochastic structure of the series.

Table 2.1 ARMA(1,1) Model Summary

Parameter	Estimate	Std. Error	T. Value
AR(1)	0.74114	0.20981	3.53244
MA(1)	0.51918	0.26440	1.96364

Portmanteau Statistic on RACF	8.72029
Probability of larger value given white noise	0.965874

Although the T-value for the MA(1) term was slightly less than 2, the ARMA(1,1) proved a far better fit than an AR(1) model so the term was retained. The portmanteau statistic on the residual auto-correlation function indicates a non-significant result. The residuals are not significantly different from a white noise series at a 96.6% significance level. Inspection of the RACF and residual integrated periodogram (figs 2.17, 2.18) were further confirmation of the strong model fit.

The estimated parameters were used to generate sequences which could then be readily scaled to the 1970s and 1980s mean and variance. Examples of synthetic sequences generated at the 1970s, and 1980s levels plotted against the historical series are shown in fig. 2.19

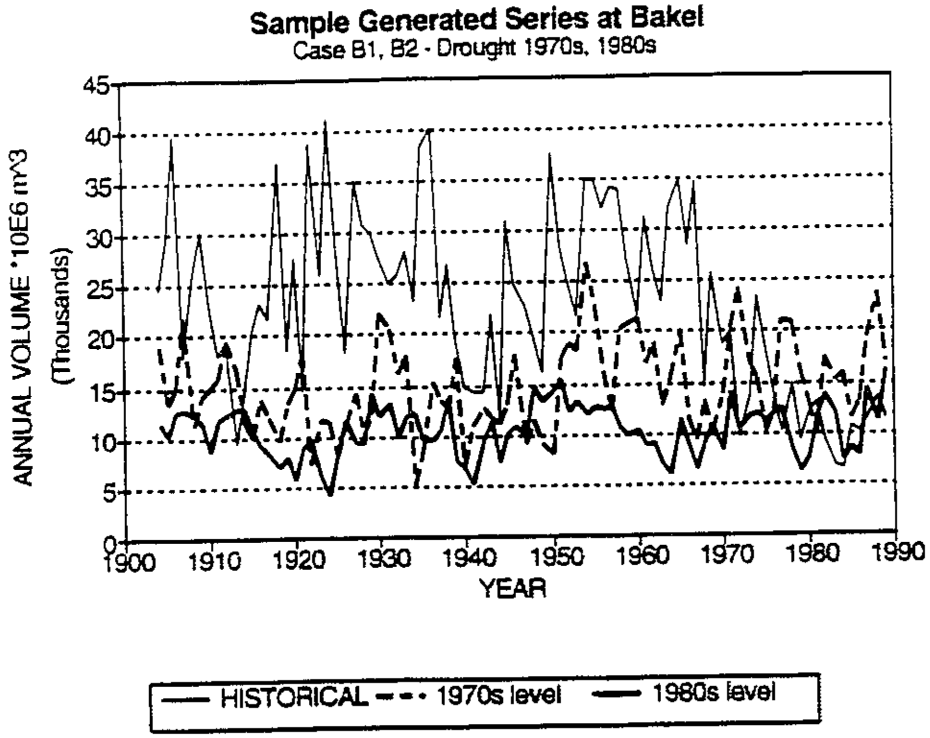


Fig. 2.19 Sample Bakel Synthetic Flows (Case B)

2.4.3 Time Series Non-Stationarity and Sahelian Drought

The fundamental assumption one invokes when building non-seasonal linear time series models of geophysical processes is that the underlying processes driving the system are stationary, that is the mean level and variance are independent of time. The validity of this assumption lies largely in the domain of conjecture. Hipel [1985] notes that some investigators hold that geophysical phenomena are inherently non-stationary and thus statistical abberations are more likely evident as the length of the record increases. Other researchers hold the seemingly equally plausible position that non-stationarity exhibited in a geophysical time series is merely a local fluctuation around a long-term stationarity. Klemes [1974] maintains that it is an exercise in futility to argue on mathematical grounds whether any particular geo-physical series is stationary or not. This debate of course dogs the whole global climate change controversy.

Yevjevich in Hipel [1985] states that, "even though the climate may change slowly over a thousands of years, within the span of a few hundred years the changes in a hydrological time series may be relatively small and therefore the time series can be considered approximately stationary." The argument is essentially that given the typical water resources development design life of 50-100 years, climatic change occurring on the scale of millennia has a negligible effect on the relevant hydrology. The unprecedented rate of desertification, landscape degradation through anthropogenic stress [Gonzalez, 1992], and declining streamflow volumes in the SRB occurring now seriously undermine the validity of these classical assumptions.

Hipel [1985] suggests that operationally, if the underlying modelling assumptions are satisfied when a stationary stochastic model is fit to a non-seasonal time series, the assumption of stationarity is validated. The converse of this argument should be equally valid. If a non-stationary component is explicitly accounted for (by detrending after 1960), and a stationary model is fit to the resulting series, does this not validate the assumption of non-stationarity?

Loucks et al. [1981] suggest that in the absence of streamflow stationarity an alternative methodology is to assume precipitation processes are stationary and use a rainfall-runoff model of the river basin. However as the isohyets in Figs. 2.1 and 2.2 clearly show, this assumption would not hold. Lamb (1985) derives an index of normalized departures at 20 pluviometric stations in south Senegal. The value of the Lamb index is simply the variable defined by standardizing the average cumulative annual precipitation at all 20 stations for a reference period of 1941-1982. Similarly Lamb defines the normalized departure of Senegal River as the annual flow volume standardized for the period 1964-1984. Fig. 2.20 shows the recent evolution of the Lamb index and Senegal River flow normalized departures.

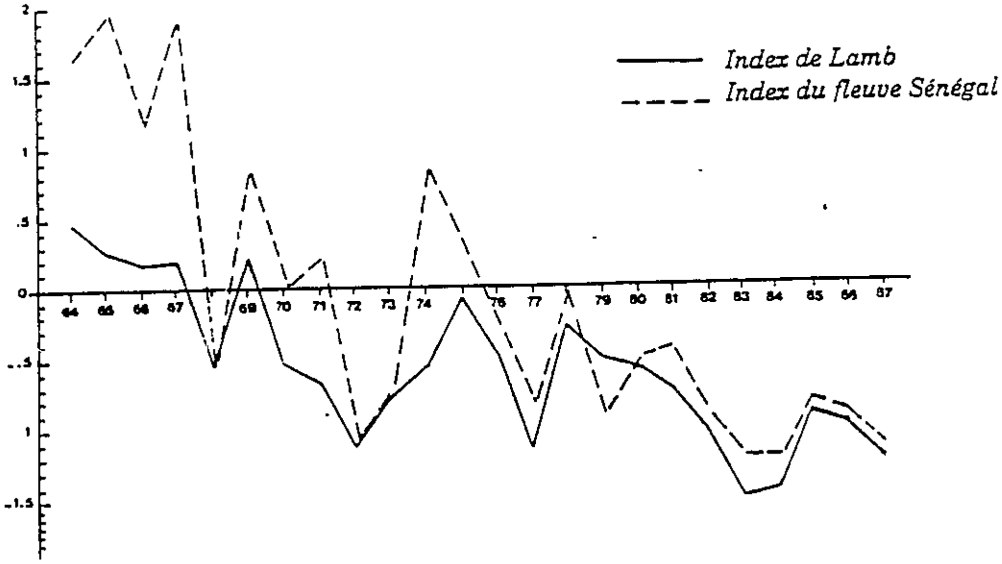


Fig. 2.20 Senegal Rainfall (Lamb index)/Senegal River Flows: Comparison of Normalized Departures [Source: Citeau, 1992]

Fig 2.20 illustrates the strong parallelism evident in the evolution of the Lamb index and the Senegal River streamflows. The pluviometric stations used to derive the Lamb index are not in the upper catchment area of the Senegal River, they are however, very much indicative of the Sahel-wide drought. Palutikoff et al [1981] also note the strong correlations between Sahelian zone pluviometery and Senegal River streamflows, and conclude that Senegal River streamflows are a very good indicator of Sahelian drought.

In a review of Sahelian pluviometric and hydrologic data, Sircoulon [1990] refers to the flow time series in the Niger and Senegal Rivers as the best indicators yet available of **fundamental climate change processes in the Sahel.**

Citeau [1992] has shown that declining Sahelian pluviometry may be related to the intensification of warm south-easterly trade winds over the eastern mid-Atlantic ocean and the Sahara desert (referred to as the *Harmattan* desert winds), possibly due to global warming. The intensified south-easterly winds have the effect of restricting the migration of the inter-tropical convergence zone (the ITCZ). The ITCZ is a zone separating the moisture-laden mid-Atlantic air mass with the dry air mass over the Sahara. If the ITCZ is restricted in its annual northward migration, the magnitude and duration of the Sahelian rainy season is curtailed.

The human reality is that, regardless of the ultimate causal agent, the drought has had a catastrophic effect on the environmental and socio-economic fabric of SRB states. SRB development models which do not specifically address the drought phenomenon and the increasing evidence of its permanent nature court gross irresponsibility.

* * *

Chapter 2 has thus served to sensitize the reader to the magnitude of the current drought in Sahelian Africa. Chapter 2 has also described the use of stochastic hydrology techniques to analyze the time series properties of Senegal River streamflows. The time series properties of Senegal River flows indicate the strong likelihood of, and will be used to simulate, continued drought conditions. The issue of water resource demand management by adopting an appropriate agricultural development policy to cope with the worst effects of drought is the subject of the next chapter.

CHAPTER 3

AGRICULTURAL DEVELOPMENT OPTIONS FOR NATURAL RESOURCES MANAGEMENT

One of the stated objectives of the OMVS in developing the Senegal River is to "establish a more stable equilibrium between men and the environment. So-called "poles-verts", regions integrating forest, windbreaks and shelter-belts around irrigation perimeters and pasture land were to be established for this purpose. In conducting global modelling studies of the basin, Gibb [1986b] notes that the pole-verts will in fact exert a dry season "contre-saison" demand for water, they assume however that it will be insignificant and exclude them from modelling studies. The same study [Gibb, 1986b] has shown meanwhile that during critical dry years, water will be fully allocated without accounting for the ecological maintenance demands.

In general the inclusion of specific environmental objectives in the SRB development program as formulated in OMVS policy, and as executed by GIBB, appears weak. Ecological objectives are compartmentalized and considered adequately treated by establishing four green poles whose combined water demand "are weak compared to that of *l'agriculture irriguee proprement dit*" [Gibb, 1986b]. Not only does this statement reflect the relative planned areal extent of the poles-verts (evidently small) but it also reveals the bias that environmental objectives are distinct and cannot be integrated with agricultural objectives. Furthermore Gibb has shown that during critical dry years, water will be fully allocated to (primarily) mono-culture irrigated agriculure while ecological demands, however modest are ignored.

The critical dry period in Gibb's study (1979-1984) seems increasingly to reflect the natural hydrological regime of the river given the evolution of the streamflows through the 1980s. Since water scarcity seems to be the status quo, it is prudent and perhaps urgent to rethink the integration of ecological objectives with agriculture development. The over-exploitation of scarce water resource for unsustainable land use practice otherwise threatens to further degrade the already highly stressed SRB environment.

3.1 The Dynamics of Desertification-Drought and Land Degradation

Falkenmark et al. (1989) present a general conceptual model of land degradation (hereinafter referred to as the Falkenmark model) that differentiates between four modes of water scarcity as the causal agent. Two modes are directly related to hydrological and climatological factors, they are;

1. ARIDITY defined as a short growing season.
2. INTERMITTENT DROUGHT manifested as recurrent years in which there is risk of crop failure.

The remaining two modes are directly related to the hydrological and climatological factors, they are;

3. LANDSCAPE DESICCATION due to soil degradation, reducing local accessibility to water.
4. WATER STRESS due to too large a population per unit of growth available from the hydrologic cycle.

The various types of water scarcity generally superimpose on each other with compounding negative effects and are linked in Falkenmark's model as shown in Fig. 3.1.

All four modes of water scarcity described are present in the SRB. The entire lower basin is a semi-arid to arid flood plain. Even in years of good rainfall, extensive rainfed agriculture is a marginal subsistence activity. Rainfed cereal can yield 0.25 - 0.4 tonnes/ha compared with irrigated yields of 4 tonnes/hectare. Recurrent drought is also a defining characteristic of the SRB. Even before the onset of the prolonged drought beginning in the early 1970s, the SRB experienced drought. The time series at Bakel (fig. 2.3) reveals the extreme inherent variability in the hydrologic record. Drought periods occur throughout the record, for example in the early 1940's. Previous drought periods were however generally of less severity and much shorter duration than the present regime.

Mode 3 and Mode 4, Landscape desiccation due to soil degradation and water stress due to overpopulation are intimately related in the case of the SRB. Falkenmark describes schematically the physical links between landscape perturbation and the ultimate social breakdown manifest as famine.

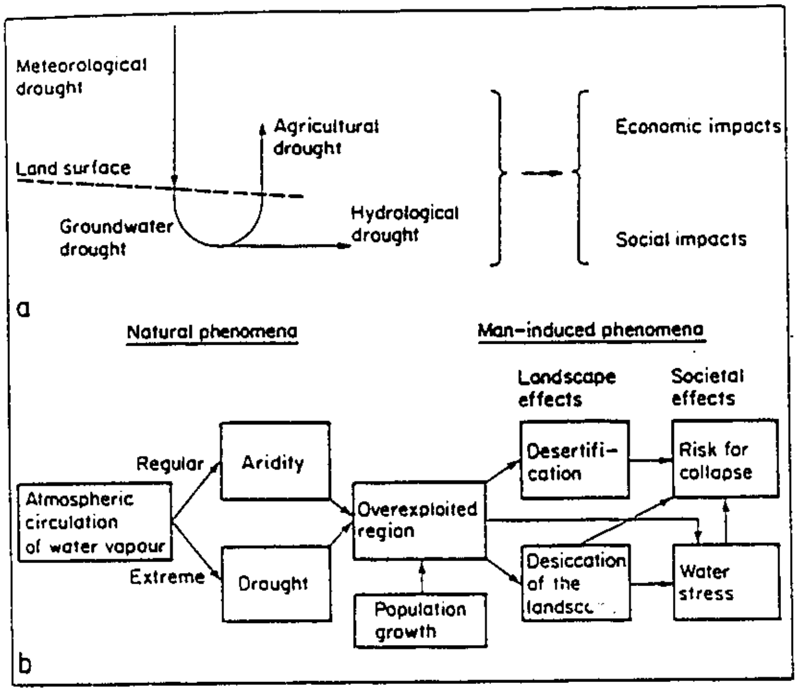


Fig. 3.1 **Linked Natural and Anthropogenic Factors in Desertification** [Source: Falkenmark et al, 1989]

Deforestation has been a particularly acute cause of land desiccation in the Senegal River valley. Deforestation for fuel is a direct response to population pressure. Despite attempts by the government of Senegal to promote the use of Natural Gas as an alternative domestic energy source, for many Senegalese charcoal remains the preferred or only available fuel source. Although the retail unit price for gas is competitive with charcoal, most Senegalese cannot, unfortunately, afford the one-time cash outlay for gas and equipment. Drought conditions have made agriculture so difficult that many farmers have turned to charcoal production for urban markets as an alternative income generating activity.

Sene [1992] refers to inappropriate agricultural practice, in particular colonial-era deforestation policies, as the root cause of ecological degradation in Senegal:

> *The destruction of these forests which provided a protective curtain against the desert winds has been the first historical factor in the ecological degradation of Senegal... the exploitation of the Senegal Acacia tree and the gonakier stands for the colonial commercial needs and the exploitation for groundnut oil, destined for the metropole have been the root cause of deforestation in Senegal while the colonial power did not take any policy of re-forestation at all.*

Mbalo [1993] describes the deforestation accompanying rice cultivation not only to clear the area for cultivation but also to destroy the habitat of pest birds. Rice cultivation, as previously noted, a major contributor to landscape desiccation, is a direct response to rapid population growth (primarily urban) and the ever increasing demand for rice. In some sense the exploitation of the resource base has simply shifted from serving the colonial metropole (Paris) to serving the new metropole (Dakar).

Frankenburger et al [1987] describe the overpopulation stress directly on the valley natural resource base that occurred when the rain stopped in the early 1970s. The diminished biomass production was below the carrying capacity required for the human and livestock populations which had flourished in the wetter hydrologic regimes of the 1950s and 1960s. Overgrazing and the resulting loss of vegetative cover exposed the topsoil to erosion and reduced water retention capacity making revegetation difficult. The vicious cycle of ecological breakdown that ensues leads quickly to social breakdown and famine as in Falkenmark's model; this is exactly what happened in the Senegal River valley in the severe drought year of 1974.

Falkenmark et al call for a re-orientation in planning towards sustainable micro-scale agricultural techniques that serve the complimentary purposes of improved land husbandry and optimal utilization of available water resources. Assuring optimal biomass production under conditions of water scarcity is key to breaking the chain of events leading to land degradation and famine. Falkenmark et al cite data from India [Salunke, 1983] which indicate that shifting to crops with lower water consumption can have both positive environmental and socio-economic consequences. The socio-economic benefits relate mostly to increased employment and diffusion of wealth which results from irrigating a greater area and employing more people with the same finite quantity of available water. Falkenmark et al correctly identify water resources as the fundamental constraint on sound semi-arid natural resources management and stresses the importance of these issues in the African context.

> *The development and spread of such micro-scale approaches as those presented above could be of crucial importance to semi-arid Africa. The transferability of these principles to the African cultural and geographical environment must be seriously contemplated in decision-making and policy design.*

Breaking the cycle of over-exploitation of land resources caused by or inducing drought and contributing ultimately to famine requires a new understanding; issues related to land-use planning and agricultural development policy are also intimately related to water resources planning. Defining alternative agriculture development policies on the basis of their social sustainability, environmental impact and fundamentally their relative water demands offers insight into the wisdom of alternative development models.

3.2 Rice Irrigation

Senegal and Mauritania, the states most dependant on the agriculture component of SRB development, suffer a serious deficit in the production of staple cereal crops. In 1988 Senegal produced only 19% of its rice consumption, Mauritania fared slightly better, producing 32% of its consumption [CILSS, 1990].

Imports of cereals, particularly rice, for primarily urban consumers, contribute greatly to foreign debt. The huge foreign exchange burden of rice importation thus dictated an agricultural development policy which stressed the development of large state-managed rice plantations to supply as high a measure of rice self-sufficiency as possible [Seck, S., 1991; Engelhard, 1991]. The regularisation of river flows permitting annual double cropping and the anticipated high productivity of the large perimeters was expected to both reduce the national cereal deficit, and provide at least in part the economic justification for the dam construction.

3.2.1 Large Rice Irrigation Perimeters: Physical Features

The large plots are characterized by the following general features: usually greater than 1000 ha in size, situated on the clayey (hollalde soil) flood plain depressions known as "cuvettes". The perimeters are diked for flood protection, and include a pump station, a distribution network of canals, a drainage system and usually a drainage sump system. Fig. 3.2 illustrates the main canal of a large rice perimeter under construction in the middle valley near the town of N'dioume. The photographs also give some indication as to the enormous scale of the operation.

Fig. 3.3 shows the pump station under consruction. Typically the pump station would consist of 2 or more pump sets with a total capacity of approximately 5000 litres /sec at a design head of 1.5-2 meters.

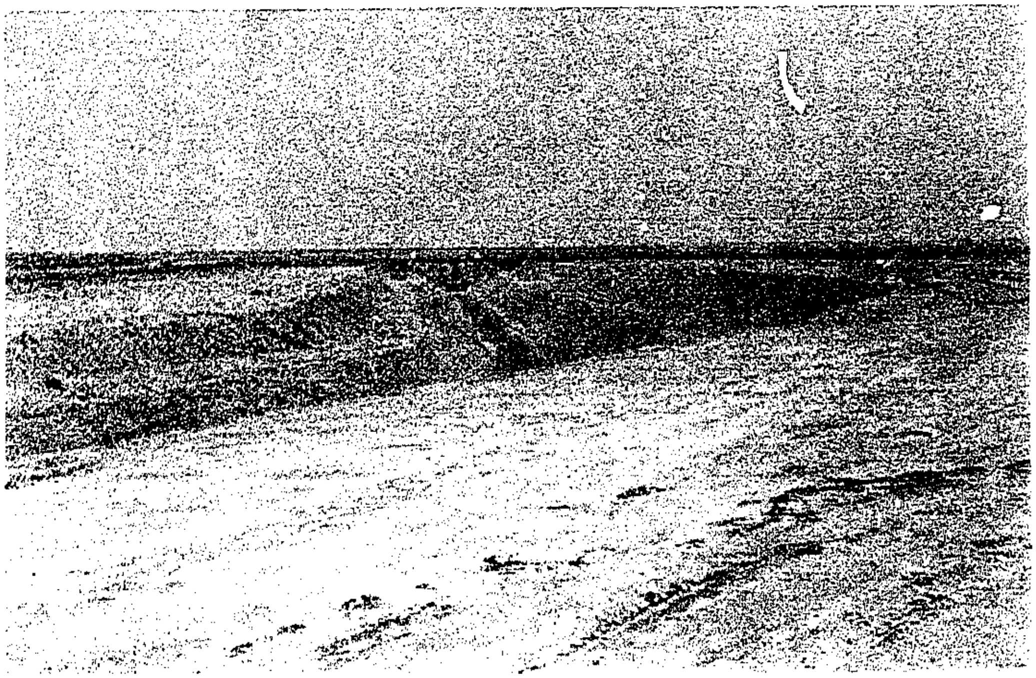


Fig. 3.2 Rice Project: Main Canal-N'dioume Region

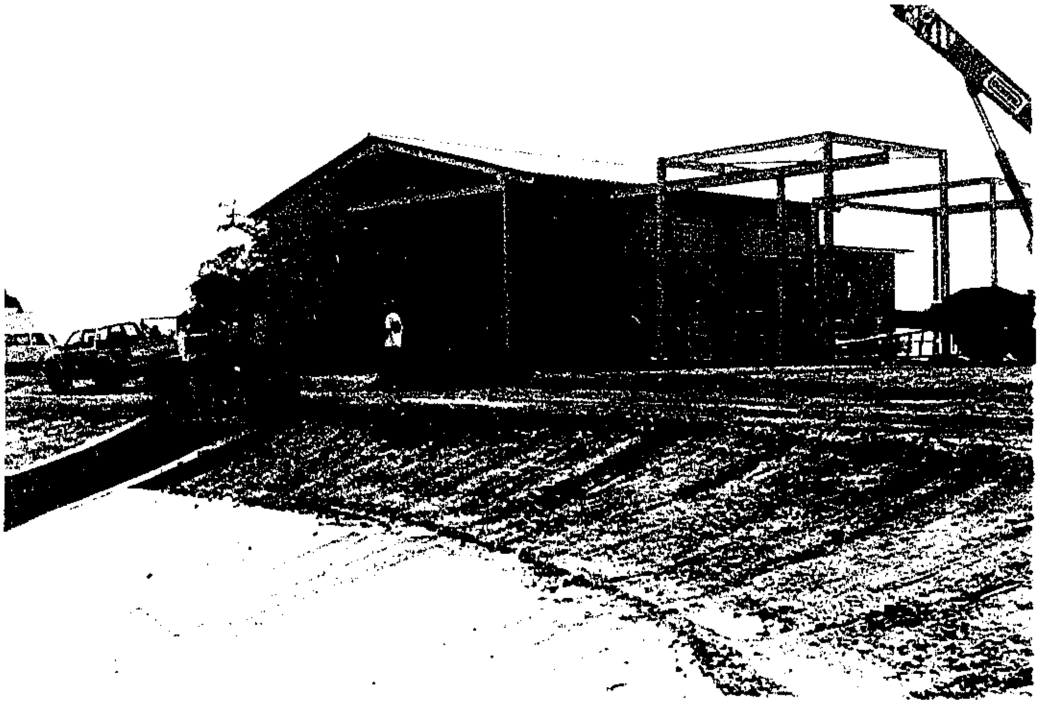


Fig. 3.3 Rice Project Pump Station-N'dioume Region

3.2.2 Large-Scale Rice Irrigation Perimeters: Socio-Economic Aspects

In 1988 large rice fields accounted for only 1.4% of the total number of irrigation projects, they comprised however 25.8% of the total area under cultivation [Seck, S., 1991]. The state manages all aspects of the enterprise from initial design to final construction and provides all the necessary financing. Development costs are approximately 5 - 7.5 million FCFA per hectare (200 FCFA= $1.00 CDN). Farmers are not involved in any phase of design or construction and join the project only at the end of construction. Management is typically highly centralized. Seck indicates that the operational complexity of the projects and the generally poor training of the work force has forced the state to provide massive subsidies to meet minimum production targets thus aggravating the state's precarious financial situation. In principle the farmers are supposed to benefit from individual holdings within the grand perimeters, however the lack of involvement in the implementation and management of the project results in high levels of worker alienation and poor productivity. The area cultivated that is actually harvested rarely exceeds 60% and CILSS [1990] reports that rice irrigation projects averaged an annual cultivation intensity of 57%, which means on average 57% of available plots were harvested. This figure is well below the design expectations of 180% (i.e. a second annual harvest on 80% of the irrigable area).

Not surprisingly the large perimeters are generally not profitable [Seck, S., 1991]. The farmer's wages, rather than being his share of the operating profit, are instead another subsidized cost. The farmers regard themselves not as partners in development but simply as employees. The farmer's alienation also results in poor maintenance and high levels of abandonment. Thirty-five percent of the large perimeters developed have been abandoned or require rehabilitation. CILSS [1990] offers the following summary of the economic performance of rice irrigation development:

> *The profitability of rice cultivation is negative in all cases, except those cases where the subsidies (rehabilitation, technical assistance and SAED inputs) are financed by international aid and in additon, if one values the opportunity cost of farm labour as zero.*

> *In the current situation, rice cultivation from investment to marketing is ruinous for the state; and for aid agencies it is equivalent to financing the purchase of rice on the international market.*

Poor drainage maintenance of rice plantations can have grave environmental consequences due to salinization effects. The large volumes of water required for rice cultivation, the high evaporation rates common in the basin, and the poor natural drainage of the cuvettes all render the rice perimeters vulnerable to salinization. Thousands of hectares of former rice production areas have already been abandoned due to salinization [M'balo, 1993].

3.3 Village Scale Irrigation Projects

Despite the economic, social and environmental problems associated with the large rice projects which are now too great to go unnoticed, the states have not yet recanted on their policy of rice production. Private investment in large irrigation projects is still actively pursued. International funding agencies however no longer fund state managed projects, preferring instead the rehabilitation of existing fields [Seck, S., 1991]. In response to the economic failure of the large perimeters, the SAED now actively supports village-scale irrigation development.

Village scale irrigation projects, *"Les Perimetres Irriguees Villageois"* (PIV's) hold claim to the sustainable development success story in the SRB. Developed and managed with strong, often sole local involvement, the PIVs have grown rapidly from a total of 1000 ha at 33 sites to 32,900 ha at 1096 sites in 1988 [Seck S., 1991]. The relative success of the PIV's is usually attributed to the following factors:

1. The severe drought which forced a change in traditional agricultural practice.
2. The availability of the simple motor-pump as an appropriate technology.
3. Peasant leadership capable of accepting new technologies without upsetting traditional leadership structures.

The state governments still exert a strong influence on the design and management of the PIV's despite their considerable autonomy. For example in Senegal, the national irrigation development board, the SAED, is responsible for site identification, creation of the principal earthen canal, some dyking, provision of pumps, delivery of inputs on credit (recently restricted), training of farmers in irrigation techniques and training of village pump operators. Any group initiating a PIV project, be they an NGO, a farmer collective, or a cooperative, must sign a contract with the SAED which also retains control over marketing surplus production. The PIV's appeal to the state is linked to their much lower development costs and higher productivity. Table 3.1 summarizes the key differences between Large Perimeters and PIVs.

TABLE 3.1

Comparison Large Rice Projects and Village Irrigation Projects: Key Features

	Large Rice Projects	**PIV Projects**
Size (ha)	>1000	10-20
Location	mostly delta	mostly valley
Construction Costs (FCFA/ha)	4 000 000	400 000-900 000
Operating Costs (FCFA/ha)	140 000	70 000
Rice Yields (T/ha)	4.1*	5
Sales to SAED	45%	10%

[Source: Huibers and Speelman, 1989]

* [other sources have quoted less favourable large project yields: 2.9 T/ha and 2.5 T/ha [Freud, 1988; CILSS, 1989]

Some PIV's devote as much as 75% of their production to rice. The basin states are increasingly keen on promoting surplus rice production on the PIV's. The wholesale shift of government policy to PIV's is however an extremely tenuous development policy despite the obvious financial appeal. A state-dictated rice policy threatens PIV's with the same socio-economic and environmental problems that befell the large perimeters.

3.3.1 The Socio-Economic Dimension of PIV Design

In a survey of rainfed agriculture methods in Sierra Leone, Richards [1986] noted the innovativeness of farmers in coping with their own agronomic and environmental constraints, and concluded that "Africa's food problems result in part from the inability or perhaps even the refusal of technicians and technical departments to assist the farmers to reach their own objectives." [Richards, 1986]

In 1983 Wageningen Agricultural University (the Netherlands) in collaboration with the West African Rice Development Association (WARDA), began an in-depth field study of 12 PIV's throughout the middle and lower reaches of the Senegal River Valley, hereinafter referred to as the Wageningen study and subsequent report. Although Richard's conclusion was not chosen *a priori* as the working hypothesis of the Wageningen project, after eight years of field study it emerged as equally true of irrigation in the Senegal River Valley. The Wageningen report concluded that the failure of irrigation development schemes was fundamentally linked to the assumptions regarding the organizational and behavioral patterns made by the designers of the schemes. These assumptions differed radically from the actual political structures that existed in the field. Successful cases of village level management were uniformly related to the adaption of the project to local socio-cultural conditions.

The existing literature regarding African irrigation development is largely divided between the strictly technical and the strictly anthropological, and thus the evaluation criteria used by either discipline are largely incompatible. The Wageningen study was thus unique in recognizing that in focusing on the technical "how" of irrigation network management, one could not overlook the question of "why" this style of irrigation management. The latter question pertains strictly to the social structure of the irrigation group. The Wageningen project was designed so that a large part of the research was performed by irrigation engineers and social scientists working in tandem. The overall goal of the study was to determine the extent to which the present crisis in irrigation development in Africa is attributable to incidents where the conventional design method is at variance with normal socio-cultural patterns.

Recounting all the major observations of the Wageningen study, however illuminating, would be exhaustive. The reader interested in the socio-economic aspects of small-scale irrigation engineering is strongly advised to consult the entire Wageningen report series. The key recommendation emerging from the study is clear and concise:

> *Only if foreign ethnocentric technical criteria are replaced by criteria devised by the irrigators themselves can irrigation schemes be expected to increase agricultural production for subsistence and eventually for market.* [Diemer and Huibers, 1991]

A typical village irrigation scheme layout is shown in fig. 3.4.

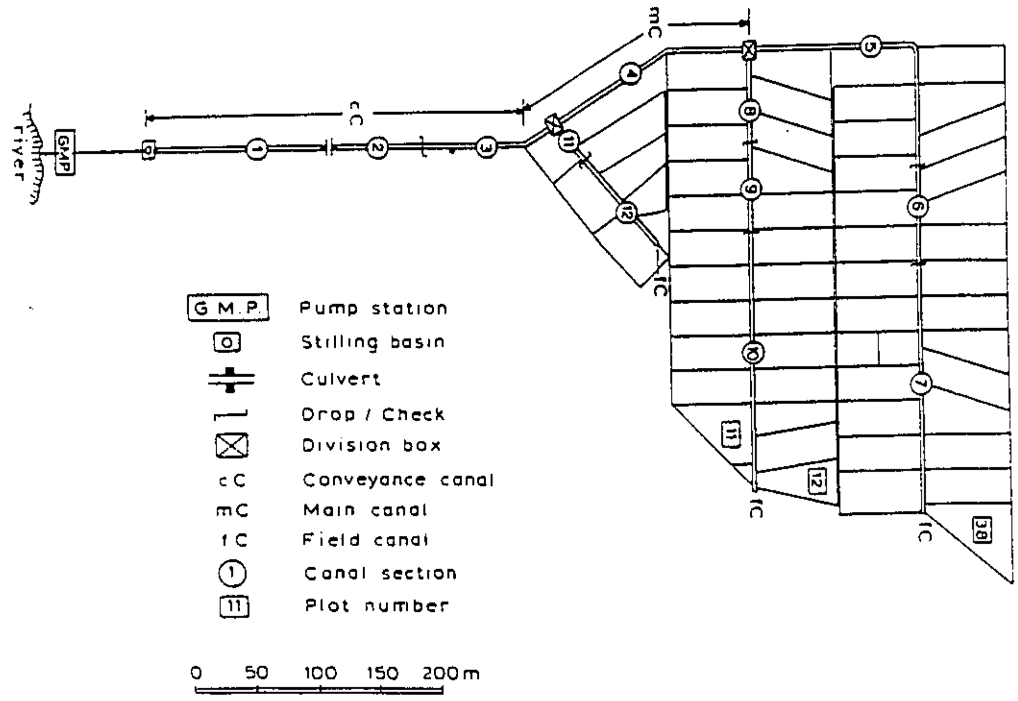


Fig. 3.4 Typical PIV Layout [Source: Diemer and Huibers, 1991]

Fig 3.4 illustrates some key characteristics of PIV's:

-they are served by a single pump set, the "groupe moto-pompe", (GMP) including 20 horsepower engine, pipes and rafts
-they use an area of about 20 ha
-small plot size (0.2-0.5 ha) for manual cultivation
-close to water source (> 1 km)

Fig. 3.5 shows a field installation of a motor-pump raft.

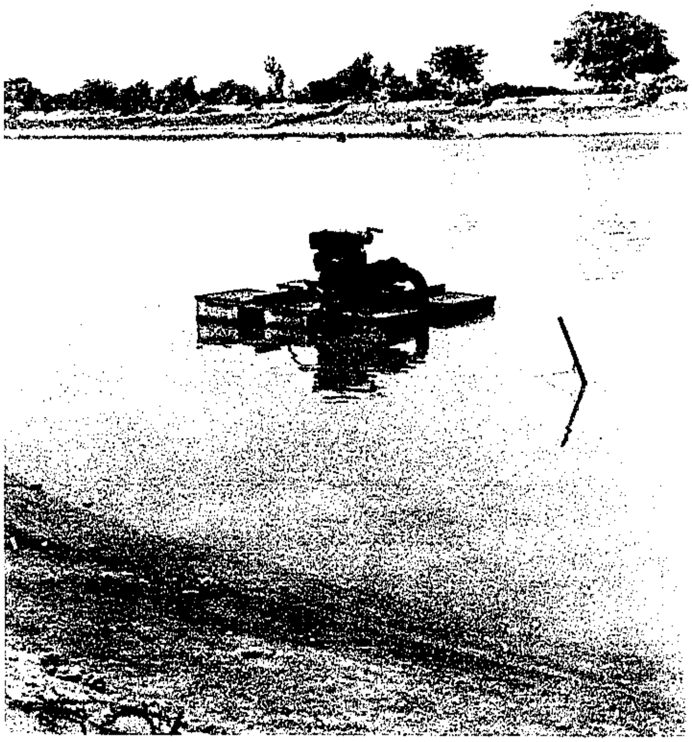


Fig. 3.5 PIV Motor-pump field installation

The canal network design is largely adapted from plantation style irrigation, where the entire scheme is considered one single farm entity. However, on the PIVs, each sub-plot which benefits one individual in the village group receives much more emphasis. As the village schemes are constructed quickly and cheaply without mechanical levelling, often some sub-plots are difficult to irrigate. Adhering to normal design and management methods should dictate that these plots be left out of the rotation of irrigation intervals for the benefit of the whole. In practice another logic prevails as each individual small-holder must benefit from his parcel. To that end he has the right to take as much water as he possibly can, within the limits of his field dikes or as defined by the political organization of the village group.

From the perspective of standard irrigation design, the allocation of water rights seems anarchic. An orderly rotation of sub-plot irrigation is only loosely followed. Each individual small-holder can appeal to have more water or water out of turn if their field is to parched. The ever changing sub-group of farmers who will soon be irrigating determine their exact order autonomously of the larger group. Water distribution may not be purely egalitarian since it is subject to the vagaries of local political power structures. This aspect is rarely abused since group solidarity assures that some form of democracy prevails. The Wageningen study for example reports on the case of a local village chief who disobeyed accepted rules by starting the pump without the presence of the designated operator. When the general assembly of small holders responded by declaring that any repair expense resulting from such abuse would be borne solely by the offender, the chief quickly stopped misbehaving. [Diemer and Huibers, 1991]

The importance of associating a village with a single autonomous village political entity cannot be overstated. Projects can fall under the jurisdiction of two adjacent villages if solely physical design criteria control network design. Poor cohesion and the need for frequent maintenance plague such dual-village schemes. The trust and solidarity which mark successful PIVs is greatly compromised when authority is split between two villages.

Requests for PIV development now generally originate with farmer collectives themselves at the village level, giving strong indication that this development policy is amenable to the socio-cultural milieu - provided that its design reflects its ownership by a unique village.

Another example of tailoring PIV design criteria to the user's objectives relates to plot subdivision. The particular example is derived from several similar incidents which occurred in the Bakel region. Typically a scheme will be organized according to an equal areal plot subdivision, such as shown in figure 3.6.

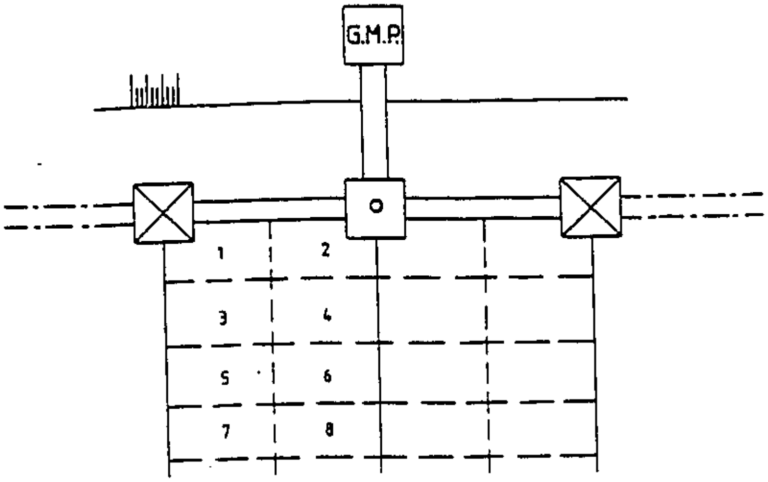


Fig. 3.6 **PIV Plot Parcelling** [source: Huibers and Speelman, 1989]

Such a division often results in plots of non-uniform soil quality and permeability, since the favoured heavier soils will generally be found in the flood plain far from the bank. Consistent with societal priorities that each farmer have access to both heavy and light soils, and to lessen the risk that any parcel is out of command, a redistribution such as shown in fig. 3.7 took place.

Unfortunately this new scheme complicates water management enormously. Each strip is comprised of many independent hydraulic sub-units according to the original layout and is irrigated simultaneously from several different field canals. If adequate consultation between the farmers and engineers had taken place prior to construction some compromise may have been achievable. In similar situations the SAED now recommends a plot subdivision with light and heavy soils irrigation separately, as shown in fig. 3.8. Individual farmers have access to both types of plots.

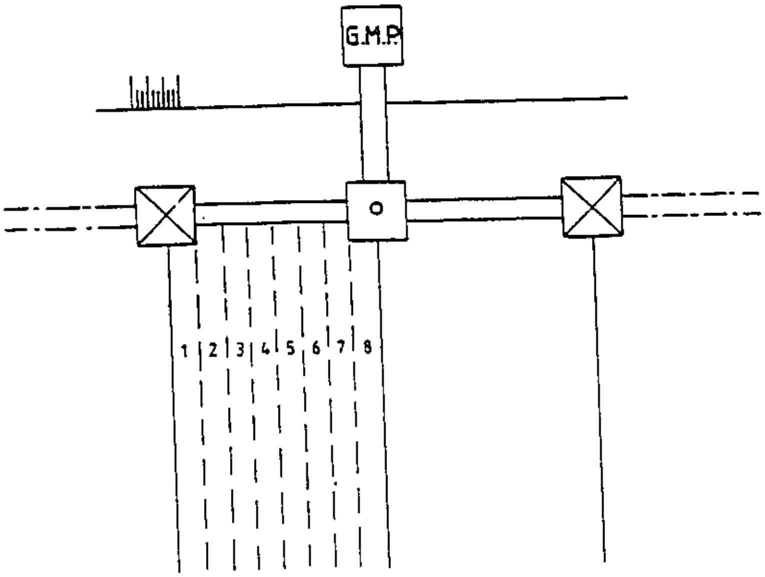


Fig. 3.7 PIV Plot Parcelling: Field Experience [source: Huibers and Speelman, 1989]

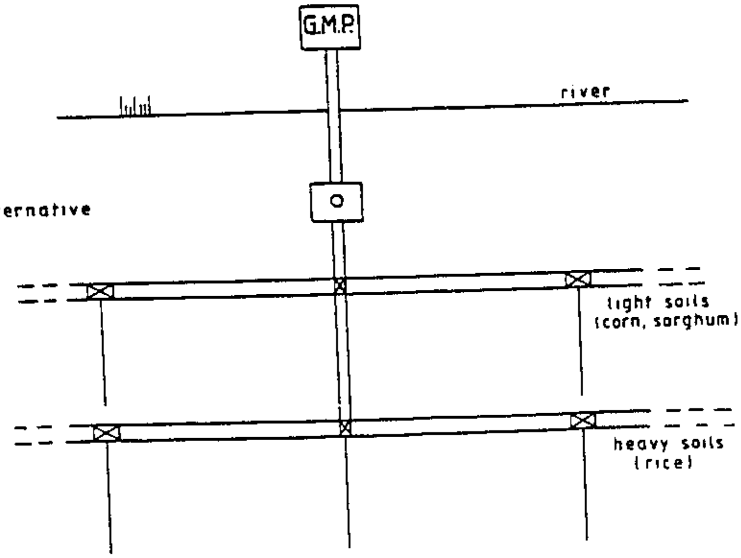


Fig. 3.8 PIV Plot Parcelling: Compromise Design [Source:Huibers and Speelman, 1989]

The effort to comprehend the farmer's objectives made on the part of the design engineer certainly pays dividends by greatly improving the projects chances of success. The alternative layout described is perhaps an acceptable hydraulic compromise between engineering efficiency objectives and social acceptability in facilitating crop diversification . However many farmers feel that a division such as this still constitutes a form of coercion on the part of the SAED towards a marketable rice surplus, compromising the farmers own objectives of individual self-sufficiency in other cereal grain production. Adams [1985] reports on an exchange between the SAED and Soninké farmers in the Bakel region of the valley which he describes as representative:

> *How much are you going to pay us for rice? 400 FCFA for a 100 kg sack. Millet is worth more than that. Rice is your concern, not ours. Here we live on millet. To leave millet for rice would be a disaster.*

More recently Brusberg [1990] similarly reported that micro-economic considerations should dictate that the SAED allow the farmers increased latitude in crop choice:

> *Some traditional crops such as sorghum, millet and wheat merit consideration because they permit the replacement of rice at a much lower production cost. With these cereals, yields greater than four tonnes per hectare under irrigation are achievable. Water and labour requirements are less compared to rice cultivation, permitting an increase in the number of cropping cycles.*

A key recommendation of the Frankenburger et al [1987] report is to substitute lower water consumptive crops such as sorghum for rice for both water resources and cultural amenability reasons. Unfortunately the macro-economic milieu and the doctrine of structural adjustment rule the day regardless of how "grotesquely" distorted the terms of trade are in international agriculture markets [*The Economist*, 1993]. The Rice Policy as dictated by government policy and executed by the SAED dies a hard death. Since increasing rice production remains the main objective of the SAED, the choice between large dedicated rice fields and small PIVs is difficult. The former, while guaranteeing a larger surplus for market, does so at hugely inflated investment and operating costs, while the latter guarantees a much higher return on investment but with smaller marketable surplus. A resulting compromise policy attempts to match the higher yields of the farmer-managed PIVs with the scale of production of large scale projects. The resulting hybrid development scheme calls for the development of intermediate (ITs) size irrigation farms . Several ITs have been constructed, they are generally in the order of several hundred hectares. Figure 3.9 illustrates a delta region IT project.

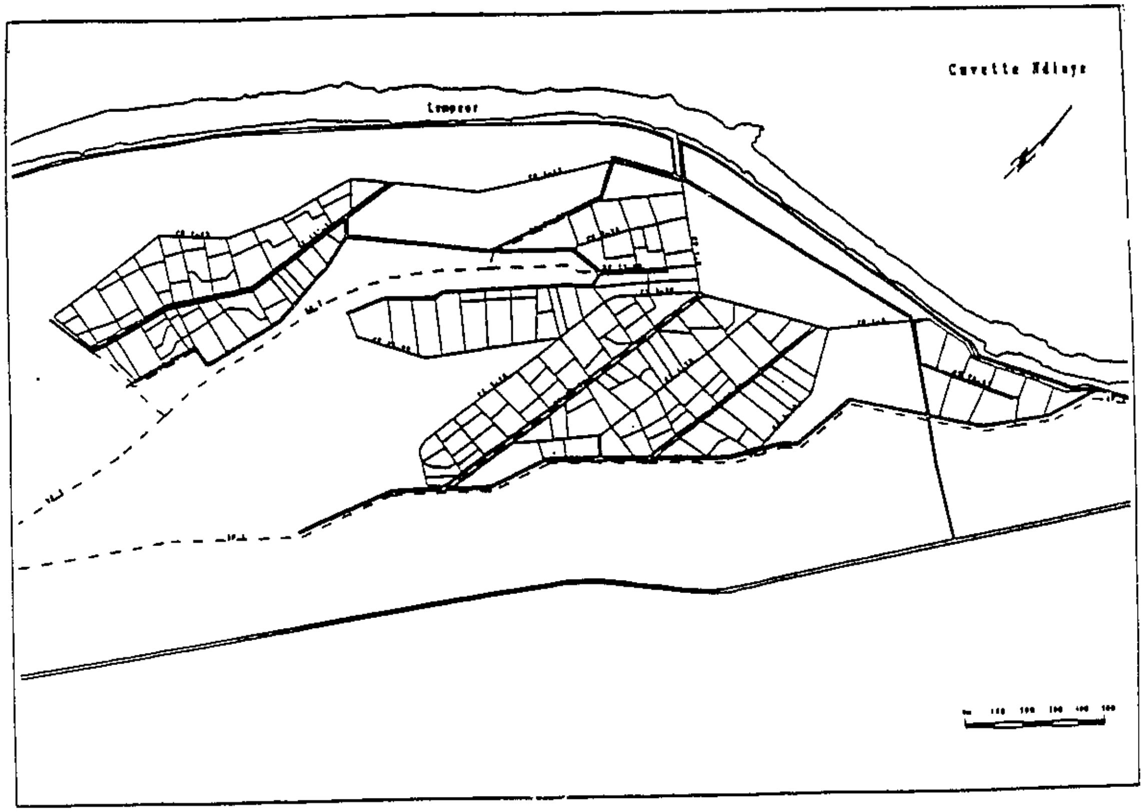


Fig. 3.9 Typical Intermediate Size Project [Source: KULeuven, 1991]

The principal hydraulic characteristics of this project are shown in Table 3.2 and Table 3.3.

Table 3.2 Intermediate Size Irrigation Project: Key Hydraulic Features:

AREA	170 ha
PUMPS	2 @ 400 Horsepower 1 @ 350 Horsepower
FLOW	2 @ 250 l/s @ 1.8 m head 1 @ 200 l/s @ 1.9 m head

Table 3.3 Intermediate Size Irrigation Project: Canal Characteristics:

	Principal	**Secondary**
Bottom Width (m)	1.2-1.5	0.5
Embankment	3/2	3/2
Water level (m)	1.0	0.65
Crest width (m)	4.0-6.0	2.5-4.3
longitudinal slope	very small	very small

[Source: KULeuven, 1991]

The much larger scale of the IT's compared with the PIV's requires mechanized earth moving and compaction. A potential technical and organizational benefit of this scale of technology is the permanent storage effect of large canals, which can reduce lag times between commencement of pumping and field application. The major presumed advantage of the IT schemes lies in the social organization of the hydraulic sub-units. Unlike the strong central control of the large perimeters, both the hydraulic design and the management of the IT's reflect the grapes on a vine concept. Individual sub-units of 50 ha are managed independently of the others by a farmer group. The sub-units share a common hydraulic network, and possibly a drainage system. The supposed advantage in this is that the motivation and self-organization of the farmers will yield PIV level output and the increased scale and intensity of operation will yield the large surplus. The latter assumption is pivotal; to assure the cropping intensity necessary to recoup development costs, planners require the farmers to give up farming activities outside the IT to concentrate on cultivation intensity within the project. Allocation of plots is not according to land tenure tradition, the planners instead choose individuals for the farmer groups according to their agronomic competence and motivation which are believed to be the key factors in assuring high intensity cultivation. Ironically, while intending to preserve the positive organizational aspects of farmer self-management, the IT planners disrupt the essential traditional and socio-political features which give the PIVs their cohesion.

Not particularly surprisingly, the few IT schemes constructed have not performed well and in a fashion radically different to expectation. Yields have only rarely matched those achieved on the PIVs despite the improved technical configuration of the IT's such as the storage function of the delivery canals. The improved water management capacity of the IT's through reduced lag times between irrigation commencement and field delivery and subsequent improved water security for the farmers proved an insignificant advantage compared with the organizational capacity and solidarity of PIV groups that compensated for the technical inadequacies of the PIV schemes [Diemer and Huibers, 1991].

Farmers almost without exception did not abandon outside activities despite this being a formal condition for working on the IT's. Contrary to a fundamental assumption by the planners, increased area and intensity of cultivation did not accompany the increase in available irrigable land. The farmers often allocated labour preferentially to their village plots (in several cases they switched the SAED mandated rice crop on the IT to tomatoes which they could market locally). The farmers chose to participate in the scheme only to the extent that they felt was an optimal level of risk avoidance. Only infrastructure development and guaranteed availability of inputs at a much higher level would make the farmers confident enough to dedicate his labour to an intensive mono-culture system. A co-requisite for economic success of the mono-culture system is a developed economy capable of sustaining inputs and market accessibility.

Aversion to and dispersion of risk is the fundamental requirement defining sound arid land agricultural management. Failure of state planners to comprehend this intensely human subsistence behaviour lies at the heart of the social alienation and low productivity that plague large and intermediate rice schemes, "For the farmers self-sufficiency in grain remains the most important, if not the only objective of production" [Diemer and Huibers, 1991]. The farmer will pursue whatever activities give him the best chance of self-sufficiency. Frankenburger et al. [1987] report for example that in the middle valley farm families will pursue rainfed cultivation on dieri, flood recession agriculture and PIV irrigation simultaneously. The distribution of resources between activities varies with the prevailing climate, effort will thus be eventually focused on the activities which seem most promising given the occurrence of rainfall in each particular year. If there are adequate rains (increasingly infrequent in recent years) more labour will be dedicated to extensive rainfed agriculture, if not, irrigation activities will receive more attention.

The prolonged drought has catalyzed the rapid spread of PIVs throughout the valley because they are a necessary option for risk minimization given the present marginality of rainfed and flood recession cultivation. Farmers choose PIV irrigation not for the prospect of large surpluses for market, but because it fits their development model of economic diversification and risk aversion under a drought regime. The Wageningen report definitively concludes the inadvisability of the state's imposition of a particular development model:

> *When the state imposes the production of a given commodity in a rigid pre-determined irrigation system, farmers can almost always escape, because very few, if any, will depend on these irrigated plots for their continued survival* [Diemer and Huibers, 1991].

3.3.2 Natural Resources Management Issues in PIV Development

The Wageningen report series is an unusually thorough discussion of the socio-economic aspects in any engineering design. It however ignores the crucial natural resources management dimensions of irrigation design.

Seck, S. [1991] for example warns of the danger of unbridled PIV development in the delta region. The design simplicity characteristic of PIVs entails almost always the absence of drainage design. Lack of drainage is not as large a problem in the valley where there is a greater proportion of permeable soils. However, this is not the case on the clayey soils of the Delta where poor drainage leads to severe salinity problems. Adequate extension service can mitigate those effects by counselling the village groups on proper drainage provision and avoidance of plots with particularly poor relief.

The last two decades of drought define the natural resource management issues of PIV development in the valley. Trees, fish and wild foods are no longer plentiful and traditional agriculture is increasingly marginal [Frankenburger et al., 1987]. Different compensating strategies adopted by farmers can be both ecologically devastating and potentially ecologically rehabilitative.

To cope with declining income from traditional sources, farmers frequently turn to woodcutting and charcoal production. The resulting deforestation coupled with over-grazing of livestock puts pressure on the remaining vegetated pasture and drives a vicious cycle of sand encroachment in productive areas, soil and wind erosion leading to a further loss in agricultural productivity, feeding back to more deforestation. The farmers' response to the continued degradation of the traditional resource base is to turn increasingly to irrigated agriculture. As stressed previously, the adoption of irrigation technology is not because of the inherent appeal of its promise of large economic rewards. It is simply one of the very few options to assure some measure of self-sufficiency.

A key recommendation from the report by Frankenburger et al. [1987] and a pivotal environmental rehabilitation element is the integration of agro-forestry techniques in and around village irrigation perimeters. Shelter-belts ("brise-vents"), cut down on wind erosion, sand encroachment and evapo-transpiration, while improving soil moisture retention. The SAED now recommends concurrent shelter-belt and PIV development. The recommended tree species for shelter-belts are listed in Table 3.4

Table 3.4 PIV Shelter-belt Development: Recommended Species

Valley	**Delta**
Eucalyptus camaldulensis	Melaenica
Prosopis	Prosopis
Acacia holocenica	Eucalyptus Camaldulensis

[Source: SAED, 1986]

Extension service and counselling are often required to reassure the farmers that the benefit of agro-forestry for soil conservation outweigh the disbenefits they fear in providing habitat for pest birds.

While the propagation of PIV development in the SRB has certainly been a relative success, it has, however not been absolute, as the PIV's also suffer from frequent under-performance which seriously compromises rehabilitative natural resources management efforts in the SRB. Complimentary natural resources management and irrigation systems management, is of course impossible without sound water resources management, particularly in arid regimes where water scarcity is acute. Poor water resources management due to poor systems management or imprudent crop choice can be equally crippling to the sustainability of irrigation projects. Fig. 3.10 illustrates the hydraulic division structure and main canal of a PIV that fell into disrepair and was abandoned.

The natural resources management benefits (soil conservation/agro-forestry) that can be associated with PIV development depend strongly on the level of extension and support service available.

Fig. 3.10 An Example of PIV Abandonment

The crop choice on PIV's also has natural resource management implications. The USAID [1984] describes the exorbitant pumping costs associated with rice cultivation in the Bakel region. The combination of the high water requirement for rice, the high soil permeability in this region, as well as the large pumping head due to both the valley relief in this region and the low water levels associated with the drought, make rice cultivation uneconomic and a poor utilization of scarce water resources. The high flow/high head demands placed on the pumps is such that conditions make them prone to frequent breakdown. Compounding the problems of pump maintenance is the generally inadequate level of extension and training supplies by the SAED. The canal networks are also frequently in poor states of repair leading to large water losses and poor irrigation efficiencies. Frankenburger et al. [1987] summarize the reasons for PIV under-performance:

- lack of water in the river
- frequent pump breakdowns
- poor levelling of parcels by farmers
- farmers inexperience with crop or water management
- indebtedness leading to withdrawal of inputs
- unavailability of improved inputs
- labour constraints
- occasional flaws in perimeter construction

Year round river regulation, now possible with the Manantali Dam would definitely improve the availability of water resources which would also improve pump performance by reducing operation head. However PIV under-performance is also closely linked to the scarcity of training extension and credit offered by the SAED. Farmers complain that even in good years thirty to forty percent of the harvest is required to repay loans to the SAED [Frankenburger et al., 1987]. This level of financial burden can and does lead to PIV abandonment for other agricultural and income generating activities frequently with much less favourable environmental impacts such as clearing more forest for extensive rainfed agriculture. Frankenburger et al. [1986] describe a particular (although common) case where farmers had turned to deforestation and charcoal production as a response to an irrigation pump failure.

The blame for the lack of extension service and credit cannot be borne by the SAED alone. SAED activities such as PIV extension have been drastically curtailed because of revamped government policy in Senegal intended to reduce subsidies to farmers. *The New Agricultural Policy* is in fact an International Monetary Fund mandated structural adjustment policy [Ominade, 1990]. The curtailment of agricultural subsidies has forced the Government of Senegal to de-emphasize the disastrous policy of subsidizing large rice irrigation projects, a beneficial development from both an economic and environmental perspective. However the cessation of subsidies for PIV and agro-forestry extension services has the equally disastrous effect of PIV abandonment, reducing food security in traditional communities forcing farmers to turn to deforestation for extensive agriculture or charcoal production.

The policy of reduced agricultural subsidies to Sahelian farmers threatened with the desertification of their land seems a sad parody of sustainable development philosophy, short-sighted and unjust. Firstly, it will compound already existing problems of desertification, environmental degradation and the ensuing refugees crowding already squalid urban areas. Secondly, compared to the large agriculture subsidies enjoyed by the agricultural producers in more northern climes, a very unfair burden is placed on populations most vulnerable to climate vagaries by those who have the power to dictate the terms of international finance.

3.4 Alternative Irrigated Agro-ecological Production Systems

3.4.1 The Roots of the Ecological Crisis in the SRB

The degradation of the once verdant river valley by the human and animal factors of deforestation, extension of cultivable land, pasture destruction by over-grazing, and compounded by the associated drought effects of low river volumes and weak annual flooding constitutes the beginning of a domino effect of vegetation degradation further south. Sene [1992] describes the destruction of the protective barrier that was the heavily wooded valley as pivotal in the ecological degradation throughout Senegal. The USAID [1984] reporting on the need for soil conservation in the valley refers to a mechanism of land degradation consequent to losing the protective valley forest; they describe, "the dust bowl conditions created by the Harmattan (desert) winds blowing in from the Mauritanian plains that before the drought lasted two to four weeks but now last seven to nine months."

The massive deforestation evidenced in the valley is both an effect of the drought, and an agent which reinforces its severity. Frankenburger et al. [1987] attributes the initial perturbation that sparked the downward spiral of environmental degradation to the onset of the drought in the early 1970s. Before then the production of wood had been in equilibrium with demand for energy and cooking purposes. Fuelwood is the only energy source generally available to people in the valley. Before the drought the vegetative cover was extensive and well enough established to support the herds that grazed there. The debilitating social effects of the resource degradation phenomenon are well known, the famine of 1973-1974 following the onset of the drought was a direct result of the precipitous decline in the productive capacity of the resource base which has not recovered. Families accustomed to three cooked meals, now manage one given the shortage of fuelwood resources. Mothers, and increasingly children, expend much labour and time gathering wood from further afield, time which would otherwise be spent nurturing children in the home. [Frankenburger et al., 1987]. Falkenmark et al. [1987] describes the process as "when lack of precipitation phenomena are filtered through an over-populated, over-exploited area, the results are desiccation of the landscape and the risk of collapse of the socio-economic system". The reader is invited to review the schematic depiction of the interaction of natural and social systems which induces desertification shown in Fig. 3.1.

De-vegetation due to deforestation for fuelwood, overgrazing or "slash and burn" clearing to expand agricultural land unleashes a positive feedback effect on several ecological scales simultaneously. At the micro scale de-vegetation destroys the soil's protective cover, the soil temperature rises, the surrounding air dries, intensifying local evapo-transpiration and increases the evaporation of precious soil moisture, rendering it susceptible to erosion, inhibiting vegetation re-establishment and encouraging more de-vegetation. At the meso-scale, the de-vegetation and the concurrent process of air temperature rise and humidity decrease, inhibits the formation of clouds reinforcing the lack-of-precipitation triggering phenomenon. At the macro scale de-vegetation and deforestation entail atmospheric CO_2 emissions from either fuelwood (charcoal) production or slash and burn clearing for extensive cultivation. Fig. 3.11 offers a diagrammatic description of the simultaneous ecological degradation processes triggered by deforestation.

Seck, M. [1992a] concluded that deforestation and agricultural activities produced 70% of greenhouse gas emissions in Senegal, Mali, and Cote d'Ivoire. Such emissions could hasten global warming due to greenhouse effects with particularly deleterious effects in Africa. Glantz [1987] makes the speculative link that Sahelian Africa may be extremely vulnerable to greenhouse effect related climate change and drought, while as noted previously, Sircoulon [1990] claims the hydrological time series of the Senegal and the Niger rivers offer the strongest evidence yet that precisely these effects are taking place in the Sahel.

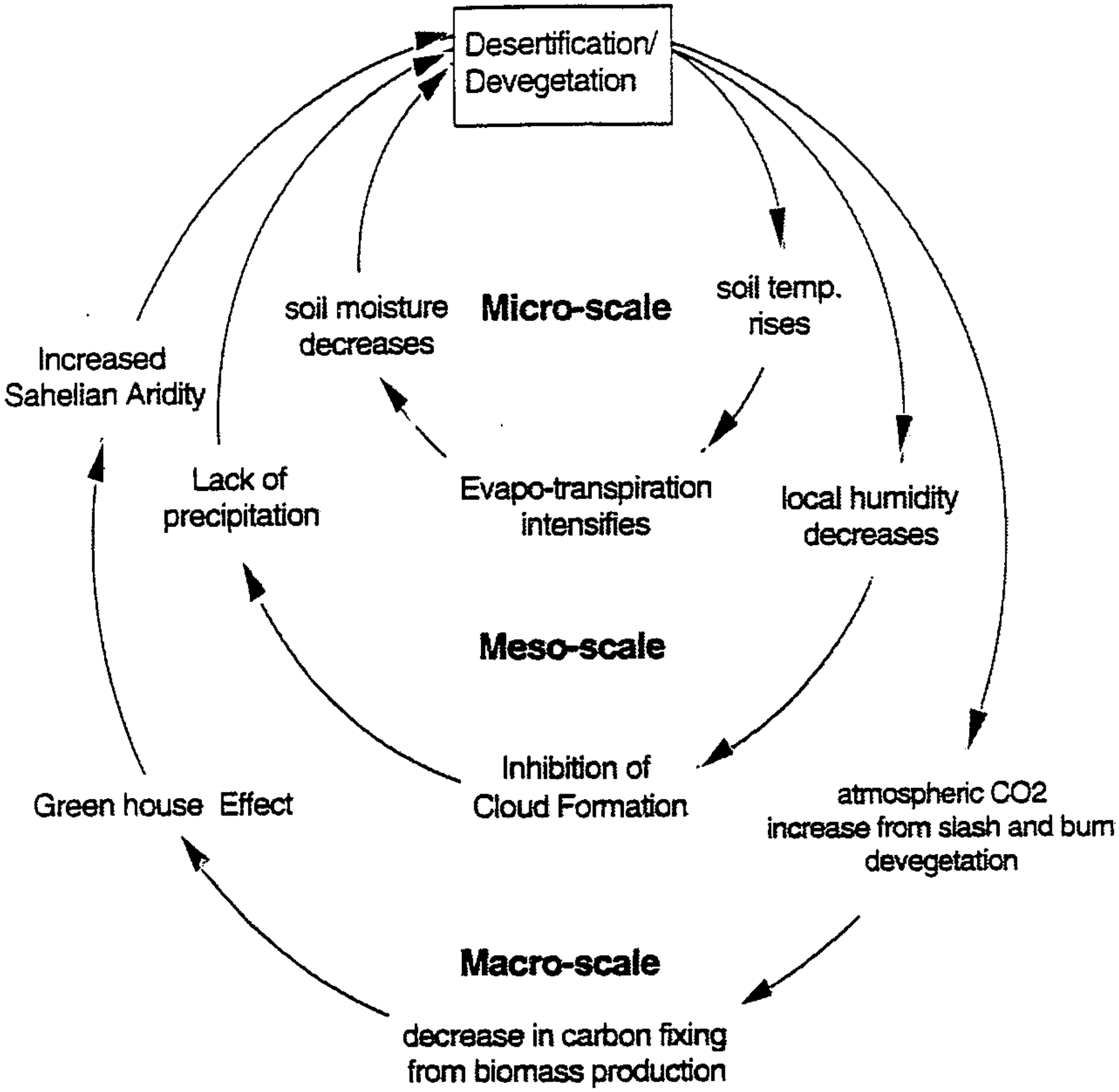


Fig. 3.11 Simultaneous Micro, Meso and Macro Scale Ecological Degradation

The confluence of natural (hydrologic, meteorologic) and anthropogenic agents in the process of Sahelian natural resource degradation leads to some debate as to whether under-development should be viewed as a cause or an effect of the drought. Periods of drought and the advance and retreat of the desert likely occur on both human and geologic time scales. The rate of desertification however strongly suggests that the anthropogenic component has greatly accelerated an otherwise natural process. Senghor

[1985] argues that the environmental degradation cannot be viewed simply as the temporal intersection of demographic pressure on a hydrologically stressed natural resource base, but must also consider the effect of mal-adapted western models of social and agricultural development policies (particularly mono-culture agriculture development) as complicit in provoking the crisis. In Senghor's opinion the positive soil conservation effects of associative cropping, common in traditional agricultural systems, and foregone by the imposition of mono-cultural production systems (peanuts in colonial days, rice presently) has strongly contributed to environmental degradation.

3.4.2 SOLUTIONS: Beyond Environmental Protection - Intensified Agriculture Systems for Environment Production

Breaking the downward spiral of environmental degradation in the Senegal River Valley forces a new perspective of proactive intervention to assist in natural systems rehabilitation. Gonzalez [1992] conducted an extensive survey of natural resource rehabilitation projects throughout Senegal. Gonzalez criticizes conventional wisdom that soil degradation can be reversed and desertification stopped only by planting as wide an area as possible with millions of fast growing trees. This philosophy is manifested in the large-scale mono-culture reforestation techniques using usually exotic species promoted by the *Direction des Eaux, Forets, Chasse, et de la Conservation des Sols*, the Senegalese government agency responsible for reforestation.

Gonzalez documents the high failure rate of these projects due to a variety of social and ecological reasons. Gonzalez instead concludes that the most promising soil conservation technique in much of Senegal is natural regeneration. Natural regeneration simply involves protection of seedlings from extensive agriculture and animal grazing. Gonzalez cites the dense stands of Acacia Albida around Bambey in the peanut basin of west central Senegal as excellent examples of what several decades of protection can accomplish. The most difficult constraints in natural regeneration are firstly, securing the social agreements between farmers and pastoralists to establish the protected zones, secondly, protecting the stands from premature harvest to feed fuelwood demands. The principal advantages of natural regeneration are the following:

- traditionally practised
- no materials needed
- no cost involved
- promotes multiple use trees
- targets hardy individual seedlings already well adapted to the local environment
- trees integrated into traditional farming and herding systems

Gonzalez's recommendations of natural regeneration hold in the Peanut Basin and the Ferlo (a large region of semi-arid sylvo-pastoral plains south of the valley). Significantly the recommendation of natural regeneration does not hold in the Senegal River Valley, here the fundamental constraint is drought. **Essentially the environmental degradation is too far advanced** to expect natural regeneration to succeed in the Senegal River valley.

Gonzalez concludes that the most promising natural resources activity for soil conservation in the valley is the introduction of irrigated vegetable gardens with associated agro-forestry. The USAID [1984] reports that soil conservation projects in the valley proved futile in the prevailing pluviometric/hydrologic regime of the valley. Their attempts to plant a hot season cover crop for soil protection succeeded only with the year-round availability of irrigation water. The field experiences in the Senegal River Valley bear out the point stressed by Falkenmark et al [1989]. Simple protection of water-stressed systems is not enough once the vicious cycle of de-vegetation has achieved a critical momentum. **Any form of natural resources management activity must strive to break the cycle of de-vegetation by maximization of biomass production by optimal management of available water resources.** In essence, the ecological degradation of the Senegal River valley is so far advanced that a combined land-water environmental management plan demands not protection of the natural resource base, but **a re-creation of the natural resource base.**

Environnement et Developpement Action-Tiers Monde (ENDA-T.M.), an international non-governmental organization based in Dakar, Senegal has attempted a direct response to stopping and reversing the environmental degradation sequence of deforestation, soil degradation and desertification. The agricultural division of ENDA, Systemes et Prospective (SYSPRO) has launched projects throughout Senegal. The SYSPRO system uses simple irrigation technology to intensify agricultural systems for year-round biomass production. The key agro-ecological features of the SYSPRO system include:

1. Heavy reliance on ecological benefits of associative cultures (inter-cropping)
2. Integrated agro-forestry through extensive wind break development
3. Use of composting
4. Simple irrigation technology (usually a single small motor-pump similar to those used on the PIVs
5. Modest external inputs of fertilizers and insecticides
6. Reliance on labour intensive rather than resource intensive cultivation to ensure optimal production levels.
7. Establishment of nurseries with emphasis on production of diverse species

SYSPRO's extensive use of inter-cropping is to a large extent an evolution and intensification of traditional agricultural systems. Taylor (1977) describes some of the ecological benefits accruing from associative cropping methods; a marked reduction (frequently 50% or more) in insecticide application for example. Intercropping species and crop rotation creates physical barriers limiting the propagation of predators from host in time and space. Composting of crop residues can also break the development cycle of disease vectors, while at once improving soil texture and nutrient content. Associative cropping will also generally entail that at least one cover crop will be present year-round, reducing insolation and soil desiccation, a vital agronomic issue in arid climates. The net effect of these associative ecological relationships is an apparent production synergy between species. Taylor reports that traditional inter-cropping maize, sorghum, manioc and potato and beans in the Cameroon uses 55% less land than if each crop was grown individually.

The agro-forestry aspects of the SYSPRO system are an essential production component. Thirty-five thousand trees (a preferred species is *leuceana lenocephala*) are planted an a typical five hectare plot. The trees act as shelter-belts for the irrigated plots. Lal [1988] provides an extensive literature survey of research on soil degradation processes in sub-Saharan Africa and concludes that shelter-belt development is extremely important for vegetation re-establishment. The shelter-belts provide a protective barrier to resist wind and water erosion and also change the local micro-climate by decreasing insolation and evapo-transpiration thus creating a favourable environment tor the establishment and growth of plants. Tree production also serves as a potential fuelwood source.

In a comprehensive review of agro-ecological rehabilitation systems in sub-Saharan Africa, Lal [1990] cites research on the further ecological benefits of agro-forestry and shelter-belt development. Hoegberg and Kvarnastroem [1982] report that *leuceana lenocephala* can fix 75 to 100 kg/hectare/year of nitrogen. Nair and Khanna [1975] have shown that deep rooted perennial such as *leuceana lenocephala* act as nutrient recycling mechanism, minimizing nutrient losses from leaching. Juo and Lal [1987] report that deep-rooted perennials also improve infiltration and soil structure which has the associated effect of improving irrigation application efficiencies.

Seck, M. [1992b] describes the SYSPRO approach of applied agro-forestry as a third generation agriculture system and the logical progression from strictly traditional systems and strictly conventional "mechanized chemical" systems, "Cultivation intensification results not from the massive application of chemical inputs but in the optimisation of the relations between species in time and space".

Declining soil productivity associated with soil degradation, coupled with demographic growth has led to attempts to increase production and revenue by increasing cultivable surface area. The "horizontal" rather than "vertical" intensification of productivity has contributed profoundly to deforestation. Vertical production intensification using irrigated agriculture can produce three times yearly which implies clearly that one can save

2 hectares out of 3 from deforestation for the same level of production. The SYSPRO approach, using available water resources sparingly to intensify agricultural production per unit area meshes with Falkenmark's call to maximize bio-mass production by optimal allocation of scarce water resources as the key to breaking the chain of events that lead from de-vegetation and soil degradation to ecological and social collapse. The downward spiral of environmental degradation at the micro and meso ecological scales is halted by "forcing" revegetation with irrigated agro-ecosystems as depicted in fig. 3.12.

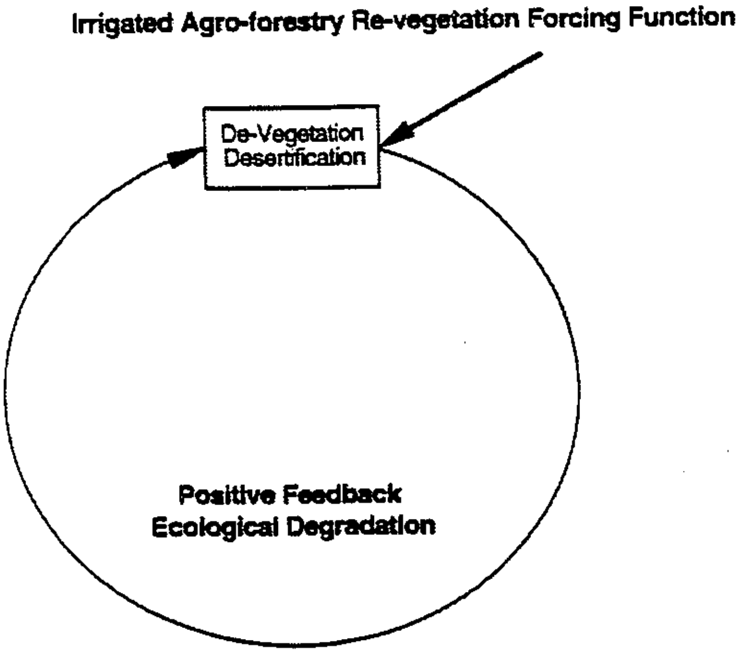


Fig. 3.12 Forcing Re-vegetation with Irrigated Agro-forestry: Schematic

In principle the SYSPRO approach also reinforces efforts to break the macro-ecologic positive feedback loop of de-vegetation and deforestation leading to greenhouse gas emissions and climate change effects and increased Sahelian aridity, leading to more de-vegetation. As stated previously, current agriculture practice and the related process of deforestation account for 70% of greenhouse gas emissions in Senegal. Intense agro-ecological production systems in tropical climates can fix 10 tonnes of atmospheric carbon equivalent per hectare per year [Riedacker and Dessus, 1991], while simultaneously avoiding the deforestation of two hectares which would release 30 tonnes of carbon equivalents to the atmosphere. Riedacker and Dessus [1991] performed a global inventory of carbon stocks and concluded that intensifying tropical agriculture primarily by increasing soil fertility proved a very efficient option to fix atmospheric carbon and slow the greenhouse effect. Increasing the productivity of agricultural land was 5 to 10 times cheaper and with a quicker positive effect than the remediative approach generally cited and occasionally practised, that being (usually mono-culture) reforestation methods.

3.4.3 The SYSPRO System in Detail

The Sebikotane, Djebi and Daga Projects: Photo Documentation

The most effective description of the SYSPRO system of third generation agriculture is in the form of the following photo documentation. SYSPRO projects at Sebikotane/Djebi and Daga, each comprising about 5 cultivated hectares are both located about 50 km south-east of Dakar. Sebikotane has been in operation since October, 1990 while Daga is in its first year of operation. Djebi began operation in 1991, directly adjacent to Sebikotane.

Fig. 3.13 illustrates a plan of Sebikotane. The five hectares is divided into 28 sub-blocks each enclosed by a wind-break border. The entire five hectare area is enclosed by several rows of trees.

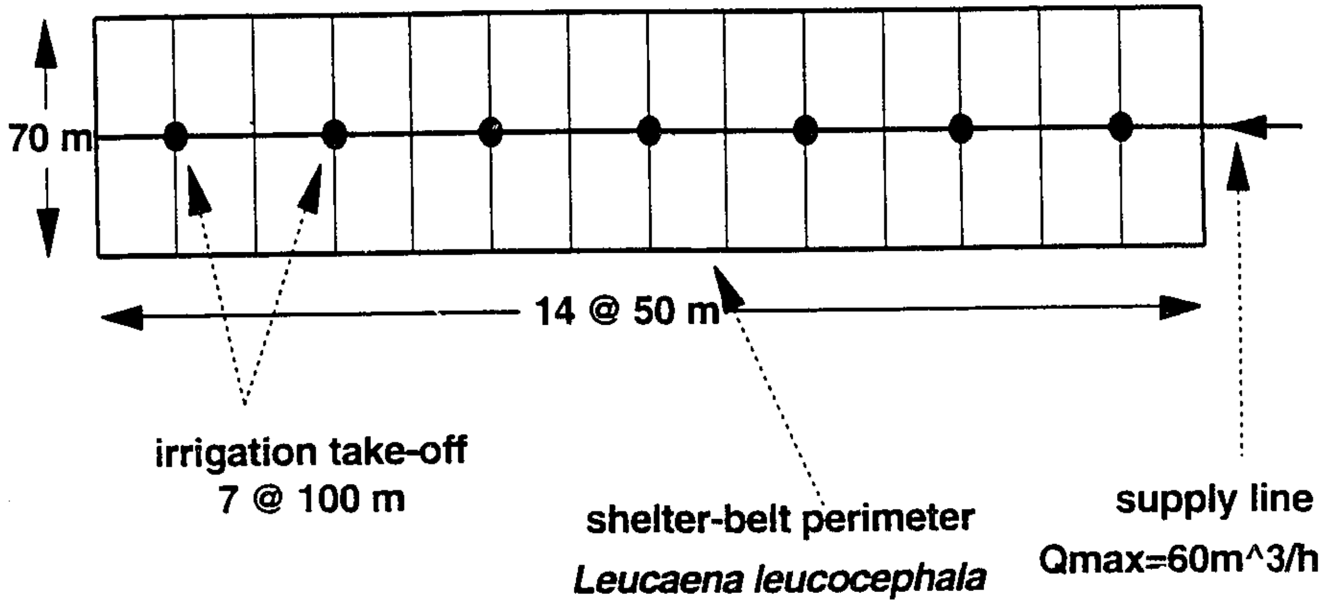


Fig. 3.13 Sebikotane Agro-forestry Project: Plan

Fig. 3.14 shows a detail of the pipe network: several PVC off-takes from the main line water the individual sub-blocks. The photograph also illustrates the single row of trees (*leuceana lenocephala)* enclosing each sub-block.

Fig. 3.14 Sebikotane Irrigation Piping System

Fig. 3.15 illustrates a detail of the irrigation system for those sub-blocks not reached by PVC off-takes. Here the main supply line is opened to feed the delivery canal. Note that the application method illustrates the watering effect of the shelter-belt as a secondary objective; what would normally be considered distribution loss is exploited by the shelter-belt development.

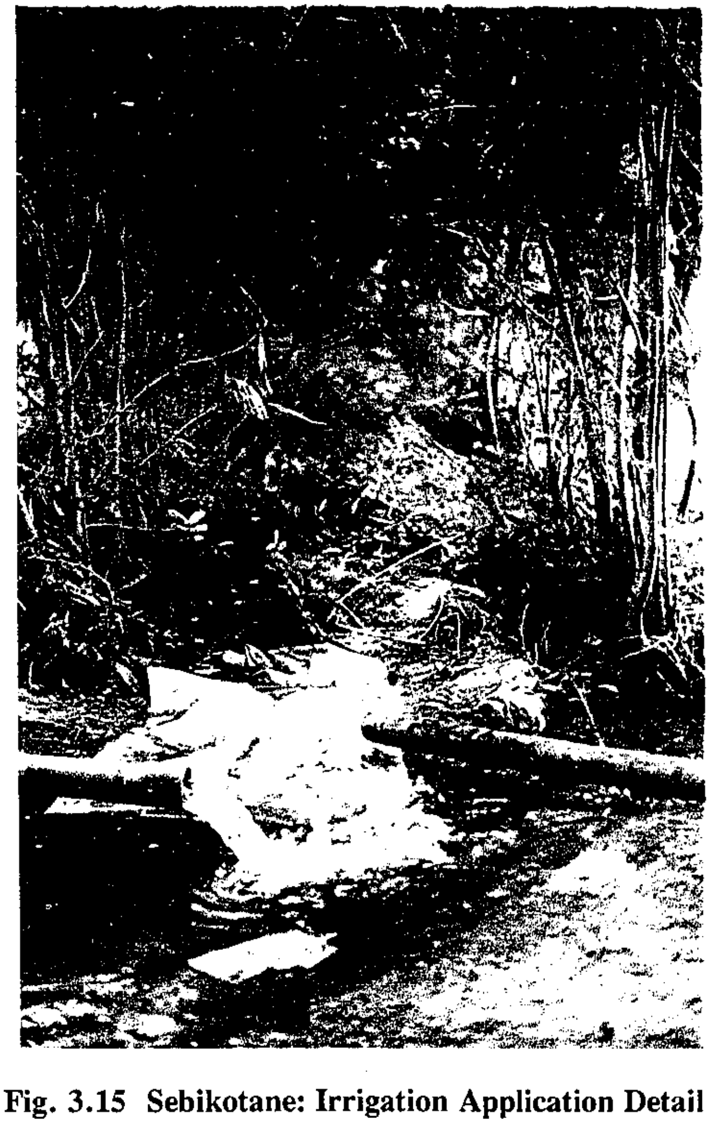


Fig. 3.15 Sebikotane: Irrigation Application Detail

Fig. 3.16 shows mature shelter-belt development after two years and the stockage of biomass from crop residues and *leucena* prunings prior to composting.

Fig. 3.16 Sebikotane: Shelter-belt Development and Biomass Stockage

Fig. 3.17 shows the compost pit and a store of compost in the background. The Leucena trees shading the compost store are no more than three years old.

Fig. 3.17 Sebikotane: Bio-mass Composting

Fig. 3.18 illustrates a crop association of tomato and cabbage.

Fig. 3.18 Sebikotane: Tomato and Cabbage Cropping Association

Fig. 3.19 illustrates a crop association of tomato and maize. Note the indirect irrigation of corn along the secondary channel, analogous to shelter-belt irrigation for the main canal of the sub-block.

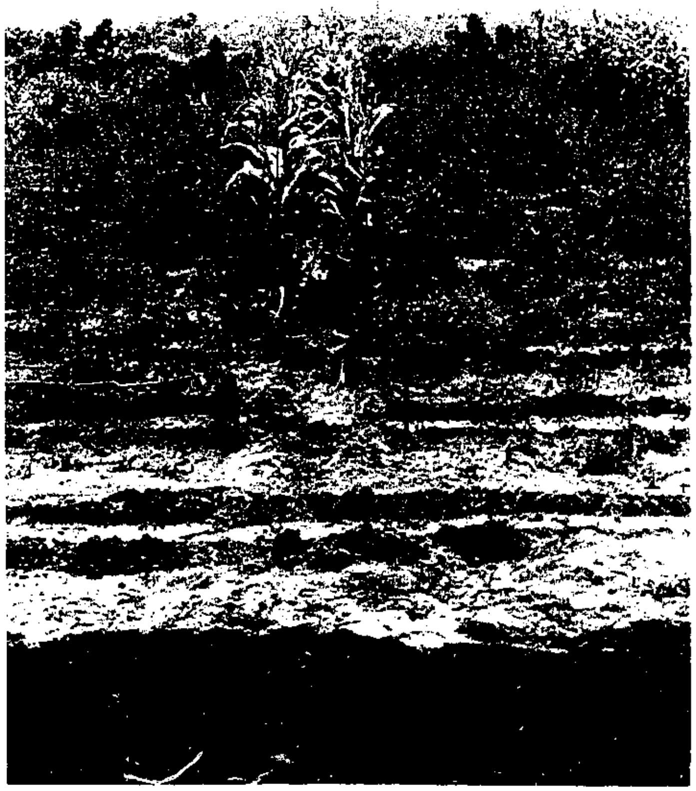


Fig. 3.19 Daga: Tomato and Maize Cropping Association

The photographs in Figs. 3.20 and 3.21 which were taken simultaneously in adjacent plots, illustrate the benefits of a labour intensive practice of staking tomatoes. The plot in fig. 3.20 is still producing several weeks after irrigation ceased because of improved root structure of the plants.

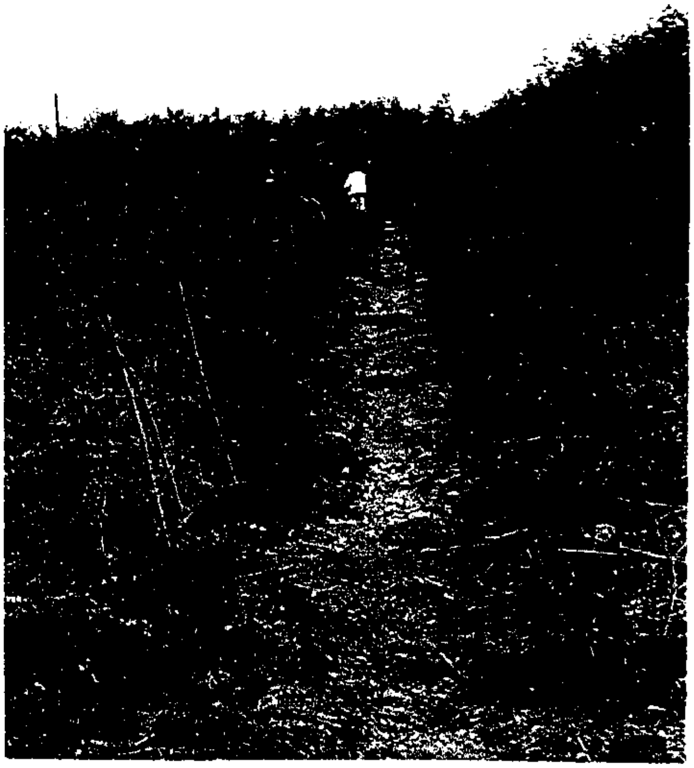


Fig. 3.20 Sebikotane: Tomato Cultivation with Staking

The plot in fig. 3.21 which was not staked has stopped producing. The root structure of these plants is less well developed, the plant is closer to the ground and more prone to surface fungi.

Fig. 3.21 Djebi: Tomato Cultivation-No Staking

Fig. 3.22 shows the occasional application of pesticides. The sparing use of imported inputs such as insecticides and fertilizer is justified for both economic and ecological reasons, and reflects the design philosophy of the system as an evolution of traditional and modern systems. Banana production is also evident in photo 3.22, banana trees are not watered directly, but are usually located in the middle or at the tail-end of tertiary canals to capture what would be otherwise lost as run-off.

Fig. 3.22 Sebikotane: Pesticide Application

Fig. 3.23 Sebikotane: Mature Vegetative Cover

Fig. 3.24 Sebikotane: Degraded Natural Milieu

Fig. 3.23 also show the integration of banana trees as tail-enders. The photograph in Fig. 3.24 was taken at exactly the same time as Fig. 3.23 but across the road from the farm. The glaring contrast depicts the harsh and degraded current environmental milieu. This region used to be thickly wooded. The contrast also reveals how much can be achieved in environment re-creation in only two years with simple irrigation technology and labour.

A discussion with Mr. Khassim N'Dour, the manager of the Groupement d'Interet Economique, (GIE) at Sebikotane, the labour collective which profits from the farm's production, revealed some insight into Sebikotane's operation. Mr. N'Dour attributed increased production in the current year to wind-break maturation as well as the continued extension from SYSPRO, and subsequent improved labour performance. He estimated composting costs (labour) to be about 25% of fertilizer costs. In his view the composting system performed excellently although the system is still in its infancy. He felt however that fertilizer applications were still an important link in the system, but that financial constraints limit application to half of what he considered optimal levels. Mr. N'Dour cited lack of short-term credit as the greatest single impediment to achieving optimal production levels. Overall Mr. N'Dour considers the farm viable. His ongoing involvement testifies to that fact. Mr. N'Dour provided the capital for infrastructure investment. SYSPRO's involvement is limited to technical and occasional credit extension.

3.4.4 SYSPRO Activities in the Senegal River Region: The Significance of Social Organization in Assuring Sustainability

The Dekh Gui Project

ENDA SYSPRO has also embarked on third generation irrigated agriculture projects in the Senegal River Delta and Valley regions. At Dekh Gui, in the Delta a Groupement d'Interet Economique (GIE) manages a SYSPRO farm on land abandoned two years ago after rice cultivation had left it too salinized for further production.

The GIE social organization is an important link in SYSPRO's development philosophy that seeks social as well as environmental rehabilitation. Seck, M. et al [1992c] describe a rupture in traditional social systems in Senegal, stemming largely from the drought and the ensuing rural exodus. The swollen ranks of the urban unemployed create severe social and economic problems. The crisis also however brings opportunity and invites innovation. The break with traditional village-based social systems, wherein village elders dominated local political life, allows considerable latitude in innovative rural development schemes.

As at Sebikotane, SYSPRO extends technical and some credit support to the GIE at Dekh Gui. Applying the SYSPRO farming system over the last two years has succeeded in rehabilitating the salinized soil, largely through the application of composting methods to improve soil macro-porosity, improve drainage and flushing of the salts. Figs. 3.25 and 3.26 illustrate the mixed cropping system employed at Dekh Gui. The white soil residue evident in photo 3.26 depicts the residual soil salinization with which the GIE must contend. Recently the Dekh Gui GIE succeeded in growing beans, a particularly salt sensitive crop.

Fig. 3.25 Dekh Gui: SYSPRO System in the Senegal River Valley

Fig. 3.26 Dekh Gui: SYSPRO System on Salinized Land from Rice Cultivation

The successes of SYSPRO projects at Sebikotane and Dekh Gui should be measured equally in technical and social terms. The projects show that irrigated agro-ecosystems can catalyze environmental rehabilitation, providing gainful employment while maintaining at least marginal economic viability. They succeed however completely outside traditional rural social organization. The participants are in no way constricted by existing village political structures and their motivation is solely out of self-interest.

The relative success of both the Perimetres Irriguees Villageois and the Groupements D'Interet Economique reflect different but parallel development approaches. PIVs succeed when irrigation design and management respect that traditional village political systems must be upheld. This may mean the design engineer will have to bite the bullet and accept that a seemingly sub-optimal canal lay-out, understanding that group cohesion will make up for the technical inadequacies. The GIEs succeed meanwhile, because their projects have the freedom to innovate completely outside traditional rural political systems. The participants are usually one generation removed from village life and have chosen to return to the country for their own economic interest. The similarity between the PIVs and the GIEs is that in both cases **the model of development is their own**. The high levels of worker alienation and resulting poor productivity experienced on the large and intermediate rice projects serve as a reminder of the danger of not adopting that paradigm of development. The experiences at Thiabsabelle, another SYSPRO project in river valley, also bear out the significance of project social organization in assuring project sustainability in a different context.

The Thiabsabelle Project

In the fall of 1989 Mauritania and Senegal engaged in armed hostilities because of a border conflict sparked by land tenure disputes and ethnic tensions, and linked to the right of access to the water resources of the Senegal River. The war created 60 000 Mauritanian refugees in Senegal, mostly of Toucoleur ethnic origin. The United Nations High Commission for Refugees (UNHCR) is charged with the care of these refugees until their status is resolved between Senegal and Mauritania at the diplomatic level. The UNHCR offers food aid and provides education services for the children. The UNHCR wishes however to lessen the refugees' dependence on them for food aid, given the present world refugee situation and the constraints on the financial resources of the United Nations. The UNHCR thus encourages all attempts to improve the refugees' food self-sufficiency through agricultural project innovations. A European non-governmental organization responded by offering financial assistance for a mixed-crop agricultural development project at the Thiabsabelle refugee camp in the middle reach of the river valley near the town of N'dioume (approximately halfway between Matam and Dagana). ENDA-SYSPRO agreed to provide the technical extension for the project.

Thiabsabelle is in a remote location on one of many large islands in the middle of the river, that characterize the braided river morphology between Matam and Dagana. The photograph in Fig. 3.27 illustrates the small ferry that one must take to reach the camp. The natural environment in the vicinity of the camp is severely degraded due to deforestation. The photograph in Fig. 3.28 was taken on the trail between the ferry and the camp. Fig. 3.29 illustrates the pirogue one must take to cross another of the many river braids to get from the camp to the island where the field project is located.

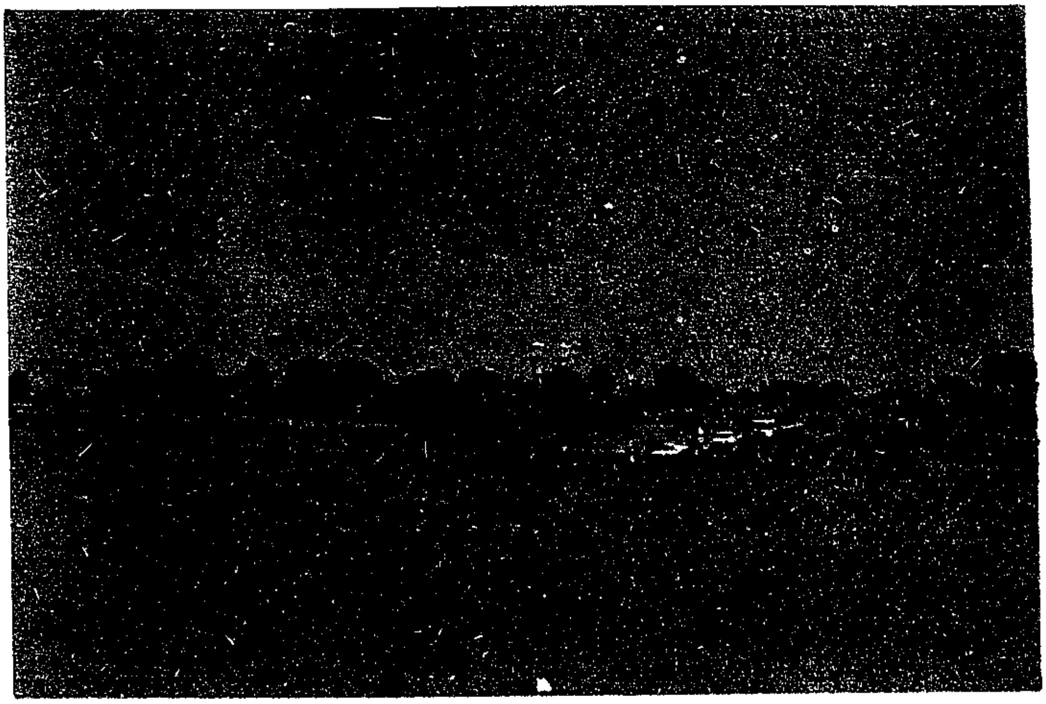


Fig. 3.27 Middle Valley Region: Road Access to SYSPRO/Thiabsabelle Camp

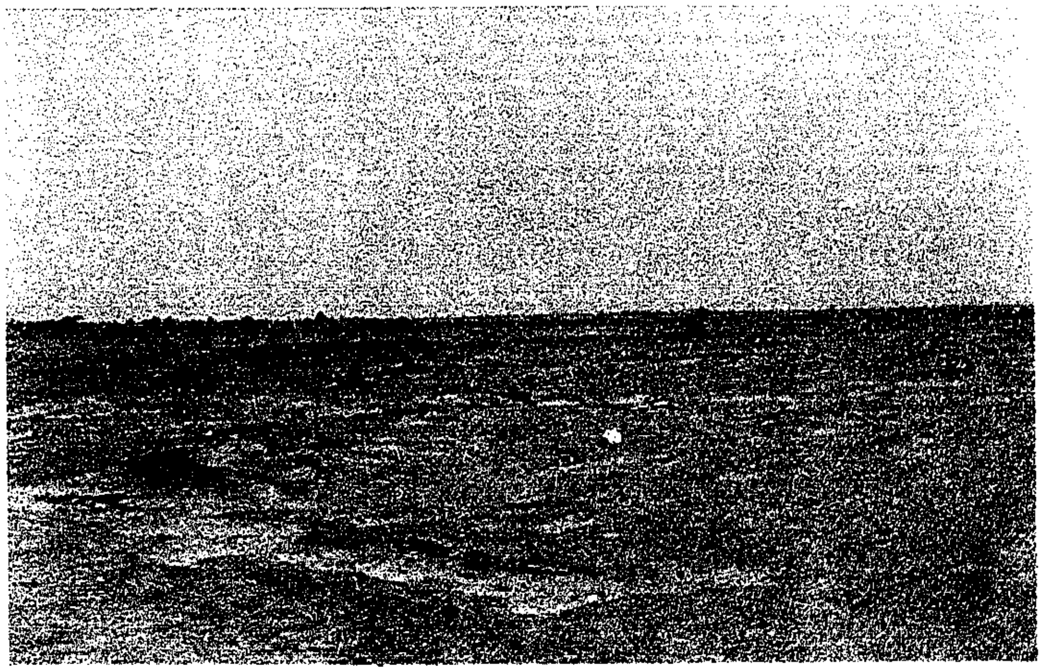


Fig. 3.28 Middle Valley Region: Massive Deforestation near Thiabsabelle

Fig. 3.29 Thiabsabelle: Pirogue Crossing to Field Project

Financing of the Thiabsabelle project was on condition that the project must be oriented to the women in the camp. Women were intended to provide labour, management and be the principal beneficiaries of the project. The decision to establish this form of social organization was made without apparent regard, or without knowledge of the fact that in traditional Toucoleur society women hold no right to land tenure [M'baye, 1966]. The project organization alienated the men to the extent that almost all of them abandoned the camp. Group photos 3.30 and 3.31 reflect the fact that only women and children remained.

Fig. 3.30 Thiabsabelle: Group Photo of Female Labour Pool

Fig 3.31 Thiabsabelle: Group Photo of Children

The flight of the adult males from the camp had a demoralizing effect on the women with a subsequent crippling effect on the project. The photographs in fig. 3.32 and 3.33 reveal the poor performance experienced on some plots. The shelter-belt had not been established and many plots suffered severe water stress.

Fig. 3.32 **Thiabsabelle: Water Stressed Crops**

The generally weak performance of the system can be attributed to several factors:

- -establishing irrigated vegetative cover on what is essentially open desert is an extremely difficult and labour intensive practice under the best circumstances.
- -the pump (shown, with technician in fig. 3.34) had broken down for a short period of time.
- -the low level of labour mobilization given the demoralized state of the camp.

Fig. 3.33 Thiabsabelle: Water Stressed Crops

The pump failure, cited by the women as the primary reason for the poor performance, need not have been that crippling. The potential labour pool of over 200 women, the availability of hand sprinklers in adequate numbers and the small size of the project (2 hectares) could have saved most of the crop, if labour mobilization had been adequate.

Fig. 3.34 Thiabsabelle: Technician with Motor-pump

Hand irrigation in this environment is extremely hard labour and only very strong group solidarity and high morale could assure the level of labour mobilization that would have been needed. Less than 10% of the women in the Camp were actively involved in the project during the duration of the visit. The disruption of traditional social structures resulted in a leadership vacuum. A "tragedy of the commons" effect took place, in that in the absence of effective leadership and clearly defined responsibilities, the women assumed that someone else would do the work.

Despite the poor labour mobilization at Thiapsabelle, there were unmistakably encouraging signs. The women who did take part chose to focus their labour on several sub-plots which they could tend given their small numbers. This is a rational response to a crisis situation. On these plots the women did manage to produce a significant amount of biomass as illustrated for example in the photo in Fig. 3.28. This small success is heartening, even under these difficult circumstances, group solidarity and simple technology can take back a small bit of the desert.

Fig. 3.35 Thiabsabelle: Successful Bio-mass Production

3.4.5 SYSPRO Crop-Water Consumption Study:

The integration of SYSPRO style agro-forestry as a sustainable agriculture development option in the SRB is a central feature in developing the model for the sustainable development of the Senegal River Basin. The precedents at Dekh Gui and Thiapsabelle reveal that the SYSPRO system is a viable form of agriculture and environmental rehabilitation in the river valley, though undeniably labour intensive. The global modelling study of the SRB focuses on the core hydrological issue of water resources availability versus the demand, as water remains the fundamental binding constraint on development. To quantify the impacts that the large-scale application of the SYSPRO system would have on the hydrological budget of the SRB, some estimate of the water demand exerted by the SYSPRO system is required. Research on irrigation crop water requirements has focused, for all intents and purposes, on mono-cultures. The water demand is assumed a function of the crop type and the open-field evapo-transpiration potential [Doorenbos and Pruitt, 1977]. There is no accounting for the positive ecological benefits of shelter-belt development and crop associations, such as local evapo-transpiration potential reduction and improved soil structure possible with SYSPRO style irrigation.

Because of the unique existence of production and water consumption records at Sebikotane, this project was thus selected as a case study for an independent investigation of the representative crop water requirements of integrated agro-forestry systems.

Sebikotane maintains records of the hectarage of various crops under cultivation by tracking the relative percentage of each inter-cropped species on each sub-block. Water consumption records are also exact at Sebikotane, though they are coarse temporally.

The water records are in the form of invoices as Sebikotane sources water from the municipal network. Production records are however approximate since much output is sold directly, or transformed artisinally for improved value-added production and sold to the informal sector outside formal records. Where adequate records existed, Sebikotane production compared favourably with national averages: figure 3.36 shows Sebikotane and national average yields compared for several crops.

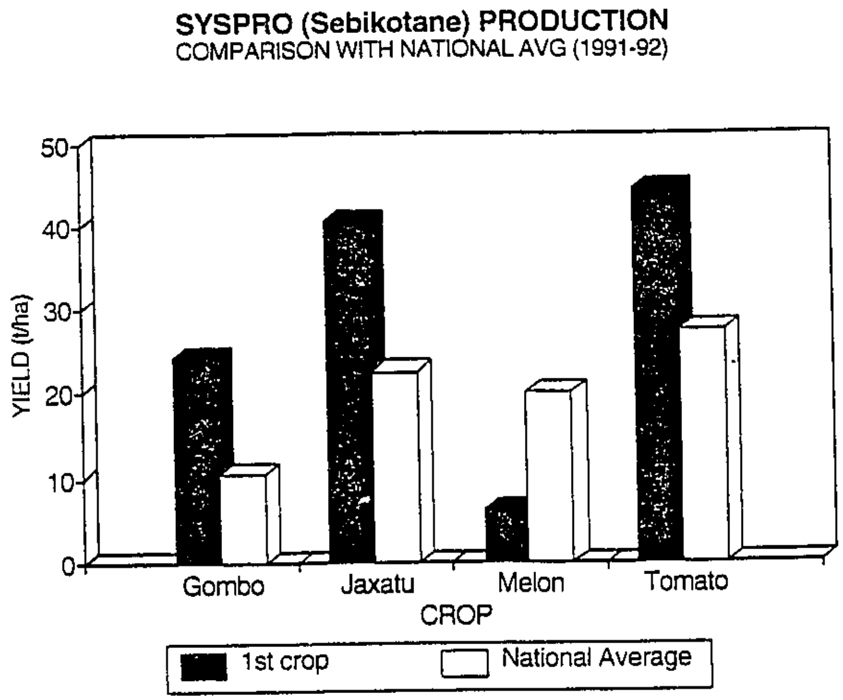


Fig. 3.36 **Comparison of Yields: Sebikotane and National Averages**

The exact field occupation records and total water consumption data available allowed estimates of aggregate crop water utilization rates. Figure 3.37 illustrates the variability of crop-water consumption with field intensity (defined as the percentage of available field area actually cultivated). Labour constraints frequently forced less than full field occupation intensities. The data shown are taken from the period outside the rainy season, when the soil moisture content without irrigation is effectively zero. Crop evapo-transpiration occurs almost completely during the daytime when plant stomata are open. The daytime temperature and relative humidity (evapo-transpiration co-factors) vary only moderately during the dry season, thus the significance of the external climate factor in the above data is slight. The effect of crop development stage is also slight since the data are aggregated over all 28 sub-blocks, each of which has a different planting date.

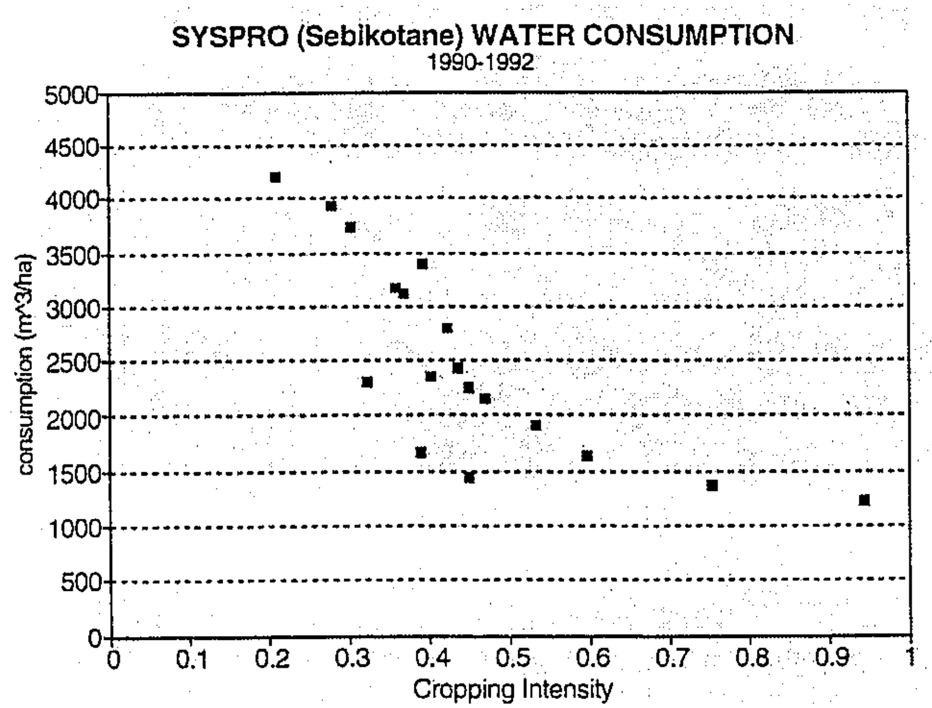


Fig. 3.37 Sebikotane: Water Consumption vs. Field Intensity

The high crop-water consumption occurring at low field intensity is largely due to low irrigation field application efficiency. The irrigation distribution system, designed for the entire plot is not efficient when only a small part of the plot is actually cultivated. Much delivered water ends up outside the root zone of the target plant. The low consumption achieved at high field intensity is apparently due to decreased insolation through synergistic crop associations. High field intensity is strongly correlated with more crops in association. Direct comparisons are difficult because the spatial and temporal resolution of the available data do not permit separating out the consumption of individual crops in association, however the aggregated consumption rates achieved at high intensity are lower and with a different within year pattern than published values for mixed vegetables.

Fig. 3.38 shows the comparison of SYSPRO (Sebikotane) and published values for mixed vegetable systems in Senegal. Note that the annual consumption pattern of the SYSPRO system reflects its year-round production capacity.

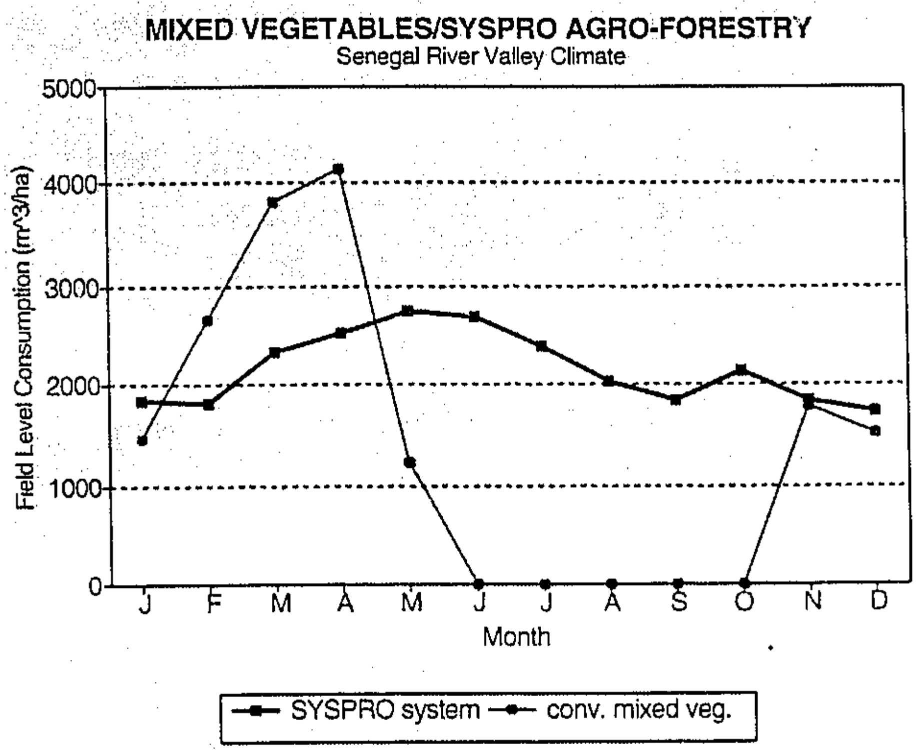


Fig. 3.38 Comparison of Water Demands: Syspro System/Conventional Mixed Vegetables

The inclusion of the data from the Sebikotane is a central element of an alternative agriculture development policy. Quantifying the basin-wide water resources impact of two different agriculture development policies, one of which features the SYSPRO system is the focus of the next section.

3.5 Demand Management through Irrigation Development Policy Choice

This section is dedicated to developing the quantitative framework for a comparative analysis of irrigation water demands. This portion of the study corresponds with element **B. Demands** in the general SRB Analytical Framework as described in the Introduction and depicted in Fig. 1.7.

As has been argued in Chapter 2, the availability of water resources places the fundamental constraint on irrigation development in the SRB. Irrigation development in the SRB should therefore optimize the allocation of the scarce resource. This statement begs the question of optimization according to which criteria. For government policy makers, this entails bringing as much rice into production as possible. However, alternative development policy aimed at providing social and ecological sustainability would have the joint objectives of providing for the food self-sufficiency for the existing villages in the SRB as well as promoting the ecological rehabilitation of the valley by promoting irrigated agro-forestry.

The two alternative development philosophies also distinguish two characteristic demand patterns for water because of the different crop mix they entail. Government policy emphasizes rice production (policy **RP**) for primarily urban consumption, while a sustainable development/natural resources management policy emphasizes cereal grain production for local consumption and mixed vegetable production with associated agro-forestry (policy **NRM**). Policy RP implies highly centralized management since farmers will not of their own volition produce large, marketable quantities of rice. Policy NRM implies de-centralized management using traditional village socio-political structures and innovative management structures such as ENDA-Syspro's GIE model. The crop-water consumption data from the field study at Sebikotane reported in sub-section 3.4.5 were integrated into the quantitative analysis which follows. The inclusion of the SYSPRO's agro-forestry development model with its inherent environmental rehabilitation aspects is a key element of policy NRM.

3.5.1 Quantifying Crop Water Consumption

The following factors affect irrigation water demands in the four major irrigation zones of the SRB.

i. The areal distribution of irrigable land in each zone according to the three major soil groups
ii. The crop mix according to zone and soil type, (a policy choice)
iii. The water requirements of each crop
iv. The irrigation efficiency as a function of crop type and soil type.

3.5.2 Distribution of Irrigable Land

Table 3.5 gives the distribution of irrigable land in each major irrigation zone in the SRB according to soil type.

Table 3.5 Distribution of Irrigable Land in the Senegal River Basin [hectares]

	Delta	Lower Valley	Middle Valley	Upper Valley
Fonde	2 680	60 686	51 576	7 118
Faux Hollalde	15 211	70 668	29 952	3 524
Hollalde	21 582	59 027	50 832	3 587
Totals	39 473	190 381	132 360	14 229
Total All Regions			376 443	

[source: FAO, 1977]

3.5.3 Crop Mix

POLICY RP:

The assumed crop mix for development policy RP is adapted from Gibb [1986b] and is consistent with OMVS planning policy. It is shown in fig. 3.39.

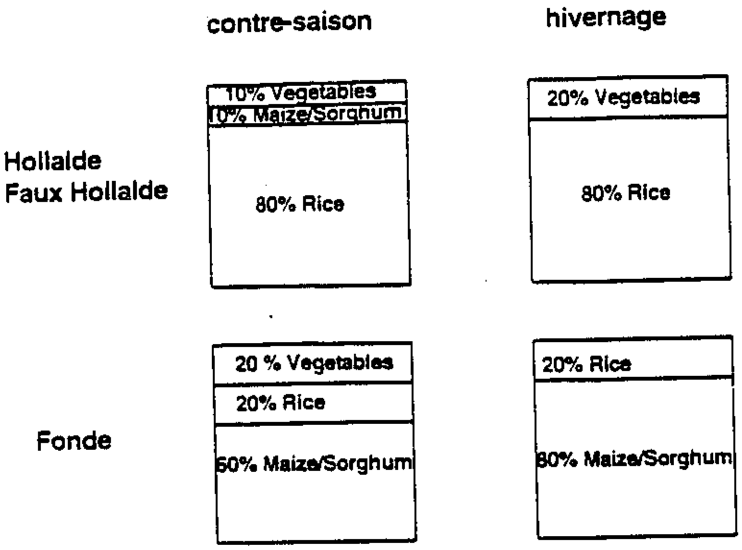
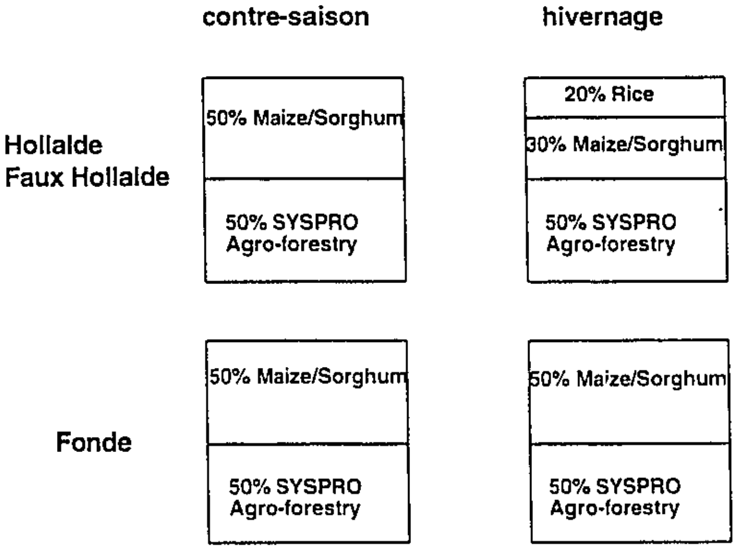


Fig. 3.39 **Rice Production Policy: Crop Mix**

The centralized management structure associated with rice production dominates this scenario, although the cereal grain production on the fonde soil is characteristic of PIV development.

POLICY NRM:

Policy NRM reflects sustainable development objectives and natural resources management and is represented by the crop choice shown in Fig. 3.40.



	contre-saison	hivernage
Hollalde Faux Hollalde	50% Maize/Sorghum 50% SYSPRO Agro-forestry	20% Rice 30% Maize/Sorghum 50% SYSPRO Agro-forestry
Fonde	50% Maize/Sorghum 50% SYSPRO Agro-forestry	50% Maize/Sorghum 50% SYSPRO Agro-forestry

Fig. 3.40 Natural Resources Management Policy: Crop Mix

Note that 50% of all irrigated land is dedicated to SYSPRO style integrated agro-forestry, with the other 50% dedicated to a crop mix typical of PIV management and farmer's preference. There is much less rice production for this policy with no rice grown at all on the fonde soil.

3.5.4 Crop Water Requirements

The crop water consumption values retained for the study are given in Table 3.6. Gibb [1986b] reports the crop-water consumption for the conventional mixed vegetable system. WARDA [1985] (the Wageningen study) reports the maize/sorghum consumption based on their experience on fourteen PIVs over eight years. SAED [1985] reports water consumption characteristics for seven field projects in the SRB. The rice consumption values retained from the SAED [1985] report for the modelling study were selected in consultation with ENDA agronomists on the basis of which best represented recent experience of working valley conditions under typical management [Seck, M., and Seck, T., 1993].

The consumption values for the SYSPRO system are based on the Sebikotane field study described earlier. Sebikotane consumption had to be adjusted for the hotter and more arid conditions of the river valley. This was accomplished by using metereologic data to compare estimates of potential crop evapo-transpiration and effective precipitation in the Sebikotane (Cap Vert region) and the river valley. The Blaney-Criddle method for the calculation the potential evapo-transpiration was applied as given in Doorenbos and Pruitt [1977].

With the exception of rice and the SYSPRO system, all the consumption figures reflect water consumption at the plant. Rice and SYSPRO values are for the crop water requirements at the top of the field, so application efficiencies are already accounted for.

Table 3.6 Representative Irrigation Water Requirements in the Senegal River Valley

[units: m^3/ha]

	rice*	maize/ sorghum+	mixed vegetable+	Syspro System*
jan	2400	1100	893	1844
feb	3420	1380	1596	1836
mar	4370	1650	2294	2337
apr	4750	800	2490	2518
may			744	2735
june				2684
july		1380		2396
aug	1810	2580		2047
sept	5210	2140		1847
oct	6060	200		2141
nov	2350		1080	1844
dec		570	919	1734

*Irrigation water requirements calculated at field outlet level
+Irrigation water requirements calculated at plant level

Note: the terms, "contre-saison" and "hivernage" are used to distinguish between the dry season and the wet season. For the purposes of this study the "contre-saison" corresponds to the first cropping cycle (January to July) while the hivernage is the wet season (hivernage) cropping cycle is from July/August to November/December. As can be seen in Table 3.6, rice exerts a strong contre-saison water demand, which represents a key water resources management problem given the natural hydrology of the Senegal River.

3.5.5 Irrigation Efficiency

To establish the net irrigation water demands on the water resources of the Senegal River, irrigation distribution and application efficiency factors must be applied. The efficiency factors account for losses in the water supply network in bringing water from the source to the field, and for losses in bringing water from the field to the root zone of the plant. Irrigation efficiencies have been notoriously over-estimated by planners who wish to make irrigation projects appear as economically attractive as possible. Conscious of this bias, where possible, field data from working projects in the SRB were used to establish crop water calculations. Irrigation efficiency factors are defined formally as follows:

i. Distribution Efficiency:

$$e_d = \frac{V_f}{V_p} \tag{3.1}$$

where:

V_f = The volume of water reaching the field outlet
V_p = The volume of water pumped into the distribution system from the river

The distribution efficiency accounts for seepage and evaporation losses in the canal network. Distribution efficiency is largely a function of soil type (the permeability determines seepage losses), and level of management as poor canal, intake and diversion structure maintenance can cause a severe drop in efficiency.

The distribution efficiency factors retained for crop water requirement calculations are given in Table 3.7

Table 3.7 Irrigation Distribution Efficiency (percentage)

SOIL TYPE

CROP	HOLLALDE	FAUX HOLLALDE	FONDE
rice	60	60	60
maize/sorghum	93	85	77
mixed vegetables/ Syspro system	93	85	77

The 60% rice distribution efficiency is a credible conservative estimate given in Gibb [1986b]. KULeuven [1991] reports on a special case of distribution efficiencies in excess of 80% being achieved on an IT rice project under very strict management. Gibb's value accurately reflects the efficiency achievable under typically poor levels of management and maintenance.

The values for the maize/sorghum and mixed vegetables/SYSPRO system are taken from Huibers et al. [1988] (the Wageningen study) who report the average distribution efficiency from their lengthy field study of 14 PIVs. Efficiencies are highest on the Hollalde soils because of the higher clay content and decreased permeability. The PIV application efficiencies are associated with cereal grain and mixed vegetable production because this is the typical management structure that grows these crops. In the absence of any other data the Wageningen data were also retained for the SYSPRO cropping system, since the scale of operations and level of technology are similar.

ii. Application Efficiency:

The application efficiency is defined as:

$$e_a = \frac{V_r}{V_f} \tag{3.2}$$

where:

V_r is volume entering root zone of the crop available for evapo-transpiration.

Application efficiency accounts for losses due to deep percolation and run-off. It is largely a function of method of application and to a lesser extent the soil type. The application efficiency values retained for analysis are given in Table 3.8 .

Table 3.8 Irrigation Application Efficiency (percentage)

CROP	Hollalde	Faux Hollalde	Fonde
rice	100	100	100
maize/sorghum	60	60	60
mixed vegetables	50	50	50
Syspro system	100	100	100

In reality the application efficiencies for the rice and SYSPRO system are of course not 100%. However, because the calculation method of irrigation water requirements (table 3.6) for these cropping systems integrates the losses between the outlet to the field and evapotranspiration by the crop (the field level consumption), the 100% values are listed here for consistency with the general formulation of the total water requirement methodology. Contrary to the general assumption that flow irrigation (the most common irrigation method in the SRB) is more efficient on heavier soils, Bos and Nugteren [1978] have shown that e_a is not highly dependant on soil type and actually improves slightly on lighter soil. If furrow lengths are not too long, improved soil permeability dominates over deep percolation losses and is preferable to the runoff losses associated with heavier soils.

Bos and Nugteren show that e_a varies from 50% to 56%. Gibb [1986a] however report the *net* efficiency (the product of application and distribution efficiencies) for maize/sorghum and mixed vegetables as 50% and 60% respectively. This is likely an over-estimate. Diemer and Huibers [1991] for example reports that actual PIV water requirements were systematically in error by about 20% in excess of SAED design standards. To more realistically capture field conditions, the net efficiency values given by Gibb were assumed to be the appropriate application efficiencies.

3.5.6 Crop Water Requirements Calculation Methodology

The net crop water requirements in each major irrigation development zone and in each month were calculated in the several steps. The indexing system is defined as follows:
i is indexed from 1 to 3 over soil types: Hollalde, Faux Hollalde, and Fonde.
j is indexed from 1 to 4 over crops: rice, maize/sorghum, mixed vegetables, SYSPRO system.
k is indexed from 1 to 4 over the major irrigation zones: Upper Valley, Middle Valley, Lower Valley and Delta.

1. Net Hectares Cultivated by Crop and Soil Type

The net hectares cultivated of crop j on soil i in region k, A_{ijk} is given by:

$$A_{ijk}=DF*p_{ijk}*h_{ik} \tag{3.3}$$

where:

DF is the basin-wide development factor, the percentage of the total potential area, 376 000 ha [FAO, 1977], that is developed.
p_{ijk} is the percentage of developed hectares of soil i in region k cultivated with crop j.
h_{ik} is the potential hectares of soil i in region k.

Note the simplifying assumptions:

i. DF is held constant over all regions, a development factor of 50% thus means that half of the potentially irrigable land is developed in each region for a total of 50%*376 000 ha=188 000 ha.

ii. that p_{ijk} is constant for all k, the crop mix does not vary with soil type across regions. The net crop mix however varies between regions according to the relative occurrence of the various soil types. Note also during the dry season ("contre-saison" - generally from January to July) the net cultivated area is further reduced by the contre-saison intensity factor, IF, such that

$$A_{ijk}=DF*IF*h_{ik}*p_{ijk} \tag{3.4}$$

OMVS development objectives state a goal of an 80% IF factor, meaning 80% of the area cultivated in the wet season remains in production for a second irrigation cycle in the dry season. Seck, S. [1991] however reports that an IF factor of 50% is rarely (if ever) achieved.

2. Net Effective Consuming Area

Crop consumption values are given as net evapo-transpiration requirements from the root zone of the plant. It is therefore necessary to scale the net hectares cultivated of each crop on each soil type by the relevant efficiency factors in delivering water to the root zone which varies with crop and soil type, hence:

$$N_{jk}=\sum_{i} E_{ij}*A_{ijk} \tag{3.5}$$

where:

N_{kj} is the net consuming area of crop j in region k (ha) and
E_{ij} is the consumption efficiency factor for crop j on soil i simply defined as the reciprocal of the net efficiency:
where:

$$E_{ij}=\frac{1}{e_{net_{ij}}} \tag{3.6}$$

$$e_{net_{ij}}=e_{d_{ij}}*e_{a_{ij}}+r \tag{3.7}$$

for all i and j. The e_d and e_a are the distribution and application efficiencies defined in Section 3.5.4. To estimate the net volume abstracted for irrigation, the percentage return flow to the river, r must also be estimated. This volume is the sum of surface runoff and percolation losses which flow back to the river and are not lost to evaporation or deep percolation. Gibb [1986b] assumes a value of 5% for all crop and soil types. In the absence of any other data on the subject, this value was retained.

3. Regional Demand Calculation

For water resources simulation and optimization study, the net water demand in each region and period is needed. The demand value is determined by summing over all crop types in each region:

$$Dem_{kt}=\sum_{j} N_{jk}*C_{jt} \tag{3.8}$$

where:

Dem_{kt} is the net irrigation water demand exerted in region k in period t (m^3), and
C_{jt} is the monthly crop water requirement (m^3/ha) as given in 3.5.3

* * *

The above methodology was used to generate demand scenarios for input into simulation and optimization study. Alternative demand scenarios were generated according to development policy RP or NRM, and the total hectares cultivated. Figure 3.41 shows a comparison of policy RP demands at 100 000 ha as calculated according to the methodology given above and as given in Gibb [1986a].

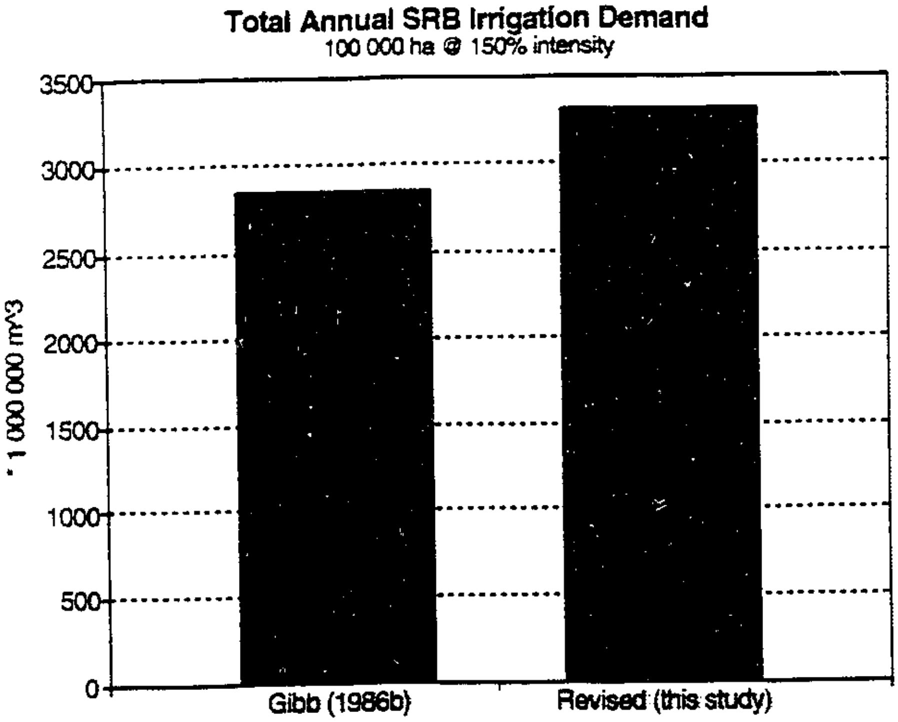


Fig. 3.41 Total Water Demand: Rice Cultivation at 100 000 ha

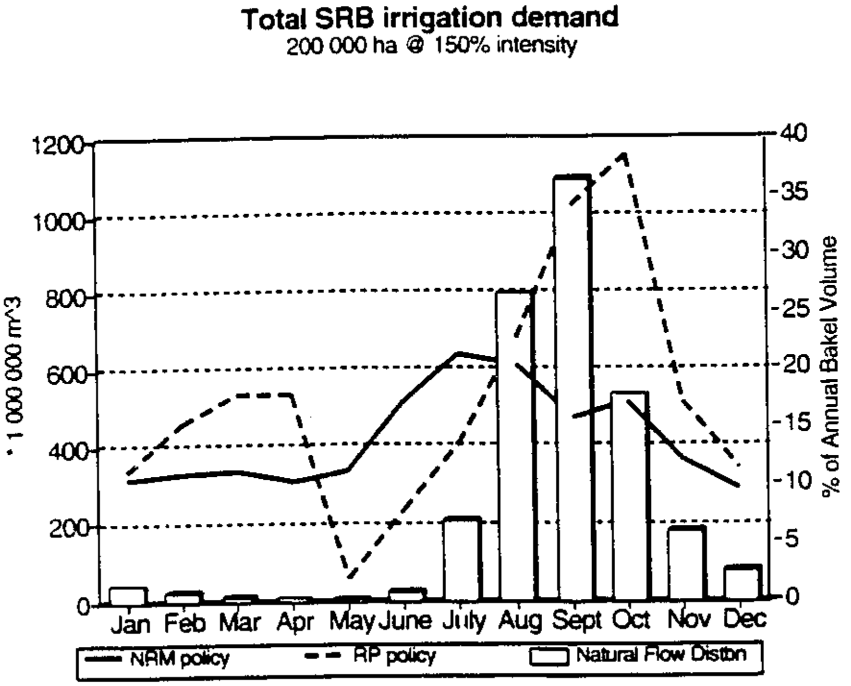


Fig. 3.42 Comparison of Total Crop Water Consumption: Policy RP vs. NRM

Fig. 3.42 Comparison of Total Crop Water Consumption: Policy RP vs. NRM

The higher values calculated according to the revised methodology can be accounted for primarily through the use of slightly higher consumption data than that used by Gibb Fig. 3.42 shows a comparison of basin wide demands at 200 000 ha and contre-saison intensity of 50% for policy RP and NRM, super-imposed on the natural within year distribution of Senegal River flows at Bakel.

As Fig. 3.42 reveals, the analysis thus far reveals the lower over-all water demand for the NRM policy. The NRM demand profile is considerably less peaked than the RP profile due primarily to the year-round production characteristics of the SYSPRO agro-forestry system. The lower over-all demand for Policy NRM is not a particularly surprising result, rice cultivation in an arid environment with over two meters of evaporation per year exerts enormous water demands. However in some sense, Policy RP is a more efficient demand profile as its demand peak more closely matches the natural flow distribution of the river. Although Policy NRM demands are substantially less, the year-round production of the SYSPRO system will require river regulation (it will draw on reservoir storage) for a longer duration. Rehabilitative environmental effects are directly linked to the development and maturation of the SYSPRO eco-system, thus maintaining the year-round productive capacity of the SYSPRO system is an essential water resources management objective.

The task of quantifying the extent of the water resources management advantages, and the impact it could have on the global SRB development program, particularly under continued drought conditions, is the subject of the next chapter, **Simulation Modelling of the Senegal River.**

CHAPTER 4

SIMULATION MODELLING OF THE SENEGAL RIVER

Chapter 4 corresponds to element C of the SRB analytical framework described in Section 1.7.1 and depicted in Fig. 1.7. At this point in the analysis a simulation model of the Senegal River is constructed to quantify the system impacts of the demand patterns given by policy RP and policy NRM.

4.1 Introduction to Water Resources Systems Simulation

The development and management of regulated water resource systems is the complex task of allocating water in time and space and attempting to balance the objectives of many complimentary and competing water uses. The various uses of water resource systems include hydro-power generation, irrigation, municipal consumption, eco-system maintenance, waste dilution and maintenance of navigable passage.

The management of a river system can readily be optimized according to the objectives of one water use, but it does so generally at the expense of other uses. Although multi-objective optimization methods have been applied to water resource systems management [Simonovic, 1989], [Duckstein and Opricovic, 1980], these methods require some subjective statement regarding the relative importance of objectives. Disregard for any of the multitude of impacts of a particular water resources development and management policy can have serious consequences and may be expensive or impossible to redress once policy and infrastructure development are finalized. Computer simulation of water resources systems is often applied as it offers a means of developing a better *a priori* understanding of the variety of impacts any particular water management strategy will have.

Computer simulation of water resources systems involves the application of physically based mathematical relationships to model the flow of water in the system. Analog (continuous time) simulation exists, however most models simulate system behaviour in discrete time steps. Discrete time simulation is generally appropriate for large-scale systems since the hydrologic data are generally measured at discrete time intervals. The fundamental governing equation for numerical models of water resources systems is the simple mass balance equation. Mass balance is applied to reservoir storage for continuity in time and to downstream flow propagation for continuity in space. More complex physical modelling is required when the time step of the simulation is shorter than the propagation time of water through the system, as in the case of flood routing. River routing algorithms with an implicit description of the hydraulic properties of the river channel are appropriate in these cases.

Simulation modelling of water resources systems was used as early as 1953 by the U.S. Army Corps of Engineers [Hall and Dracup, 1970]. Hufschmidt and Fiering [1966] first utilized synthetic streamflow data in water resources simulation study. The use of synthetic data allows the evaluation of system performance for hydrologic regimes other than the sole historic time series.

While water resources simulation models have achieved a high level of technical sophistication in recent years, their practical application is hindered by the information gap between the systems analysts and the decision makers. The decision making process in water resources development and management issues (at best a complex balance between technical and socio-political issues) is complicated in the case of international river basins where decision making authority rests with multiple agencies, often with competing agendas. Trans-national river basins comprise approximately half of the earth's land mass and are populated by more than 50% of the world's population. [Vlachos, 1986].

In 1986, the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria initiated a project entitled, "Decision Support Systems for Managing Large International Rivers". The project was motivated by, "the recognition that problems of water management and environmental protection, especially involving trans boundary issues and disputes, are as much in need of improved institutions and processes as improved scientific understanding" [Salewicz, 1991]. Specifically the objectives of the project were to develop tools to assist the decision making process in water resource management through the development and use of interactive graphically based computer simulation software for water resources systems. The software package, known as *An Interactive River Simulation Program* or IRIS makes extensive use of interactive graphics intending to facilitate the transmission of policy impacts from the system analyst to the decision makers. The objective in developing and promoting the use of this product was to stimulate the "open-forum" exploration of management options amenable to all affected parties which would not necessarily emerge from pure optimization study.

Salewicz [1991] reports on the application of the IRIS methodology to two transnational river systems, the Danube in Europe, and the Zambezi in Africa. Salewicz states that the political volatility and the tendency for each state to act in its own interest can impede such study, "since the political implications of the expected results can be unacceptable to decision makers." Salewicz concludes that the independent "hydrologic knowledge is therefore absolutely necessary to separate objective facts and problems from their political context." The convergence of several factors made the SRB study an appropriate and potentially fascinating application of simulation modelling using IRIS; the trans-national nature of the SRB, the availability of independent high quality hydrologic data from 1904 through the French research agency ORSTOM, and the impact that assumptions regarding the system hydrology should have on river basin development policy.

4.2 An Interactive River Simulation Program (IRIS): A Brief Introduction

IRIS, the software package developed at IIASA was applied to the SRB. IRIS is a graphical user interface (GUI) driven computer program for water resources systems simulation. IRIS operates under MS-DOS in the PC environment. IRIS makes extensive use of its GUI for the system configuration data input and the output of system performance data.

IRIS simulates the spatial and temporal allocation of water in a river system. Its intended application is the interactive evaluation of water resource system performance for alternative system configurations (i.e. the size and location of reservoirs), management policy (i.e. reservoir operation and diversion allocations) and input hydrology (historic or synthetic). System performance refers to the system's ability to meet demand targets for irrigation, municipal consumption and hydropower generation.

4.2.1 IRIS Modelling Inputs

Inputs to the IRIS simulation program are as follows:

i. Schematic representation of the system.
ii. Hydrologic data; gauge locations, evaporation and seepage loss functions
iii. Reservoir and hydro-electricity production parameters
iii. Reservoir operation rules and diversion allocation functions
iv. Historic or synthetic streamflow sequences

The following sub-sections discuss the above elements in more detail.

4.2.2 Schematic Representation of the System

The input of the system configuration in IRIS is accomplished by defining a series of inter-connected nodes and links. The links are uni-directional vectors which represent natural river reaches or diversion channels through which water flows from node to node. Nodes generally represent gauge locations, reservoir locations or diversion locations. If a node is defined as having none of the above functions, the volume of water delivered on the inflow link is identical to the volume on the outflow link. Hydro-power plants are located on links and can be either run-of-the river plants, or they can benefit from storage if they are located downstream of storage nodes. Fig. 4.1 gives an example of a system configuration in IRIS.

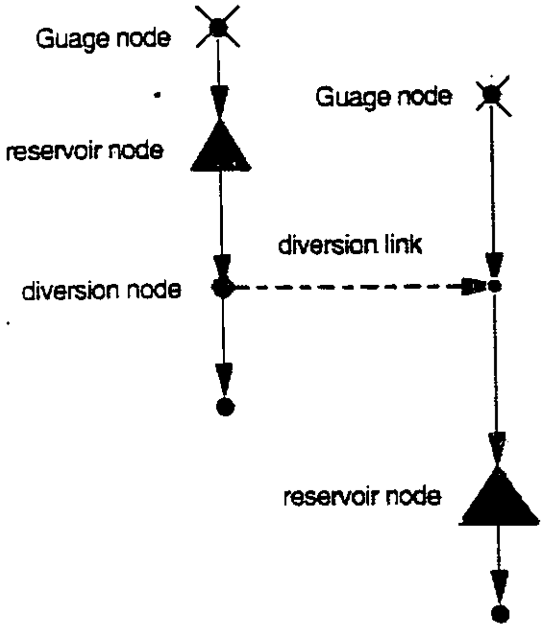


Fig. 4.1 IRIS System Configuration Example.

4.2.3 Hydrologic Data; Gauge Locations, Loss Functions and Flow Continuity

Every node defined in IRIS must be either a gauge location or be assigned a gauge flow multiple. A gauge location is a point in the system where an input file containing one or more replicates of a historic or synthetic streamflow time series is fed into the simulation. This time series represents what the natural (unregulated) flow volume would be at that point in the system. The unregulated flow must be estimated at every node in order to calculate the incremental natural inflow along the link (reach). If a node is not defined as a gauge location it must be assigned a gauge flow multiple, f. The gauge flow multiple assigns some multiple (less or greater than 1.0) of the unregulated flow at a gauge location upstream of the node. The natural incremental flow along a link which augments the regulated flow is the difference of the unregulated flow at the downstream and upstream nodes of the link. The incremental flow thus integrates the net effect of natural inflows less any losses for that reach of the river. If a node's gauge flow multiple of gauge location immediately upstream of it is less than 1.0 this implies that the evaporation and seepage losses dominate along the river reach and a loss function should be included. The flow modelling assumptions are defined as follows.

$$Q_b=Q_a+I_{ab} \tag{4.1}$$

where:

Q_a is the simulated flow at node a,
Q_b is the simulated flow at node b,
G_a is the unregulated (natural) guage flow at a,
G_b is the unregulated (natural) guage flow at b, and
I_{ab} is the incremental flow along river reach ab
such that:

$$I_{ab}=fG_a-G_b \tag{4.2}$$

This spatial mass balance concept of flow propagation is illustrated in Fig. 4.2.

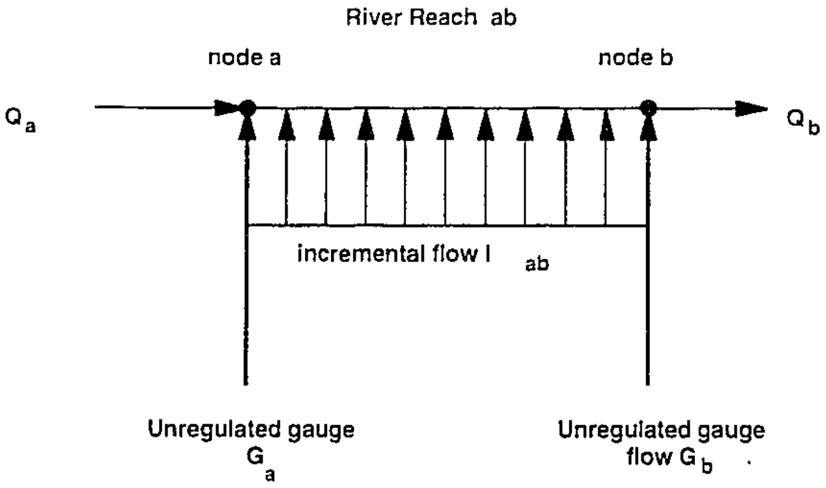


Fig. 4.2 Flow Propagation in IRIS

If the gauge flow multiple f is less than 1.0 or if node B is a gauge location and G_b-G_a is less than zero, IRIS calculates the incremental flow I_{ab} as zero. In this case a loss function of the form given in Fig. 4.3 should be included. The inflow at b is thus:

$$Q_b=(1-l_{ab})Q_a \tag{4.3}$$

where:

l_{ab} is the percentage volumetric flow loss of the natural regime along the river reach ab. The loss function need not be a linear relationship, simple regression on the natural regime hydrology proved adequate in the case of the SRB model.

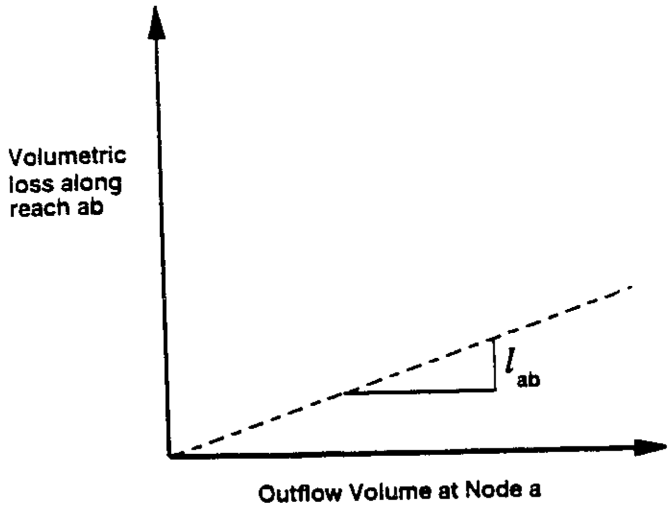


Fig. 4.3 Evaporation and Seepage Loss Function in IRIS

Simple mass balance equations for flow continuity adequately model flow propagation when the time step of the simulation is longer than the residence time of flow in the system. When this is not the case flow routing is required; several options for flow routing are available in IRIS. These features were not applicable to the Senegal River study. Gibb [1986b] has estimated the flow propagation time between Manantali and Diama as less than one month for all regulated and natural flow regimes. Since a one month time-step was used in the IRIS simulation of the Senegal River, no river routing options were employed. Discussions with ORSTOM hydrologists also confirmed the adequacy of this modelling assumption [Albergel and Bader, 1993].

4.2.4 Reservoir and Hydropower Characteristics

To simulate reservoir storage, IRIS requires the reservoir capacity, the reservoir volume-surface area relationship and the natural evaporation occurring at the reservoir surface in each time step of the simulation. IRIS calculates the reservoir storage based on a volumetric mass balance equation as follows.

$$s_t+i_t-r_t-L_t=s_{t+1} \tag{4.4}$$

where:

s_t is the initial storage in period t,
i_t is the reservoir inflow during period t,
r_t is the reservoir release during period t, and
L_t is the estimated evaporation loss occurring in period t, calculated as follows:

$$L_t=l_t(A(s_t)+A(s_{t+1}))/2 \tag{4.5}$$

where:

l_t is the natural evaporation occurring at the reservoir surface in period t (units: [length]),and,
$A(s_t)$ is the surface area-volume relationship at the reservoir (units: [length^2])

Equations 4.4 and 4.5 can thus be solved through iteration in each period.

IRIS simulates hydropower production on the basis of a generalized head-storage relationship defined for reservoirs upstream of hydro plants. The upstream storage is calculated according to equation 4.4. A constant head relationship can be defined for run-of-the river plants. The period average net head on the turbines is calculated as follows:

$$H_n=(H_t(s_t)+H_{t+1}(s_{t+1}))/2 \tag{4.6}$$

where:

$H_t(s_t)$ is the generalized head-storage relationship defined for the reservoir.

IRIS does not calculate head variations due to tailwater fluctuations which occur in real time operations. This approximation is generally valid except when the simulation time step is very short.

In general, hydro-power production is defined (in continuous time) by the following equation:

$$P=\rho QHe \tag{4.7}$$

where:

P is the power production (kilowatts),
ρ is the density of water (9.81 kN/m^3),
Q is the turbine flow (m^3/s),
H is the effective head on the turbine (m), and
e is the plant efficiency (generally .85 - .90)

Similarly IRIS calculates flow in discrete time according to the following equation:

$$E_t=H_n*r_t*Pf \tag{4.8}$$

where:

E_t is the energy production in Mega-Watt Hours (MWH)
H_n is the net head as calculated in equation 4.6
r_t is the average volumetric flow through the turbines in period t, and
Pf is plant factor, which is simply a scale factor that integrates water density, effeciency and the number of hours of power production in each simulation time step.

The maximum energy production in each period is constrained by the plant capacity which is required input data.

4.2.5 Rule Curves for Reservoir Operation

Reservoir releases are a fundamental system control which reflects policy preferences regarding various water uses. IRIS simulates reservoir operation through the use of rule curves. Kuiper [1965] describes the classical derivation of rule curves for reservoir operation. Loucks and Sigvaldason [1982] outline the use of reservoir rule curves of form similar to those used in IRIS. Reservoir rule curves are used to divide reservoir storage into different zones for each period of operation. An example of a set of rule curves is given in figure 4.4. Target release values are assigned to each zone for each period.

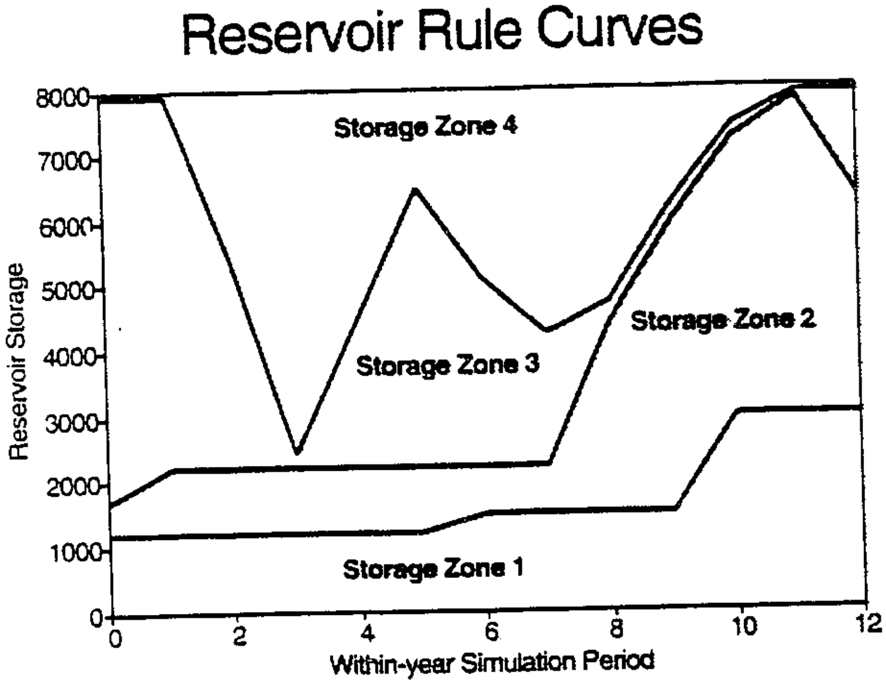


Fig. 4.4 Reservoir Rule Curve Representation in IRIS

The target reservoir release is based on the storage volume at the beginning of the simulation time step. If the reservoir inflow, the initial storage, and the initial target release result in a change in the storage zone during the simulation time step, the actual reservoir release will be the average of the target releases for the neighbouring storage zones.

The location of the storage zones and the release targets can be based on established operating preference for the system (i.e. the provision of specific reservoir zones for conservation storage, flood control, etc.), the results of pure optimization analysis, or some combination of the two based on iterative simulation. The reservoir rule curves for the principle storage node in the Senegal River system, the Manantali reservoir, were derived from a dynamic programming optimization algorithm which explicitly addressed the competing objectives of hydro-power generation and irrigation withdrawals. The optimization principles applied in the study are fully described in Chapter 5. Using rule curves to define a flood control zone is not required in IRIS since reservoir spilling will occur automatically.

4.2.6 Diversion Allocations

The other principle system control in IRIS is the diversion allocation function. Diversion allocation functions represent the quantity of incoming water at a diversion node that is diverted into the diversion link, reducing the flow in the outgoing link. The diversion allocation is some function of the total inflow volume and is represented in IRIS by a function of the form in Fig. 4.5. The dotted line defines the upper bound on the diversion arguments and represents a 100% allocation.

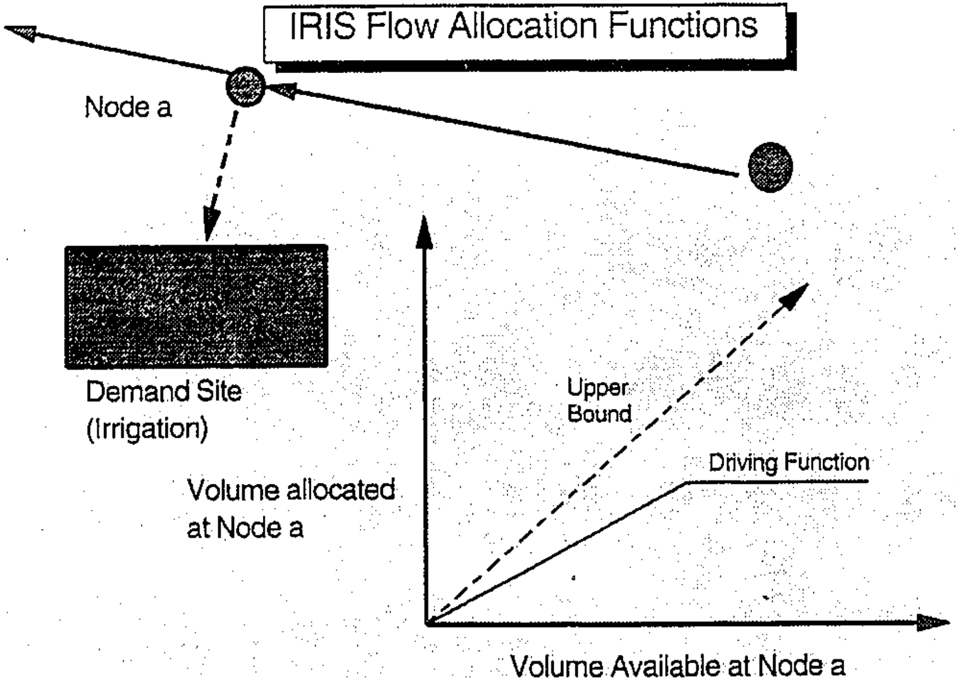


Fig. 4.5 Diversion Allocation Function Representation in IRIS

IRIS does not calculate backwater elevation. If a diversion node always possesses sufficient elevation head relative to the diversion link, the 100% diversion control as implied by this form of the diversion function is valid, otherwise the potentially allocatable volume is a function not only of the inflow volume (upstream conditions), but also of the river level at the diversion node which is influenced by downstream conditions such as backwater effects from the Diama dam. This issue is relevant in the case of the Senegal River system with respect to the diversion of water upstream of the Diama dam at Richard Toll into the proposed Lac de Guiers-Canal du Cayor complex for the primarily municipal demands at Dakar. The diversion volume available at Richard Toll is function of the elevation head there, relative to the level in the Canal du Taouey which feeds Lac de Guier, and not simply the inflow volume. The implications of this for the global modelling study of the Senegal River system are described in the following Sections; **4.3: The Configuration of the Senegal River System in IRIS**, and **4.4: The Lac de Guier - Canal du Cayor Complex.**

4.3 The Configuration of the Senegal River System in IRIS

4.3.1 Schematic System Representation

The Senegal River system was configured for simulation in IRIS as shown in Fig. 4.6. The diversion links furthest upstream in the system represent three major irrigation zones: the Upper, Middle and Lower valley as delineated for analysis of demands in Section 3.5. The mode of water abstraction is not strictly a single diversion, although the pumping stations associated with large rice projects approximate this effect, but rather the distributed abstraction by pumping stations along the reach of the river. This modelling approximation is adequate for the resolution of this simulation study.

The fourth diversion link represents the Taouey canal feeding Lac de Guiers, which is a single diversion point. The Taouey canal is presently used to divert irrigation water to a 7000 hectare sugar cane operation near Richard Toll. Canal du Cayor development plans call for Taouey canal improvements to ensure the annual filling of Lac de Guiers for Cap Vert (Dakar) demands [BCEOM, 1988].

Irrigation demands in the fourth major zoned defined in Section 3.5 are met through releases from the Diama reservoir. This model captures the essential physical reality of the system. The recent completion of both the right and left bank dykes at Diama, creates a long narrow backwater that can extend past Richard Toll. Irrigation withdrawals into the Delta region occur from any of several release points along the dykes.

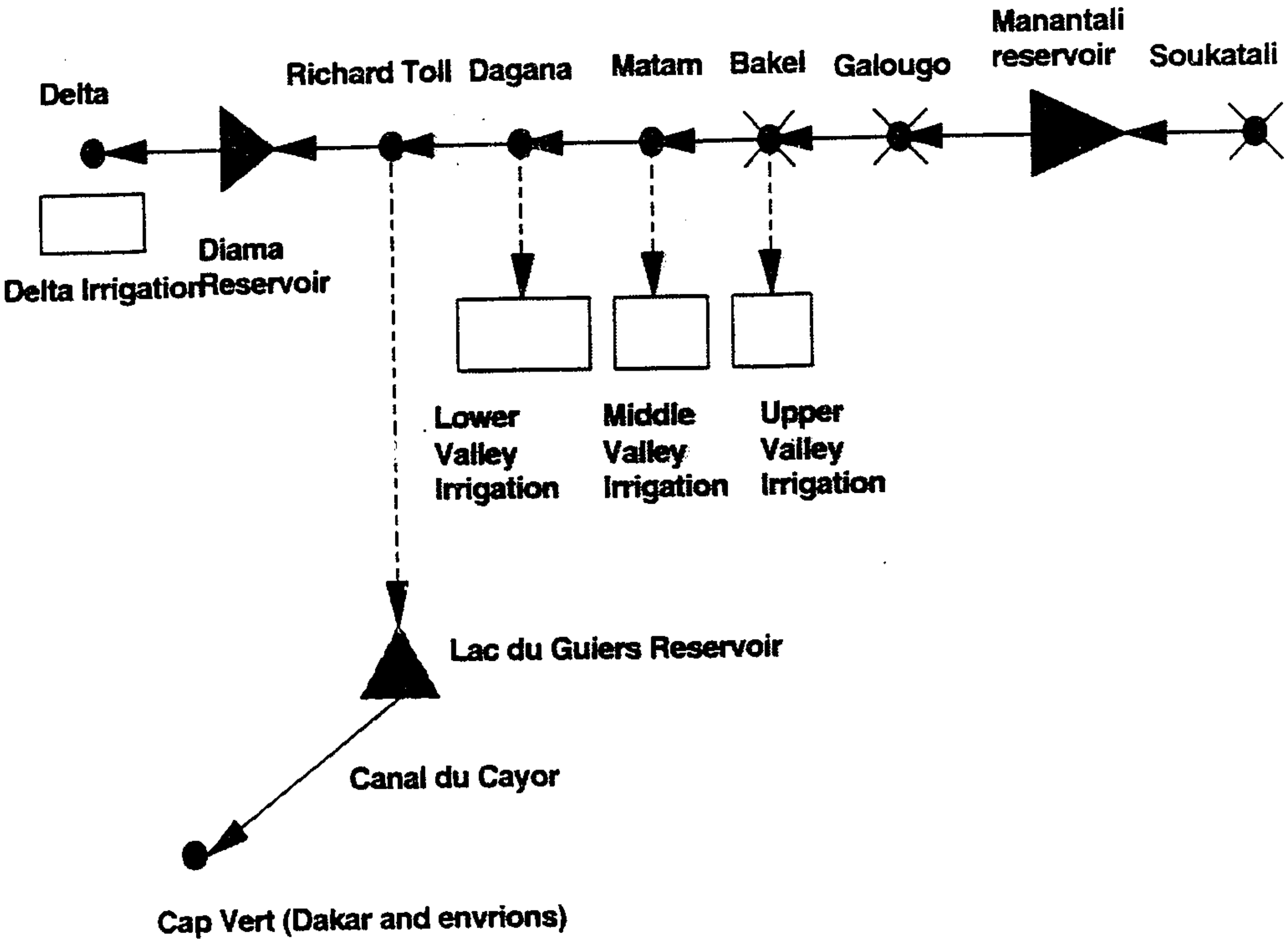


Fig. 4.6 Schematic Representation of the Senegal River System in IRIS

4.3.2 Configuration of Hydrological Data

The configuration of hydrological data through the specification of the inflows and loss functions is effectively the calibration of IRIS to the hydrologic conditions of the Senegal River. IRIS is a mass balance model which does not require the calibration of physical parameters to model flow propagation. The exception to this is the case of flood routing. The details of the calibration exercise to model the floodplain storage effects in the lower valley are described in this section also.

Inflows

The hydrological data used in the simulation of the Senegal system are based on the stochastic analysis of the streamflows at Bakel as described in section 2.4

The primary objective of the study was to investigate the management of the system under continued drought conditions. Generated sequences of annual volumes at Bakel for the no drought, 1970s level drought and 1980s level drought were used to generated annual volumes at two other gauge locations in the system, Soukatali and Galougo, through simple regression analysis. The use of the gauge location at Soukatali captures the effect of the Bafing tributary inflows into the Manantali reservoir while Galougo captures the effect of Bakoye tributary contributions. The Bakel gauge location integrates the flow contribution of the furthest downstream major tributary, the Faleme and marks the point of maximum flow in the system. Figs. 4.7a and b show the high level of correlation between Soukatali, Galougo and Bakel.

The generated annual volumes were then disaggregated into monthly volumes for consistency with the monthly times step used in the simulation. The method-of-fragments disaggregation was applied. Savic et al. [1989], have shown the method of fragments to be a relatively robust technique. In the method of fragments N years of historical monthly streamflow data are ranked according to increasing magnitude of annual flow.

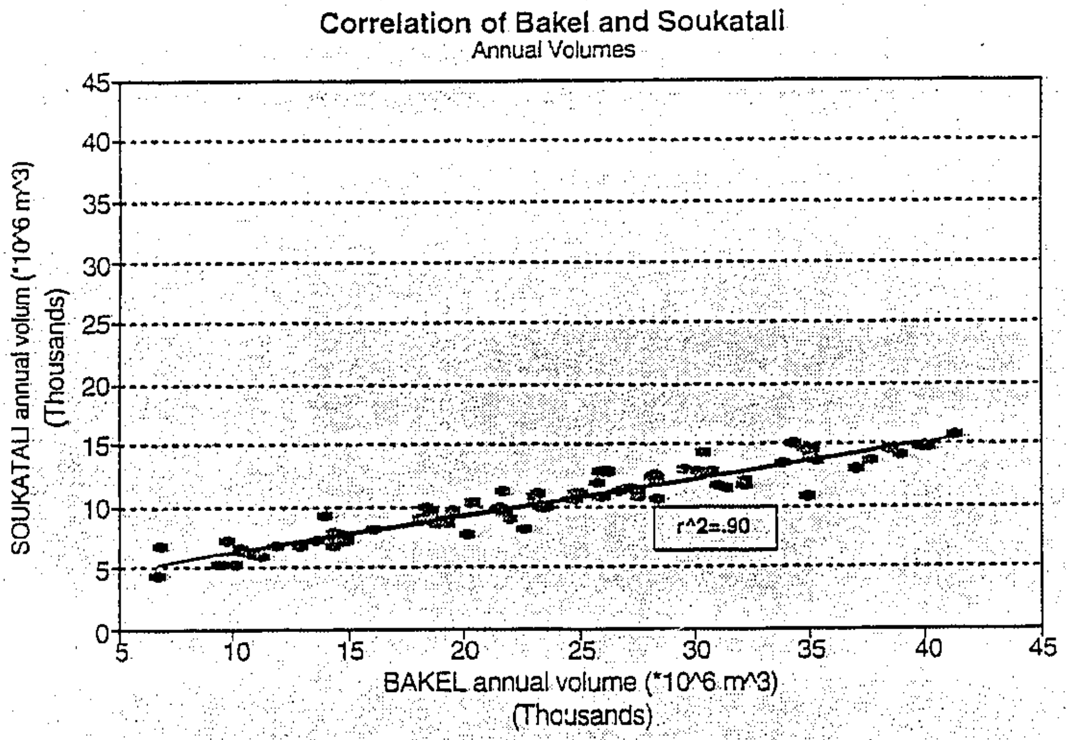


Fig. 4.7a Correlation of Bafing River Tributary Annual Volumes at Soukatali

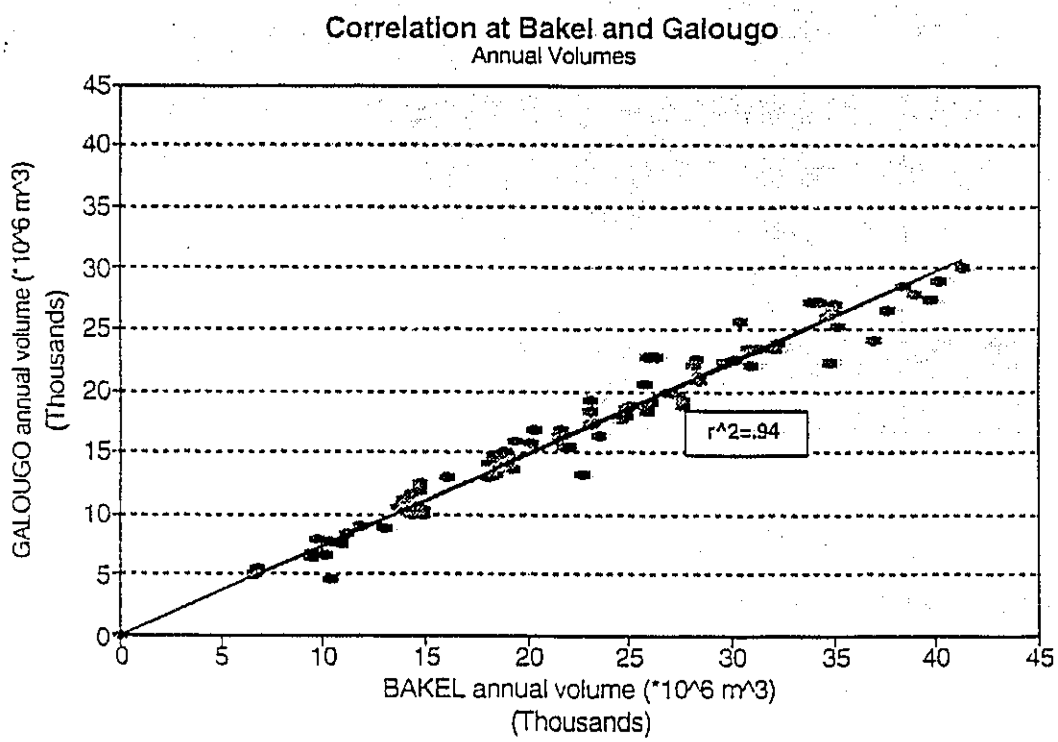


Fig. 4.7b Correlation of Bakoye River Tributary Annual Volumes at Galougo

N classes are thus formed, the lower limit on class 1 is zero, and class N has no upper limit. Monthly fragments are formed by standardizing monthly volumes by the annual volume for each class. The generated annual volumes are disaggregated according to the monthly fragments for the appropriate class as in equation 4.9.

$$Q_i = f_{ij} X \tag{4.9}$$

Q_i is the generated monthly flow volume for i=1,12
f_{ij} is the fragment coefficient for month i=1,12 and class j=1,N
X is the generated annual flow volume

Thirty years of concurrent historical monthly data (1955-1984) were used to establish the class dependant monthly fragments. The period chosen represents the period with the highest level of data fidelity and the widest possible range of Senegal River flow conditions. Valencia and Schaake [1973] present a more sophisticated disaggregation process which preserves the historical seasonal variance and covariance properties of the disaggregated process. The hydrology of the Senegal River is very much dominated by processes occurring at the annual level (the annual flood event), thus the detailed preservation of seasonal statistical properties was deemed of less importance.

Losses

Downstream of Bakel the river valley is less deeply incised and the climate is more arid, as a result evaporation and seepage losses dominate. Regression analysis on the natural flows were used to establish loss functions for the Bakel-Matam and the Matam-Dagana reaches. Only hydrologic data up to 1975 (the pre-irrigation era) was used to establish the loss functions and is thus not influenced by irrigation withdrawals.

Between Bakel and Matam the river naturally loses 13% of its annual volume as shown in Fig. 4.8. On a monthly basis the in-stream volume losses varied erratically from 8% to 25%, no distinct seasonal pattern could be discerned, therefore the 13% volume loss was assumed to hold across all months.

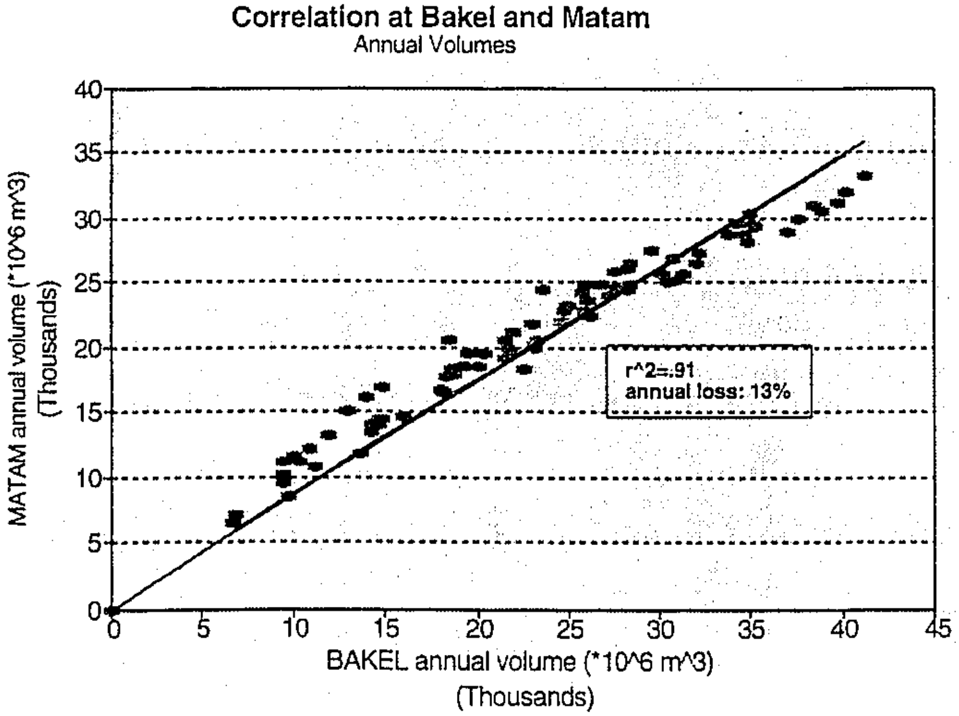


Fig. 4.8 Bakel - Matam Natural Flow Regime

Between Matam and Dagana, the braided river morphology dominates as numerous river braids flow through a broad flood plain. Fig. 1.5 shows the valley cross-section in the middle valley where the flood plain begins to widen. Losses in this reach of the river are high. Fig. 4.9a, 4.9b and 4.9c show the natural in-stream volume loss between Matam and Dagana for January, July and September respectively. The natural regime losses during these months varied only slightly from 29% to 33% according to the natural regime regression analysis and was assumed to hold for all flow regimes from January to September. The lowest flow months could not be included for estimating the natural regime loss function in this river reach because seawater intrusion occurred as far upstream as Dagana during the low flow season. This phenomena had the effect of distorting the stage calibration of the station there. With the completion of the Diama salt barrage, seawater intrusion no longer occurs.

The use of simple linear regression to estimate the loss function, particularly in September is clearly a rough approximation of physical reality. The slope of the loss function (1 minus the slope shown in Figs. 4.9a, b and c) increases in the high flow regime as the river breaches the main channel in flood stage and much flow goes into flood plain storage. Losses to storage and evaporation and seepage associated with the decreased hydraulic radius account for the higher losses. The reader is invited to review Fig. 1.5 which depicts the middle valley channel cross section, where the flood plain begins to widen.

The low flow range loss function is lower because of the larger hydraulic radius associated with main channel flow. There exists however very little data with which to estimate the low flow loss function. The gauge station at Dagana has not been active since 1965 and the hydrologic record contained many missing measurements up to this date. Some of the missing data in the high flow years has been corrected with regression analysis. Almost all the low flow years occurred after 1965. ORSTOM has attempted physical modelling to estimate flow propagation from Matam to Dagana for the post 1965 period, however modelling results have thus far not been adequate [Albergel and Bader, 1993].

It was necessary to estimate the behaviour of the low flow loss function since this represents the flow regime critical to the study of system management under continued drought conditions. Piece-wise linearization would have fit the high flow regime better, but would have also significantly under-estimated the low flow regime loss function. The zero-intercept regression retained over-estimates the low flow loss function but not greatly. The weaker regressions in January and July (figs. 4.9a and b) representing much lower flow regimes confined to the main channel gave similar losses.

The use of statistical models to capture the essential features of the floodplain storage effects in the high flow season is the next discussion topic.

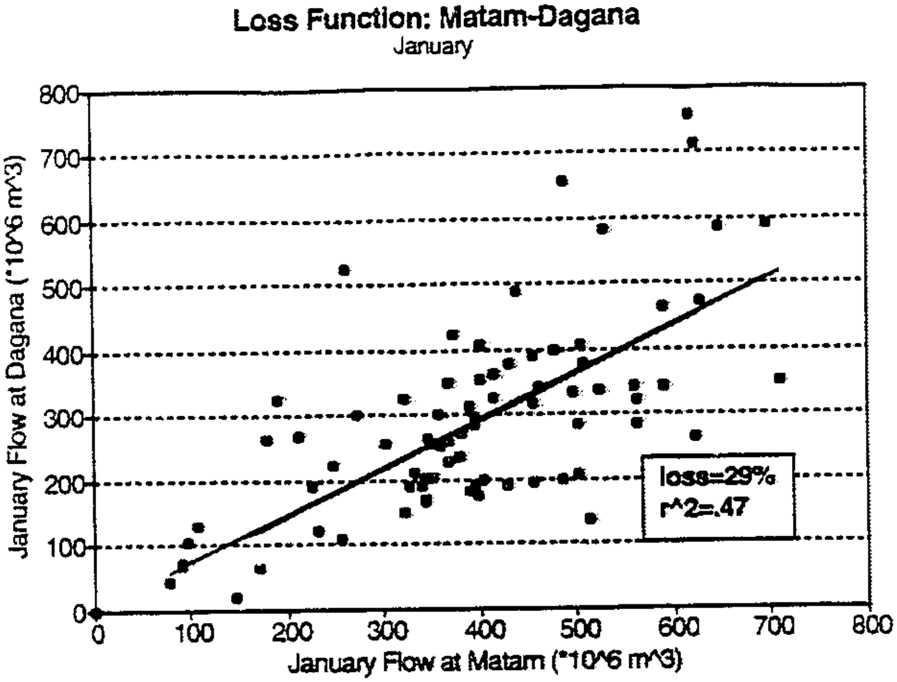


Fig. 4.9a Matam - Dagana Natural Flow Regime - January

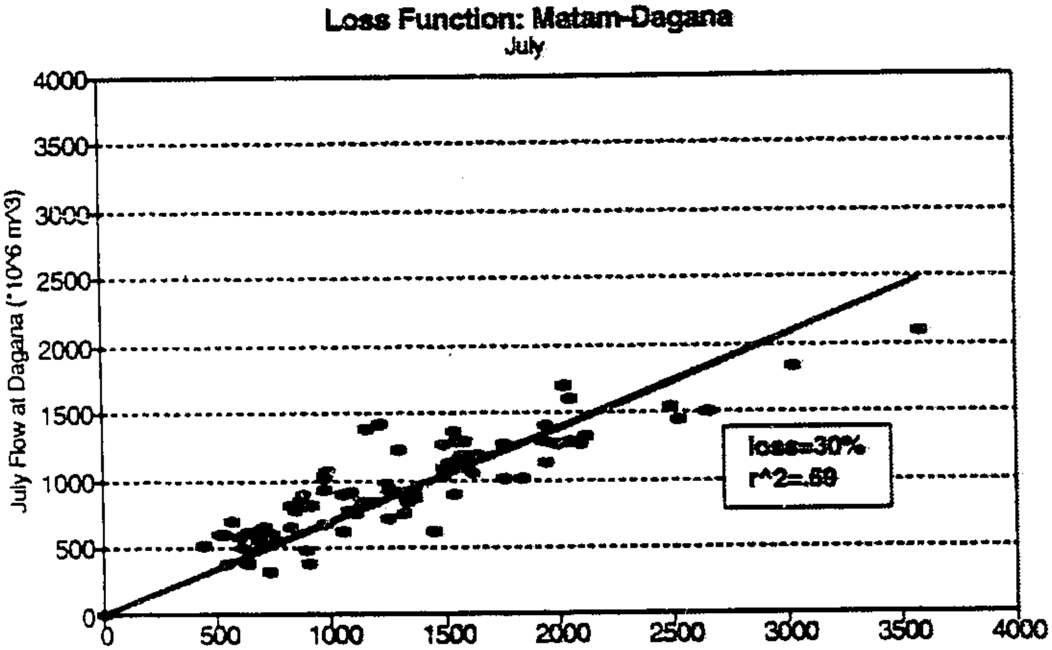


Fig. 4.9b Matam - Dagana Natural Flow Regime - July

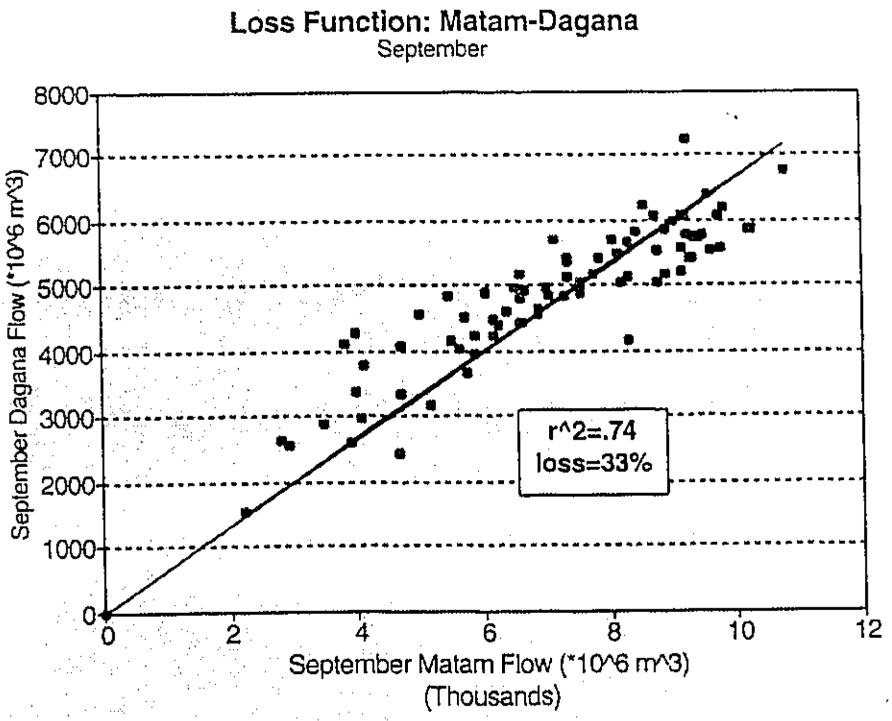


Fig. 4.9c Matam - Dagana Natural Flow Regime - September

During the high flow months (September, October, November and December) a flood plain storage effect controls the volume at Dagana. The high flows at Matam during these months are lagged by about one month in flood plain storage (with considerable volume loss). Fig. 4.10 illustrates this effect. Note that after the September flood-peak at Matam, Dagana volumes are greater than Matam volumes. This is the flood recession effect.

Fig 4.11a, 4.11b and 4.11c show the strong correlation between October, November and December Dagana flows and the previous month Matam flows which reflect the flood plain storage period of about one month.

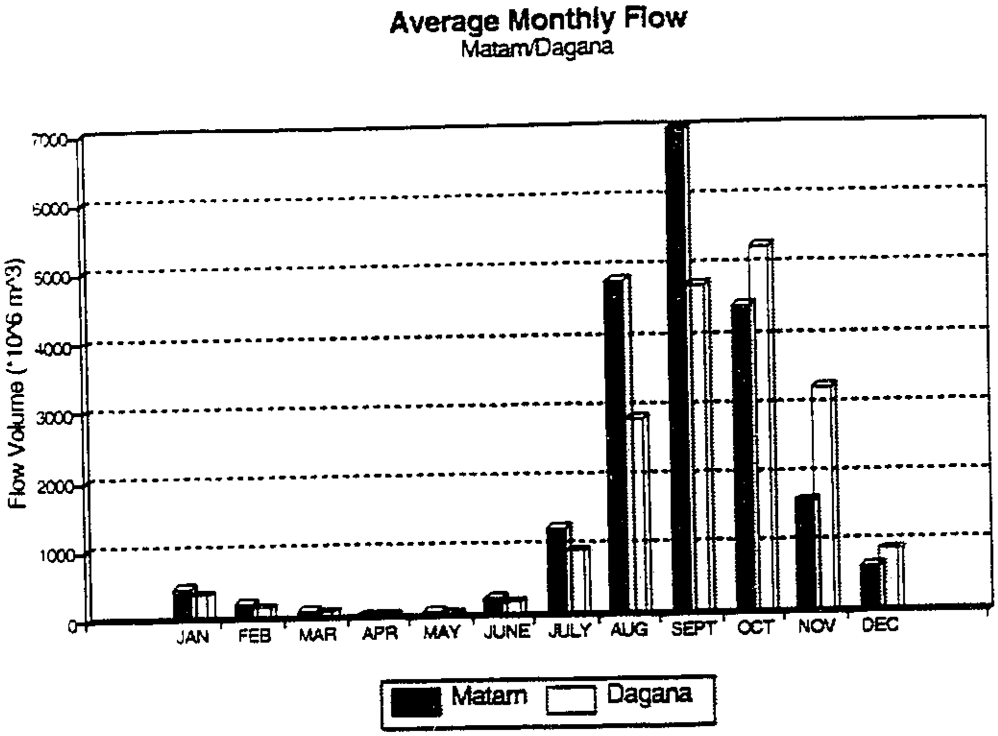


Fig. 4.10 Matam - Dagana Flood Recession Effect

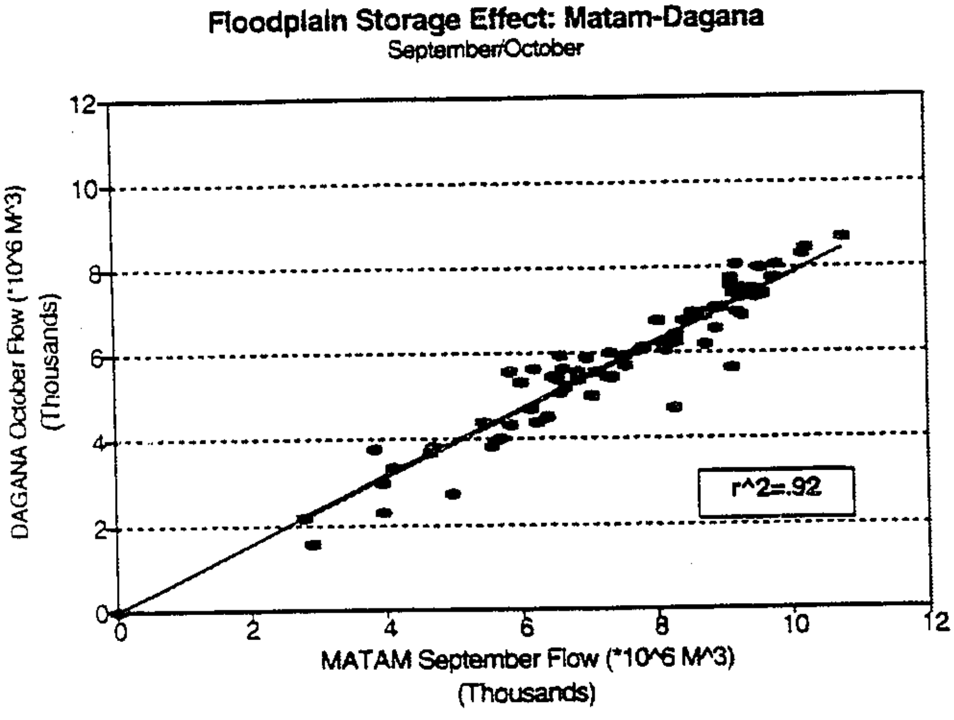


Fig. 4.11a Matam - Dagana: Floodplain Storage Lag Effect - October

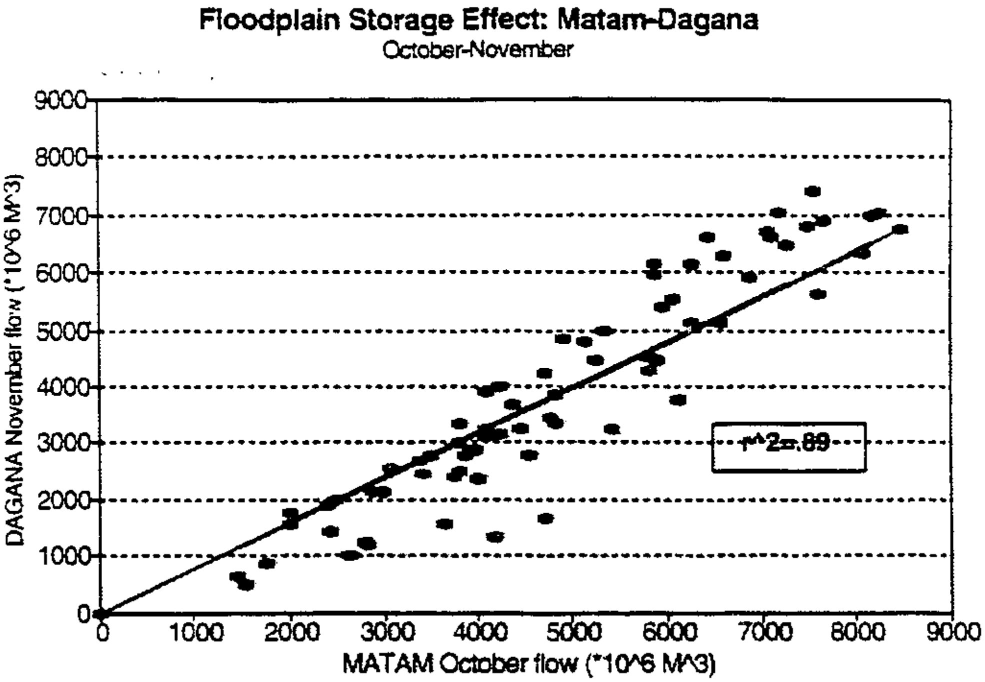


Fig. 4.11b Matam - Dagana: Floodplain Storage Lag Effect - November

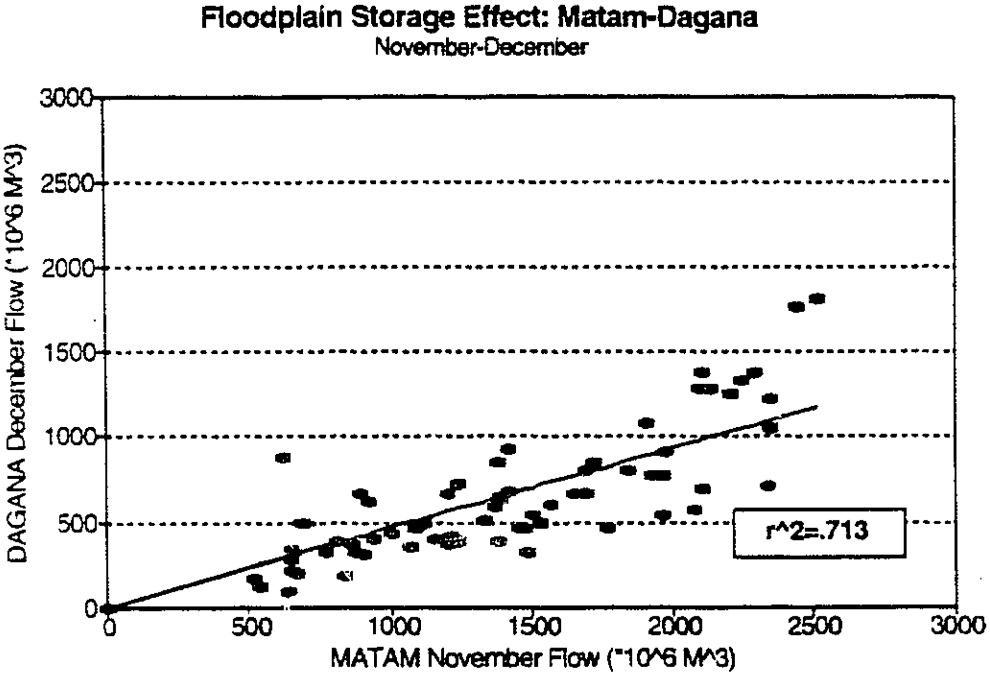


Fig. 4.11c Matam - Dagana: Floodplain Storage Lag Effect - December

It was deemed important to preserve these flood recession effects since the significant volumes involved can be used to augment diversion volumes at Richard Toll for the annual filling of Lac de Guiers. The period dependant flood plain storage effects are not readily amenable to the modelling assumptions in IRIS. For example the natural incremental volumes from flood recession occurring between Matam and Dagana during October, November and December are dependant on the September, October and November Matam outflows. Thus IRIS simulation had to be carried out in two stages. In the first stage, IRIS was used to simulate the allocation of water as far downstream as Matam. The simulated Matam outflows in the high season (after Matam zone irrigation abstractions, corresponding to the middle valley diversion) are the volumes which will go into flood plain storage. The values were extracted from the simulation output and were used to calculate the month lagged Dagana inflow according to the natural regime regression analysis. In the second stage, the simulation was restarted at Dagana with the new Dagana inflows. The net effect of this simplified modelling approach is that the September and October Dagana flows are both dependant on the September flood-peak at Matam. ORSTOM hydrologists were consulted extensively in developing this approach [Albergel and Bader, 1993].

The assumption of this flood recession modelling approach is that the regulated regime will not be vastly different from the natural regime which was used to develop the regression parameters. This is likely a reasonable assumption because the Manantali reservoir controls only 40-50% of the flow in the system and seasonal flooding effects will still be present.

The alternative to the simplified statistical modelling of the Senegal River flood plain hydrology is detailed physical modelling. However ORSTOM hydrologists confirm that the problems posed by the extremely complex braided river morphology, the permeable soil and arid conditions have proven intractable to several attempts to construct physical models [Albergel and Bader, 1993].

The remaining significant losses in the system are incurred through evaporation at the Diama and Lac de Guiers reservoirs. The data pertaining to these phenomena are presented in the following section.

4.3.3 Configuration of Reservoir and Hydro-power Data

The configuration of the Senegal River system in IRIS was completed with the input of the following reservoir data at Diama, Lac de Guiers and Manantali:

Active Storage Volume-Surface Area Relationships

Table 4.1 Diama: Active Storage Volume-Surface Area

elevation (m, IGN)	0	0.6	1.0	1.5	2.5
Volume (m^3*10^6)	0	83.4	148	250	585
Surface Area (km^2)	133	148	174	235	435

[source: Gibb, 1986b]

Note: The maximum level at Diama has been raised to 2.5 m with the completion of the right bank dyke, the volume-surface area data at this level are extrapolated from Gibb [1986b] as recommended by Albergel and Bader [1993].

Table 4.2 Lac du Guiers: Active Storage Volume-Surface Area

elevation (m, IGN)	0	0.5	1.0	1.5	1.8
Volume (m^3*10^6)	0	90	210	335	410
Surface Area (km^2)	180	222	258	288	308

[Source: BCEOM, 1988]

Table 4.3 Manantali: Active Storage-Surface Area

elevation (m, IGN)	187	192	198	204	208
Volume (m^3*10^6)	0	1500	3500	6100	7900
Surface Area (km^2)	275	300	375	425	477

[Source: Gibb, 1986b, Groupement Manantali, 1978]

Monthly Evaporation at Reservoir Surface

Table 4.4 Diama and Lac du Guiers: Monthly Evaporation

month	jan	feb	mar	apr	may	june	july	aug	sept	oct	nov	dec
net evap. (mm)	203	213	252	251	248	200	183	140	122	210	202	191

[Source: Gibb, 1986b, Groupement Manantali, 1978]

Table 4.5 Manantali: Monthly Evaporation

month	jan	feb	mar	apr	may	june	july	aug	sept	oct	nov	dec
net evap. (mm)	119	147	197	197	167	31	0	0	0	11	59	62

[source: Groupement Manantali, 1978]

Note: July to September have a negative net evaporation due to net positive precipitation, however IRIS does not accept negative values thus the small volume gains due to precipitation were added to inflows in these months.

Manantali Hydro-power Production

Table 4.6 Manantali Hydro-power Production Characteristics

Plant Capacity: 200 MW

elevation (m, IGN)	187	190	194	196	198	200	202	204	206	208
Volume (m^3*10^6)	0	900	2600	2800	3500	4300	4800	6100	6900	7900
Power Output (MW)	138	161	189	200	200	200	200	200	200	200
Turbine Flow (m^3/s)	517	544	561	559	532	507	484	464	445	428
Net Head (m)	32.2	33.5	38.1	40	42.6	44.7	45	48.8	50.9	52.9

Note: The above table was derived with the use of a real-time Manantali reservoir simulation program, known as "Simulsen", developed by ORSTOM [Bader, 1991]. The data were used to estimate the Storage - Net head curve required for IRIS input.

4.4 The Lac du Guiers - Canal du Cayor Complex

The proposed Lac du Guiers - Canal du Cayor complex will be an essential element of the Senegal River system if it is constructed. To capture the water resources demands the project will place on the global Senegal River system water budget, the project was the focus of an independent modelling study in IRIS using the data given in Section 4.3.2.

4.4.1 Project Background

Dakar, Senegal is experiencing explosive population growth due to both a high natural growth rate in Senegal and massive rural-urban migration because of the drought. The high growth rate has put great stress on Dakar's municipal water supply. Eighty percent of Dakar's water supply is currently furnished from aquifers in the Cap Vert region, the peninsula which environs the city of Dakar and juts into the Atlantic. The remaining 20% of the water supply is delivered via pipeline from Lac du Guiers, 300 km to the north.

A recent study reported by Potworowski [1990], concluded that the aquifers supplying Dakar are being over-used and show signs of serious salt-water intrusion. To prevent permanent saltwater contamination of these aquifers and to accommodate future growth in Dakar, the Ministry of Hydraulics plans to augment the municipal water supply by vastly increasing abstractions from Lac du Guiers. The ministry intends to accomplish this through the construction of the Canal du Cayor.

The Canal du Cayor project proposes to bring water from the Senegal River to the Cap Vert region of Senegal through intermediate storage at Lac du Guiers. Lac du Guiers, a natural depression located south of Richard Toll, would be filled during the high flow season and the stored water would then be used for the following purposes:

-meeting year-round requirements (not covered by other resources) of the Dakar region until the year 2020.
-creating irrigation perimeters in the regions crossed by the canal.
-recharging groundwater in the Cap Vert region (to be accomplished mainly through the relaxation of demands placed on them)
[BCEOM, 1988]

A map of the proposed project, including the location of its associated management structures is shown in fig. 4.12.

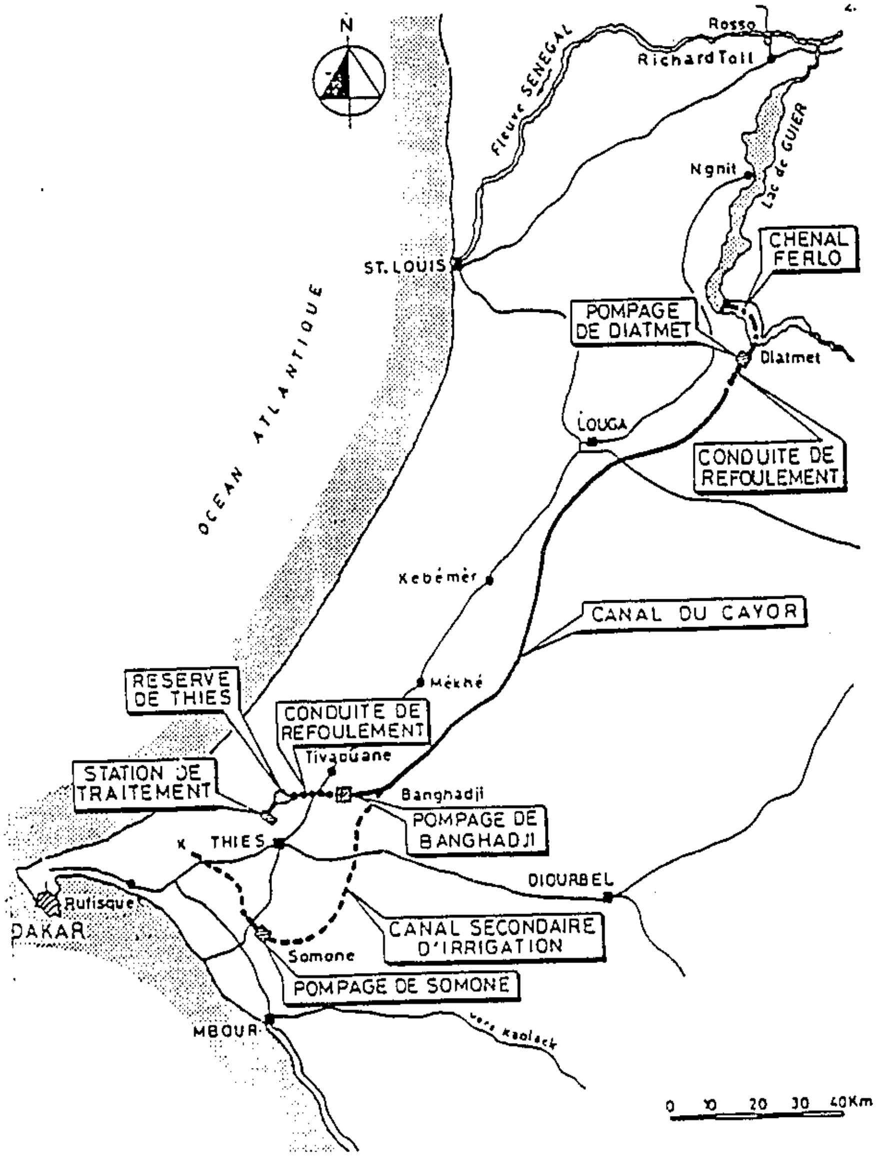


Fig. 4.12 Proposed Canal du Cayor: Plan [source: MEACC, 1993]

4.4.2 Canal du Cayor Water Resources Issues: Implications for Senegal River Management

In 1988 a European engineering consortium, headed by the French firm BCEOM completed a feasibility study of the Canal du Cayor project. The BCEOM study includes a general water resources budget for the Dakar region present and future. The BCEOM analysis accounts for projected population growth. irrigation development and associated water abstractions along the canal, and the utilization of groundwater resources from regions more distant to Cap Vert.

The relevant conclusions of the report with respect to the global Senegal River development plan concern the projected year 2020 raw water requirements at the head of the canal at Lac du Guiers. These demands must be met in the annual filling of the lake from the Senegal River. The total water demands on Lac du Guier are given in Table 4.7

Table 4.7 Projected Net Water Demands at Lac du Guiers

(all units $*10^6$ m^3)

month	jan	feb	mar	apr	may	june	july	aug	sept	oct	nov	dec
year 2001	40.4	41.6	46.1	45.4	38.7	34.7	30.0	30.4	30.4	32.0	34.0	37.2
year 2020	60.6	62.1	69.4	67.8	56.4	50.8	43.6	44.8	44.8	47.1	50.4	55.4

[Source: BCEOM, 1988]

The demands in Table 4.7 include the portion of the Dakar water supply that is already met by the existing pipeline from Lac du Guier, direct lake abstractions for agriculture in the adjacent Ferlo valley, and the raw water requirements at the head of the Canal du Cayor destined for Dakar and environs. In defining these demand scenarios, BCEOM clearly delimits their analysis, "It is specified that in the corresponding studies the water resources were not considered to be a limiting factor, with the obvious reserve that this should be subsequently verified" [BCEOM, 1988].

BCEOM thus does not study the effect of filling Lac du Guiers on the over-all management of the Senegal River. They do however acknowledge that it constitutes a non-trivial demand, particularly under drought river flow conditions.

The BCEOM report recommends a single annual filling-emptying cycle for the lake. Operating Lac du Guiers in this fashion has several advantages, primarily profiting from the natural yearly filling that occurs in the flood season. Other advantages include:

- -controlling the growth of aquatic plants and disease vectors by annually de-watering the banks
- -Allowing flood recession crops to be grown on the banks
- -decreasing the lake's salinity caused by the encroachment of the salt tongue during the drought and before the completion of Diama.

To meet the Canal du Cayor raw water requirements, BCEOM suggests the following intake profile. These intakes must be supplied by Senegal River diversions at Richard Toll.

November to July: 52×10^6 m^3 / month

August to October: 237×10^6 m^3 /month

There exists however a fundamental problem: Lac du Guiers is not engineered storage, it is merely a shallow natural depression with very high evaporation losses. BCEOM acknowledges that storage is insufficient to meet year round demands even if the lake is successfully filled during the flood season.

A simple simulation model of the system was constructed in IRIS and is shown in Fig. 4.13. The simulation model used the Lac du Guier physical data presented in section 4.3.3 and quickly verified that if the lake was filled according to the above inflow profile, spilling would occur and scheduled withdrawals and evaporation would empty the lake before the next filling season.

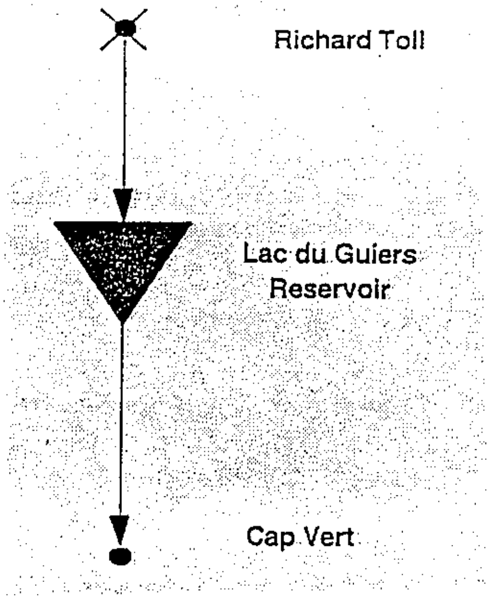


Fig. 4.13 Schematic of Lac du Guiers - Canal du Cayor IRIS model.

The same simulation model was used to determine an intake pattern which could sustain the required year-round withdrawal pattern. The objective was to have the intake pattern as peaked as possible and centred in the flood season, thus minimizing the inflows required during the dry season. High dry season inflows require regulation at Diama or substantial Manantali releases to maintain sufficient elevation head at Richard Toll for diversion into the Taouey Canal feeding Lac du Guiers. Bader [1991] has shown that with the backwater effect of Diama when full, it would be possible to maintain adequate head at Richard Toll even under very low upstream flow conditions. Operating the Diama reservoir in this fashion may significantly compromise other objectives, since Diama must be drawn down in the dry season to meet Delta zone agricultural demands. The extent to which this conflict exists should be the focus of a detailed physical modelling study.

Figure 4.14 shows a comparison of Lac de Guiers inflow profiles. The inflows are the required diversion volumes from Richard Toll to meet the total net demands at Lac du

Guier as given in Table 4.7. The thin line in the inflow profile suggested by the BCEOM [1988] cause the reservoir to spill at the end of the flood season (November-December), with deficits occurring from April to June of the following year. The alternative inflow profiles were estimated using an IRIS model of just Lac du Guiers. The 2020 inflow profile avoids spillage, however the inflow profile is centred later in the season to avoid deficits in the critical period the following spring.

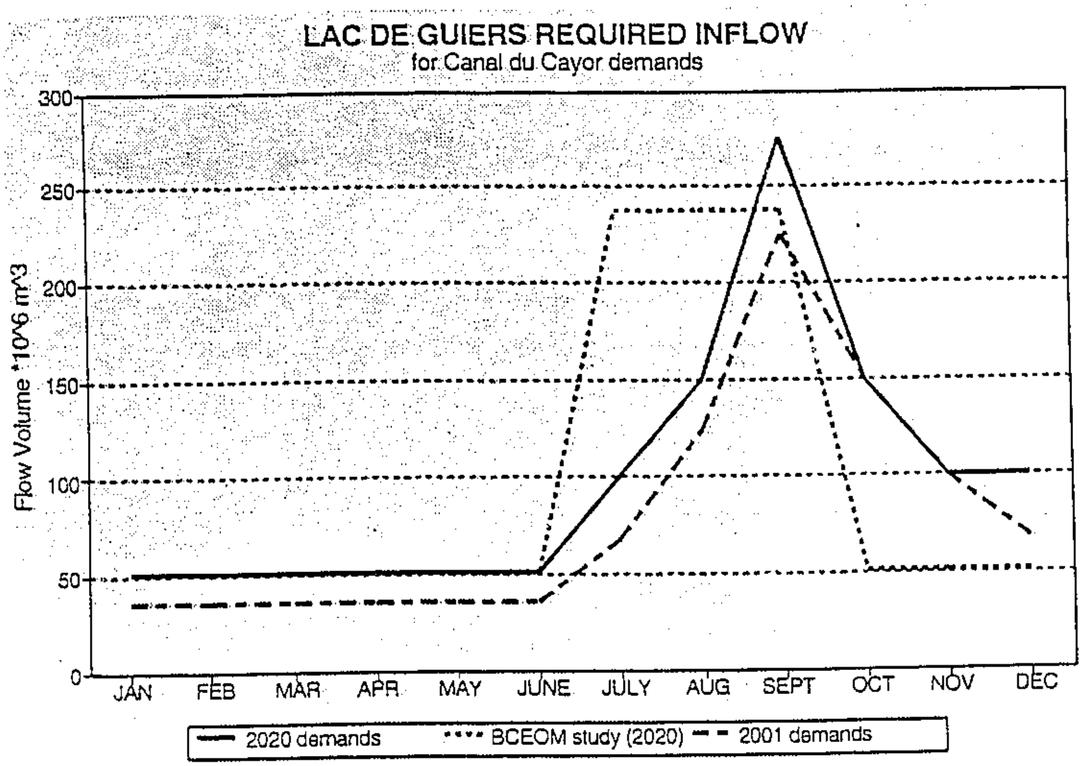


Fig. 4.14 Lac du Guiers Inflow Profiles

The BCEOM and the revised 2020 inflow profile (this study) abstract the same volume of water over the whole year (within 1%), only the within year distribution has changed. The increased diversion requirements later in the year will likely influence Manantali and/or Diama regulation depending on policy choice and the general hydrological regime of the river.

The inflow profile required to meet the projected 2001 Canal du Cayor raw requirements reveals an important operational aspect of Lac du Guiers. Although the projected 2001 requirements are 33% less than the 2020 level, the required inflow volumes are only 20% less than the inflow volumes at the 2020 level. Since the lake functions effectively as a broad, shallow evaporating pan, the lower storage volumes associated with the 2001 demands are subject to a higher relative evaporation loss. The total evaporation loss at the 2020 level is 45%. The total evaporation loss at the 2001 level is 54%. This effect will be even more pronounced if the intended operation of the Canal du Cayor is at less than the 2001 demand level. Thus for all further simulation study, the 2020 inflow profile was adopted as the operational demand pattern, since operating the Canal du Cayor for lower demand levels is sub-optimal and has no great impact on the Senegal River diversion requirements.

Fig. 4.15 gives a comparison of irrigation and Lac du Guiers demands at a irrigation development level of 275 000 hectares (RP policy).

The Lac du Guiers - Canal du Cayor demands are approximately 14% of irrigation requirements at this development level. The Senegalese Ministry of Hydraulics has similarly claimed that all Lac du Guiers diversion requirements amount to only 13% of the irrigation requirements at a (Senegal-only) development level of 240 000 hectares [MEACC, 1993]. However at lower irrigated agriculture development levels, the municipal demands comprise a much higher percentage of irrigation demands. Fig. 4.16 shows a comparison of demands at a 150 000 hectare irrigation development level (NRM policy). For this development level and policy, Lac du Guiers diversion requirements comprise 37% of the total irrigation requirements.

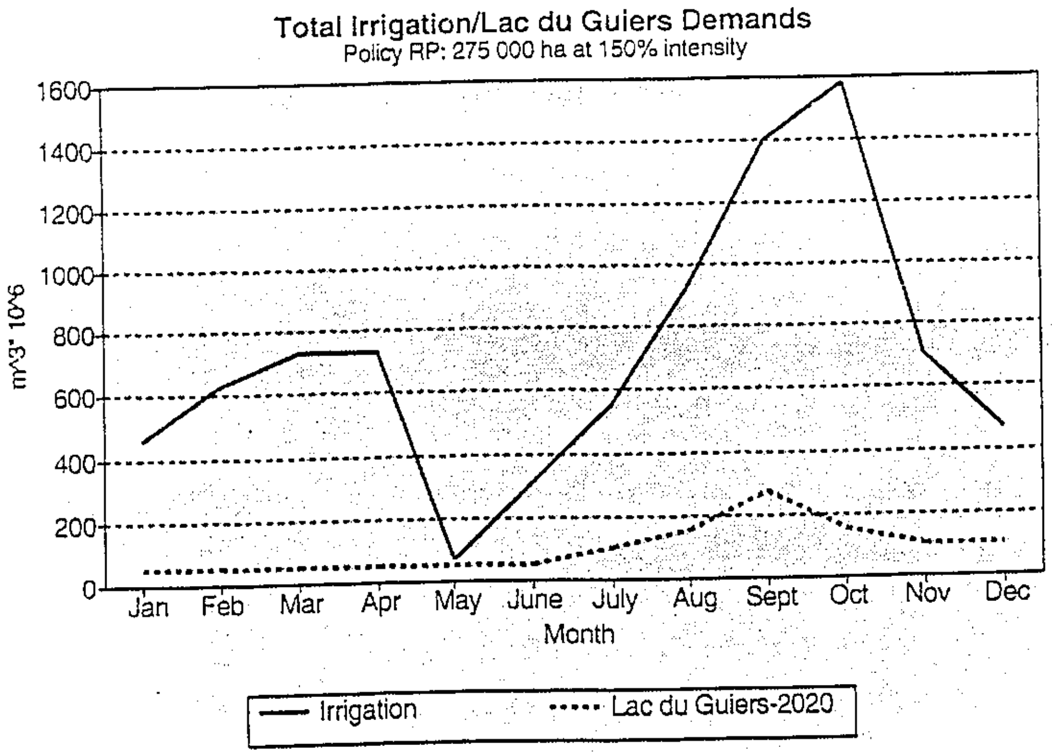


Fig. 4.15 Total Irrigation and Lac du Guiers demands (275 000 ha)

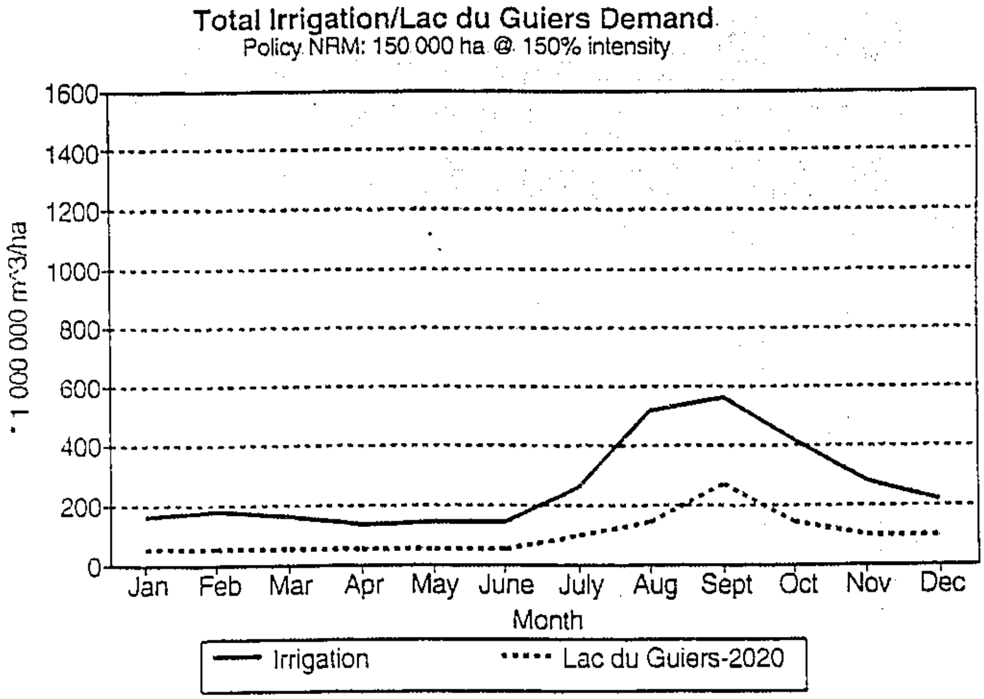


Fig. 4.16 Total Irrigation and Lac du Guiers demands (150 000 ha)

The fundamental constraint on irrigation development is of course the global water resources availability as defined by the hydrologic regime. The fact that Cap Vert requirements exert a large demand on the global Senegal River water resources budget, and will constrain the areal extent of irrigated agriculture development, under continued drought conditions, has not been the subject of intense scrutiny. The simulation modelling analysis conducted as part of this study addresses this issue directly.

* * *

Chapter 4 has described the simulation principles applied and the physical data utilized in the simulation modelling study of the Senegal River. Chapter 4 has also reported the simulation results from the sub-problem of Lac du Guiers-Canal du Cayor diversion allocations. The impact of Lac du Guiers diversions on the water resources management of the Senegal River introduces the issue that competition for water will exist under drought conditions.

Given that competition for water does exist in the Senegal River system, there remains the issue of how to optimally allocate water to the various uses. In the context of the IRIS simulation model, this relates to the need to set system controls; namely the rule curves for Manantali reservoir operation, and the diversion allocation functions. The application of dynamic programming optimization principles to derive these system controls is the subject of the next chapter.

CHAPTER 5

THE APPLICATION OF DYNAMIC PROGRAMMING OPTIMIZATION TO THE SENEGAL RIVER SIMULATION MODEL

Chapter 5 corresponds to element **D. Systems Management Optimization** in the general water resources systems analysis framework described in Section 1.7.1 and depicted in Fig. 1.7.

5.1 Optimization Methods in Water Resources Systems Analysis

One of the most important advances made in water resources engineering in the last 30 years is the application of optimization techniques to the planning, design and operation of water resources systems. The mathematical principles underlying the optimization techniques were originally developed in the fields of operations research and management science. The application of optimization methods require the formulation of objective functions and constraints. Objective functions reflect the desire to maximize/minimize some economic, social or environmental benefit/cost through the management of the water resource system. Constraints reflect the physical or resource availability limitations on the system which define the range of feasible management strategies. The now classic textbook, *Water Resource Systems Planning and Analysis* [Loucks et al., 1981] serves as an excellent introduction to the field of water resource system optimization.

One of the more successful applications of optimization techniques in water resources has been in the study of reservoir management and operation [Yeh, 1985]. Reservoir operation objectives include hydro-power generation, irrigation, municipal consumption, navigation, water quality enhancement, eco-system maintenance. Objectives in reservoir optimization models are generally a function of storage and release volumes. The formulation of objective functions which accurately capture the effective social welfare, environmental and economic benefits accruing to reservoir operation is exceedingly difficult and invariably involves a subjective statement regarding the relative importance of objectives (Hence the utility of simulation to gain an understanding of the impacts of any particular optimization scheme).

The set of constraints on reservoir optimization models include; the mass-balance continuity in time equation, minimum and maximum permissable storage limitations, minimum release requirements and hydro-power generation limitations.

No general general reservoir optimization algorithm exists, although many different methodologies have been applied. Yeh [1985] presents a thorough review of various reservoir management and operation models that have been applied in both theory and practice. The available optimization methods generally fall into two categories; Linear programming (LP), and dynamic programming (DP). Variations of LP of increased sophistication include chance-constrained LP and stochastic LP. DP variations of greater sophistication include discrete differential DP, reliability constrained DP and stochastic DP. Chance-constrained, reliability-constrained and stochastic schemes of both LP and DP varieties address the issue of uncertainty in reservoir inflow hydrology. The solution methodology generally involves deriving an equivalent deterministic problem formulation using probability distribution or serial correlation properties of the natural inflow hydrology.

The choice between LP and DP is largely subjective. Solution algorithms are readily available for LP. LP is however limited in that all relationships between variables are assumed linear, this is a weakness in the case of hydro-power production which is a non-linear function of reservoir storage and release. LP is also limited in that the constraint set in real situations can easily exceed several thousand equations [Loucks, 1968]. Due to the nature of the LP solution algorithm, the inclusion of additional constraints increases execution time. High speed computation makes this less problematic however.

No general algorithms exist for DP, thus the application of DP requires a considerable time investment in algorithm development. DP however offers several advantages; the additional constraints reduce computation requirements, non-linear relationships between variables are easily formulated, and DP can readily be applied to complex problems by decomposing the problem into a series of sub-problems which are then solved recursively.

The attributes which made the use of DP optimization preferable in the case of the Manantali reservoir/Senegal River application were primarily its non-linear and decomposability properties. The basic principles of dynamic programming are discussed in Section 5.2. The application of DP to the reservoir management is the subject of Section 5.3

5.2 The Principle of Optimality in Dynamic Programming

The fundamental concept on which all dynamic programming optimization rests is the application of the *principle of optimality* [Bellman, 1957]. While conceptually straightforward, the principle is often difficult to apply. An illustrative example will best serve to familiarize the reader with the principle.

Consider the simple resources allocation problem in Fig. 5.1. The overall objective at the outset of the problem is to allocate X units (in this simple case X=5) of some scarce resource at successive network stages in some optimal manner. The benefit accruing to each allocation at each stage, j is defined by some unique benefit function $R_j(x_j)$. For example the benefit of allocating 3 units at the first stage is denoted as $R_1(3)$, and of allocating 2 units at the third stage, $R_3(2)$.

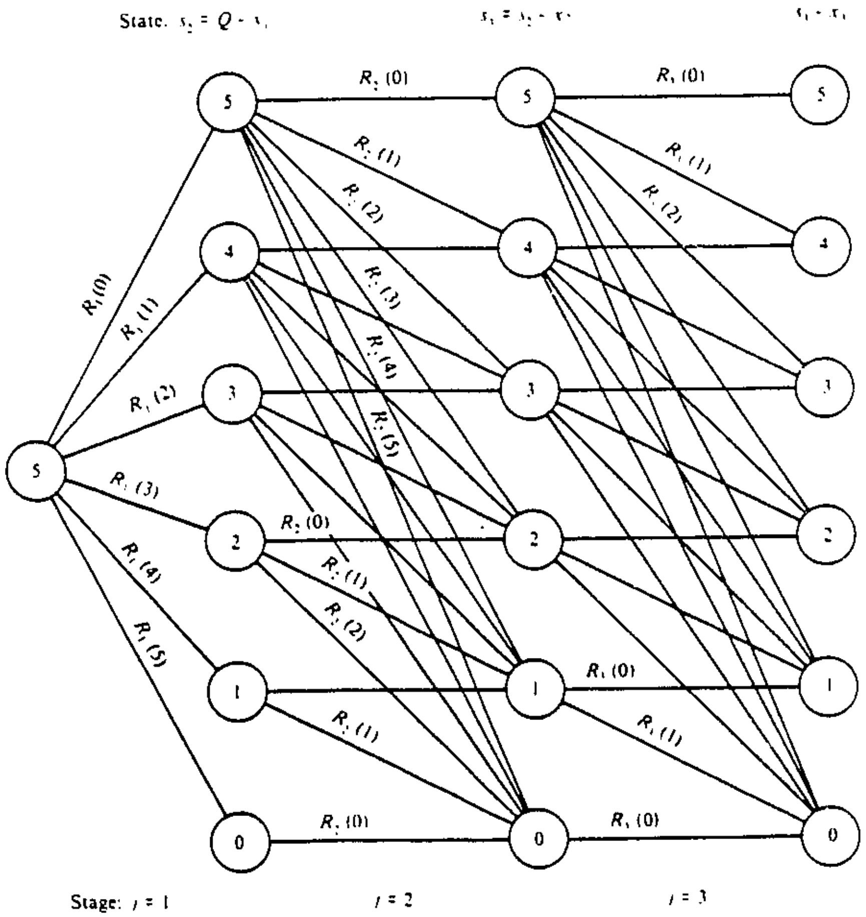


Fig. 5.1 Example: Dynamic Programming Network Problem [source: Loucks et al, 1981]

The numbered nodes define the *state* of the system at each stage by the resource remaining, s_j. The links in the figure represent feasible allocations, x_j, (the system *control*) given the current system state. The global objective is thus to control the allocation of the remaining resource across all stages of the system to maximize net benefits. The problem can be solved by brute-force enumeration of all possible allocations, however the number of calculations required quickly becomes impossible, given the number of possible states and stages for any real-world problem.

The problem is solved much more efficiently by invoking Bellman's principle of optimality which states, "no matter in what state of what stage one may be, in order for a policy to be optimal, one must proceed from that state and stage in some optimal manner." Noting the similarity of Bellman's principle with the Danish philosopher/theologian Kierkegaard's central teaching that at whatever station in life one finds oneself, one must strive to do the most noble thing *at that moment*, some authors have referred to the "Bellman-Kierkegaard" principle of optimality.

In general the principle of optimality can be solved through forwards or backward recursion. A backward recursion, consistent with the expression of the principle given will be applied to the problem in Fig. 5.1. The general recursion equation can be defined as:

$$f_j(s_j)=\mathit{maximum}[R_j(x_j)+f_{j+1}(s_j-x_j)] \tag{5.1}$$

where:

s_j is the amount remaining of the total resource at stage j, and
$f_{j+1}(s_j-x_j)$ is the value of the objective function for the optimal allocation of the resource remaining after x_j is allocated.

The problem is solved moving backwards from the last stage. The maximum of all $R_3(x_3)$ defines $f_3(s_3)$. This means that if we are in stage 3 with one allocation left to go we know how much resource, x_3, should be allocated of the total resource remaining, s_3. The problem is now shifted one stage back. For all states s_3 one enumerates all feasible ways of arriving at state s_2 by the allocation of x_2. The objective is to maximize the $R_2(x_2)+f_3(s_3)$. Note that $f_3(s_3)$ is fixed since once in state s_3 we already know the optimal path. When the maximum benefits $f_2(s_2)$ are calculated for each state s_2, the problem can be shifted back one stage and the enumeration of feasible ways of arriving at state s_1 through the allocation of x_1 begins. Again the calculation of $f_1(s_1)$ in equation 5.1 is dependant on prior knowledge of $f_2(s_2)$ since once in state s_2 we know the optimal path. When $f_1(s_1)$ is calculated the problem is solved as one has determined the optimal allocations at every stage to maximize benefits.

The advantage of applying dynamic programming is the huge reduction in computational efficiency compared to brute-force enumeration of all possible system states. Dynamic Programming suffers however from the so-called curse of dimensionality as computation time grows exponentially with the number of states one must consider. The necessary dynamic programming approximation of continuous real-world phenomena by specifying discrete system states is the subject of the next section, the **Application of Dynamic Programming to Reservoir Management.**

5.3 The Application of Dynamic Programming to Reservoir Management

The multi-stage decision model for reservoir operation is illustrated in figure 5.2.

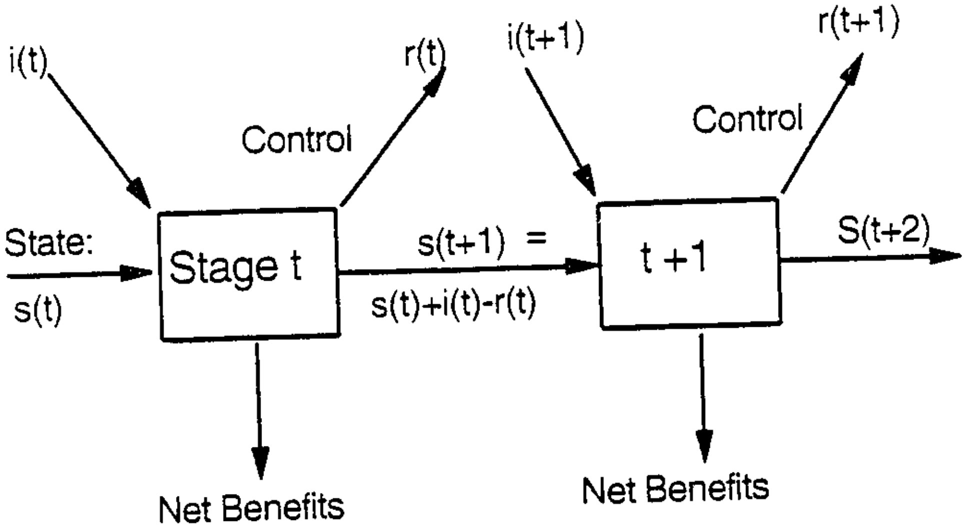


Fig 5.2 Multi-stage Dynamic Programming Decision Model for Reservoir Operation

[Adapted from Loucks et al, 1981]

The sequential operation of a reservoir can be approximated (ignoring for the moment evaporation and seepage losses) by simple continuity equation in every period t:

$$s_{t+1}=s_t+i_t-r_t \tag{5.2}$$

where:

s_t is the reservoir storage (the system state) in each period t,
i_t is the (period average) reservoir inflow in period t, and
r_t is the reservoir release (the system control) in each period t.

In general reservoir operation provides some benefit in each period. Reservoir operations are frequently optimized according to the minimization of deviations from some target storage and release values in each period [Loucks et al., 1981]. Target storage and release values typically represent hydropower, irrigation, ecological and recreation objectives. If for example, reservoir operation seeks to simply minimize the squared deviations from storage and release targets in each period the net benefits in each period can be denoted as:

$$NB_t=-[(TS_t-s_t)^2+(TR_t-r_t)^2] \tag{5.3}$$

where:

NB_t are the net benefits accruing in each period (the negative sign simply implies that the deviations should be minimized),
TS_t is the target storage in period t, and
TR_t is the target release in period t.

The objective is to determine a steady state release policy which maximizes net benefits. The problem is stated formally as a dynamic programming problem by defining the general backwards recursion equation as follows (Note the use of the continuity equation given in Eqn. 5.2):

$$f_t(s_t)=Maximum[Nb_t(s_t,r_t)+f_{t+1}(s_t+i_t-r_t)] \tag{5.4}$$

subject to (in all periods t) the maximum release constraint:

$$r_T \leq s_t+i_t \tag{5.5}$$

the minimum release (spilling) constraint:

$$r_t \geq s_t+i_t-K \tag{5.6}$$

and the reservoir capacity constraint:

$$s_t \leq K \tag{5.7}$$

where:

K is the active storage reservoir capacity.

The solution of the reservoir problem entails finding an optimal release r_t^* for every possible storage state in all periods. The solution is obtained by solving Eqn. 5.4 recursively for each storage state beginning in some arbitrarily chosen final period of operation, for example month 12 of year N and proceeding backwards for several years. The convergence criteria for achieving a steady-state policy is met when the optimal releases in each storage state and period are unchanging from year to year. This is referred to as the **stationary solution.**

No well-developed theory exists to establish the conditions under which a stationary solution exists, however Loucks et al. [1981] state that generally convergence is achieved after cycling through three or four years. The stationary solution is simply a tableau of optimal releases, r^*_{tj}in each period t and storage state j. If the discretization of the storage and release states is adequate, by simple graphical transcription, this tableau is equivalent to the rule curve representation of reservoir operation such as given in chapter 4.

The solution approach described is referred to as deterministic dynamic programming (DDP) since the inflow hydrology, the period average i_t's, are assumed known. An extension of the deterministic approach is referred to as stochastic dynamic programming (SDP) and involves a statistical description of the inflow hydrology, in most applications a lag-one Markov process. The recursion equation 5.4 is modified as follows:

$$f_t(s_t)=Maximum[Nb_t(s_t,r_t)+\sum_k P^t_{jk}f_{t+1}(s_t+i_{jt}-r_t,i_{kt})] \qquad (5.8)$$

where:

P^t_{jk} represents the transition (conditional) probability of flow i_k in period t+1 given an inflow of i_j in period t.

Karamouz and Houck [1987] have shown through comparative simulation that SDP provides better operational rules than DDP for small reservoirs (capacity equal to 20%

of the mean flow). However for large reservoirs (capacity greater than 50% of the mean flow), the DDP generated operating rules are more efficient. For all hydrological scenarios examined in the Senegal River study, the capacity of the principal storage in the system, the Manantali reservoir, was well in excess of 50% of the mean annual inflow thus the DDP methodology was applied. The details of the application of DDP optimization to the operation of the Manantali reservoir is the subject of the next section.

5.4 The Application of Deterministic Dynamic Programming to the Manantali Reservoir

Storage State Discretization

Due to the nature of DP, reservoir storage must be discretized into storage zones. Each storage zone represents a feasible system state. The number of storage zones is a trade-off between preserving a good approximation of the storage continuum and minimizing execution time. The extreme seasonal variability of the Senegal River hydrology required that reservoir release volumes be relatively finely resolved. To preserve the approximation of the storage continuum (through the continuity equation) both the storage state and release volume increments were set to $100 * 10^6$ m^3.

Storage states were delineated according to the frequently applied "classical scheme" [Karamouz and Vasiliadis, 1992], where the number of storage states, SDN is given by:

$$SDN=\frac{K}{s_{inc}} \tag{5.9}$$

where:

SDN is the number of storage states,
K is the active reservoir storage capacity (Manantali: $K=7900 * 10^6$ m^3)
s_{inc} is the storage state increment (Manantali: $s_{inc}=100 * 10^6$ m^3)

Thus for Manantali, SDN=79. The storage states are calculated according to:

$$S_k = \frac{S_{inc}}{2} + (k-1)S_{inc} \qquad (5.10)$$

The zero and full storage states are therefore not included, the lowest storage state, $s_1=50*10^6$ m^3, and the highest storage state, $s_{79}=7850*10^6$ m^3.

Objective Function Formulation

Reservoir DP applications frequently use an objective function of the form given in equation 5.3. The cost function may not be parabolic, but some similar, concave upward, empirically derived function is usually applied to penalize deviations from an "ideal" target release and storage state in each period. Specifying the target storage and release state and the cost functions associated with deviations from them assumes a deep conventional economic knowledge of the system studied. Specifying the cost functions implies for example, a knowledge of the marginal value of hydro-power production, the marginal value of irrigated land and the social and ecological cost of reservoir drawdown to name just a few examples. In the case of Manantali, the hydro-power turbines have not been installed, the power grid has not yet been constructed and the local population is in the process of adapting to dislocation and reservoir filling. Thus specifying target operating states and cost functions on deviations from target states would be strictly an exercise in conjecture.

The objective function was instead simplified to reflect physical objectives rather than some speculative economic objective. The hydro-power objective was simply to maximize energy production in each period. Energy production is proportional to the product of net head and release. Using a linear approximation of the head-storage relationship given in Table 4.6, the general recursion equation became:

$$f_t = maximum(R_t(ms_t + H_o) + f_{t+1}(s_t + i_t - r_t)) \qquad (5.11)$$

subject to:

Eqns. 5.5, 5.6, 5.7, and

$$R_t(ms_t+H_o)\leq 200*730.5 \qquad (5.12)$$

where:

m is the slope of the linearized head-storage relationship.
H_o is the net head at 0 active storage, and
200*730.5 is the maximum energy production (MWH) per period. (Plant Capacity: 200 MW, hours per period (month): 730.5)

The explicit inclusion of irrigation and municipal objectives for release volumes is the subject of the next section. The characteristic hydrology of the Senegal River dictated that a novel approach be adopted that links reservoir operation in time with the spatial allocation of downstream flow allocations which is the subject of the next section.

5.5 Linking Reservoir Operation to Allocation Function Definition

Generally dynamic programming models applied to reservoirs with irrigation supply as a primary function, use a single lumped seasonal target release as representative of downstream irrigation demands. Mohan and Keskar [1991] give a typical example of this. In the case of the Senegal River study, the use of a single lumped seasonal release target distorts the physical reality of the system, primarily because of the arid zone hydrology of the Senegal River valley. The total volume of water available for meeting irrigation demands is a function of where the water is abstracted from the system because strong loss functions dominate the middle and lower valley. Setting a single lumped seasonal release target thus gives no information on how the instream volume defined by the release, downstream tributary contributions, and arid zone losses, should be allocated in space to optimally and/or equitably meet regional demands.

The objective function should therefore reflect the cost/benefit of some optimal partitioning of the downstream flow volume. The global optimization problem was thus conceptualized as a two dimensional DP space-time recursion. In the time domain the recursion is on the reservoir state as defined in Eqn. 5.11. In space the recursion is on on the instream flow-volume state at successive stages, in this case the downstream allocation zones. Conceptually the space domain recursion is given in fig. 5.3.

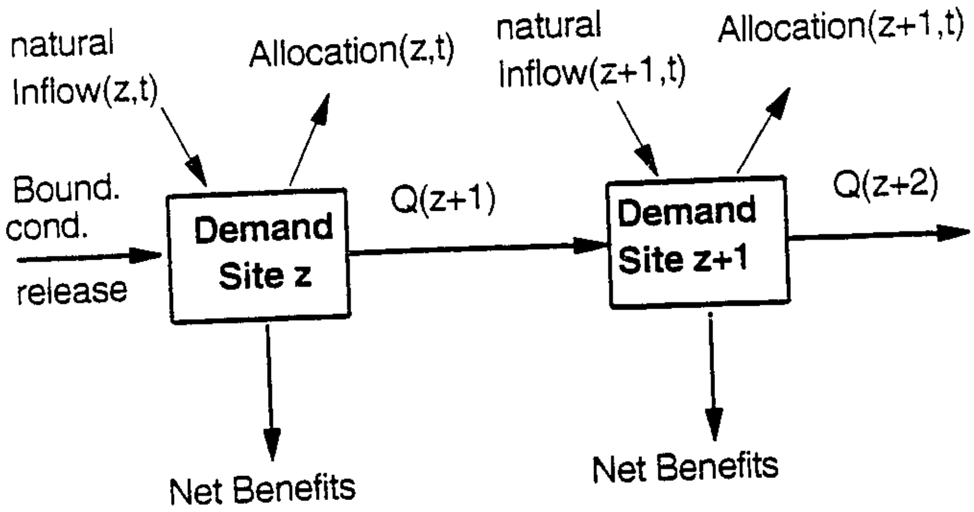


Fig. 5.3 Space-Domain Dynamic Programming Decision Model for Flow Allocation

The space and time domains are linked by the definition of the reservoir release in each period. The reservoir release defines the upstream flow volume boundary condition, thus for this application a forward moving recursion is more appropriate. The forward moving recursion maps the boundary condition reservoir release downstream according to the period average inflows, loss functions and allocations to demand sites. The objective function is based on the minimization of squared deviations from the target demand levels at all downstream allocation sites. The cost functions could conceivably be far more elaborate, reflecting different crop priority, and the marginal value of a unit of irrigated land in each period. Again, however in the context of the SRB development planning problem, such cost function definition would be extremely speculative and arbitrary.Conceptually the linked time-space recursion model is linked as shown in fig. 5.4.

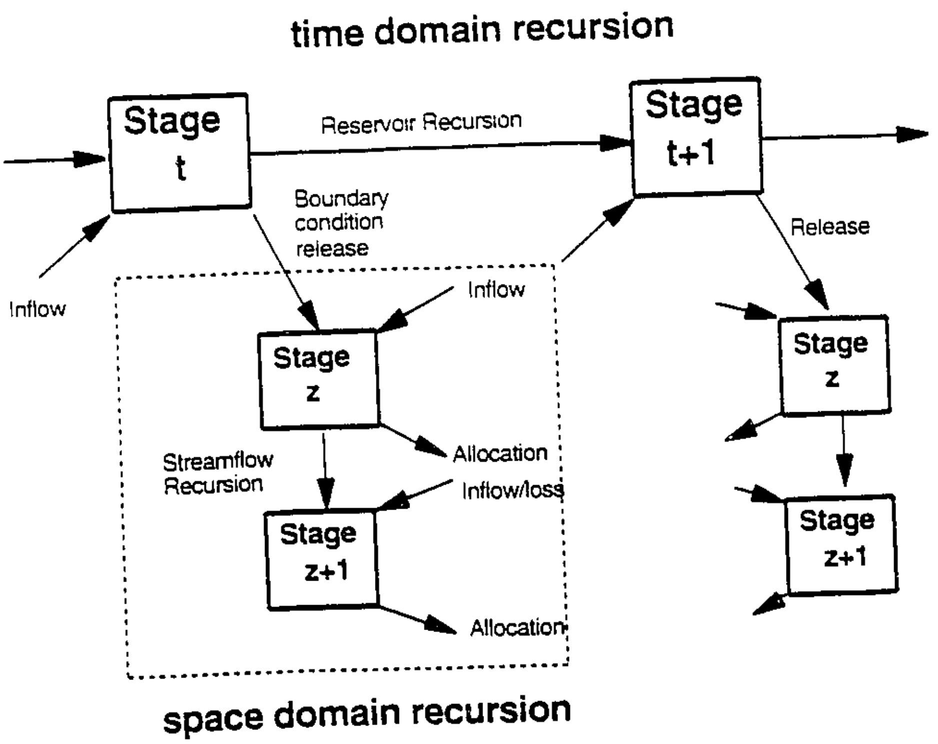


Fig. 5.4 Linked Space-Time DP Reservoir Operation/Flow Allocation Model

At the boundary condition (the interface of the space and time recursion) the continuity equation which defines the recursion relationship in every period t, is:

$$R_t+NQ_{1t}=A_{1t}+Q_{2t} \tag{5.13}$$

where:

R_t is the release in period t,
NQ_{1t} is the natural incremental inflow augmenting the release between the reservoir and the first allocation zone,
A_{1t} is the volume allocated to the furthest upstream demand zone,
Q_{2t} is the flow volume downstream of the furthest upstream demand zone.

The general continuity relationship for the recursion at z demand zones (in all periods t):

$$Q_{tz}=Q_{tz+1}-NQ_{tz}+A_{tz} \tag{5.14}$$

NQ_{tz} represents the discrete, period average incremental inflow volume occurring along

the river reach between demand zones z and z-1,
Q_{tz} is the flow volume downstream of demand zones z-1, and
A_{tz} is the volume allocated to the demand zone z.

When arid zone hydrology applies (downstream of Bakel) the continuity relationship is defined as:

$$Q_{tz}=\frac{Q_{tz+1}+A_{tz}}{NQ_{tz}} \tag{5.15}$$

where:
NQ_{tz} in this case represents a percentage total volume loss.
This representation of arid zone loss functions is consistent with both the physical reality of the system as determined by the natural regime regressions given in chapter 4 as well as the simulation modelling assumptions in IRIS.

The forward general recursion equation, defining the system state as the instream flow volume Q_{tz+1}, is as follows:

$$f_{tz+1}(Q_{tz+1})=minimum[NB(A_{tz})+f_{tz}(Q_{tz})] \tag{5.16}$$

where:
$NB(A_{tz})$ is the net benefits function, defined in this application as the minimization of squared deviations of the allocation volume and the target demands at all z demand sites as follows:

$$NB(A_{tz})=-(DEM_{zt}-A_{tz})^2 \tag{5.17}$$

For irrigation demand zones, Upper Valley, Middle Valley, and Lower Valley, DEM_{zt} is equivalent to the regional irrigation demand, Dem_{kt} given in equation 3.8. The target demands are thus simply the tableau of monthly irrigation demands in each zone as specified by the development policy scenario and level of development as described in Chapter 3, as well as the municipal demands given by the year 2020 Lac de Guiers-Canal du Cayor inflow demand profile shown in Fig. 4.14. The demands associated with the furthest downstream demand zone, the delta region, were not included in the spatial allocation optimization algorithm. This methodology was primarily because delta zone allocations are not met by instream abstraction or diversion but by Diama reservoir releases. Preliminary simulation investigation revealed that Diama generally possessed sufficient over-season storage so that no Manantali dry season release was required for specific delta demands.

The solution of the general model entails solving the space component first by calculating the total allocation penalties associated with every feasible boundary condition release state in each period. The allocation penalties are simply the sum of the squared deviations from target demand levels, the magnitude of which is determined by the release state, the natural inflow/losses and the allocation at all downstream sites.

One of the primary reasons for applying the space recursion is that it estimates the optimal diversion allocation functions at all downstream allocation sites which are required in IRIS simulation. The space recursion is solved for all feasible release states which defines a wide instream flow volume range. The forward recursion solves for the optimal allocation at each allocation site for each boundary condition release state. After the dynamic program algorithm has solved for the allocation at the last downstream site, a trace-back algorithm establishes the optimal allocation and the flow volume state at all the allocation sites for each boundary condition release state. The trace-back is performed for each boundary release state, and each trace-back pass provides another ordered pair of arguments for the diversion allocation function at the current site and for the current site. Fig. 5.5 provides an example of the diversion arguments from the DP trace-back used to estimate the slope of the diversion allocation function in IRIS. The plateau represents sufficient flow for full demand satisfaction.

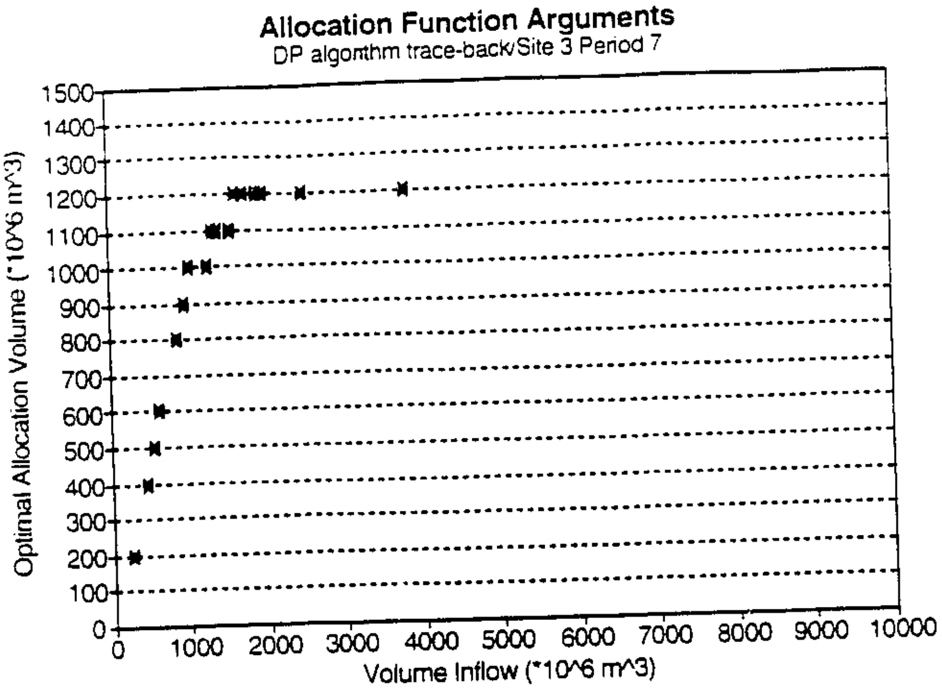


Fig. 5.5 The Use of Space DP for IRIS Diversion Allocation Function

When the total allocation penalties are solved for each boundary condition release in each period they can be used in the time domain reservoir operation model. The allocation penalties are introduced directly into the general recursion equation for reservoir operation given in equation 5.11 which becomes:

$$f_t = maximum(R_t(mS_t + H_o) + TOTPEN_{rt} + f_{t+1}(s_t + i_t - r_t)) \qquad (5.18)$$

where:

$$TOTPEN_{rt} = -\sum_{z} NBA^{*}_{rzt} \qquad (5.19)$$

where:

NBA^{*}_{rzt} are the penalties associated with the optimal allocation at demand zone z for boundary release r in period t.

The reservoir model thus does not penalize the release deviations from some lumped demand target in each period. The release policy is instead conditioned by the total penalties representing an optimal allocation of the downstream flow volume as defined by the upstream boundary condition release state for each period.

An explicit trade-off between hydro-power and irrigation objectives is possible by weighting the tableau of allocation penalties by some scalar. The general recursion equation is thus:

$$f_t = maximum(r_t(ms_t + H_o) + W * TOTPEN(r_t) + f_{t+1}(s_t + i_t - r_t)) \qquad (5.20)$$

where:
W is an arbitrary weight on allocation penalties, hereinafter referred to as the irrigation weight.

Through experimentation it was established that a range of 0-100 represented an adequate range of irrigation weight values. A weight of 0 represents a pure hydro-power production policy. Fig. 5.6 illustrates the final rule curves of the form given in fig. 4.4 based on a pure (W=0) policy. Fig. 5.7 represents an irrigation policy (W=100). The significantly lower curves for the irrigation policy represents fundamentally a willingness to sacrifice storage (and turbine head) in order to meet dry season irrigation demands.

SRB policy as formulated by the OMVS has always stressed irrigation objectives as the development priority, thus it may appear to be inappropriate to consider system optimization for hydro-power production. Horowitz [1990] however has noted that although the World Bank has not been an active player in SRB development until now, their preferred management policy would be to optimize Manantali operation for hydro-power for the Dakar market. The impact of a hydro optimized management strategy on irrigation development objectives will be discussed along with all the results from the simulation study in chapter 6.

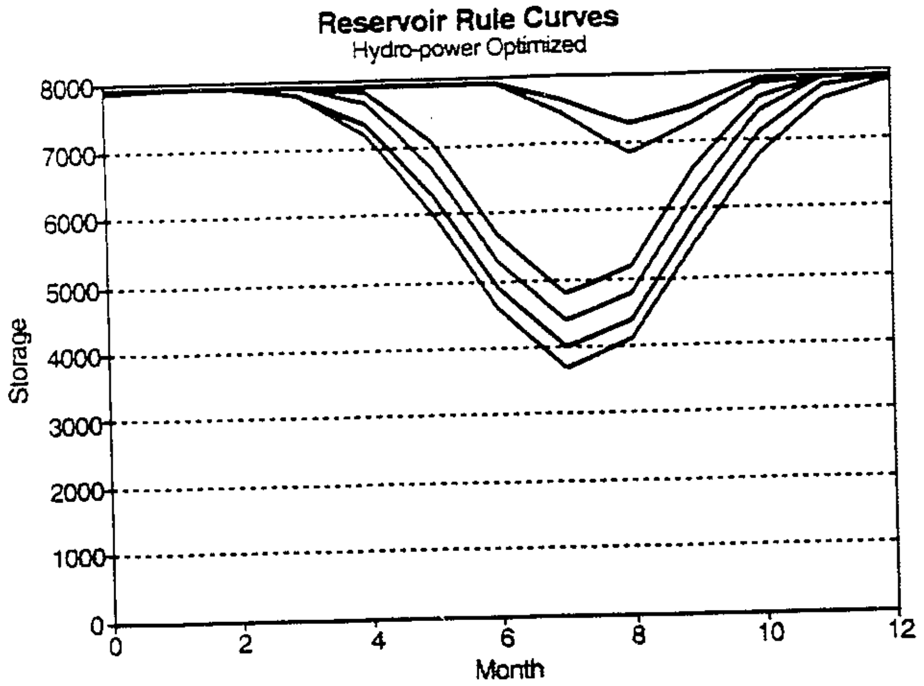


Fig. 5.6 Example of Hydro-power Optimized Reservoir Rule Curves

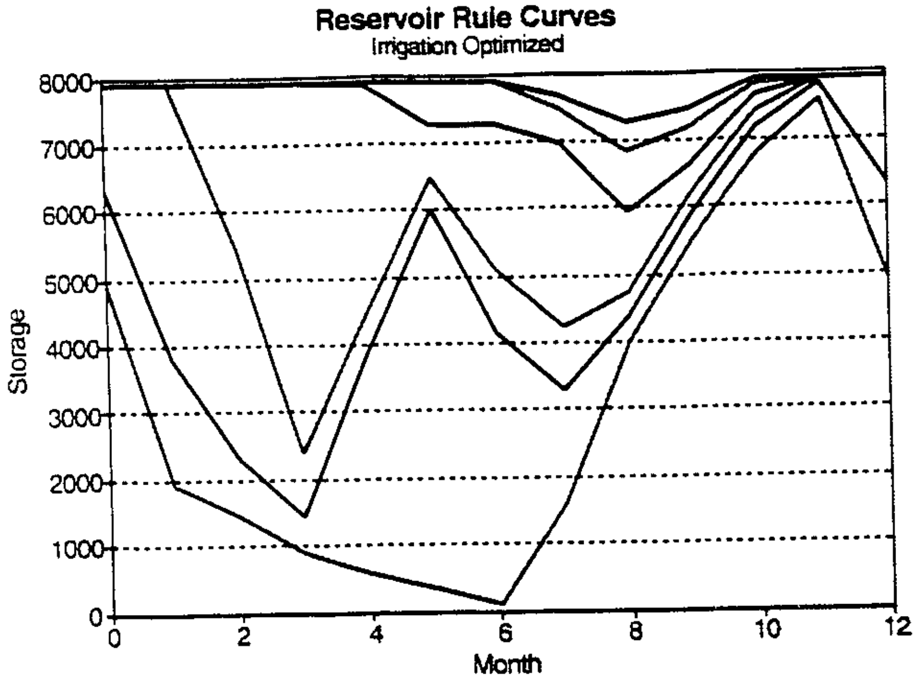


Fig. 5.7 Example of Irrigation Optimized Reservoir Rule Curves

CHAPTER 6

SYSTEM PERFORMANCE EVALUATION OF THE SENEGAL RIVER SIMULATION MODEL

Chapter 6 summarizes the hydrologic and development scenarios evaluated with the simulation model. The details of the simulation methodology and the simulation results for all scenarios are then presented. Chapter 6 corresponds with element **E. SYSTEMS PERFORMANCE** in the Water Resources Analysis Framework of Section 1.7.1 and depicted in Fig. 1.7

6.1 Scenarios Evaluated with Simulation

Various hydrologic and development policy scenarios were evaluated using IRIS. The first objective was to establish the areal extent of irrigated agriculture throughout the Senegal River valley which could be supported at 80% or greater reliability, given the water resource demands exerted by the policy. The secondary objective was to determine the hydro-power production and reservoir storage characteristics at the Manantali reservoir. Except where specifically noted, the system was optimized for irrigation, consistent with the first development objective of the OMVS.

The following hydrologic and development policy scenarios were evaluated using IRIS.

Scenario A

The assumed hydrology is similar to the pre-1960s era. The stochastic analysis and synthetic data generation methodology is given Section 2.4.2 and corresponds to Case A-No drought.

Development Policy

The agricultural development policies considered correspond with policies RP and NRM defined in Section 3.5.

1. Policy RP:	mono-culture rice dominated agricultural development policy with crop mix and crop water consumption characteristics as defined in Section 3.5.
2. Policy NRM:	Small-farmer and natural resources rehabilitation policy with crop mix and crop water consumption characteristics as defined in Section 3.5.

Both policies RP and NRM include the water resource demands placed on the system by the inclusion of the Lac du Guiers-Canal du Cayor complex in the development scenario. The Lac du Guiers demand is that given in Fig. 4.15 (the year 2020 projected demand).

Scenario B1

The assumed hydrology is similar to the 1970s level drought. The stochastic analysis and synthetic data generation methodology are given in Section 2.4.2 and corresponds to Case B1-1970s level drought.

Development Policy

The development policies considered are identical to those in Scenario A.

Scenario B2

The assumed hydrology is similar to the 1980s level drought. The stochastic analysis and synthetic data generation methodology are given in Section 2.4.2 and corresponds to Case B2-1980s level drought.

Development Policy

1. Policy RP: mono-culture rice dominated agricultural development policy with crop mix and crop water consumption characteristics as defined in Section 3.5., with Lac du Guiers demand included (identical to policy 1 of Scenarios A and B1).
2. Policy NRM: Small-farmer and natural resources rehabilitation policy with crop mix and crop water consumption characteristics as defined in Section 3.5., with Lac du Guiers demand included (identical to policy 2 of Scenarios A and B1).
3. Policy Strong NRM/Lac du Guiers demands excluded: Demand profile identical to Policy 2, with Lac du Guiers excluded from system management.
4. Policy RP/Hydro-power optimized: Demand profile identical to Policy 1, with Manantali operation optimized for hydro-power production.

The inclusion of Policies 3 and 4 illustrates two radically different development philosophies for coping with drought at the current level. As the drought continues, the metro-pole (Dakar) will continue to experience exponential population growth. Development objectives (food and energy production and water supply) are thus focused solely on serving the metro-pole (Policy 4). Conventional development models have a strong orientation toward this sort of policy.

Policies 3 and 4 are included only for hydrologic scenario B1, since in the general socio-political context, these more severe policy options would be driven only be the most severe environmental conditions (continued drought).

Policy 3 illustrates the anti-pole development philosophy; the development priority is instead focused on one of the root causes of abject urban poverty, the drought induced rural exodus. A policy which focuses on providing the most water for the agro-pole, to maximize the number of food self-sufficient villages (PIV's) and the number of agro-forestry projects (SYSPRO style GIE's) represents such a policy.

6.2 Simulation Methodology

6.2.1 Hydrologic Data Input

For each hydrological scenario investigated, 10 replicates of 20 years of synthetic annual flow volume data at Bakel were generated according to the methodology presented in Section 2.4.2. Annual volumes at gauge stations Soukatali and Galougo were calculated according to their strong correlation to Bakel volumes. The generated annual volumes were then disaggregated to monthly volumes for consistency with the monthly time-step used in the simulation study. The generated monthly flow time series (10 replicates * 20 years * 12 months) at gauge stations Soukatali, Galougo and Bakel were the raw input flow files to the IRIS simulation model.

6.2.2 Optimized System Control Input

The hydrologic data generated for each hydrologic scenario were also utilized in the pre-optimization phase. The generated and disaggregated Soukatali data were averaged over all years and replicates to provide the set of i_ts (period average inflows) in the continuity Eqn. 5.2 for the Manantali DP algorithm. The differenced, period-averaged Bakel and Soukatali generated flow series were input to the spatial allocation DP algorithm of Section 5.5. These values were the $NATQ_{1t}$'s of Eqn. 5.13, the natural incremental flow occurring between the release point and the first allocation zone. Downstream of Bakel, the arid zone loss functions given in Section 4.3.2 were input into the allocation algorithm as Eqn. 5.15 applied. The policy dependant irrigation and Lac du Guiers demands calculated in Sections 3.5 and 4.4.2 comprised the target demand input (Eqn. 5.17) for the spatial allocation DP algorithm. Except where specifically noted, the irrigation weight, W (Eqn. 5.20) was held at 100, consistent with an irrigation optimized development policy.

The simultaneous solution of the two-dimensional reservoir-allocation DP algorithm provided the input control parameters for the IRIS simulation study; the reservoir rule curves, and the diversion allocation functions. The organization of input to the simulation study with IRIS is depicted schematically in Fig. 6.1.

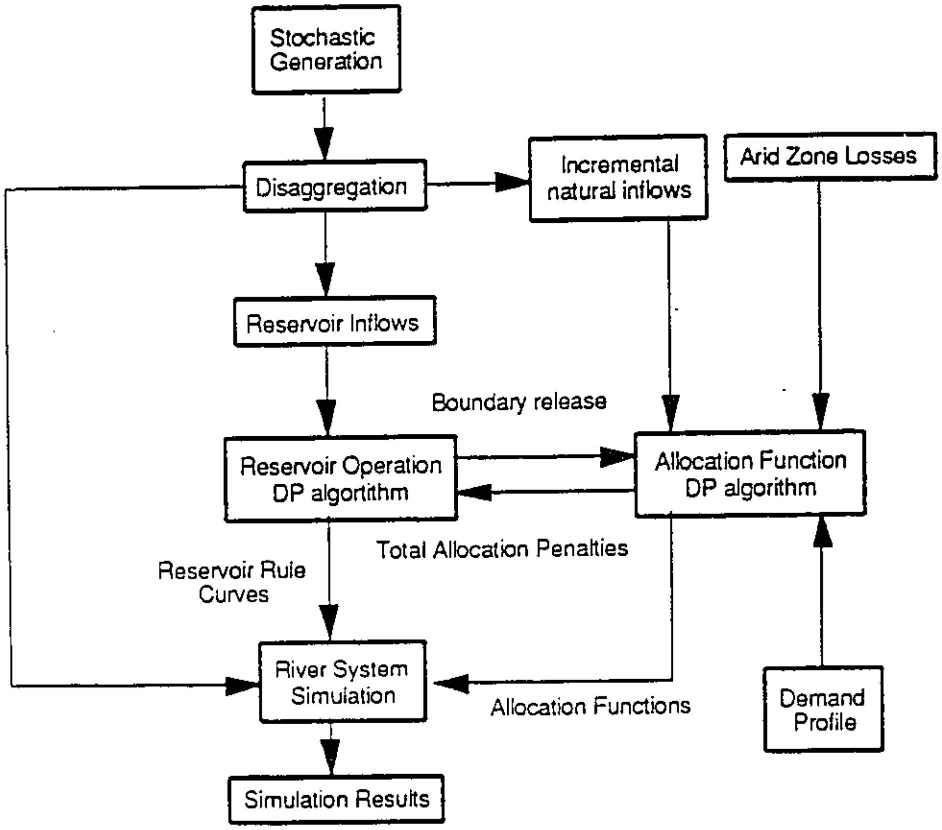


Fig 6.1 Schematic Organization of Simulation Inputs

6.3 Simulation Results and Discussion

This section summarizes the demand reliability and hydro-power production characteristics of all hydrologic and policy scenarios considered. For all scenarios, 10 replicates of 20 years of monthly disaggregated generated hydrologic data were simulated to establish the system performance characteristics. Each replicate thus produced simulation results for 240 monthly timesteps. In all cases an 80% threshold was used as the demand satisfaction reliability screen to determine the extent of irrigation development possible. The reliability screen was defined as the full satisfaction of regional irrigation demands in 80% of the simulated time periods. The 80% reliability threshold was applied equally to the Lac du Guiers-Canal du Cayor municipal demands.

Preliminary simulation results clearly indicated that the lower demands exerted by Policy NRM allowed the use of a higher contre-saison intensity factor (variable **IF**, in Eqn. 3.4, which is the percentage of land remaining in production for a second cultivation cycle). IF applies to the contre-saison crop-mix depicted in Figs. 3.39 and 3.40. Due to the year-round production characteristics of the SYSPRO agro-forestry system, the IF factor applied during the low during the low river flow period from January to July.

6.3.1 Scenario A - No Drought

Table 6.1 Scenario A-No Drought Simulation Summary

Development Policy	Irrigation Weight, W	Hectares	Contre-Saison Intensity, IF	Avg. Ann. Energy (GWH)	95% Rel. Power (MW)
1. RP	100	275 000	50	1002	58.2
2. NRM	100	297 000	65	996	49.9

Figs. 6.2a, b, and c. and 6.3a, b, and c show the reliability summary, multiple replicate Manantali power and storage traces for Policy RP and Policy NRM respectively.

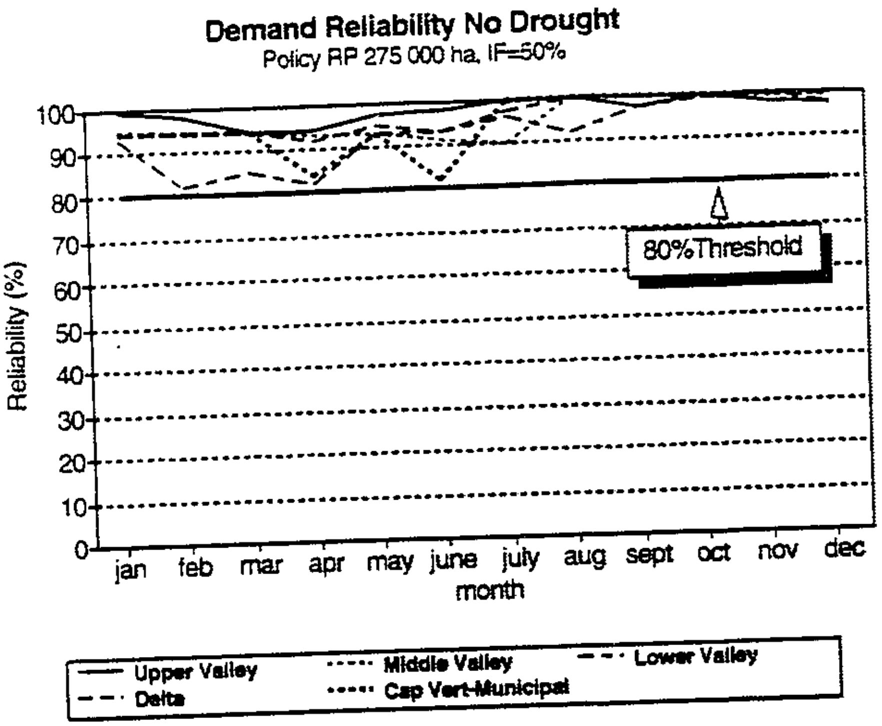


Fig. 6.2a Scenario A - Policy RP Reliability Summary

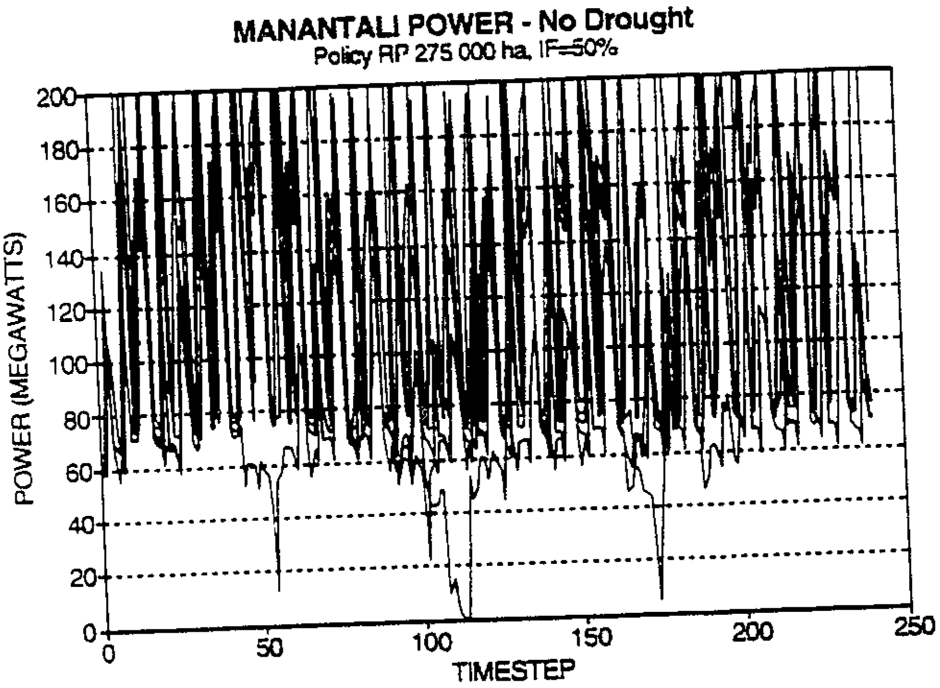


Fig 6.2b Scenario A - Policy RP Manantali Power Production

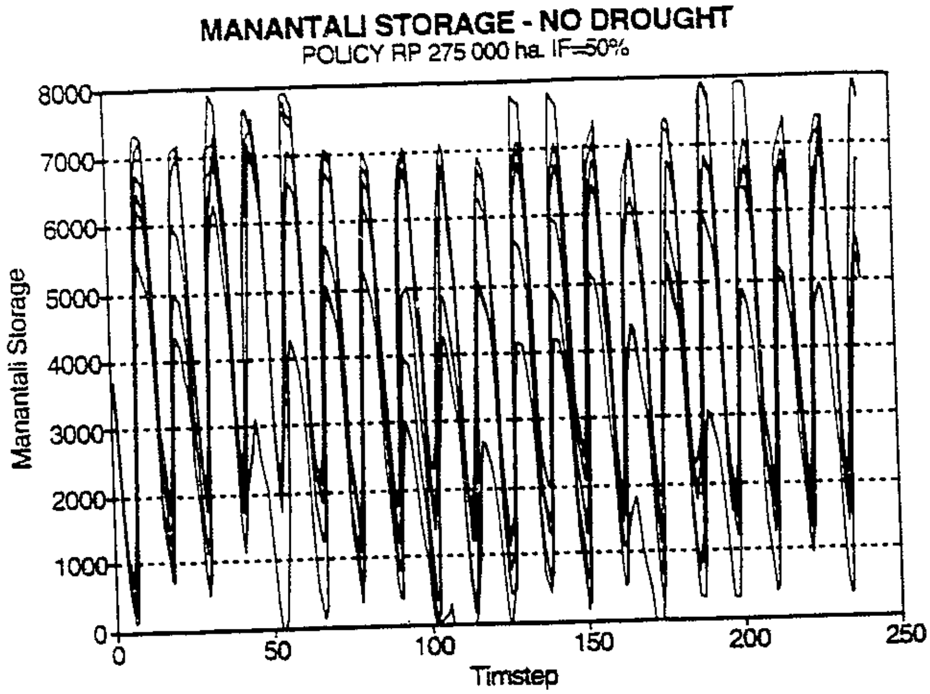


Fig 6.2c Scenario A - Policy RP Manantali Storage

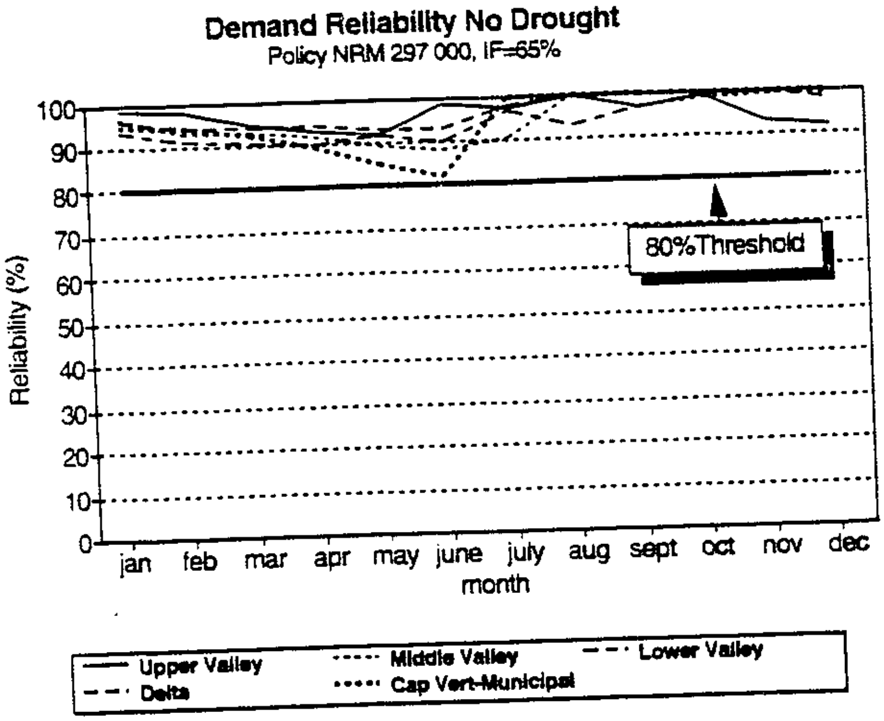


Fig. 6.3a Scenario A - Policy NRM Reliability Summary

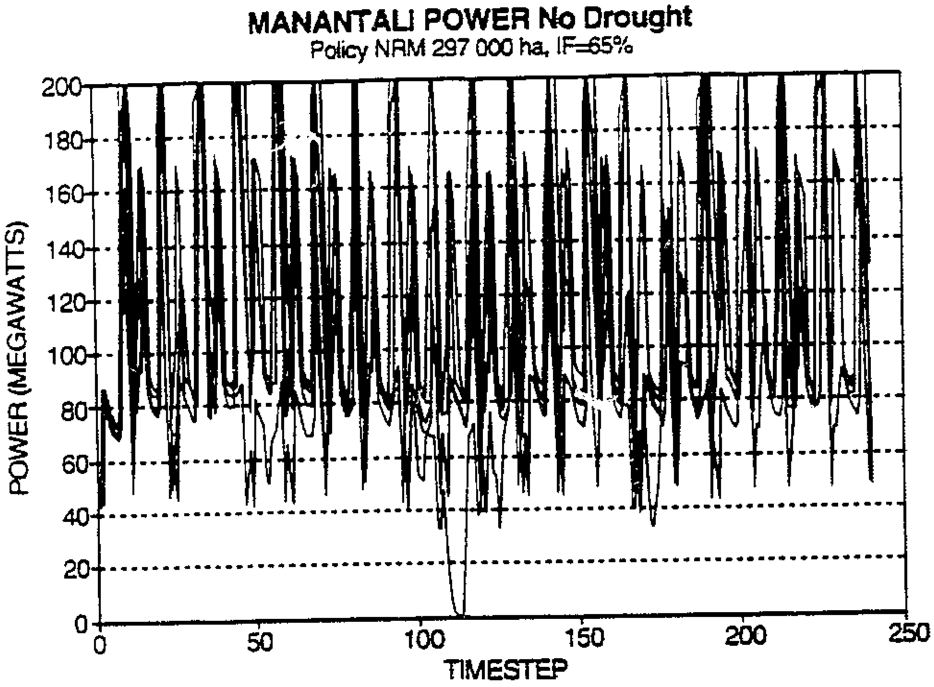


Fig 6.3b Scenario A - Policy NRM Manantali Power Production

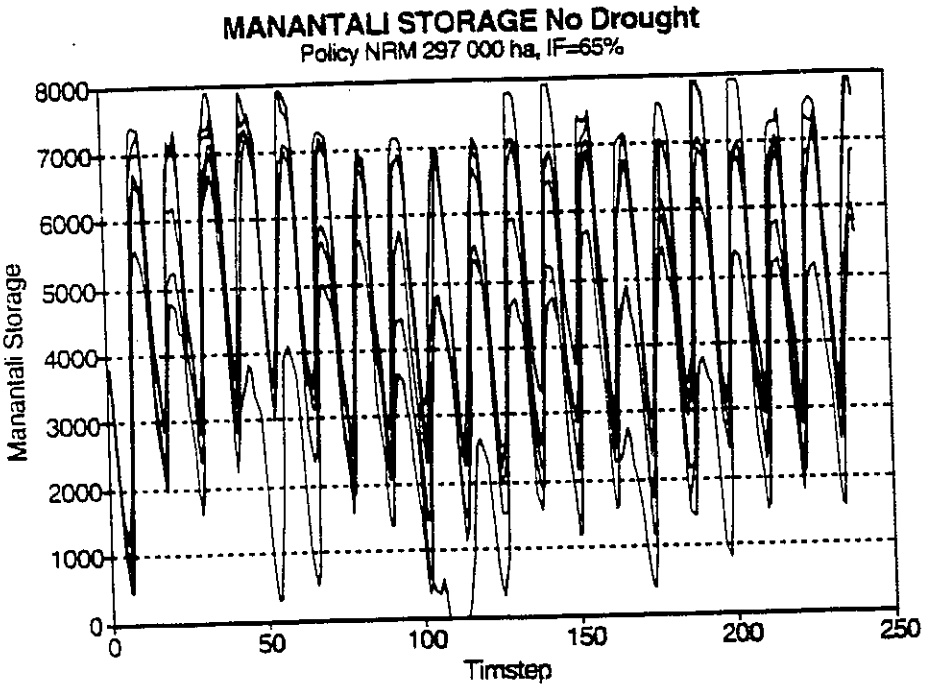


Fig 6.3c Scenario A - Policy NRM Manantali Storage

6.3.2 Scenario B1 - 1970s Level Drought

Table 6.2 Scenario B1-1970s Level Drought Simulation Summary

Development Policy	Irrigation Weight	Hectares	Contre-Saison Intensity	Avg. Annual Energy Production (GWH)	95% Reliable (Firm) Power (MW)
1. RP	100	130 000	50	600	32.1
2. NRM	100	145 000	65	609	28.4

Figs. 6.4a, b, and c. and 6.5a,b, and c show the reliability summary, multiple replicate Manantali power and storage traces for Policy RP and Policy NRM respectively.

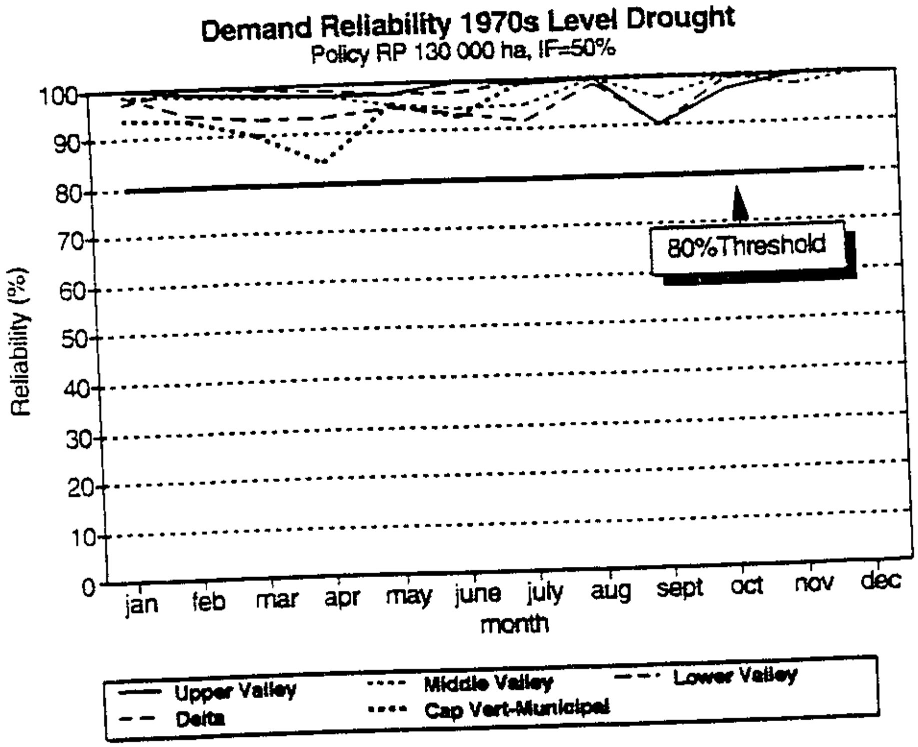


Fig. 6.4a Scenario B1 - Policy RP Reliability Summary

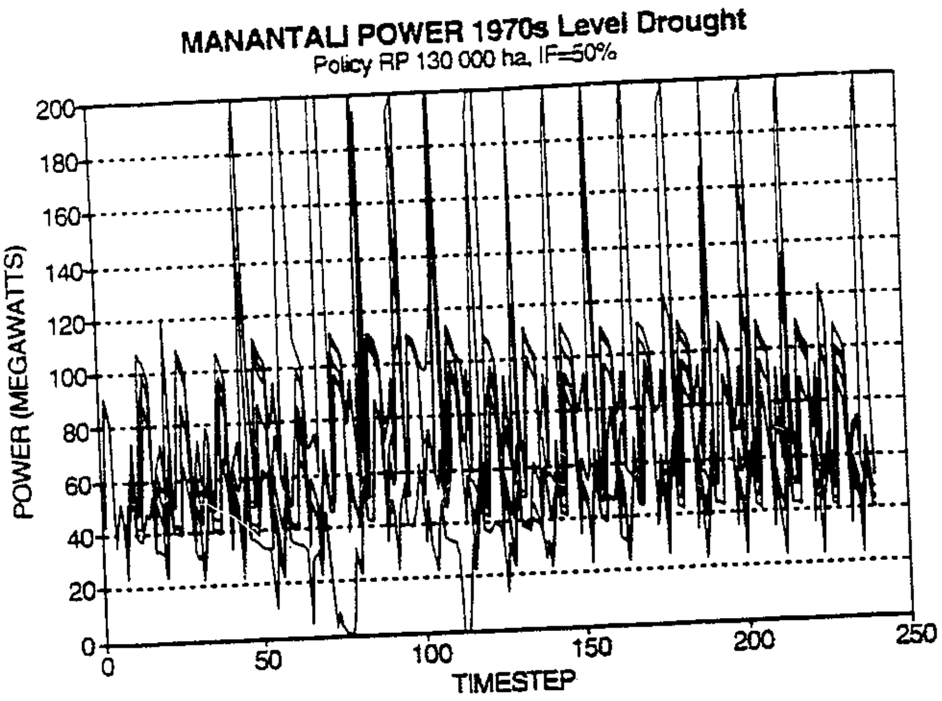


Fig. 6.4b Scenario B1 - Policy RP Manantali Power Production

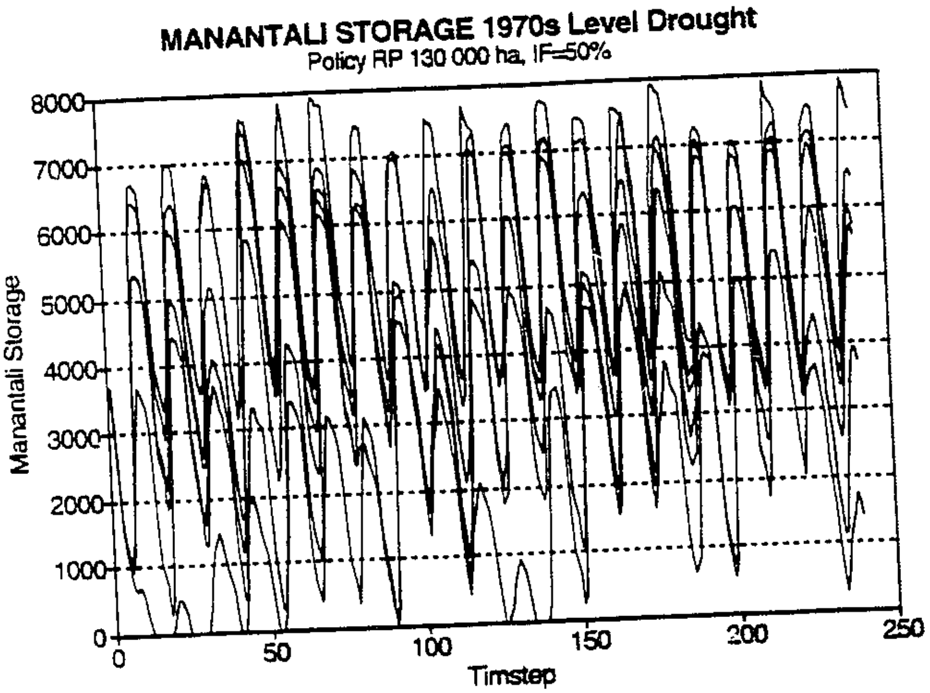


Fig 6.4c Scenario B1 - Policy RP Manantali Storage

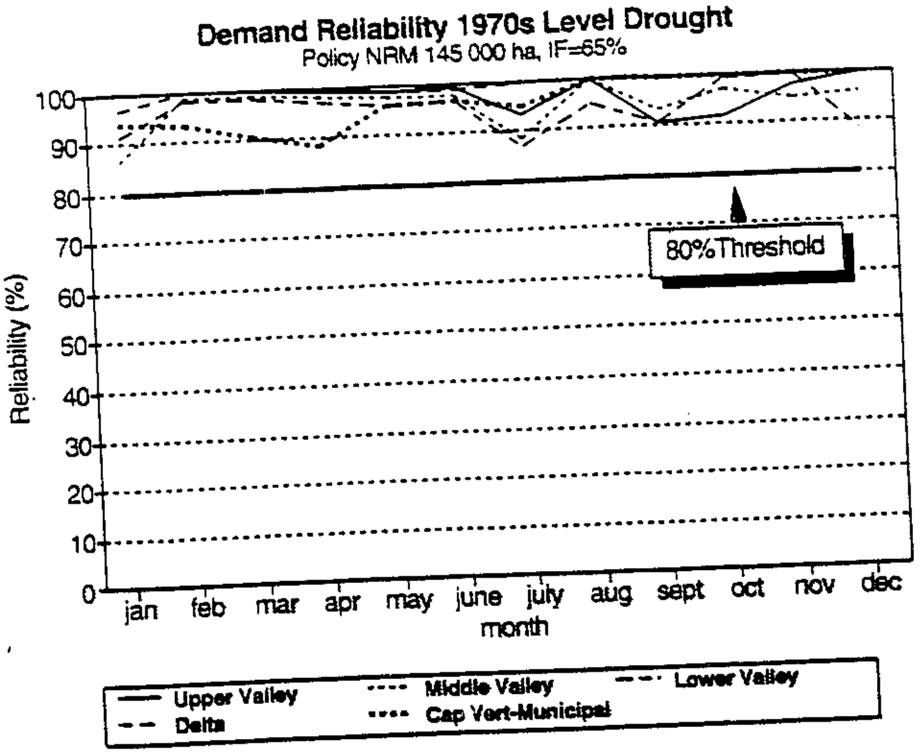


Fig. 6.5a Scenario B1 - Policy NRM Reliability Summary

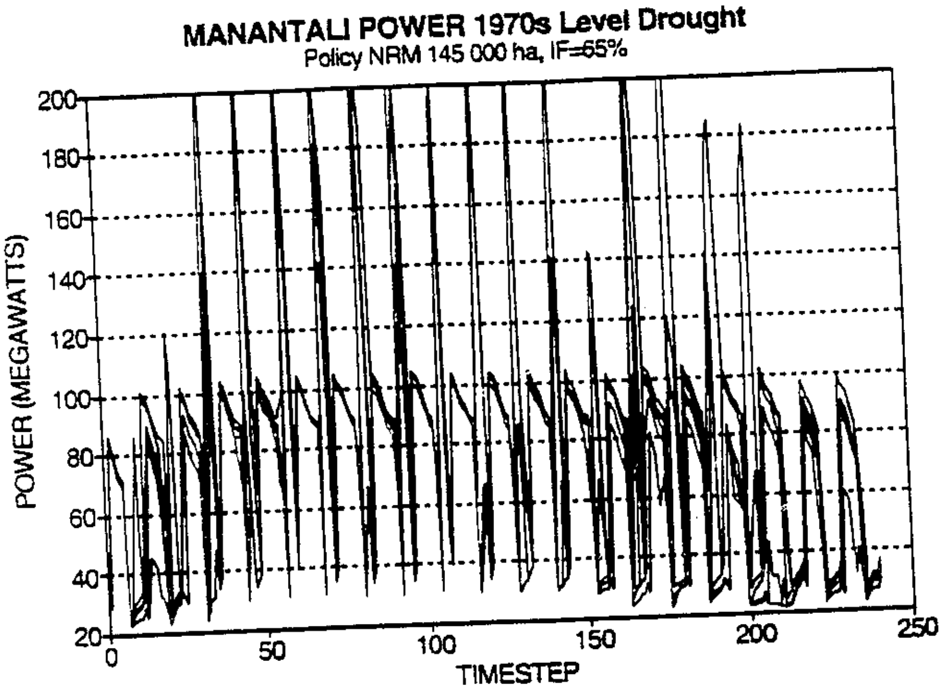


Fig 6.5b Scenario B1 - Policy NRM Manantali Power Production

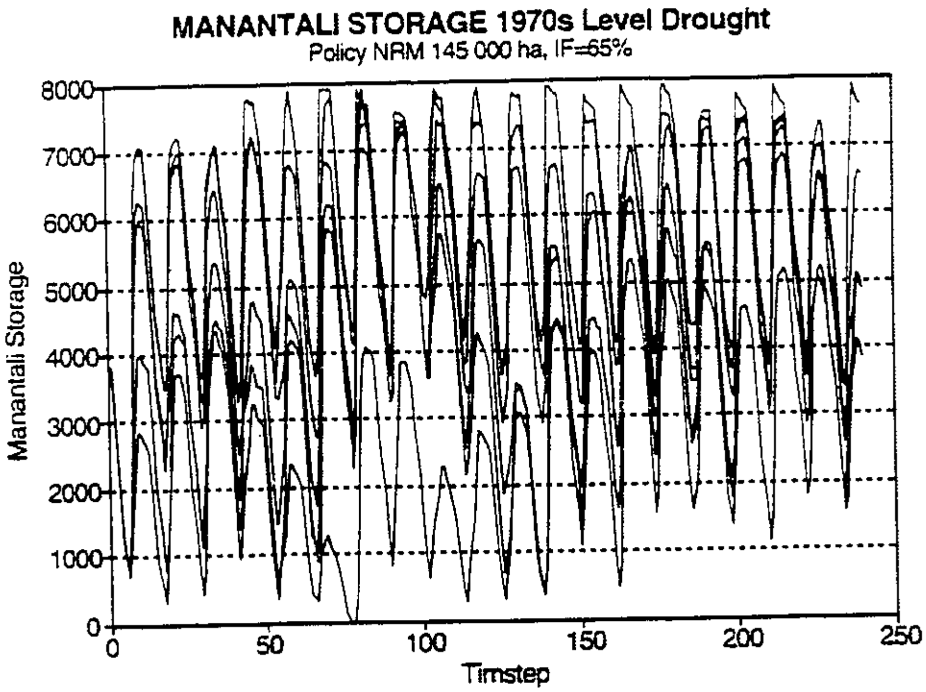


Fig 6.5c Scenario B1 - Policy NRM Manantali Storage

6.3.3 Scenario B2 - 1980s Level Drought

Table 6.3 Scenario B2-1980s Level Drought Simulation Summary

Development Policy	Irrigation Weight	Hectares	Contre-Saison Intensity	Avg. Annual Energy Production (GWH)	95% Reliable (Firm) Power (MW)
1. RP	100	100 000	50	464	26.3
2. NRM	100	115 000	65	440	27.2

Figs. 6.6a, b, and c. and 6.7a,b, and c show the reliability summary, multiple replicate Manantali power and storage traces for Policy RP and Policy NRM respectively

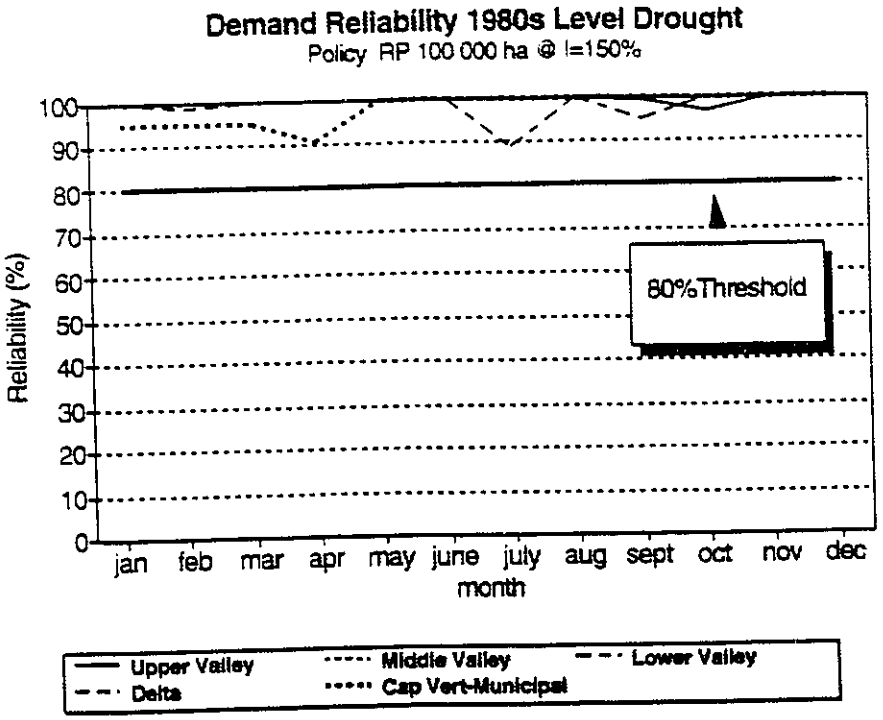


Fig. 6.6a Scenario B2 - Policy RP Reliability Summary

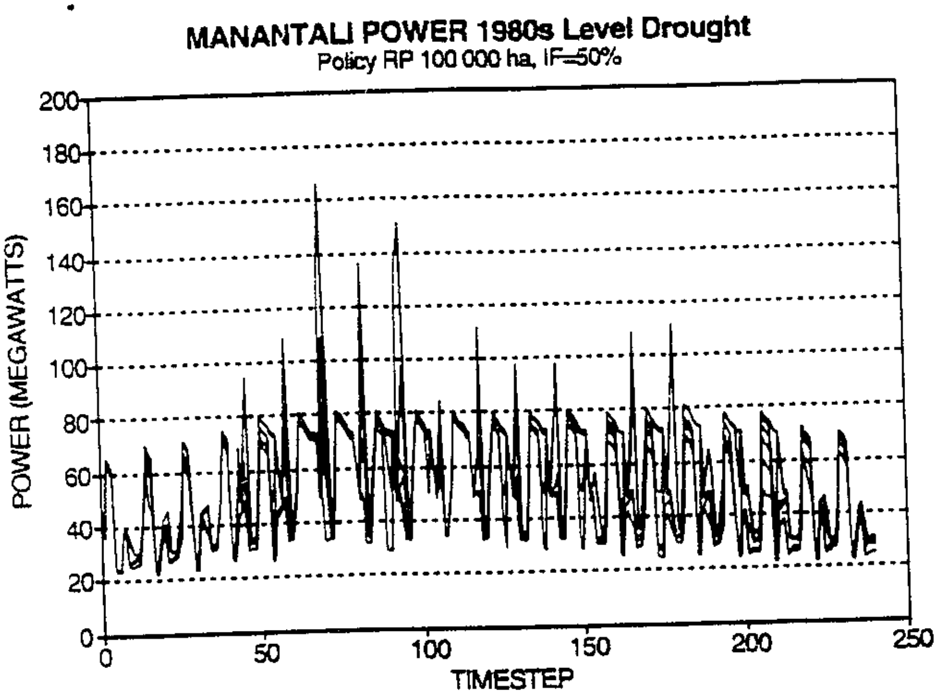


Fig 6.6b Scenario B2 - Policy RP Manantali Power Production

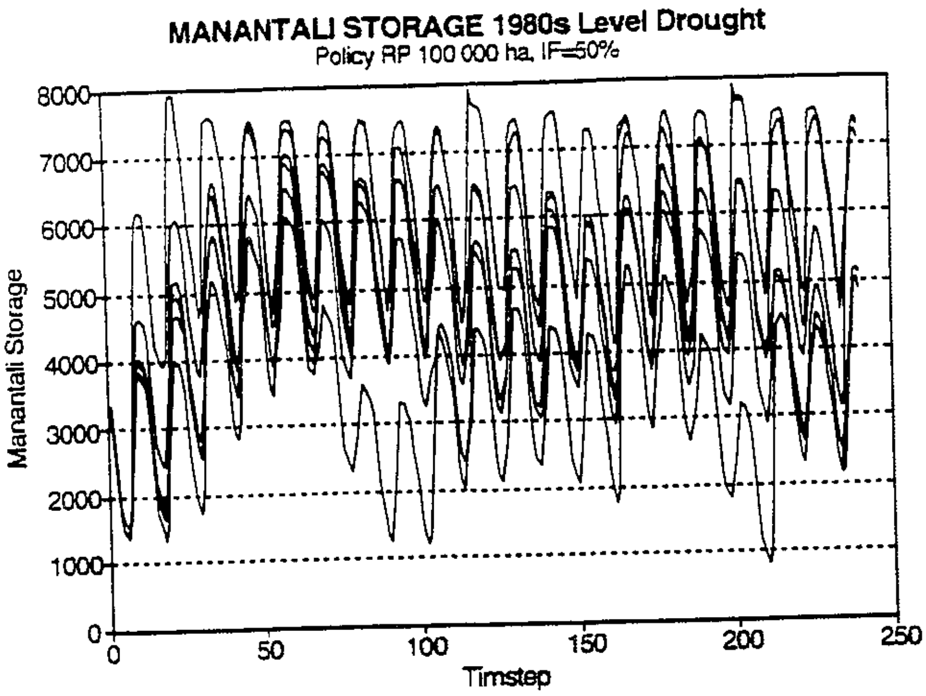


Fig 6.6c Scenario B2 - Policy RP Manantali Storage

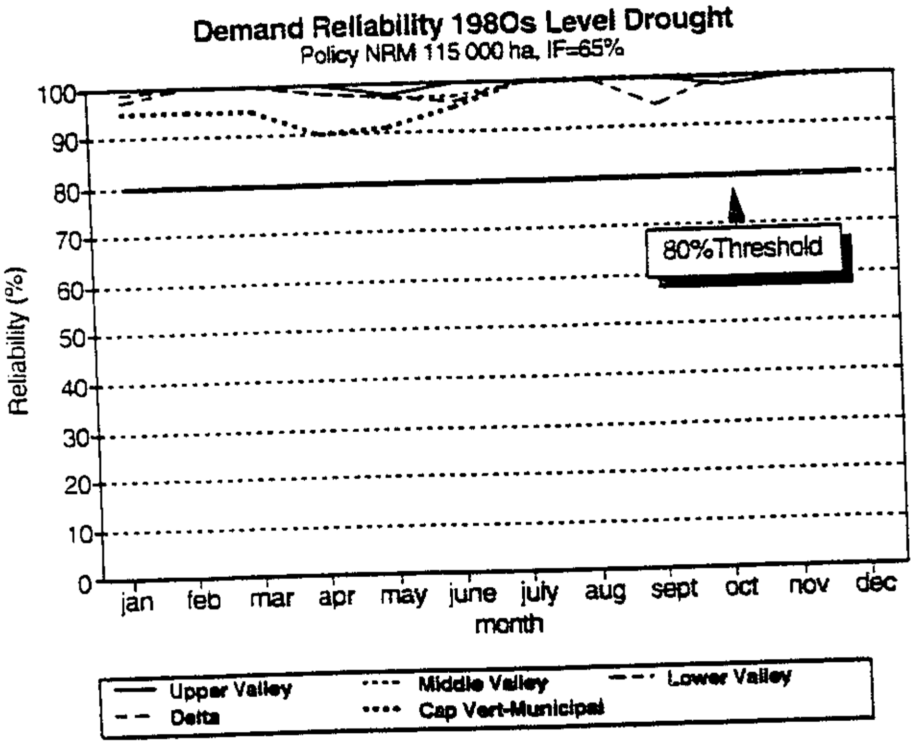


Fig. 6.7a Scenario B2 - Policy NRM Reliability Summary

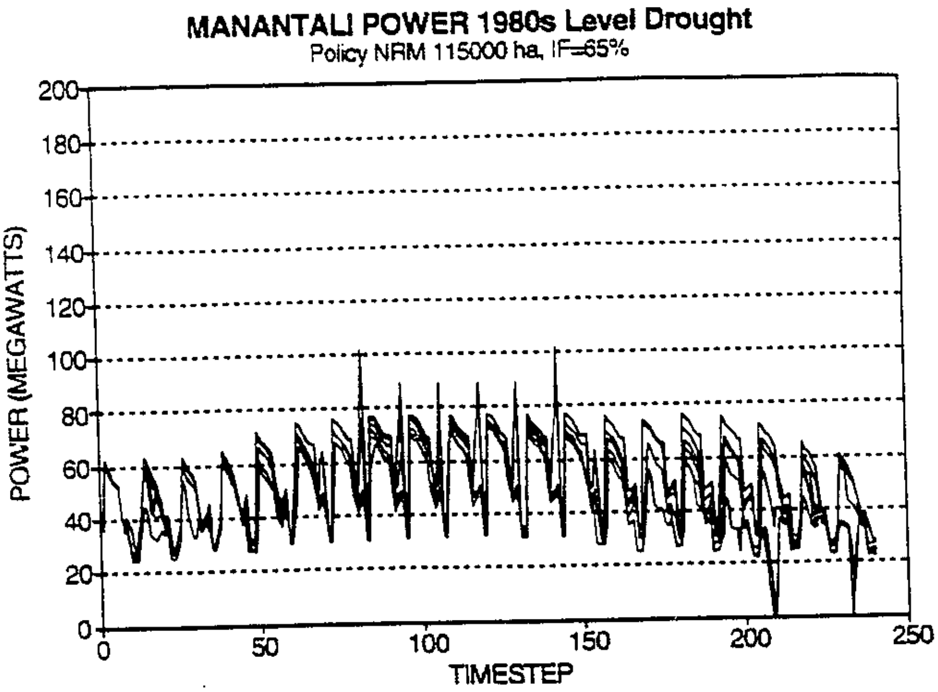


Fig 6.7b Scenario B2 - Policy NRM Manantali Power Production

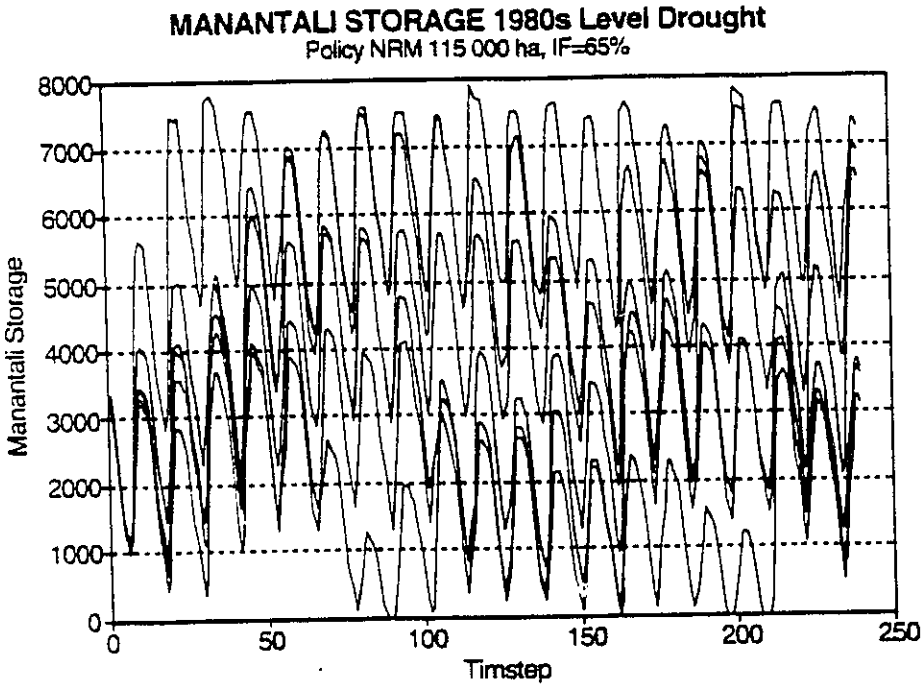


Fig 6.7c Scenario B2 - Policy NRM Manantali Storage

6.3.4. Scenarios A, B1, B2: Summary and Discussion

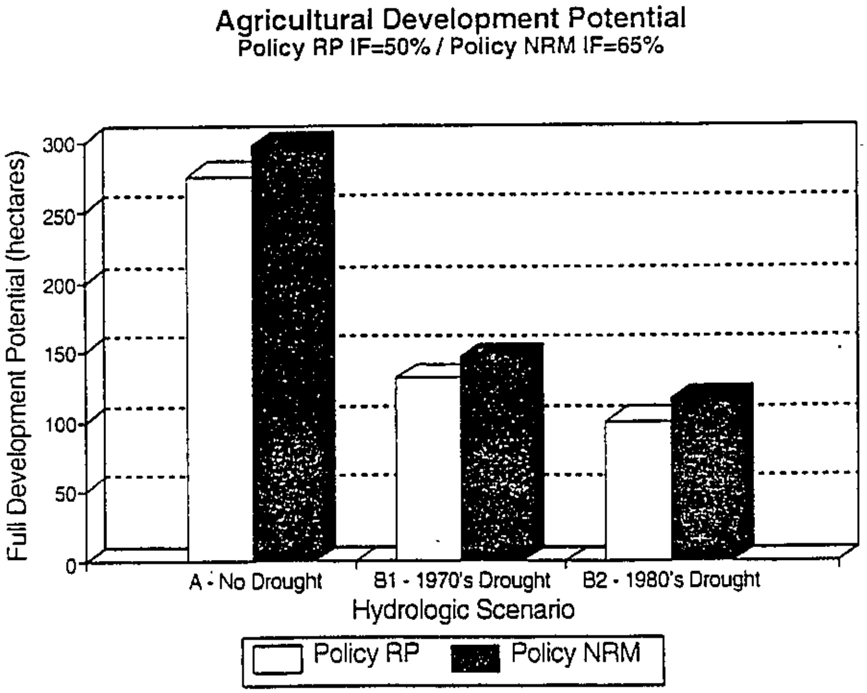


Fig. 6.8 Summary of Simulation Results: Scenarios A, B1, B2

Table 6.4 Summary of Simulation Results: Scenarios A, B1, B2

Hydrologic Scenario	Policy	Annual Energy Production (GWH)	95% Reliable (Firm) Power
Scenario A	RP	1002	58.2
	NRM	996	49.9
Scenario B1	RP	600	32.1
	NRM	609	28.4
Scenario B2	RP	464	26.3
	NRM	440	27.2

The simulation modelling exercise indicates that for hydrologic scenario A, a 275 000 ha policy RP development potential at a contre-saison development potential of 50% and 80% or better reliability is achievable. The 100% development target of 376 000 hectares originally stated by the OMVS [Platon, 1981] is not achievable. For hydrologic scenarios B1 and B2, which most closely resemble the current conditions in the SRB, full development potential is reduced substantially.

For all scenarios considered, reservoir storage is drawn down heavily during the contre-saison period. The contre-saison demands thus place the binding constraint on agriculture development. Increasing the IF factor increases the water demand during the contre-saison, decreasing irrigation reliability during this period. Fig. 6.2a for example shows that the 80% threshold chosen would not envelope reliability if the IF factor was greater than 50%. Fig 6.3a shows that although the NRM demand profile is not as peaked in the flood season (Fig. 3.42), the lower overall demand allowed a conservative upward revision of the IF factor to 65%. For both policies it may be hydrologically feasible to irrigate a larger area at low contre-saison intensities, this is however, impractical from both an infrastructure development perspective and a natural resources management perspective. The installation of irrigation infrastructure is too expensive, even on a small scale, to allow most of that infrastructure to remain idle for all but one irrigation cycle. Furthermore, if irrigated agriculture has natural resources management objectives such has agro-forestry, water resources management must account for the year-round demand pattern exerted by such production systems.

Under the drought conditions of hydrologic scenarios B1 and B2, the available storage at Manantali is a greater percentage of the basin hydrologic budget. This is reflected in part by the improved storage dependant reliability for both policies. A higher IF factor could have possibly been used, this however would come at the expense of reservoir performance since storage is being used heavily. For example in Figs. 6.4c and 6.5c increased contre-saison releases associated with a higher IF factor would cause the reservoir to empty more frequently yet. To formally resolve the issue of which IF factor to use requires a complex and subjective multi-objective compromise between irrigation reliability and the severity of reservoir failure. Empirically, consideration of both irrigation reliability and reasonable reservoir operation indicated that the 50% and 65% RP and NRM IF factors utilized were appropriate.

The higher reliability achieved by both policies for scenarios B1 and B2 is also likely attributable to the assumptions made on the stochastic processes driving hydrological scenarios B1 and B2. The stochastic process is scaled to the mean and variance of the annual flow volumes which occurred during the 1970s and 1980s. Although the absolute volumes are small, the variance is relatively small as well, thus the generated sequences for this scenario are less erratic and irrigation development is less vulnerable to year to year fluctuations. The pre-1960s Senegal River hydrology was naturally very erratic. The reader is invited to review the sample sequences in Figs. 2.14 and 2.19 which reflect this phenomenon. Whether or not a hydrological regime stable at the 1970s or 1980s level will behave in this fashion is a matter of pure speculation.

A advantage of policy RP was discernable in terms of hydro-power production. Total annual energy production varied by only 1% between policies for hydrologic scenarios A and B1. The 95% firm power (defined here simply as the minimum power available 95% of the time) was higher for policy RP in all cases, however the relative advantage decreased in the drought scenarios. The firm power available is related to the duration of low storage/low head periods. More precisely in the case of a reservoir such as Manantali, with a clearly defined draw-down and replenishing periods, the firm power is related to the slope of the release demands exerted on the reservoir relative to the slope of the reservoir inflow profile. The use of a simulation model with a time-step of one month may therefore be too coarsely resolved to capture these physical subtleties, nonetheless the firm power calculation is included here for illustrative purposes.

In the case of Manantali, firm power is a function of the available storage in the months of May, June and July. Visual inspection of the storage traces for scenarios A and B1 (figs. 6.2c, 6.3c, 6.4c, 6.5c) indicate that Policy RP empties the reservoir more frequently despite providing a higher firm power value. This is a somewhat anomalous result but is likely related to the more peaked demand profile that Policy RP exerts. Policy RP draws on storage more quickly from January to May and thus is more vulnerable to failure if the inflows are weak. Policy NRM has a smoother demand profile, storage is drawn down more slowly as the contre-saison period extends to July. Reservoir storage is therefore in a low storage state for a longer duration.

For scenario B2, the hydro-power characteristics were somewhat different. Policy RP produced 5% more power than Policy NRM. The 115 000 hectare development potential under policy NRM for this scenario is probably close to the extreme upper bound as reservoir storage is drawn down frequently which could account for the reduced energy production.

The simulation results for all scenarios indicate that the Lac du Guiers-Cap Vert fares poorly relative to the other regions, suggesting the satisfaction of Cap Vert municipal demands are constraining agricultural development. The impact of a strong NRM policy that relaxes the Lac du Guiers-Cap Vert demands and pursues only natural resources management objectives and excludes municipal demands are presented in the next section.

6.3.5 Scenario B2 - 1980s Level Drought/Strong Natural Resources Policy

Table 6.5 Scenario B2-1980s Level Drought/Strong Policy NRM Simulation Summary

Development Policy	Irrigation Weight	Hectares	Contre-Saison Intensity	Avg. Annual Energy Production (GWH)	95% Reliable (Firm) Power (MW)
1. NRM	100	170 000	65	480	31.1

The simulation results reported above correspond to the strong natural resources management policy defined as policy 3 under Scenario B2 in Section 6.1. To simulate this policy, Manantali operation was optimized for a demand pattern that did not include Lac du Guiers demands. The Lac du Guiers demands were simply excluded from the solution of the spatial allocation DP algorithm (Section 5.5). In the solution of Eqn. 5.20, **TOTPEN**(r_t) does not reflect any penalty on Lac du Guiers demands. Optimization in this case determines a far more favourable reservoir operating policy. The total development potential rose to 170 000 hectares at a constant contre-saison intensity of 65%. The power production and storage traces, figs. 6.9a and b reflect the improved hydro-power production and reservoir management characteristics. Annual energy production rose to 480 GWH and firm power increased to 31.1 MW. The much improved reservoir management over Scenario B2 Policy NRM is largely due to ceasing the large additional contre-saison releases needed to assure adequate filling of Lac du Guiers for Cap Vert demands.

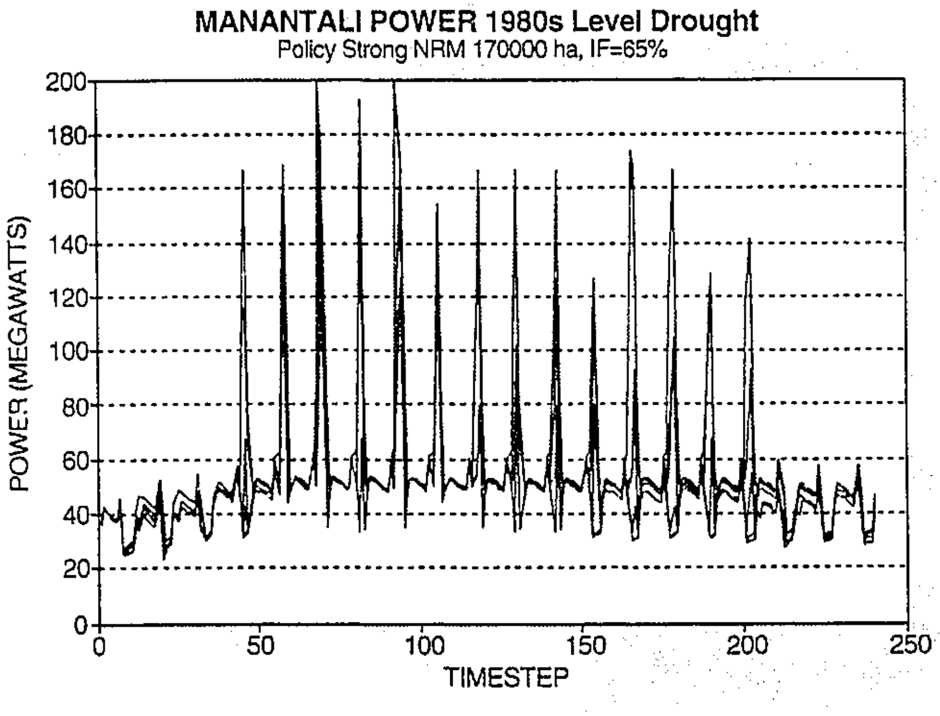


Fig 6.9a **Scenario B2 - Policy Strong NRM Manantali Power Production**

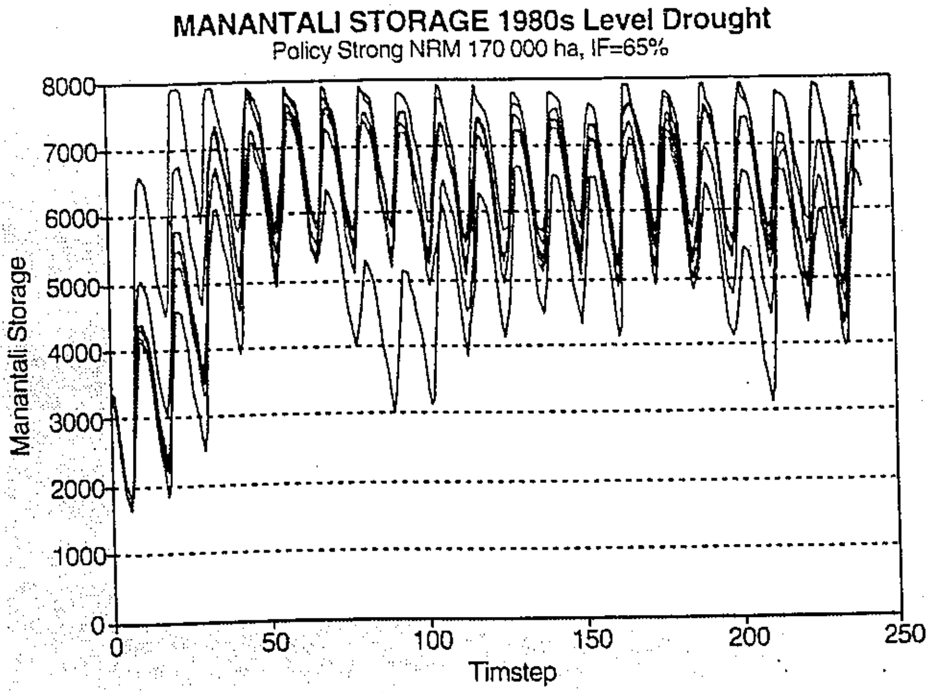


Fig 6.9b Scenario B2 - Policy Strong NRM Manantali Storage

Inspection of the reliability summaries in figs 6.9c and 6.9d reflects different assumptions on the operation of the Taouey Canal at Richard Toll, which feeds Lac du Guiers. In Fig. 6.9c no flow is diverted into Lac du Guiers at any time. In fig 6.9d flow is allocated to Lac du Guiers as in Scenario B2 Policy NRM (Section 6.3.3), however the flow availability has changed since Manantali is no longer operated for the Lac du Guiers demand pattern. Although Lac du Guiers still profits from the high season flows, storage is insufficient to meet the year-round Cap Vert demands and the lake is emptied almost every year by May.

Available volumes at Richard Toll need not be met by strictly Manantali releases. Diama regulation can provide sufficient backwater elevation at Richard Toll to maintain the necessary diversion volumes for Lac du Guiers [Bader, 1992]. The extent to which this would compromise Delta irrigation development and reliability is not possible to estimate with a model such as IRIS which does not calculate backwater elevations.

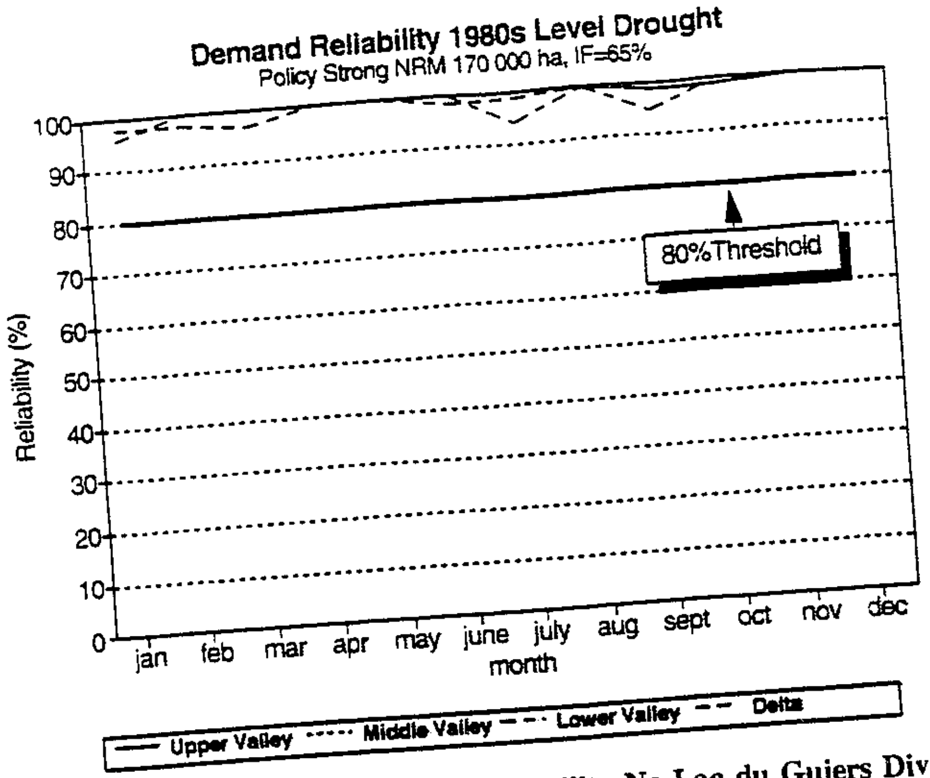


Fig 6.9c Scenario B2 - Strong NRM Reliability-No Lac du Guiers Diversion

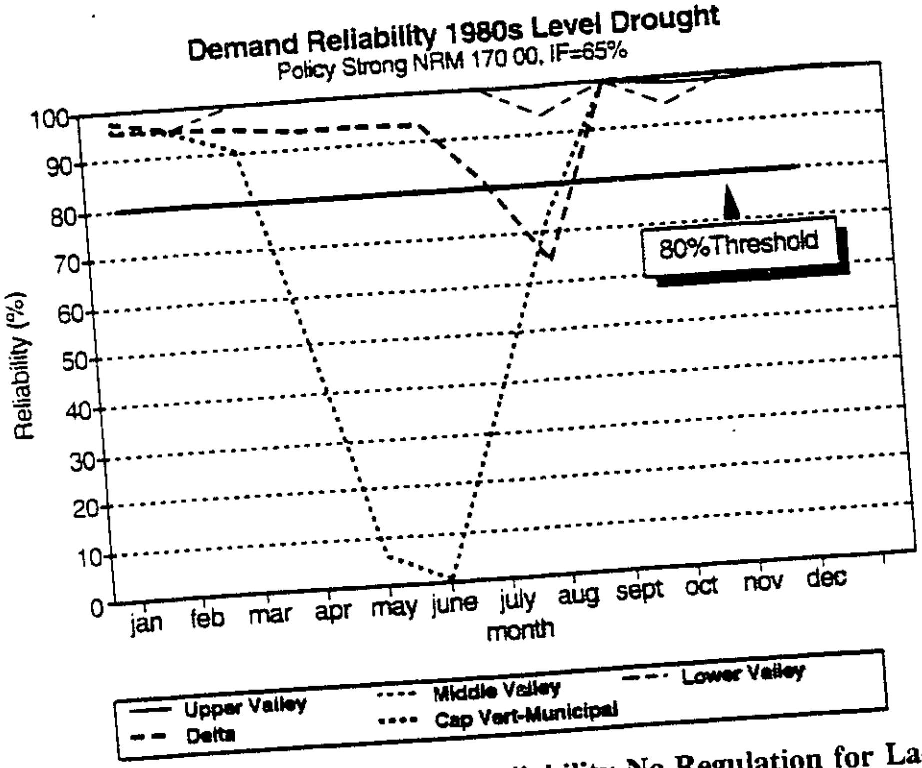


Fig 6.9d Scenario B2 - Strong NRM Reliability-No Regulation for Lac du Guiers

The trade-off between delta irrigation and Cap Vert demands is visible in Figs. 6.9c and 6.9d. Delta reliability decreases significantly in the second case because the high season flows which would fill Diama and provide year-round delta irrigation is now diverted into Lac du Guiers. Diama does not reliably fill to meet all delta demands in the following contre-saison. Gibb [1986b] report the result from a physical simulation study of the Diama - Lac du Guiers system. They conclude that if the current drought conditions persist it would be impossible to further develop irrigated agriculture in the delta and fill Lac du Guiers reliably with Diama regulation. In the same study, Gibb use a greater active storage capacity at Lac du Guiers than is available according to BCEOM [1988].

It is strongly recommended that the entire system be the subject of a revised physical simulation study. Such an exercise could identify the optimal combination of Diama regulation and Manantali releases which provide the reliable Lac du Guiers year-round inflows. The total potential irrigation development in this case is between 115 000 and 170 000 hectares. The significant result is that Manantali regulation for Lac du Guiers demands definitely constrains agricultural development objectives in the valley and delta under the prevailing hydrologic regime.

6.3.6 Scenario B2 - 1980s Level Drought/Policy RP Hydro-power Optimized

Table 6.6 Scenario B2-1980s Level Drought/Policy RP Hydro-power Optimized Simulation Summary

Development Policy	Irrigation Weight	Hectares	Contre-Saison Intensity	Avg. Energy Prod.(GWH)	95% Reliable Power (MW)
RP	50	85 000	50	474	28.0
RP	10	85 000	50	484	30.4
RP	1	85 000	50	487	31.3
RP	0	85 000	50	490	31.9

The simulation results reported above correspond to the Policy RP/hydropower optimized case defined as policy 4 under Scenario B2 in section 6.1, with increasing emphasis on hydro-power production. Preliminary simulation results indicated that a 100 000 ha development level could not be reliably supported under a hydro-power optimized policy. Thus an 85 000 ha development level was assumed for hydro-power optimization simulation. Hydro-power production was optimized by placing increasingly less emphasis on the penalties associated with irrigation demands by decreasing the value of W in the reservoir recursion equation 5.20 until the objective function reflected only hydro-power objectives. Figs 6.10a, 6.10b and 6.11a, 6.11b contrast the power production and storage traces at irrigation weight=50 and irrigation weight=0 respectively. A strong tendency to maintain high storage by curtailing contre-saison releases is evident in the hydro-power optimized case. The effect of decreased irrigation weights on irrigation reliability is shown in figs. 6.12a, b, c and d.

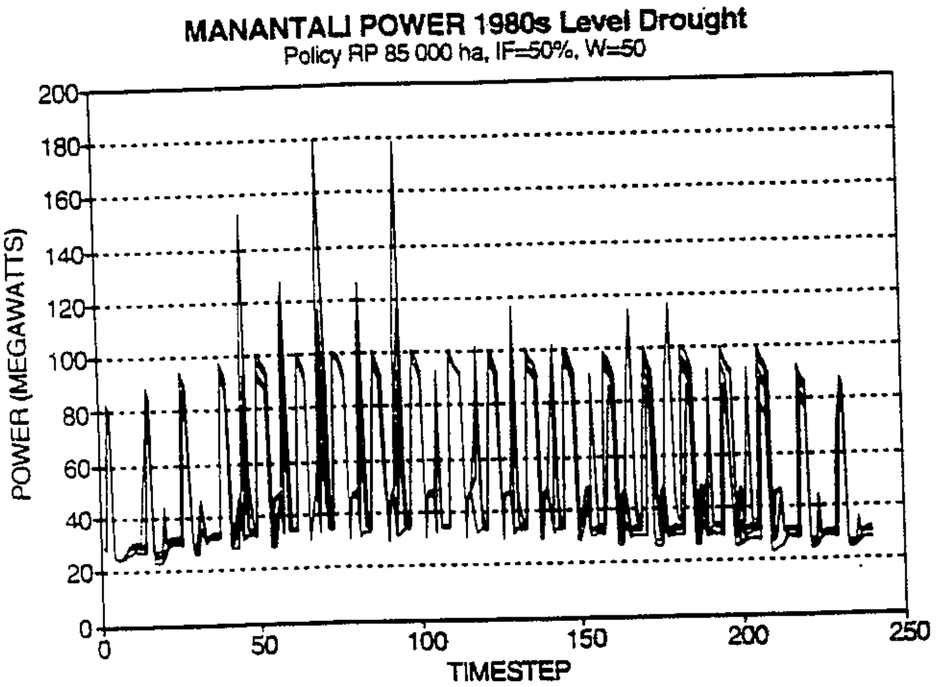


Fig 6.10a Scenario B2 - Policy RP Manantali Power Production, Irrigation Wt.=50

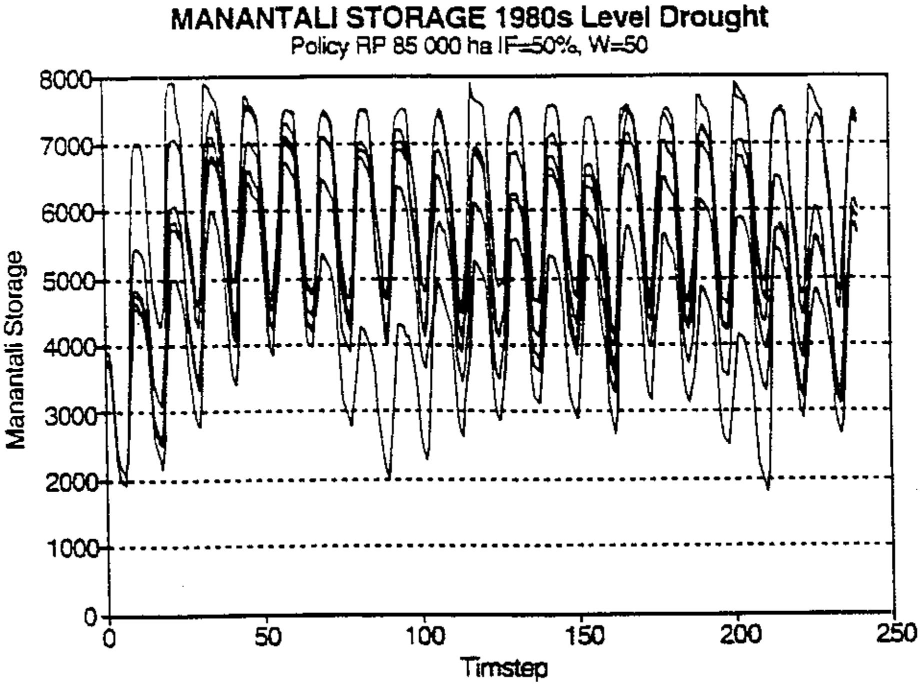


Fig 6.10b Scenario B2 - Policy RP Manantali Storage, Irrigation Weight=50

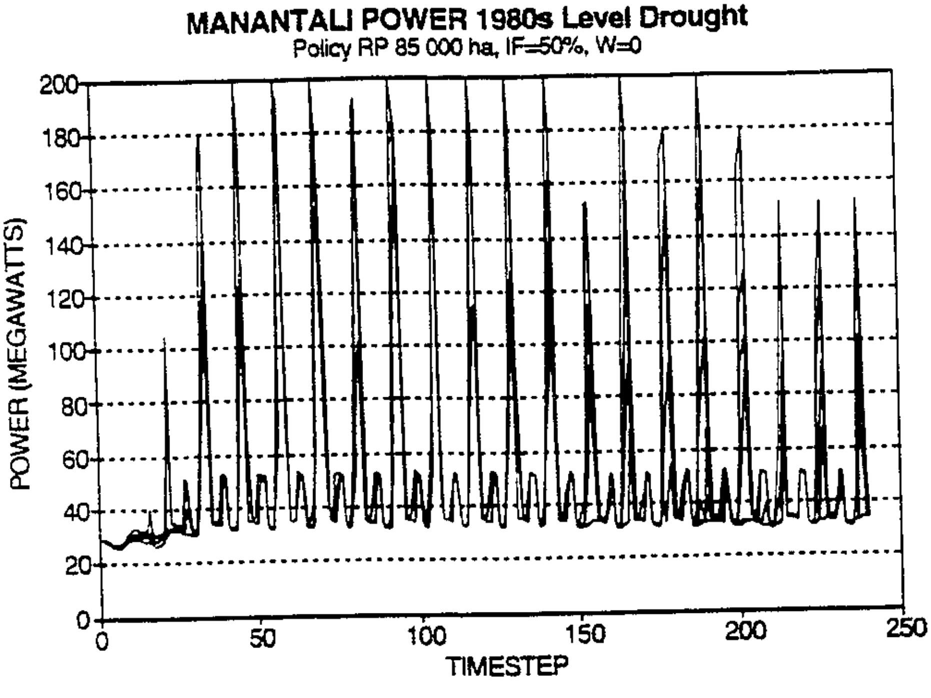


Fig 6.11a Scenario B2 - Policy RP Manantali Power Production, Irrigation Wt.=0

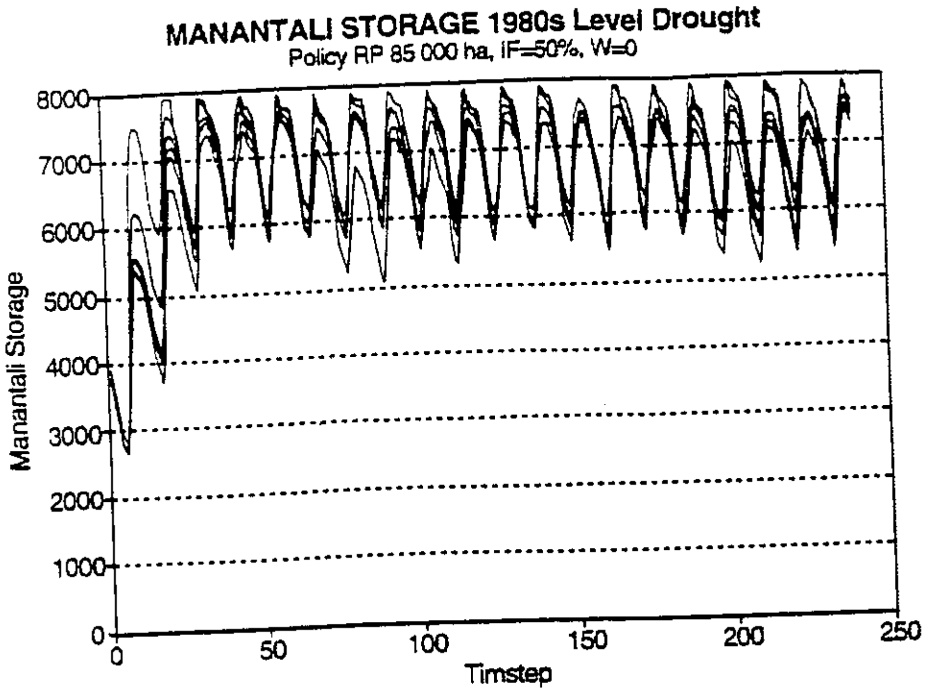


Fig 6.11b Scenario B2 - Policy RP Manantali Storage, Irrigation Weight=0

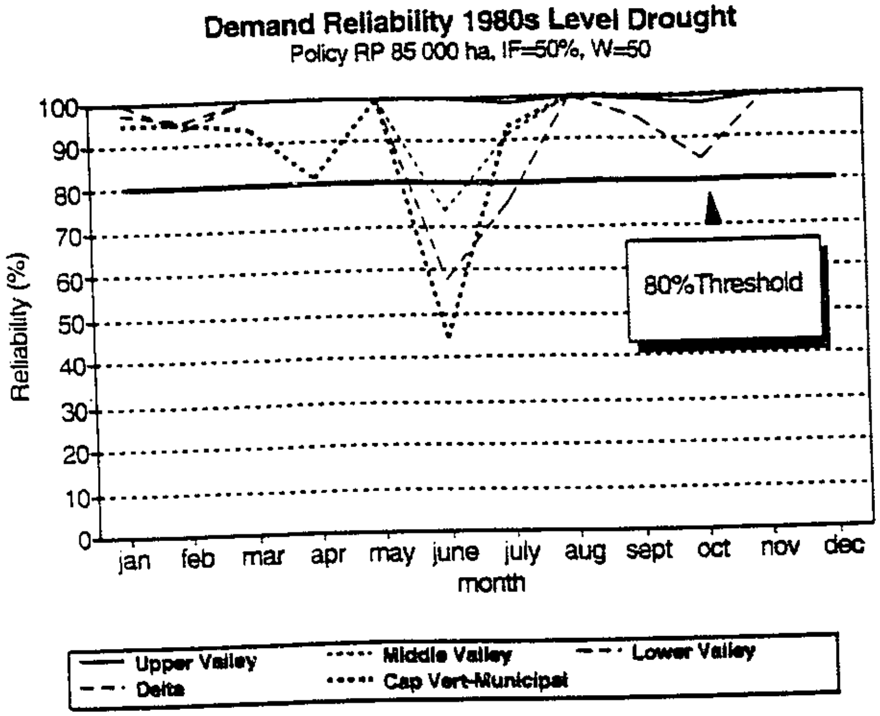


Fig. 6.12a Scenario B2 - Policy PR Irrigation Weight=50 Reliability Summary

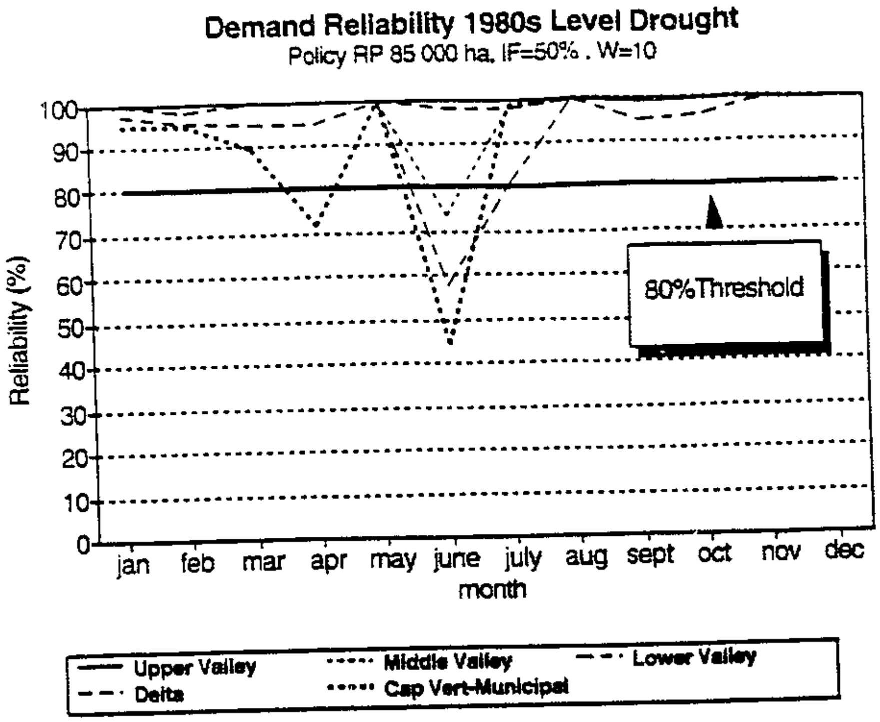


Fig. 6.12b Scenario B2 - Policy PR Irrigation Weight=10 Reliability Summary

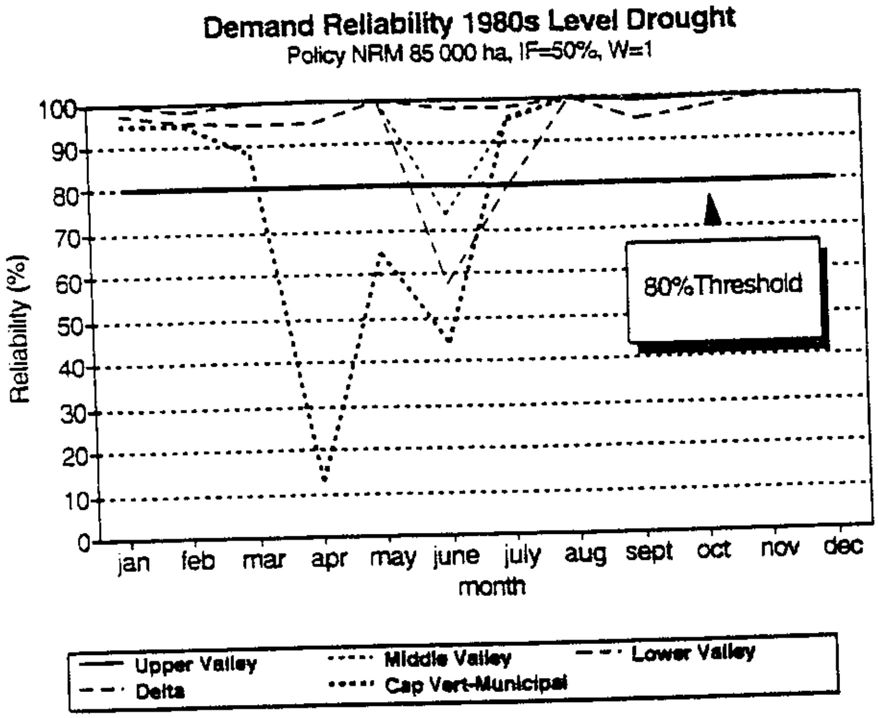


Fig. 6.12c Scenario B2 - Policy PR Irrigation Weight=1 Reliability Summary

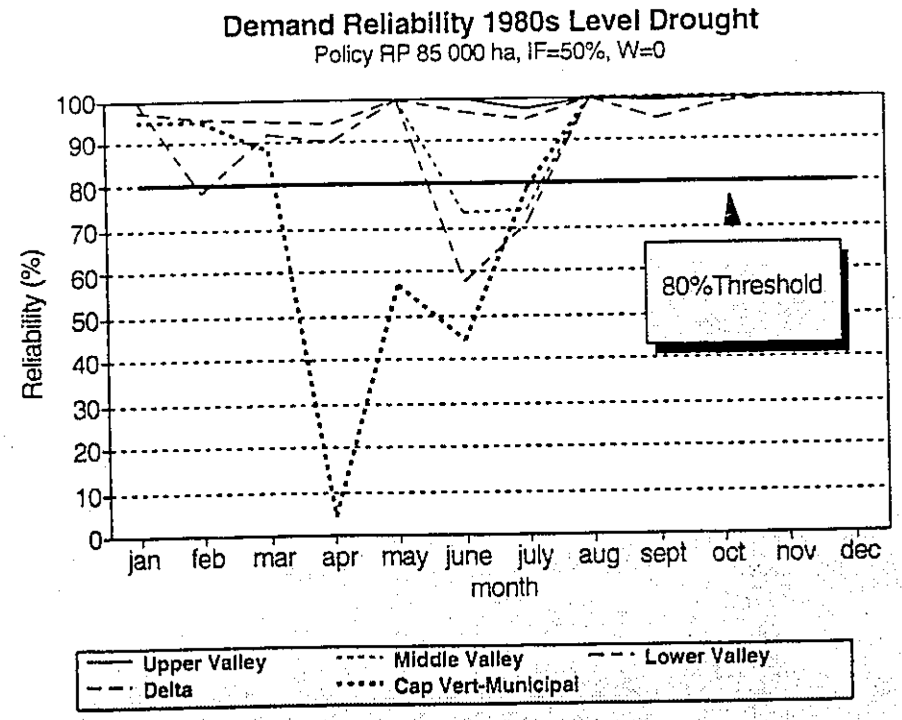


Fig. 6.12d Scenario B2 - Policy PR Irrigation Weight=0 Reliability Summary

The general result from the hydro-power optimization study is that power production can increased at a substantial cost to irrigation. Annual power production increases 5% from 464 GWH (Table 6.3) to 490 GWH. The Manantali reservoir has clearly defined reservoir filling and emptying periods, therefore a high degree of complementarity exists between irrigation and hydro-power objectives and further optimization of hydro-power benefits is probably not worthwhile. Cap Vert reliability fares the worst with Manantali optimization for hydro-production, indicating again that Lac du Guiers is highly dependant on Manantali contre-saison releases to maintain adequate inflows. The implicit result is that if the filling of Lac du Guiers could be eliminated from the demand profile, the saved contre-saison releases could be used to expand rice cultivation, similar to the basic result from the strong NRM policy. Such a policy would however serve contradictory ends; the policy of rice cultivation intends to serve the demands of the metro-pole as does the Lac du Guiers-Canal du Cayor complex. Curtailing one objective to enhance the other would probably not be a palatable development option from a political perspective since it would at least appear to decrease the net benefits to the metro-pole from river development.

The contrast between the full agricultural potential for both policies reported in Section 6.3.4 and the strong NRM and RP (hydro-optimized) policies for hydrological scenario B2, 1980s level drought, is shown in Fig. 6.13. The full development potential under Policy RP/hydro-optimized is limited to as little as half of Policy strong NRM.

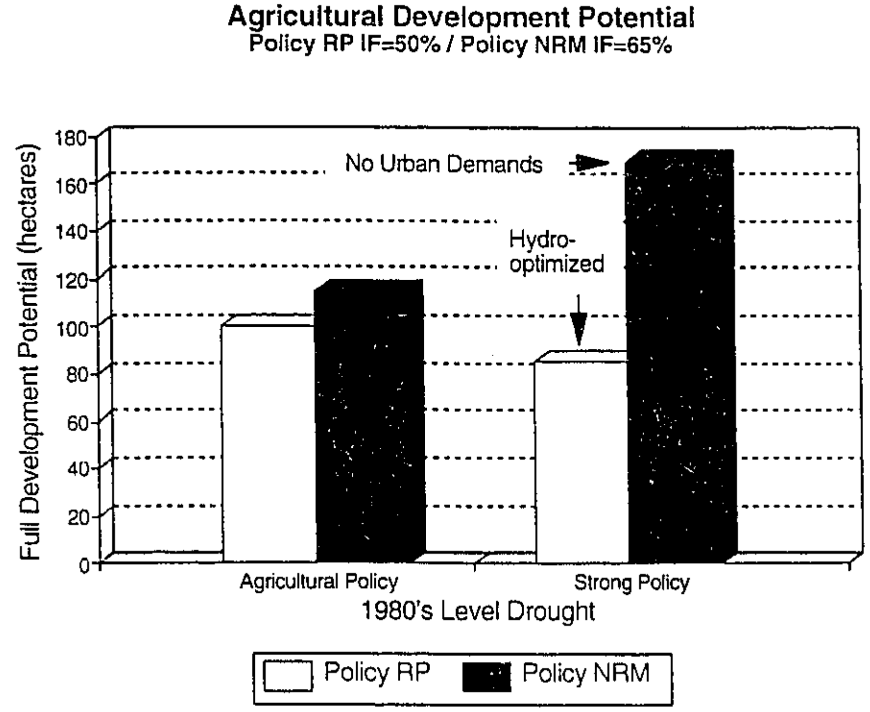


Fig. 6.13 Summary of Simulation Results: Scenario B2 - Strong Policy

The comparison of simulation results for strong Policy RP and strong Policy NRM for hydrologic scenario 2B reveals the large difference in the full agricultural development potential for these policies. The simultaneous provision of hydro-power, rice production and municipal water supply would limit the full agricultural development potential to as little as half of what could be developed if the system was instead operated for village-scale irrigation and dedicated agro-forestry production only under policy NRM.

Some care should be exercised in interpreting the results from the hydro-power optimization study. The hydro-power production results indicate that, in principle, the novel space-time DP algorithm for reservoir management formulated in this study, is behaving as expected. The results are not however globally optimal, the use of the linear approximation of the head-storage curve in Eqn. 5.20 serves to drive storage upward although the net head (Table 4.6) is relatively flat in this region. Reservoir response may be to curtail irrigation releases excessively to preserve storage (and head), although in reality the incremental gain in head is slight. Real-time reservoir operation could probably improve the power production characteristics without as significant a reduction in irrigation reliability.

Research effort was devoted to the multi-disciplinary nature of the river basin development problem, thus the properties of the DP algorithm were not explored in great detail. The use of the space-time conceptual model of reservoir management may however prove an interesting area for further research, particularly in incorporating stochastic effects of both reservoir inflows and natural downstream inflows.

CHAPTER 7

CONCLUSIONS

Development plans for the Senegal River basin, which entail a massive social transformation from traditional flood recession cultivation to irrigated agriculture, have stagnated badly. A vicious circle of landscape degradation, desertification and rural displacement set in motion by the onset of the Sahel-wide drought that began almost three decades ago and exacerbated by the conventional rural development policy poses the greatest threat to the social, economic and ecological revitalization of the once verdant Senegal River valley.

An analysis of the Senegal River water resources budget from 1904 to 1990, represented by the annual streamflow volumes near the confluence of all the major tributaries at Bakel, provided evidence of the severity and possibly permanent nature of the drought. A stochastic time series decomposition of Senegal River streamflows indicated that a stationary ARMA model could be fit to the model only after removing a downward trend component at the onset of the drought. Other researchers have linked meterological phenomena driving the drought to global warming effects and have cited Senegal River hydrology as one of the best indicators yet available of climate change effects.

The compelling evidence of climate change induced water scarcity offers a strong rationale to embark on a new river basin development plan. The conventional river basin model, based on macro-economic policy objectives, stresses irrigated rice production for primarily urban markets and has been a financial and social failure. The ecological effects of rice cultivation in the arid climate of the river valley reinforces the worst effect of climate change induced desertification as rice projects have been plagued with high levels of abandonment due to land degradation.

The effects of a continued rice production policy (Policy RP) versus a agricultural development policy that stresses social and environmental sustainability objectives (Policy NRM) were compared on the basis of their relative impact on the water resources budget of the Senegal River. A water resource systems analysis, optimization and simulation framework was adopted for the study, as the assumed system hydrology poses the fundamental geo-physical constraint on the development potential of either agricultural policy.

A key research result from the study is that a viable alternative agricultural development policy does in fact exist. Such a policy incorporates long-term sustainabilty objectives by incorporating;

i. proven culturally acceptable village-scale irrigation development. Village irrigation projects have been well researched, they possess good micro-economic characteristics. With adequate rural extension services village-scale irrigation projects can contribute to environmental protection by establishing shelter-belts for land-scape stabilization.

ii. innovative irrigated agro-forestry projects which focus directly on redressing the primary effects of desertification, by re-integrating urban population back into the countryside and maximizing biomass production and diversity by optimal utilization of scarce water resources.

The results from the water resource system analysis, optimization and simulation study are as follows:

-Policy RP had a two peaked water resources demand profile, the first peak corresponded to the dry season irrigation cycle, the second peak corresponded with the wet season irrigation cycle. The second demand peak closely matched the natural water availability from the Senegal River.

-Policy NRM had a more uniform annual demand profile and a lower over all water resources demand. The uniform demand exerted is related to the year-round production of the irrigated agro-forestry development model.

-For both development policies, meeting dry season irrigation requirements through reservoir regulation placed the binding constraint on over-all development potential.

-For all hydrological scenarios investigated the lower over-all demand of Policy NRM allowed greater over-all development potential, Policy RP had however generally slightly better hydro-power production characteristics.

-For all hydrological scenarios Policy NRM can be maintained at a 65% contre-saison intensity compared to only 50% for Policy RP. This is a key result as it indicates that operationally the ecologically important year-round productive capacity of the SYSPRO agro-forestry system can be maintained. For example at the Sebikotane project case study presented, two out of three of the 28 irrigation sub-blocks (fig. 3.13) can be active year-round, sufficient to maintain the integrity of the SYSPRO eco-system.

-The water resource demand of the proposed Lac du Guiers - Canal du Cayor system to meet urban water requirements comprises a high portion of the total water availability under continued drought condition and will constrain irrigated agricultural development. Using Senegal River water to meet urban demands in the Cap Vert region via the Canal du Cayor is inefficient. On an annual basis approximately half the volume diverted from the river will be lost to evaporation in Lac du Guiers before entering the Canal du Cayor. The canal is also subject to high evaporation losses.

-The construction of the Canal du Cayor is a supply side development response which reinforces the fundamental obstacle to SRB development, the collapse of the traditional rural society under environmental and economic pressure. The Canal du Cayor is an element of the conventional SRB development model which utilizes water resources to serve urban interests (the metropole). Simulation results indicate that under continued drought conditions, SRB development policy that serves the metropole through the simultaneous provision of municipal water demands, hydro-power production and irrigated rice production could limit the full agricultural development potential to as little as half of what could be developed under an alternative strong NRM policy. The strong NRM policys is dedicated exclusively to maximizing available water to sustainable rural development projects such as PIV's and SYSPRO-style agro-forestry projects.

CHAPTER 8

RECOMMENDATIONS

8.1 Research Recommendations

The results from the Senegal River study provide the hydrologic, environmental and socio-economic justification for an SRB development policy shift to a sustainable development/natural resources management focus. Such a policy shift requires complimentary research on the operational feasibility of implementing such a policy.

The simulation results presented in this study depend on the policy NRM demand profile. The NRM demand profile is based on a unique case study of the SYSPRO agro-forestry project at Sebikotane. The SYSPRO system should be the subject of further field research from agronomic, engineering and sociological perspectives. Confirmation of the inverse relationship between crop-water consumption and cropping intensity presented in this study (fig. 3.37) would provide valuable insight into the beneficial ecological interactions of multi-species crop associations in arid climates.

The Canadian International Development Agency (CIDA) has recently approved a multi-million dollar agro-forestry project on the Gambia River near Tambacounda, Senegal. The project will be implemented by ENDA-SYSPRO. At 1000 hectares, it will be by far the largest SYSPRO project yet developed, and affords an excellent opportunity to establish a test field for detailed agronomic and engineering study. CIDA's involvement as the principal funding agency also offers a convenient avenue for collaborative

Canadian research. The Tambacounda project also provides an excellent opportunity for research on the sociological dimension of the large-scale implementation of the ENDA-SYSPRO's GIE model of reverse urban-rural labour migration.

The Diama-Lac du Guiers complex should be the subject of detailed physical modelling to establish more precisely the irrigation impacts of Manantali and Diama regulation intended to assure the year-round filling of Lac du Guiers. The full agricultural development potential will be reduced substantially under continued drought conditions and by a policy which preferentially serves urban interests. The simulation results presented in this study bound the problem, however more detailed physical modelling could define the impacts more precisely. These recommendations are discussed in more detail in section 6.3.4.

8.2 Development Policy Recommendations

The international donor community which is being asked to fund the Canal du Cayor project should be made aware that under continued drought conditions, which shows no evidence of abating, the construction of the canal is a supply side engineering response which compromises alternative agricultural development and both concretely and symbolically reinforces the collapse of the traditional rural society by serving solely urban interests. There exists great potential for water demand management in Dakar as the municipal infrastructure is in extremely poor repair. Rather than transport water several hundred kilometres, subject to huge losses in both storage and transmission before supplying a municipal network that is also subject to high losses, every effort should instead be expended to reduce existing municipal losses and practice demand management in Dakar.

The proposed Canal du Cayor project is an expensive and elaborate project. The scarce financial, technical and water resources which would be committed to the project could be much better utilized in providing the simple infrastructure required for PIV and SYSPRO agro-forestry development. Concurrent water resources and agricultural development would then be properly focused on redressing the worst effects of Sahelian drought and the subsequent social collapse, rather than reinforcing them.

APPENDIX A

MAP OF SENEGAL
VEGETATION DEGRADATION

République du Sénégal

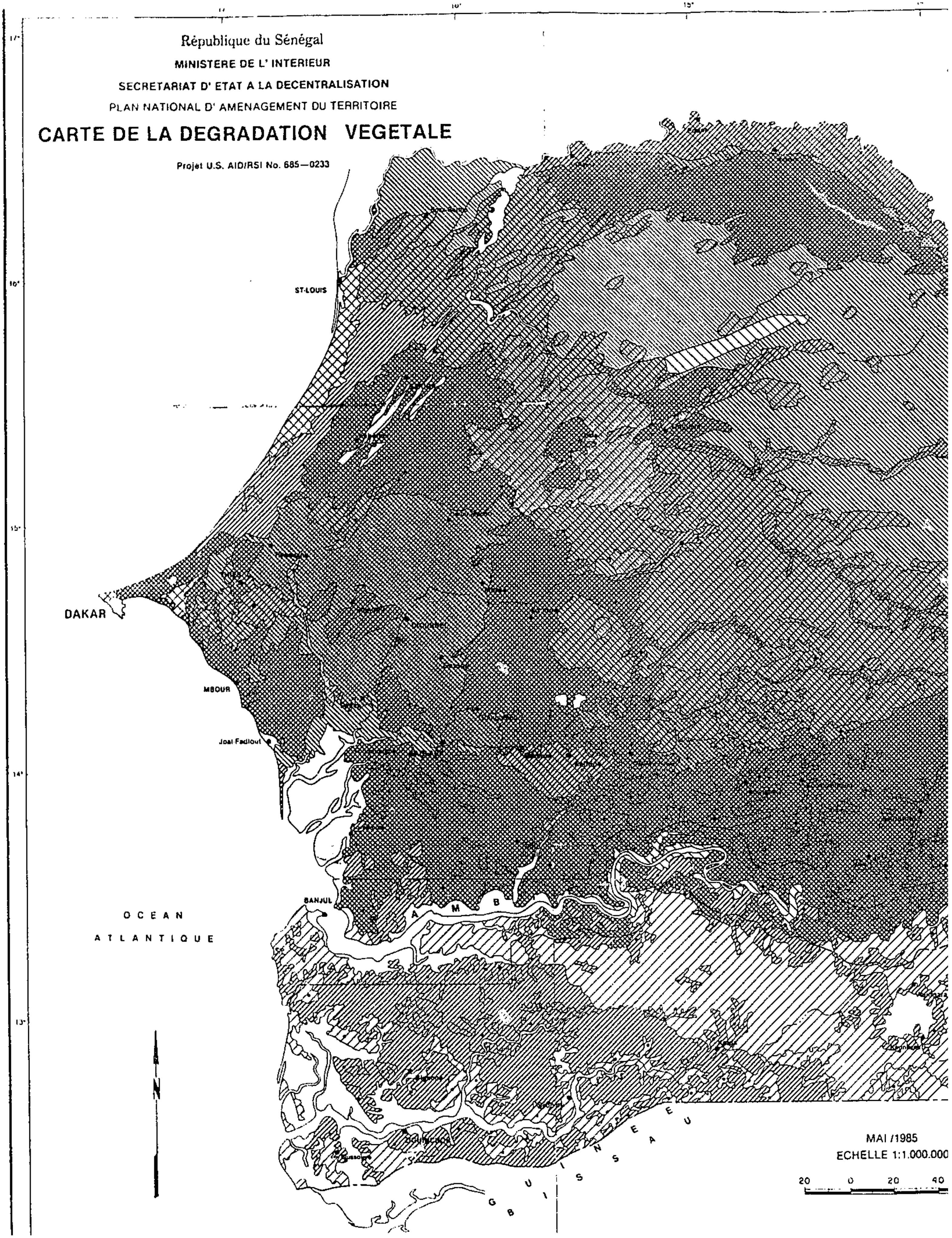
MINISTERE DE L' INTERIEUR

SECRETARIAT D' ETAT A LA DECENTRALISATION

PLAN NATIONAL D' AMENAGEMENT DU TERRITOIRE

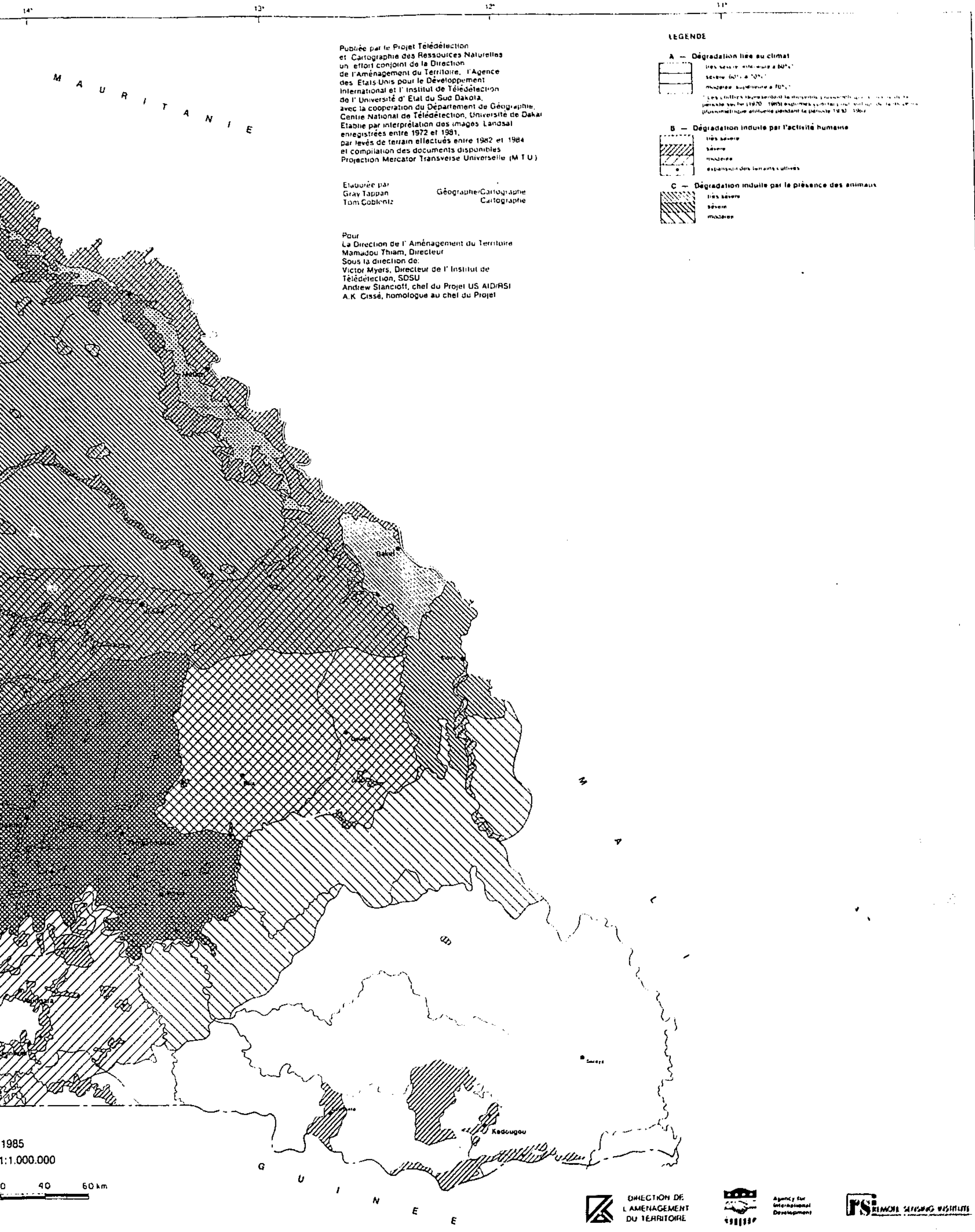
CARTE DE LA DEGRADATION VEGETALE

Projet U.S. AID/RSI No. 685—0233



MAI /1985

ECHELLE 1:1.000.000



Publiée par le Projet Télédétection
et Cartographie des Ressources Naturelles
un effort conjoint de la Direction
de l'Aménagement du Territoire, l'Agence
des Etats-Unis pour le Développement
International et l' Institut de Télédétection
de l' Université d' Etat du Sud Dakota,
avec la cooperation du Département de Géographie,
Centre National de Télédétection, Université de Dakar
Etablie par interprétation des images Landsat
enregistrées entre 1972 et 1981,
par levés de terrain effectués entre 1982 et 1984
et compilation des documents disponibles
Projection Mercator Transverse Universelle (M T U)

Elaborée par
Gray Tappan Géographe/Cartographe
Tom Coblentz Cartographe

Pour
La Direction de l' Aménagement du Territoire
Mamadou Thiam, Directeur
Sous la direction de:
Victor Myers, Directeur de l' Institut de Télédétection, SDSU
Andrew Stancioff, chef du Projet US AID/RSI
A.K. Cissé, homologue au chef du Projet

LEGENDE

A — Dégradation liée au climat

très sévère (inférieure à 60%)*
sévère (60% à 70%)*
modérée (supérieure à 70%)*

* Les chiffres représentent la moyenne [illegible] période sèche (1970 - 1985) exprimés [illegible] pluviométrique [illegible] pendant la période 19[illegible]

B — Dégradation induite par l'activité humaine

très sévère
sévère
modérée
expansion des terrains cultivés

C — Dégradation induite par la présence des animaux

très sévère
sévère
modérée

1985
1:1.000.000

0 40 60 km

DIRECTION DE L'AMENAGEMENT DU TERRITOIRE
Agency for International Development
REMOTE SENSING INSTITUTE

APPENDIX B

COMPUTER PROGRAMS

```
C     PROGRAM SENGEN-STOCHASTIC GENERATION AND DISAGGREGATION OF
C        STREAMFLOWS AT IRIS GAUGE STATIONS FOR SCENARIO B1 AND B2
C     This program generates synthetic streamflows at the following
C     stations in the Senegal River Basin:
C     S=1, BAKEL
C     S=2, SOUKATALI
C     S=3, GALOUGO
C     S=4, MATAM
C     S=5, DAGANA
C     The streamflow generation algorithm is based on the linear filter
C     model of stochastic processes as given by Box & Jenkins (1970).
C     Annual volumes at Bakel are generated using an input random
C     sequence from a normal distribution. Annual volumes at the other stations
C     are linearly correlated with the volume at Bakel using coeffecints
C     from simple regression.  The annual volumes at each site are then
C     disaggregated using a method of fragments as given by Savic et al
C     (1989).  Note 30 years of monthly data, and thus 30 class intervals
C     are used at each site for disaggregation.
C     IMPLICIT NONE
      INTEGER   J, N, NR, NREP, NS, T, S
      REAL A, B, F, M, X, Z, LIM, Q, THETA1, PHI1, MEAN, XCUM, XAVG
      REAL NATQ1, NATQ2, NATQ3, NATQ4, NATOT1
      REAL SOUKQ, SOUKT, NATQ5, STD, QMAX, Z1, Z2
      DIMENSION A(90), F(5,30,12), LIM(5,31), M(5), B(5), X(5,90), Z(90)
      DIMENSION Q(5,90,12),NATQ1(12),NATQ2(12),NATQ3(12),NATQ4(12)
      DIMENSION NATQ5(12),NATOT1(12)
      DIMENSION SOUKQ(12), SOUKT(12)
      DATA Z1/0.0/
      DATA Z2/0.0/
C     ARMA(1.1) coeffecients based on time series analysis at Bakel
C     1904-1989 with linear trend removed after 1960
C     raw data is standardized variate of annual flow volumes
C     in millions of cubic meters per year
      DATA PHI1/.74114/
      DATA THETA1/.51918/
C     mean is adjusted to simulate the different hydrologic scenarios
C     corresponding to the decades 1960s, 1970s, 1980s
C     seed values taken from middle year of the decade i.e 1965,1975,1985
C     note: means are from historical decades, standard deviations are
C     calibrated values to reproduce historical variance for the decade
C     see worksheet decgraph.wq1
C     decade 1970s
c     DATA MEAN/15278.1/
c     DATA STD/4844/
```

```
c     DATA Z(1)/.65971/
C     decade 1980s
      DATA MEAN/10533.73/
      DATA STD/2350/
      DATA Z(1)/.128146/
      DATA NS/5/
C     regression coeffecients based on linear regression of annual volumes
C     at stations 2 to 5 against station 1
      DATA M(2)/0.424/
      DATA M(3)/0.745/
      DATA M(4)/0.867/
      DATA M(5)/0.0/
      DATA B(2)/0/
      DATA B(3)/0/
      DATA B(4)/0/
      DATA B(5)/0/
      WRITE(*,*)'How many years of data do you wish to generate?'
      READ(*,*)N
      WRITE(*,1)N
  1   FORMAT('How many replicates of',I3,' years of data to generate?')
      READ(*,*)NREP
C     read in monthly fragments
      OPEN(2,FILE='FRAGMENT.DAT')
C     option to open file to check level of output
      OPEN(4,FILE='LEVELCHK.OUT')
      DO 10 S=1,5
          DO 5 K=1,30
              READ(2,205)(F(S,K,J),J=1,12)
  5       CONTINUE
          DO 6 K=1,30
              READ(2,206)LIM(S,K+1)
  6       CONTINUE
C         generate lower and upper class limits
          LIM(S,1)=0.0
          LIM(S,31)=999999.0
C          WRITE(*,*)F(S,1,1)
C          WRITE(*,*)F(S,30,12)
C          WRITE(*,*)LIM(S,2)
 10   CONTINUE
C     initialize counters for period averages over all replicates
C     for natural incremental flows for input into "DIVERT"
C     algorithm and for Soukatali (Manantali) inflows for input
C     into "RESERVDP" optimization algorithms
      DATA (NATOT1(J),J=1,12)/12*0.0/
```

```
      DATA (SOUKT(J),J=1,12)/12*0.0/
      OPEN(3,FILE='NOISE.DAT')
C     noise.dat must contain (n+2)*nrep records
C     recall that for an ARMA(1,1) process current time step is dependant
C     on correlation with previous time step, current shock and shock at
C     shock at previous time step: i.e.
C     x(t)=phi(1)*x(t-1)-a(t)-theta(1)*a(t-1)+mean
      QMAX=0.0
      DO 200 NR=1,NREP
          DO 15 T=1,N+1
              READ(3,*)A(T)
 15       CONTINUE
          XCUM=0.0
          DO 100 T=2,N+1
              Z(T)=PHI1*Z(T-1)+A(T)-THETA1*A(T-1)
C              simply redefine t baseline internally above
              X(1,T)=Z(T)*STD+MEAN
C              optional read out to check level only and terminate
              XCUM=XCUM+X(1,T)
C              now generate other volumes at s=2 to 5 using
C              coeffs from regression.
              DO 20 S=2,5
                  X(S,T)=X(1,T)*M(S)+B(S)
 20           CONTINUE
              WRITE(4,207)(X(S,T),S=1,5)
              DO 35 S=1,3
                  DO 30 K=1,30
                      IF(X(S,T).GE.LIM(S,K).AND.X(S,T).LT.LIM(S,
     1                K+1))THEN
                          DO 25 J=1,12
                              Q(S,T,J)=X(S,T)*(F(S,K,J)/100)
                            IF(Q(S,T,J).GT.QMAX)QMAX=Q(S,T,J)
 25                       CONTINUE
                          GOTO 33
                      END IF
 30               CONTINUE
 33               CONTINUE
 35           CONTINUE
C             Daganan flows set to zero except to account for oct-dec
C             floodplain storage recession effects.  Dagana oct-dec
C             are strongly linearly correlated with month previous
C             Matam flows.
C             In second iteration following simulation
C             Dagana is correlated with simulated regulated flows at Matam
```

```
C           from Iris output.
C           Unlike assumptions in Iris, the oct-dec Matam flows cannot be
C           considered independant of upstream regulated volume.
C           now compute period averages of natural inflows between
C           between guage stations, i.e. the average difference
C           between MATAM and BAKEL is the natural inflow
C           available at MATAM which augments the upstream volume.
C           note: natural incremental inflow at BAKEL is the natural inflow
C           between BAKEL and SOUKATALI, i.e. GALOUGO contribution
C           implicit.  Note also:  negative nat. increments are
C           possible indicating arid zone hydrology dominates.
C           This is accounted for in IRIS, and in optimization
C           with loss functions.
            DO 50 J=1,12
C                natural augmentation at BAKEL (BAKEL-Soukatali)
                NATQ1(J)=Q(1,T,J)-Q(2,T,J)
                NATOT1(J)=NATOT1(J)+NATQ1(J)
C                natural augmentation at MATAM
C                note natural incremental flow at Richard Toll,
C                the next diversion (irrigation) site is assumed
C                to be zero.
C                use this loop to compute SOUK averages
                SOUKT(J)=SOUKT(J)+Q(2,T,J)
 50         CONTINUE
 100      CONTINUE
          XAVG=XCUM/N
C          WRITE(4,*)'BAKEL AVG:'
C          WRITE(4,*)XAVG
C          WRITE(*,*)(Q(1,2,J),J=1,12)
C          WRITE(*,*)(Q(4,2,J),J=1,12)
          IF(NR.GT.1)GOTO 125
C          skip header statements
C          format output for direct read by IRIS
          OPEN(6,FILE='SENQ.FLW')
          WRITE(6,*)'FLOW FILE for Senegal River Basin'
          WRITE(6,*)' 1',N,'    12', NREP, NS
          WRITE(6,*)'BAKEL'
          WRITE(6,*)'SOUKAT'
          WRITE(6,*)'GALOUGO'
          WRITE(6,*)'MATAM'
          WRITE(6,*)'DAGANA'
 125        DO 150 T=2,N+1
              DO 140 J=1,12
                  WRITE(6,209)T-1, J, (Q(S,T,J),S=1,3), Z1, Z2
```

```
 140          CONTINUE
 150       CONTINUE
C    feed in last generated value as first value for next replicate
     Z(1)=Z(N+1)
 200 CONTINUE
C    compute period averages over all replicates of natural inflows
C    write out natural inflows (natq's) to be read by "DIVERT"
C    optimization routine.
     OPEN(6,FILE='NATQ.OUT')
     DO 201 J=1,12
C          calculate period average nat increments
C          force all nat. increments positive (losses always negligible)
C          except in explicit losing regimes defined below where % loss
C          is defined for compatibility with DIVNAT.FOR and simultion
C          hydrologic assumptions
           NATQ1(J)=NATOT1(J)/(N*NREP)
           IF(NATQ1(J).LT.0)NATQ1(J)=0.0
           NATQ2(J)=-86.7
C          distribute annual loss from bakel to matam evenly over all
C          months even though some months may show small gains, small positive
C          natqs will however distort the general losing regime under
C          regulation see notes of 93.04.20
           NATQ4(J)=0.0
           NATQ5(J)=0.0
 201 CONTINUE
C    explicit definition of different loss/gain regimes matam dagana in
C    floodplain see \iris\siminput\lossgain\
     NATQ3(1)=-70.0
     NATQ3(2)=-70.0
     NATQ3(3)=-70.0
     NATQ3(4)=-70.0
     NATQ3(5)=-70.0
     NATQ3(6)=-70.0
     NATQ3(7)=-70.0
     NATQ3(8)=-57.0
     NATQ3(9)=-66.0
     NATQ3(10)=-113.0
     NATQ3(11)=-202.0
     NATQ3(12)=-149.0
     DO 202 J=1,12
          WRITE(6,210)NATQ1(J),NATQ2(J),NATQ3(J),NATQ4(J),NATQ5(J)
 202 CONTINUE
C    now write out Manantali inflows (SOUKAT period averages
C    over all replicates) for input into optimization "RESERVDP"
```

```
      OPEN(7,FILE='MANQIN.OUT')
      DO 203 J=1,12
          SOUKQ(J)=SOUKT(J)/(N*NREP)
          WRITE(7,210)SOUKQ(J)
203   CONTINUE
      WRITE(7,*)'QMAX=!!!???',QMAX
205   FORMAT(F8.2,5(F5.2),6(F6.2))
206   FORMAT(F8.2)
207   FORMAT(6(1X,F10.3))
208   FORMAT(5(2X,I4))
209   FORMAT(I2,2X,I2,2X,5(F10.3))
210   FORMAT(5(F10.3))
300   STOP
      END

C     PROGRAM CASEAGEN STOCHASTIC GENERATION AND DISAGGREGATION
C       AT IRIS GAUGE LOCATIONS FOR SCENARIO A
C     This program generates synthetic streamflows at the following
C     stations in the Senegal River Basin:
C     S=1, BAKEL
C     S=2, SOUKATALI
C     S=3, GALOUGO
C     S=4, MATAM
C     S=5, DAGANA
C     The streamflow generation algorithm is based on the linear filter
C     model of stochastic processes as given by Box & Jenkins (1970).
C     Annual volumes at Bakel are generated using an input random
C     sequence from a normal distribution.  Annual volumes at the other stations
C     are linearly correlated with the volume at Bakel using coeffecints
C     from simple regression.  The annual volumes at each site are then
C     disaggregated using a method of fragments as given by Savic et al
C     (1989).  Note 30 years of monthly data, and thus 30 class intervals
C     are used at each site for disaggregation.
C     IMPLICIT NONE
      INTEGER   J, N, NR, NREP, NS, T, S
      REAL A, B, F, M, X, Z, LIM, Q, THETA1, PHI1, MEAN, XCUM, XAVG
      REAL NATQ1, NATQ2, NATQ3, NATQ4, NATOT1, NATOT2, NATOT3, NATOT4
      REAL SOUKQ, SOUKT, NATQ5, STD, MLAG,QMAX, Z1, Z2, AK, BK, FREQ
      DIMENSION A(90), F(5,30,12), LIM(5,31), M(5), B(5), X(5,90), Z(90)
      DIMENSION Q(5,90,12),NATQ1(12),NATQ2(12),NATQ3(12),NATQ4(12)
      DIMENSION NATQ5(12),NATOT1(12),NATOT2(12),NATOT3(12),NATOT4(12)
      DIMENSION SOUKQ(12), SOUKT(12), MLAG(12)
      DATA Z1/0.0/
```

```
      DATA Z2/0.0/
C     ARMA(1,1) coefficients based on time series analysis at Bakel
C     1904-1989 with linear trend removed after 1960
C     raw data is standardized variate of annual flow volumes
C     in millions of cubic meters per year
      DATA PHI1/.74114/
      DATA THETA1/.51918/
C     see worksheet decgraph.wq1
      DATA MEAN/26903.13/
C     Fourier coefficients for period regeneration at f=FREQ
      DATA PI/3.141593/
      DATA AK/3133.175/
      DATA BK/-2864.72/
      DATA FREQ/0.0348837/
      DATA STD/6380/
      DATA Z(1)/1.1898/
      DATA NS/5/
C     regression coeffecients based on linear regression of annual volumes
C     at stations 2 to 5 against station 1
      DATA M(2)/0.424/
      DATA M(3)/0.745/
      DATA M(4)/0.867/
      DATA M(5)/0.0/
      DATA B(2)/0/
      DATA B(3)/0/
      DATA B(4)/0/
      DATA B(5)/0/
C     one month lag regression coefficients for dagana vs matam
C     i.e. dagana (oct) vs. matam (sept) accounts for floodplain
C     storage lag effects.  The oct-dec flows at dagana are linear
C     function of sept-nov matam flows.  SEE \QDBASE\ONDREGR.WQ1
      DATA MLAG(10)/.765886/
      DATA MLAG(11)/.784536/
      DATA MLAG(12)/.539872/
      WRITE(*,*)'How many years of data do you wish to generate?'
      READ(*,*)N
      WRITE(*,1)N
    1 FORMAT('How many replicates of',I3,' years of data to generate?')
      READ(*,*)NREP
C     read in monthly fragments
      OPEN(2,FILE='FRAGMENT.DAT')
C     option to open file to check level of output
      OPEN(4,FILE='LEVELCHK.OUT')
      DO 10 S=1,5
```

```
        DO 5 K=1,30
            READ(2,205)(F(S,K,J),J=1,12)
 5      CONTINUE
        DO 6 K=1,30
            READ(2,206)LIM(S,K+1)
 6      CONTINUE
C        generate lower and upper class limits
        LIM(S,1)=0.0
        LIM(S,31)=999999.0
C        WRITE(*,*)F(S,1,1)
C        WRITE(*,*)F(S,30,12)
C        WRITE(*,*)LIM(S,2)
 10  CONTINUE
C    initialize counters for period averages over all replicates
C    for natural incremental flows for input into "DIVERT"
C    algorithm and for Soukatali (Manantali) inflows for input
C    into "RESERVDP" optimization algorithms
     DATA (NATOT1(J),J=1,12)/12*0.0/
     DATA (NATOT2(J),J=1,12)/12*0.0/
     DATA (NATOT3(J),J=1,12)/12*0.0/
     DATA (NATOT4(J),J=1,12)/12*0.0/
     DATA (SOUKT(J),J=1,12)/12*0.0/
     OPEN(3,FILE='HINOISE.DAT')
C    noise.dat must contain (n+2)*nrep records
C    recall that for an ARMA(1,1) process current time step is dependant
C    on correlation with previous time step, current shock and shock at
C    shock at previous time step: i.e.
C    x(t)=phi(1)*x(t-1)-a(t)-theta(1)*a(t-1)+mean
     QMAX=0.0
     DO 200 NR=1,NREP
         DO 15 T=1,N+1
             READ(3,*)A(T)
 15      CONTINUE
         XCUM=0.0
         DO 100 T=1,N
             Z(T)=AK*COS(2*PI*FREQ*T)+BK*SIN(2*PI*FREQ*T)
             X(1,T)=Z(T)+A(T)
C            optional read out to check level only and terminate
             XCUM=XCUM+X(1,T)
C            now generate other volumes at s=2 to 5 using
C            coeffs from regression.
             DO 20 S=2,5
                 X(S,T)=X(1,T)*M(S)+B(S)
 20          CONTINUE
```

```
            WRITE(4,207)(X(S,T),S=1,5)
            DO 35 S=1,3
               DO 30 K=1,30
                  IF(X(S,T).GE.LIM(S,K).AND.X(S,T).LT.LIM(S.
     1            K+1))THEN
                     DO 25 J=1,12
                        Q(S,T,J)=X(S,T)*(F(S,K,J)/100)
                        IF(Q(S,T,J).GT.QMAX)QMAX=Q(S,T,J)
 25                  CONTINUE
                     GOTO 33
                  END IF
 30            CONTINUE
 33            CONTINUE
 35         CONTINUE
C           Dagana flows set to zero except to account for oct-dec
C           floodplain storage recession effects.  Dagana oct-dec
C           are strongly linearly correlated with month previous
C           Matam flows.
C           In second iteration following simulation
C           Dagana is correlated with simulated regulated flows at Matam
C           from Iris output.
C           Unlike assumptions in Iris, the oct-dec Matam flows cannot be
C           considered independent of upstream regulated volume.
C           now compute period averages of natural inflows between
C           between guage stations, i.e. the average difference
C           between MATAM and BAKEL is the natural inflow
C           available at MATAM which augments the upstream volume.
C           note: natural incremental inflow at BAKEL is the
C           between BAKEL and SOUKATALI, i.e. GALOUGO contribution
C           implicit.  Note also:  negative nat. increments are
C           possible indicating arid zone hydrology dominates.
C           This is accounted for in IRIS, and in optimization
C           with loss functions.
            DO 50 J=1,12
C                 natural augmentation at BAKEL (BAKEL-Soukatali)
                NATQ1(J)=Q(1,T,J)-Q(2,T,J)
                NATOT1(J)=NATOT1(J)+NATQ1(J)
C                 natural augmentation at MATAM
C                 note natural incremental flow at Richard Toll,
C                 the next diversion (irrigation) site is assumed
C                 to be zero.
C                 use this loop to compute SOUK averages
                SOUKT(J)=SOUKT(J)+Q(2,T,J)
 50         CONTINUE
```

```
100       CONTINUE
         XAVG=XCUM/N
C         WRITE(4,*)'BAKEL AVG;'
C         WRITE(4,*)XAVG
C         WRITE(*,*)(Q(1,2,J),J=1,12)
C         WRITE(*,*)(Q(4,2,J),J=1,12)
         IF(NR.GT.1)GOTO 125
C         skip header statements
C         format output for direct read by IRIS
         OPEN(6,FILE='SENQ.FLW')
         WRITE(6,*)'FLOW FILE for Senegal River Basin'
         WRITE(6,*)'1',N,'     12', NREP, NS
         WRITE(6,*)'BAKEL'
         WRITE(6,*)'SOUKAT'
         WRITE(6,*)'GALOUGO'
         WRITE(6,*)'MATAM'
         WRITE(6,*)'DAGANA'
 125       DO 150 T=1,N
              DO 140 J=1,12
                   WRITE(6,209)T, J, (Q(S,T,J),S=1,3), Z1, Z2
 140           CONTINUE
 150       CONTINUE
 200  CONTINUE
 C    compute period averages over all replicates of natural inflows
 C    write out natural inflows (natq's) to be read by "DIVERT"
 C    optimization routine.
      OPEN(6,FILE='NATQ.OUT')
      DO 201 J=1,12
 C          calculate period average nat increments
 C          force all nat. increments positive (losses always negligible)
 C          except in explicit losing regimes defined below where % loss
 C          is defined for compatibility with DIVNAT.FOR and simultion
 C          hydrologic assumptions
            NATQ1(J)=NATOT1(J)/(N*NREP)
            IF(NATQ1(J).LT.0)NATQ1(J)=0.0
            NATQ2(J)=-86.7
 C           distribute annual loss from bakel to matam evenly over all
 C           months even though some months may show small gains, small positive
 C           natqs will however distort the general losing regime under
 C           regulation see notes of 93.04.20
            NATQ4(J)=0.0
            NATQ5(J)=0.0
  201  CONTINUE
  C    explicit definition of different loss/gain regimes matam dagana in
```

```
C     floodplain see \iris\siminput\lossgain\
      NATQ3(1)=-70.0
      NATQ3(2)=-70.0
      NATQ3(3)=-70.0
      NATQ3(4)=-70.0
      NATQ3(5)=-70.0
      NATQ3(6)=-70.0
      NATQ3(7)=-70.0
      NATQ3(8)=-57.0
      NATQ3(9)=-66.0
      NATQ3(10)=-113.0
      NATQ3(11)=-202.0
      NATQ3(12)=-149.0
      DO 202 J=1,12
          WRITE(6,210)NATQ1(J),NATQ2(J),NATQ3(J),NATQ4(J),NATQ5(J)
  202 CONTINUE
C     now write out Manantali inflows (SOUKAT period averages
C     over all replicates) for input into optimization "RESERVDP"
      OPEN(7,FILE='MANQIN.OUT')
      DO 203 J=1,12
          SOUKQ(J)=SOUKT(J)/(N*NREP)
          WRITE(7,210)SOUKQ(J)
  203 CONTINUE
      WRITE(7,*)'QMAX=!!!???',QMAX
  205 FORMAT(F8.2,5(F5.2),6(F6.2))
  206 FORMAT(F8.2)
  207 FORMAT(6(1X,F10.3))
  208 FORMAT(5(2X,I4))
  209 FORMAT(I2,2X,I2,2X,5(F10.3))
  210 FORMAT(5(F10.3))
  300 STOP
      END


C     ****************************************************************
C     *********************PROGRAM DIVERT*****************************
C     Program employs forward dynamic programming algorithm to estab-
C     lish optimal diversion volumes at downstream diversion points
C     Algorithm is solved at the boundary condition where RT(R) the res-
C     ervoir release is the initial state variable.  The subroutine
C     must be solved for NR boundary conditions for each period.
      INTEGER Z,NDZ,NQ,NQS,DIVOPT,RT,DIV,QINC,Q,T,QMIN,QMAX,D,
     1NDV,QREC,IQREC,NQREC,R,DIVARG,QARG,NR,NUMPER,RMIN,
     2RMAX
```

```
      REAL FOPT,LGF,RQREC,FGLOBE,NATQ,DEM,DEVFAC,QFX
      DIMENSION DIVOPT(5,200),DIV(60),FOPT(5,200),Q(200),NQTRAC(5,200)
      DIMENSION NATQ(12,10),DEM(12,10),FGLOBE(12,60),DIVARG(12,60,5)
      DIMENSION QARG(12,60,5),RT(60)
      DATA NUMPER/12/
      DATA QINC/100/
C     DATA QINC/1000/
      DATA NDZ/4/
      DATA NDV/30/
C     DATA NDV/20/
C     read monthly demands at each irrigation zone (diversion site)
C     as calculated and exported by "DEMAND.WQ1", note the demands
C     are a function of irrigable area, crop mix, soil type, and
C     irrigation management.
      WRITE(*,*)'ENTER NATFLOW INCREMENT FACTOR'
      READ(*,*)QFX
      OPEN(3,FILE='R100CS50.DAT')
      READ(3,*)DEVFAC
      WRITE(*,*)'DEVELOPMENT FACTOR',DEVFAC
      DO 2 T=1,12
         READ(3,102)(DEM(T,Z),Z=1,NDZ)
         WRITE(*,102)(DEM(T,Z),Z=1,NDZ)
 2    CONTINUE
C     read monthly incremental flows at each diversion site.  Note
C     that each diversion site corresponds with guage sites as
C     configured in IRIS, with the exception of the last 2 (furthest
C     downstream) sites, R.Toll and Delta where the incremental flow is zero.
C     These inflows are assumed to be the difference in monthly flows
C     at adjacent guages as generated by "SENGEN".  The differences are
C     averaged over all years and replicates for each hypothesized
C     hydrologic scenario.
C     difference
      OPEN(4,FILE='NATQ.OUT')
      DO 4 T=1,12
         READ(4,102)(NATQ(T,Z),Z=1,NDZ)
         DO 3 Z=1,NDZ
            IF(NATQ(T,Z).GE.0)NATQ(T,Z)=QFX*NATQ(T,Z)
 3       CONTINUE
         WRITE(*,102)(NATQ(T,Z),Z=1,NDZ)
 4    CONTINUE
      DATA RMIN/100/
C     DATA RMIN/2000/
      DATA RMAX/3500/
C     initialize release state array
```

```
      NR=(RMAX-RMIN)/QINC+1
      DO 7 R=1,NR
          RT(R)=RMIN+(R-1)*QINC
C          WRITE(*,*)RT(R)
  7   CONTINUE
C     initialize array for state variable, Q(z+1), i.e. the state variable
C     is defined as the state AFTER stage z.  Q(z=1) is the
C     boundary condition, RT(R).
      DATA QMAX/12000/
C     for contistincy in indexing flow states, min flow equals
C     flow increment.
      QMIN=QINC
      NQS=(QMAX-QMIN)/QINC+1
      DO 8 NQ=1,NQS
          Q(NQ)=QINC*NQ
C          WRITE(*,*)Q(NQ)
  8   CONTINUE
C     initialize control variable array (diversion volume)
C     note: zero diversion possible
      DO 9 D=1,NDV
          DIV(D)=QINC*(D-1)
  9   CONTINUE
C     *******************************************
C     primary outer loop commences below (DO 50).  Entire algorthm executed
C     for every within-year-period (typically 12 months).  Demand
C     pattern varies in space and time.
C     *******************************************
      DO 50 T=1,NUMPER
C     *******************************************
C     secondary outer loop commences (DO 40).  Solves for optimal
C     diversion at every stage for every feasible boundary condition, RT(R),
C     the reservoir release state, in a given T.
C     *******************************************
      DO 40 R=1,NR
C     fill diversion states
C     fill release states
      DO 20 Z=1,NDZ
          DO 15 NQ=1, NQS
              FOPT(Z,NQ)=10E15
C              apply boundary conditions at first stage
              IF(Z.EQ.1)THEN
                  DIVOPT(Z,NQ)=RT(R)-Q(NQ)+NATQ(T,Z)
C                  first stage continuity at the boundary, i.e.
C                  q(z+1)=rt(r)+natq(t,z)-divopt(z,nq)
```

```
C            defines unique release, must be > 0
            IF(DIVOPT(Z.NQ).GE.0)THEN
               FOPT(Z.NQ)=(DEM(T.Z)-DIVOPT(Z,NQ))**2
            ELSE
               DIVOPT(Z.NQ)=0
               FOPT(Z.NQ)=10E15
            END IF
          ELSE
            DO 10 D=1.NDV
C            define recursive flow relationship depending on the
C            hydrologic regime (humid or arid), note stage z=1
C            (boundary condition) assumed humid.
               IF(NATQ(T.Z).LT.0)THEN
C               arid hydrology assumption applies.
C               natq(t.z) is interpreted as % total vol. loss/gain
C               gain is in the case of flood plain storage recession
                  LGF=-NATQ(T.Z)/100.0
                  RQREC=(Q(NQ)+DIV(D))/LGF
                  IQREC=(RQREC/QINC)*QINC
C                  round off state variable to interval
C                  of qinc
                  IF((RQREC-IQREC).LT.(.5*QINC))THEN
                     QREC=IQREC
                  ELSE
                     QREC=IQREC+QINC
                  END IF
               ELSE
C               assume humid zone hydrology applies where
C               natq(t.z) represents a constant volume gain:
                  QREC=Q(NQ)-NATQ(T,Z)+DIV(D)
               END IF
C               test for minimum and maximum diversion constraints
               IF(QREC.LT.QMIN)THEN
                  F=10E15
               ELSE IF(QREC.GT.QMAX)THEN
                  F=10E15
C               else general recursion equation
               ELSE
                  NQREC=QREC/QINC
                  F=(DEM(T.Z)-DIV(D))**2+
     1             FOPT(Z-1.NQREC)
               END IF
               IF(F.LT.FOPT(Z.NQ))THEN
                  FOPT(Z.NQ)=F
```

```
                    DIVOPT(Z,NQ)=DIV(D)
                    NQTRAC(Z,NQ)=NQREC
                  END IF
 10             CONTINUE
                IF(FOPT(Z,NQ).EQ.10E15)THEN
                  DIVOPT(Z,NQ)=0
                END IF
              END IF
 15       CONTINUE
 20    CONTINUE
C      now find global optimum and trace back to develop diversion
C      arguments for general diversion allocation rules in IRIS
C      find global optimum for current period and boundary condition
c      WRITE(*,*)FOPT(NDZ,1)
       FGLOBE(T,R)=FOPT(NDZ,1)
       NTRACE=1
       DO 25 NQ=1,NQS
          IF(FOPT(NDZ,NQ).LT.FGLOBE(T,R))THEN
             FGLOBE(T,R)=FOPT(NDZ,NQ)
             NTRACE=NQ
          END IF
 25    CONTINUE
C      trace back along optimal route to develop arguments
       DO 30 Z=NDZ,2,-1
          DIVARG(T,R,Z)=DIVOPT(Z,NTRACE)
C         refer to problem schematic: qarg is the previous state+nat inflow
C         i.e. the volume that stage z "sees" in simulation
          IF(NATQ(T,Z).LT.0.0)THEN
C              arid / flood plain recession hydrology case
             QARG(T,R,Z)=(NQTRAC(Z,NTRACE)*QINC)*(-NATQ(T,Z)/100)
          ELSE
C              humid hydrology case
             QARG(T,R,Z)=NQTRAC(Z,NTRACE)*QINC+NATQ(T,Z)
          END IF
          NTRACE=NQTRAC(Z,NTRACE)
 30    CONTINUE
C      include arguments at boundary condition
       IF(NATQ(T,1).LT.0.0)THEN
          QARG(T,R,1)=RT(R)*(1+(NATQ(T,1))/100)
       ELSE
          QARG(T,R,1)=RT(R)+NATQ(T,1)
       END IF
       DIVARG(T,R,1)=DIVOPT(1,NTRACE)
 40    CONTINUE
```

```
 50 CONTINUE
C    now write out diversion arguments at all diversion sites and
C    in all periods.
     OPEN(6,FILE='DIV297.ARG')
     DO 80 Z=1,NDZ
         WRITE(6,*)'DIVERSION SITE',Z
         DO 70 T=1,NUMPER
             WRITE(6,*)'PERIOD',T,' DEMAND',DEM(T,Z)
             WRITE(6,*)'FLOW VOLUME  DIVERSION VOLUME'
             DO 60 R=1,NR
                 WRITE(6,90)QARG(T,R,Z),DIVARG(T,R,Z)
 60          CONTINUE
 70      CONTINUE
 80 CONTINUE
 90 FORMAT(3X,I6,6X,I6)
C    now write out tableau of total diversion penalties (optimal
C    case) for each boundary condition (reservoir release state) and
C    in each period.
     OPEN(7,FILE='DIV297.PEN')
     WRITE(7,*)'TABLEAU OF TOTAL PENALTIES ASSOCIATED WITH OPTIMAL'
     WRITE(7,*)'DIVERSION POLICY IN EACH PERIOD FOR EACH RELEASE STATE'
     WRITE(7,*)'DEVELOPMENT FACTOR=',DEVFAC
     WRITE(7,105)(T,T=1,12)
     DO 100 R=1,NR
         WRITE(7,109)RT(R)
         DO 99 T=1,NUMPER
             WRITE(7,*)FGLOBE(T,R)
 99      CONTINUE
 100 CONTINUE
 102 FORMAT(5(F10.3))
 105 FORMAT('RELEASE',12(I2,4X))
 109 FORMAT(I4)
 110 FORMAT(12(I5,1X))
 150 STOP
     END

C****************DYNAMIC PROGRAMMING FOR RESERVOIR*****************
C****************************OPERATION************
C*************************HENRY DAVID VENEMA******************************
C******************DEPARTMENT OF CIVIL ENGINEERING**********************
C************************UNIVERSITY OF OTTAWA****************************
C****************************JULY  1992*********************************
C
C    The following algorithm for reservoir operation by dynamic program-
```

```
C     ming follows the methodology and assumptions given in Loucks et al.
C     "Water Resources Systems Planning and Analysis", Prentice-Hall, 1981.
C     pp. 40-44.
C*********************VARIABLE DECLARATION*****************************
C                    ********************
C      IMPLICIT NONE
      INTEGER K, N, T, NREC, TREC, S, R, NS, NR, ST, RT, I, NUMPER, NMAX
     1,INC, ROPT, SUM, RMIN, RMAX, MAXR, POWR
      DIMENSION ST(80), RT(80), I(12), ROPT(20,12,80)
C     counters for years of simulation, within year period, adjusted cou-
C     nters for recursion equation (year and period), counters discretized
C     storage and release zones, number of discrete storage and release
C     zones, discrete storage and release values, average period inflows,
C     number of within-year periods (i.e 12), number of years simulated.
C********************************************************************
      REAL FOPT, FTOT, TS, TR, FOBRES, DIVPEN, WEIGHT, P, Q,MHEAD, BHEAD
      REAL POWER, MAXPOW
      DIMENSION FOPT(20,12,80), DIVPEN(12,80)
C     arrays for optimal values of objective function and release of year
C     N, period T and storage zone S, intermediate value of objective
C     function of storage S and release R.
C********************************************************************
      DATA MAXR/1500/
      DATA MHEAD/0.002752/
      DATA BHEAD/31.89/
      DATA MAXPOW/146100./
c     DATA SCALE/1000000/
c     DATA NUMPER/12/
      WRITE(*,*) 'This program reads reservoir parameters: capacity,'
      WRITE(*,*) 'target storage and release, minimum and maximum'
      WRITE(*,*) 'release, average monthly inflows, and the tableau'
      WRITE(*,*) 'of penalties associated with downstream diversion'
      WRITE(*,*) 'targets as calculated in DIVNAT.FOR'
      WRITE(*,*) 'a HYDROPOWER OR IRRIGATION DOMINATED RELEASE POLICY '
      WRITE(*,*) 'IS CONDITIONED BY THE RELATIVE WEIGHTING OF THE '
      WRITE(*,*) 'DIVERSION PENALTIES'
      WRITE(*,*)'CONVERGENCE CAN TAKE SEVERAL MINUTES PLEASE BE PATIENT'
      WRITE(*,*) 'on convergence, execute program ZONES to produce'
      WRITE(*,*) 'optimal operational rule curves'
C********************************************************************
C     WRITE(*,*)'CHOOSE WEIGHT (EXPONENTIAL) ON STORAGE PENALTY FUNC.
C     READ(*,*)Q
C     WRITE(*,*)'CHOOSE WEIGHT (EXPONENTIAL) ON RELEASE PENALTY FUNC.'
C     READ(*,*)P
```

```
      WRITE(*,*)'CHOOSE WEIGHT ON IRRIGATION (1-200)'
      READ(*,*)WEIGHT
      OPEN(3,FILE='CONVERGE.DAT')
      OPEN(5,FILE='RELEASE.OUT')
C     read number of years of recursion, number of within year periods
C     read reservoir capacity
C     read incremental unit of discrete storage and release states
C     read minimum release
C     read maximum release
C     read target storage and target release
C     read dicretized period inflows (assumed hydrologically stationary)
      READ(3,*)NMAX, NUMPER
      READ(3,*)K
      READ(3,*)INC
      READ(3,*)RMIN
      WRITE(*,*)RMIN
      READ(3,*)RMAX
C     READ(3,*)(TR(T),T=1, NUMPER)
C     WRITE(*,*)(TR(T),T=1,NUMPER)
      READ(3,*)(I(T),T=1, NUMPER)
C******************************************
C     define the number of storage states
C     and fill the storage state array
C     use classical scheme ref: Karamouz & Vasiliadis WRR(28), 1992
      NS=(K/INC)+1
      WRITE(*,*)NS
      WRITE(*,*)INC
      DO 107 S=1,NS
C           ST(S)=(INC/2)*(2*S-1)
          ST(S)=(S-1)*INC
C           WRITE(*,*)S, ST(S)
 107  CONTINUE
C     define the number of release states
C     fill the release state array
      NR=(RMAX-RMIN)/INC+1
      DO 108 R=1,NR
          RT(R)=RMIN+(R-1)*INC
          WRITE(*,*)RT(R)
 108      CONTINUE
C     open divpen reads here
      OPEN(6,FILE='DIV100.PEN')
      READ(6,*)
      READ(6,*)
      READ(6,*)
```

```
     READ(6,*)
     DO 110 R=1,NR
          READ(6,*)
          DO 109 T=1,12
               READ(6,*)DIVPEN(T,R)
109         CONTINUE
110  CONTINUE
C    initialize counters for last year (N=1) and last period (T=NUMPER)
C    backward dynamic recursion.
     N=1
     T=NUMPER
C    this if block corrects for between year recursion
C    program flow returns here for each period of recursion
111  IF(T.LT.1)THEN
          TREC=1
          NREC=N
          T=NUMPER
          N=N+1
     ELSE
          TREC=T+1
          NREC=N
     END IF
C    optimal releases initially set infeasible
     DO 130 S=1,NS
          FOPT(N,T,S)=10E15
          ROPT(N,T,S)=-100
C              this do block calculates objective function for all release
C              and storage states.
          DO 120 R=1,NR
               IF(RT(R).GT.MAXR)THEN
                    POWR=MAXR
               ELSE
                    POWR=RT(R)
               END IF
               POWER=(POWR*(MHEAD*ST(S)+BHEAD))
               IF(POWER.GT.MAXPOW)THEN
                    POWER=MAXPOW
               END IF
C                   boundary condition
               IF(N.EQ.1.AND.T.EQ.NUMPER)THEN
                    FOBRES=-1*POWER+WEIGHT*DIVPEN(T,R)
C                   apply capacity and maximum release constraints
               ELSE IF((ST(S)+I(T)-RT(R)).GT.K)THEN
                    FOBRES=10E15
```

```
         ELSE IF(ST(S)+I(T).LT.RT(R))THEN
            FOBRES=10E15
C         general recursion equation
         ELSE
             FOBRES=-1*POWER
   1         +FOPT(NREC,TREC,(ST(S)+I(T)-RT(R))/INC+1)
   2         +WEIGHT*DIVPEN(T,R)
C             "+1" in above recursion corrects for mapping
C              storage S=1, ST=0
          END IF
          FTOT=FOBRES
          IF(FTOT.LT.FOPT(N,T,S))THEN
             FOPT(N,T,S)=FTOT
             ROPT(N,T,S)=RT(R)
          END IF
 120    CONTINUE
C       upper bound on infeasibility
C       IF(FOPT(N,T,S).GE.10E9)THEN
C          FOPT(N,T,S)=10E9
C          ROPT(N,T,S)=-100
C       END IF
 130 CONTINUE
C    branch out on completion of recursion
    IF(N.GE.2.AND.T.EQ.1)THEN
       WRITE(*,205)N
       SUM=0
       DO 160 T=1, NUMPER
           DO 158 S=1, NS
               IF(ROPT(N-1,T,S).NE.ROPT(N,T,S))THEN
                    SUM=SUM+1
                END IF
  158       CONTINUE
  160    CONTINUE
        IF (SUM.EQ.0)THEN
           NMAX=N
           WRITE(*,206)N
           GOTO 170
        ELSE
           WRITE(*,207)N
           T=0
        END IF
     ELSE
        T=T-1
     END IF
```

```
      GOTO 111
 170  CONTINUE
C     WRITE(5,*)TS
C     WRITE(5,*)P
      WRITE(5,*)WEIGHT
      WRITE(5,*)K
      WRITE(5,*)RMIN
      WRITE(5,*)NS
 172  WRITE(5,185) (T, T=1,NUMPER)
      DO 175 S=1,NS
          WRITE(5,180) NMAX, ST(S), (ROPT(NMAX,T,S),T=1, NUMPER)
 175  CONTINUE
      DO 177 S=1,NS
          DO 176 T=1,NUMPER
              WRITE(5,*) FOPT(NMAX,T,S)
 176      CONTINUE
 177  CONTINUE
 178  FORMAT(12(1X,F4.1))
 179  FORMAT(12(1X,I4))
 180  FORMAT(I2, 3X, I4, 3X, 12(1X,I4))
 181  FORMAT(1X, I1, 1X, I2, 3X, I4, 3X, 12(1X,F4.1))
 185  FORMAT('YEAR',1X,'STORAGE', 12(3X,I2))
 200  FORMAT(I2,1X,I2,2X,F10.7)
 205  FORMAT('year', I1,' checking for convergence')
 206  FORMAT('convergence in', I1,'   years')
 207  FORMAT('no convergence in', I1,'   years')
      STOP
      END
```

```
C*********************PROGRAM RULECURV****************************
C***********this program generates the reservoir release*********
C*******curves for interactive input into IRIS simulation*********
C****************************************************************
      INTEGER NCURVE,NUMPER,NS,K,RMIN,S,NMAX,ROPT,ROPTMX,J,CRVLIN,
     1INC,ST,T,SCALE,CRVOUT,FINOUT,RELOUT
      REAL CRVINC,CRVREL
      DIMENSION CRVREL(10),CRVLIN(12,10),ROPT(12,80),ST(80),
     1CRVOUT(12,10),RELOUT(10),FINOUT(13,10)
      DATA NUMPER/12/
      WRITE(*,*)'This program generates the reservoir release rule'
      WRITE(*,*)'curves for interactive input into IRIS simulation'
      WRITE(*,*)'EXECUTE QUATTRO PRO MACRO "CURVES" AFTER THIS'
      WRITE(*,*)'          FOR GRAPHICAL OUTPUT'
      WRITE(*,*)'how many release zones do you wish to use?:'
      READ(*,*)NCURVE
      IF(NCURVE.GT.8)THEN
          WRITE(*,*)'IRIS is constrained to a maximum of 8 zones'
          WRITE(*,*)'how many release zones do you wish to use?:'
          READ(*,*)NCURVE
          IF(NCURVE.GT.8)THEN
              WRITE(*,*)'only 8 release zones will be used'
              NCURVE=8
          END IF
      END IF
      OPEN(5,FILE='RELEASE.OUT')
C     READ(5,*)TS
C     READ(5,*)P
      READ(5,*)WEIGHT
      READ(5,*)K
      READ(5,*)RMIN
      READ(5,*)NS
      READ(5,*)
      DO 15 S=1,NS
          READ(5,75)NMAX,ST(S),(ROPT(T,S),T=1,12)
 75       FORMAT(I2,3X,I4,3X,12(1X,I4))
C         find the largest release for this steady state policy
 15   CONTINUE
      WRITE(*,*)ROPT(12,8)
      ROPTMX=0
      WRITE(*,*)ROPTMX
      DO 35 T=1,NUMPER
        DO 30 S=1,NS
          IF(ROPT(T,S).GT.ROPTMX)THEN
```

```
            ROPTMX=ROPT(T,S)
         END IF
30       CONTINUE
35    CONTINUE
      WRITE(*,*)ROPTMX
      WRITE(*,*)RMIN
      WRITE(*,*)NCURVE
      CRVINC=(ROPTMX-RMIN)/(NCURVE-1)
      WRITE(*,*)CRVINC
      WRITE(*,*)'all release units in millions of cubic meters/month'
      WRITE(*,*)'Steady State Policy - Maximum release:',ROPTMX
      WRITE(*,*)'Minimum release constraint (navigation/ecology):',RMIN
      WRITE(*,*)'Release zones incremented by:',CRVINC
      WRITE(*,*)'If increment is too small, re-run "RULES"  with fewer
     1zones'
C     define the releases associated with each zone
      DO 36 J=1,NCURVE
         CRVREL(J)=RMIN+(J-1)*CRVINC
 36   CONTINUE
C     redefine storage state increment
      INC=K/NS
C     WRITE(*,*)INC
C     the following routine defines the storage values that delineate
C     between different release zones for all periods
C     When the steady state release is greater than the upper bound
C     for that zone (crvrel(zone j)), the storage level that marks the
C     boundary is the current storage state less half the storage state
C     increment.  Recall the classical definition of storage states def-
C     at the mid-point of the storage interval.  Refer Karamous & Vasiliadis
C     WRR(28), 1992.
C     begin search in all periods for zone boundaries
      DO 50 T=1,NUMPER
         J=1
 39      CONTINUE
C        search for next zone boundary here 'crvlin(t,j+1)', same period
         IF(J.EQ.NCURVE)THEN
C        skip do loop at 40, period complete
            CRVLIN(T,J)=K
            GOTO 41
         END IF
         DO 40 S=1,NS
            IF(ROPT(T,S).GT.CRVREL(J))THEN
               CRVLIN(T,J)=ST(S)-(INC/2)
               J=J+1
```

```
               GOTO 39
            ELSE IF(S.EQ.NS)THEN
C            this else if upperbounds the current release zone to
c            capacity, since the steady state release in the highest
C            storage state (ns), is less or equal to the release def-
C            ined for that zone.
               CRVLIN(T,J)=K
               J=J+1
               GOTO 39
            END IF
 40       CONTINUE
 41       CONTINUE
        J=1
 50   CONTINUE
      WRITE(*,*)CRVLIN(3,3),CRVLIN(3,2)
C     scale storage ordinates for output according to size of reservoir
      IF(K.GT.1000)THEN
         SCALE=1000
      ELSE
         SCALE=100
      END IF
      DO 55 J=1,NCURVE
         DO 52 T=1,NUMPER
            CRVOUT(T,J)=CRVLIN(T,J)
 52      CONTINUE
 55   CONTINUE
C     WRITE(*,*)CRVOUT(3,3),CRVOUT(3,2)
C     now set actual zone releases (interpolate between zone limits)
C     first zone is the minimum release
      RELOUT(1)=CRVREL(1)
      DO 56 J=2,NCURVE
         RELOUT(J)=(CRVREL(J)-CRVREL(J-1))*0.75+CRVREL(J-1)
 56   CONTINUE
C     now correct storage ordinates from mid-points of periods to end
C     points of periods by linear interpolation
      DO 58 J=1,NCURVE
         DO 57 T=2,NUMPER
            FINOUT(T,J)=(CRVOUT(T-1,J)+CRVOUT(T,J))/2
 57      CONTINUE
         FINOUT(1,J)=(CRVOUT(NUMPER,J)+CRVOUT(1,J))/2
         FINOUT(13,J)=FINOUT(1,J)
 58   CONTINUE
      OPEN(6,FILE='CURVES.OUT')
C     write the output noting scaling to "curves.out"
```

```
      WRITE(6,*)TS, P, WEIGHT
      WRITE(6,*)'  STORAGE ORDINATE/END OF PERIOD FOR EACH RELEASE ZONE'
      WRITE(6,79)(T,T=0,NUMPER)
      DO 60 J=1,NCURVE
        WRITE(6,80)J,RELOUT(J),(FINOUT(T,J),T=1,NUMPER+1)
60    CONTINUE
79    FORMAT('"ZONE""RELEASE"',13(I2,3X))
80    FORMAT(2X,I1,3X,I4,2X,13(1X,I4))
85    FORMAT(8X,12(2X,I4))
      STOP
      END
```

```
C******************POWER PRODUCTION CALCULATION*********************
C*****This Program Reads INTERACTIVE RIVER SIMULATION output***********
C**and calculates annual energy production and monthly power production
C******************************************************************
      REAL BLK1,BLK2,BLK3,ENERGY
      INTEGER  N, L, NLINK, T, TMAX, R, REPMAX, NNODE
      DIMENSION ENERGY(16,20,240)
      WRITE(*,*) 'THIS BABY STRIPS OUT MANANTALI ENERGY PRODUCTION'
      DATA TMAX/240/
      WRITE(*,*) 'ENTER NUMBER OF REPLICATES:'
      READ(*,*) REPMAX
      DATA NNODE/16/
      OPEN(5,FILE='R100.OUT')
      OPEN(6,FILE='MWATT.OUT')
      OPEN(7,FILE='HPTS.OUT')
      NLINK=NNODE-1
      DO 90 T=1,TMAX
        READ(5,*)
        READ(5,*)
        READ(5,*)
        READ(5,*)
        DO 80 R=1,REPMAX
         DO 50 N=1,NNODE
           READ(5,98)
50       CONTINUE
           READ(5,*)
         DO 60 L=1, NLINK
           READ(5,98)NL,BLK1,BLK2,BLK3,ENERGY(L,R,T)
C******note that link flows and storage are discarded (blanks)****
```

```
C******since energy is the only link variable of interest at this**
C******if these variables become of interest simply declare dimensions
C******of appropriate variables
 60    CONTINUE
       IF (R.LT.REPMAX) THEN
       READ(5,*)
       READ(5,*)
       END IF
 80    CONTINUE
 90   CONTINUE
 98   FORMAT(I4,4(1X,F9.2))
 99   FORMAT(I4,4(1X,F9.2))
 100  FORMAT(10(F8.2))
 105  FORMAT(F9.2)
C*********OUTPUT FILE SET UP FOR QIN ONLY (ALL REPLICATES)******
C*****SIMPLY REPLACE QIN BELOW FOR VARIABLE OF INTEREST*********
C*****FLAGS CAN BE SET UP ON INPUT TO SPECIFY WHICH VARIABLE****
C****************AND NODES SHOULD BE OUTPUT*******************
      NL=2
      WRITE(6,*)TMAX,REPMAX
      WRITE(6,*)'ENERGY at Manantali'
           DO 120 T=1,TMAX
              WRITE(6,100)((ENERGY(NL,R,T)/730.5),R=1,REPMAX)
 120          CONTINUE
 125     CONTINUE
      WRITE(7,*)TMAX,REPMAX
      WRITE(7,*)'ENERGY ON LINK ',NL
      DO 140 R=1,REPMAX
         WRITE(7,*)'REPLICATE ',R
            DO 130 T=1,TMAX
               WRITE(7,105)ENERGY(NL,R,T)
 130          CONTINUE
 140  CONTINUE
      STOP
      END


C*******************IRIS OUTPUT PROCESSOR*****************************
C*****This Program Reads INTERACTIVE RIVER SIMULATION output***********
C*****and outputs simulated time series of all variables at all nodes**
C*****for further analysis.  Note: Qinflow is the only variable written
C*****out to process.out currently.  Modify code as necessary for other
C*****variables as necessary.  See also comments below****************
```

```
C*********************H.D.Venema-April 92***************************
C******************************************************************
      REAL BLK1,BLK2,BLK3,QIN
      INTEGER NX, N, L, NLINK, T, TMAX, R, REPMAX, NNODE
      DIMENSION QIN(16,20,240)
      WRITE(*,*) 'THIS BABY STRIPS OUT INFLOWS AT ALL NODES'
      DATA TMAX/240/
      WRITE(*,*) 'ENTER NUMBER OF REPLICATES:'
      READ(*,*) REPMAX
      DATA NNODE/16/
      OPEN(5,FILE='N6.OUT')
      OPEN(6,FILE='PROCQIN.OUT')
C*****how to open this file according to character var. input above?
C     WRITE(6,*) TMAX, REPMAX, NNODE, NAME
      NLINK=NNODE-1
      DO 90 T=1,TMAX
        READ(5,*)
        READ(5,*)
        READ(5,*)
        READ(5,*)
        DO 80 R=1,REPMAX
         DO 50 N=1,NNODE
           READ(5,98)NX,QIN(N,R,T),BLK1,BLK2,BLK3
  50      CONTINUE
           READ(5,*)
         DO 60 L=1, NLINK
           READ(5,98)
C******note that link flows and storage are discarded (blanks)****
C******since energy is the only link variable of interest at this**
C******if these variables become of interest simply declare dimensions
C******of appropriate variables
  60      CONTINUE
          IF (R.LT.REPMAX) THEN
          READ(5,*)
          READ(5,*)
          END IF
  80      CONTINUE
  90    CONTINUE
  98    FORMAT(I4,4(1X,F9.2))
  99    FORMAT(I4,4(1X,F9.2))
  100   FORMAT(I4,1X,F9.2)
C*********OUTPUT FILE SET UP FOR QIN ONLY (ALL REPLICATES)******
C*****SIMPLY REPLACE QIN BELOW FOR VARIABLE OF INTEREST*********
C*****FLAGS CAN BE SET UP ON INPUT TO SPECIFY WHICH VARIABLE****
```

```
C*****************AND NODES SHOULD BE OUTPUT*******************
     WRITE(6,*)NNODE,TMAX,REPMAX
     DO 130 R=1,REPMAX
        WRITE(6,*)'REPLICATE ',R
        DO 125 N=1,NNODE
           WRITE(6,*)'NODE NUMBER',N
           DO 120 T=1,TMAX
              WRITE(6,100) T, QIN(N,R,T)
 120          CONTINUE
 125       CONTINUE
 130  CONTINUE
     STOP
     END


 C       PROGRAM REL.FOR
 C       CALCULATES DEMAND SATISFACTION RELIABILITY FROM SIMULATION
 OUTPUT
      REAL VAR,QPERF,DEM,REL,COUNT
      INTEGER TMAX,REPMAX,NM,M,Y,NDEMZ,NN,NDZ
      INTEGER R,N,X,NY,NNODE,T,Z
      DIMENSION NODE(16),MONTH(12),QPERF(16,20,20,12),DEM(12,7)
      DIMENSION NDEMZ(7),COUNT(12),REL(12,7)
      WRITE(*,*)'********DEMAND RELIABILITY****************'
      WRITE(*,*)'***********JANUARY 1993************************'
      DATA NDZ/7/
 C     these are the fixed iris node numbers of the demand nodes, i.e.:
 C     hautval=5
 C     moyenval=7
 C     basseval=9
 C     ldeguiers=11
 C     delta=14
 C     Diama nav. contstaint=13
 C     Cap Vert=12
      DATA NDEMZ(1)/5/
      DATA NDEMZ(2)/7/
      DATA NDEMZ(3)/9/
      DATA NDEMZ(4)/11/
      DATA NDEMZ(5)/14/
      DATA NDEMZ(6)/10/
      DATA NDEMZ(7)/12/
 C     Cap Vert inflow demands (municipal) assumed constant
      DATA DEM(1,7)/62.5/
      DATA DEM(2,7)/63./
```

```
      DATA DEM(3,7)/70.3/
      DATA DEM(4,7)/68.7/
      DATA DEM(5,7)/57.4/
      DATA DEM(6,7)/51.7/
      DATA DEM(7,7)/44.5/
      DATA DEM(8,7)/45.7/
      DATA DEM(9,7)/45.7/
      DATA DEM(10,7)/48/
      DATA DEM(11,7)/51.4/
      DATA DEM(12,7)/56.3/
      OPEN(6,FILE='PROCQIN.OUT')
      READ(6,*)NNODE,TMAX,REPMAX
      NY=TMAX/12
C     the first block breaks the output time series down into
C     node,replicate,year,month indexed for the process variable
      DO 30 R=1,REPMAX
         READ(6,*)
            DO 25 N=1,NNODE
            READ(6,*)
            M=1
            Y=1
            DO 20 T=1,TMAX
               READ(6,150)X,VAR
               QPERF(N,R,Y,M)=VAR
               IF(T.EQ.Y*12)THEN
                  Y=Y+1
                  M=1
               ELSE
                  M=M+1
               END IF
 20         CONTINUE
 25      CONTINUE
 30   CONTINUE
C     now read in demands at all demand nodes for reliability calculation
      OPEN(7,FILE='NRM297.DT3')
      OPEN(8,FILE='RELY.1')
      READ(7,*)
      DO 35 M=1,12
         READ(7,155)(DEM(M,NN),NN=1,5)
 35   CONTINUE
      DO 40 M=1,12
         DEM(M,6)=236.0
 40   CONTINUE
      OPEN(9,FILE='DEMCHK.OUT')
```

```
      DO 45 M=1,12
          WRITE(9,155)(DEM(M,NN),NN=1,5)
 45   CONTINUE
C     note: the same structure can be used for further equity or
C     statistical calculations
      DO 75 NN=1,NDZ
          DO 50 M=1,12
              COUNT(M)=0.0
 50       CONTINUE
          DO 70 R=1,REPMAX
              DO 65 Y=1,NY
                  DO 60 M=1,12
                  IF(QPERF(NDEMZ(NN),R,Y,M).GE..95*DEM(M,NN))THEN
                          COUNT(M)=COUNT(M)+1.0
                     END IF
 60               CONTINUE
 65           CONTINUE
 70       CONTINUE
C         now calc. period reliability as a pecentage for the curent node
          DO 72 M=1,12
              REL(M,NN)=(COUNT(M)/(REPMAX*NY))*100.0
 72       CONTINUE
 75   CONTINUE
C     no write out the period reliabilities at all nodes
      WRITE(8,*)'DEMAND SATISFACTION RELIABILITY (%)'
      WRITE(8,*)'   BAKEL    MATAM    DAGANA LDGUIERS    DELTA  NAV
     1IGATE   CAPVERT'
      DO 100 M=1,12
          WRITE(8,160)(REL(M,NN),NN=1,NDZ)
 100  CONTINUE
 150  FORMAT(I4,1X,F9.2)
 155  FORMAT(5(F10.3))
 160  FORMAT(7(F10.3))
         STOP
      END
```

REFERENCES

Adams, A. (1985). *La terre et les gens du Fleuve*. Paris, Harmattan.

Akaike, H. (1974). "A New Look at the Statistical Model Identification", *IEEE Trans. Automat. Con.*, AC-19:716-723.

Albergel, J and J. C. Bader (1993). personal communication

Bader, J. C. (1991). *SIMULSEN Logiciel de Gestion de la Retenue de Manantali au Pas de Temps Journalier-Notice d'Utilisation*, OMVS/ORSTOM, Dakar.

Bader, J. C. (1991). *Calcul de la Courbe de Remous du Barrage de Diama-Logiciel Corediam*, Dakar, OMVS/ORSTOM.

BCEOM (1988). *Cayor Canal Feasibility Study, Synthesis Report*, Republic of Senegal, Ministry of Hydraulics.

Belman, R. E., (1957) *Dynamic Programming*, Princeton University Press, Princeton, N.J.

Biswas, Asit K. (1992). "The Aswan High Dam Revisited", *Ecodecision* 6, pp. 67-69.

Box, G. and G. M. Jenkins (1970). *Time Series Analysis: Forecasting and Control.* San Francisco, Holden Day.

Bos, M. G. and J. Nugteren (1978), *On Irrigation Efficiencies.* International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

Brusberg, F. E. (1990). *Analyse des donnees de reference et etude socio-economique pour la period d'hivernage 1989-1990.* Projet de gestion de l'eau et de l'irrigation, Rapport Intermediare, Harza Engineering Company, Technical Assitance Team. Contrat USAID no. 685-0280. Devres Inc., Bethesda, MD and Bakel, Senegal.

CILSS (1989). *Etude de l'amelioraton du developpement des cultures irriguees au Senegal.* Comite Permanent Inter-Etats de Lutte contre la Secheresse dans le Sahel, Dakar.

CILSS (1990). *Problematique des Politiques Rizicoles en Pays Sahelien, Rapport de Synthese*, Comite Permanent Inter-Etats de Lutte contre la Secheresse dans le Sahel, Bruxelles.

CILSS (1990). *Problematique des Politiques Rizicoles en Pays Sahelien, Volume 3, Le Senegal*, Comite Permanent Inter-Etats de Lutte contre la Secheresse dans le Sahel, Bruxelles.

Citeau, J. (1990). *Les Satellites Meteorologique, Une Approche Nouvelle de la Connaissance du Climat du Sahel*, These du Doctorat de l'Universite Paul Sabatier, Centre d'Etudes Spatiale des

Rayonnements, Toulouse, France

Diemer, G. and F. P. Huibers (1991). *Farmer-managed irrigation in the Senegal valley: Implications for the Current Design Method.* End-of-project report. WARDA/Wageningen Agricultural University, Water Management Project. St. Louis and Wageningen.

Diallo, Diouf, Hannan, Ndiaye, and Prevost (1991). AVHRR Monitoring of Savanna Primary Production in Senegal, West Africa 1987-1988. *International Journal of Remote Sensing* 12(6), pp. 1259-1279.

Diouff, Abdou (1992) in "Manantali et Diama Les Barrages de l'Espoir", *Le Soleil*, November 2, 1992. Dakar.

Diouf, Diallo, and Marks (1990). "Commentaire d'une Carte de production vegetale du Senegal: hivernage 1989", *Biologie Geologie* 3, pp. 527-532.

Doorenbos, J. and W. O. Pruitt (1977). *Guidelines for Predicting Crop Water Requirements-FAO Irrigation and Drainage Paper 24*, Food and Agriculture Organization of the United Nations, Rome

Duckstein, L. and S. Opricovic (1980). "Multi-objective Optimization in River Basin Development", *Water Resour. Res.* 16(1), 14-20.

Engelhard, Philippe (1991). "La Vallee 'revistee' ou les 'Enjeux de l'apres barrage" cinq ans plus tard" in Bernard Crousse, Paul Mathieu, Sidy, M. Seck, eds., *La Vallee du Fleuve Senegal*, Karthala, Paris.

Falkenmark, M., Jan Lundqvist and Carl Widstrand (1989). "Macro-scale water scarcity requires micro-scale approaches: aspects of vulnerability in semi-arid development", *Natural Resources Forum* 13(4) pp. 258-267.

Food and Agricultural Organization (1977). *Etude Hydro-Agricole du Bassin du Fleuve Senegal*, Rapport de Synthese des Etudes et Travaux, FAO, Rome.

Food 2000 (1987). *Global Policies for Sustainable Agriculture.* Report to the World Commission o Environment and Development, Zed Books, London.

Foret, A. (1888). *Un Voyage dans le haut Senegal*, St. Louis, Paris.

Frankenburger, Timothy R., Eric Arnould, Alex Cunard, Oumar Aw, Margaret Norem, M. Priscilla Stone, Bruce Horwith (1987). *Farming Systems Research Along the Senegal River Valley: A Rainy Season Reconnaissance Survey in The Middle Valley Between Podor and Matam, Senegal*, Senegal Agriculture Research Project II, College of Agriculture, University of Arizona, Tuscon, Arizona.

Freud, C. (1988). *Quelle Cooperation?*, Karthala, Paris.

Gannet, Fleming, Corrdry and Carpenter (1980). *Assessment of the Environemtal Effects of Proposed Developments in the Senegal River Basin. Final Report (Synthesis) and Plan of Action.* Oranisation pour la Mise en Valeur du Fleuve Senegal, Dakar.

GERSAR (1990). *Plan Directeur de Developpement Integre Pour la Rive Gauche de la Valee du Fleuve Senegal-Schema Directeur de Dagana Annexes A a E Document Definitif*, Republique du Senegal, Ministere du Plan de la Cooperation/Programme de Nations-Unies pour le developpement/Banque Internationale pour la Reconstruction et le Developpement.

GIBB (1986). *Etude de la Gestion des Ouvrages Communs de L'OMVS*, Rapports Phase 1 - Volume 1C Analyse de la situation actuelle, Annexes A-D. Sir Alexander Gibb and Partners, Electricite de France and Euronconsult/OMVS, Dakar.

GIBB (1986). *Etude de la Gestion des Ouvrages Communs de L'OMVS*, Rapports Phase 2 - Volume 2A Scenarios d'Utilisation de l'eau. Sir Alexander Gibb and Partners, Electricite de France and Euronconsult/OMVS, Dakar.

GIBB (1987). *Study of the Management of the OMVS Common Works*, Reports Phase 2 - Volume 2A Water Use Scenarios, Summary Report. Sir Alexander Gibb and Partners, Electricite de France and Euronconsult/OMVS, Dakar.

Glantz, Michael H. (1987). "Drought in Africa", *Scientific American* 256(6), pp. 35-40.

Gleick, P.H. (1987). "Regional Hydrologic Consequences of Increases in Atmospheric CO2 and other Trace Gasses", *Climatic Change* 10, 137-161.

Goldsmith, Edward and Nicholas Hildyard (1984). *The Social and Environmental Effects of Large Dams*, Sierra Club Books, San Francisco.

Gonzalez, Patrick (1992). *New Directions and Old Lessons of Internationally-Financed Natural Resource Projects in Senegal.* Energy and Resources Group, University of California, Berkeley.

Groupement Manantali (1978). *Etude d'Execution du Barrage et de l'Usine Hydro-electrique de Manantali-Rapport Final:Actualisation des donnees de base, Annexe 2: hydrologie-mission A.1.2.* OMVS/Groupement Manantali

Hall, W. A. and J. A. Dracup (1970). *Water Resources Systems Engineering.* McGraw-Hill Book. Co., New York

Hipel, Keith W. (1985). "Time Series Analysis in Perspective", *Water Resources Bulletin* 21(4), pp. 609-623.

Hipel, K. W., A. I. Mcleod and W. C. Lennox. (1977). "Advances in Box-Jenkins Modelling I. Model Construction:, *Wat. Res. Res.* (13)3: 567-575.

Horowitz, M. H. (1990). "Donors and Deserts: The Political Ecology of Destructive Development in the Sahel", *African Environment* Vol. VII(25-28). ENDA, Dakar.

Hoegberg, P. and M. Kvarnastroem (1982). "Nitrogen fixation by the woody legume Leucaena leucocephala in Tanzania", *Plant Soil* 66: 21-28

Huibers, F. P., B. Fall and A. A. Samb (1988). *Projet Gestion de l'eau. Bilan mi-terme des resultats de la recherche.* WARDA/Wageningen Agricultural University, Water Management Project. St. Louis and Wageningen.

Huibers, F. P. and J. J. Speelman (1989). *Water Management in Village Irrigation Schemes of the Senegal River Valley: Technical Aspects.* WARDA/Wageningen Agricultural University, Water Management Project. St. Louis and Wageningen.

Hufschmidt, M. M. and M. B. Fiering (1966). *Simulation Techniques for Design of Water Resources Systems.* Harvard University Press, Cambridge, MA.

ICRISAT (1987) *Soil, Crop and Water Management Systems for Rainfed Agriculture in the Sudano-Sahelian Zone: proceedings of an International Workshop*, International Crops Research Institute for the Semi-Arid Tropics, Patancheru, India.

IIASA (1990a) *IRIS: An Interactive River System Simulation Program - General Introduction and Description.*, IIASA, Laxenburg, Austria.

IIASA (1990b) *IRIS: An Interactive River System Simulation Program - User's Manual Version 1.1*, IIASA, Laxenburg, Austria.

Juo, A. S. R., and R. Lal (1977). "Effect of fallow and continuous cultivation on the chemical and physical properties of an Alfisol in western Nigeria", *Plant Soil* 47: 567-584.

Karamouz, M. and M. H. Houck (1987). "Comparison of Stochastic and Deterministic Dynamic Programming for Reservoir Operating Rule Generation", *Water Resources Bulletin* 23(1):1-9.

Karamouz, M. and H. V. Vasiliadis (1992). "Bayesian Stochastic Optimization of Reservoir Operation Using Uncertain Forecasts", *Water Resour. Res.*, 28(5):1221-1232.

Kellor, J. (1990). "A Wholistic Approach to Irrigation Scheme Water Management" in R. K. Sampath and Robert A. Young, eds., *Social, Economic and Institutional Issues in Third World Irrigation Management*, Westview Press, Boulder, CO.

Kite, G. (1989), "Use of Time Series Analysis to Detect Climate Change", *J. Hydrol.*, 111: 259-

279.

Kite, G. W., and Adamowski, K. (1973). "Stochastic Analysis of Lake Superior Elevations for Computation of Relative Crustal Movement", *J. Hydrol.*, 18:163-175.

Klemes, V. (1974), "The Hurst Phenomenon: A Puzzle?", *Water Res. Res.*, 10(4):675-688.

Kolawole, Are (1989). "Under-performance of Nigerian Irrigation Systems", *Water International*, 5(2), pp. 125-135.

Kuiper, E. (1965). *Water Resources Development Planning, Engineering and Economics*, Butterworth and Co., London.

KULeuven (1991). *Analyse du Bilan d'eau de deux cuvettes du delta du fleuve Senegal 1990*, Projet Gestion de l'Eau Co-operation Scientifique KULeuven-SAED, Bulletin No. 3, SAED, St. Louis, Senegal.

Lal, Rattan (1988). "Soil Degradation and the Future of Agriculture in sub-Saharan Africa", *J. Soil Water Cons.*, Nov-Dec, 1988, 444-451.

Lal, Rattan (1990). "Low-resource Agriculture Alternatives in sub-Saharan Africa', *J. Soil Water Cons.*, Jul-Aug, 1990, 437-445.

Lamb, P. (1985) "West African Rainfall Index", *Climate Diagnostic Bulletin*, 85/10, NOAA/Nws ed., Washington.

Lemarquand, David G. (1990). "International Development of the Senegal River", *Water International*, 15, 223-230.

Loucks, D. P. (1968). *Computer Models for Reservoir Regulations*, J. Sanit. Eng. Div., Am. Soc. Eng., 94(SA4), 668-671.

Loucks, D. P., J. R. Stedinger and D. A. Haith (1981). *Water Resources Systems Planning and Analysis*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Loucks, D. P., and O. T. Sigvaldason (1982). "Multiple-Reservoir Operation in North America." In: *The Operation of Multiple Reservoir Systems*, Z. Kaczmarek and J. Kindler (eds.), International Institute for Applied Systems Analysis, Laxenburg, Austria.

Mbalo, N (1993) Forestry Engineer, ENDA-SYSPRO, Dakar (personal communication)

M'baye, K. (1966). "Le Regime des Terres au Senegal" in Arthur Nylander, ed., *Le Droit de la Terre en Afrique (au Sud du Sahara)*, Association Internationale des Sciences Juridiques, Maisonneuve et Larose, Paris, 1971.

Mcleod, Ian A., Hipel, K. W. and Lennox, W. C. (1977). "Advances in Box-Jenkins Modeling 2. Applications", *Wat. Res. Res.*, 13(3):577-586.

MEACC (1993). *Canal du Cayor, l'espoir.* Ministere de l'Hydraulique/Mission D'Etude et d'Ammenagement du Canal du Cayor, Dakar

Ministere du Developpement Rural (1984). *Nouvelle Politique Agricole*, Republique du Senegal, Ministere du Developpement Rural, Dakar.

Ministere de l'Interieur (1985). *Plan National d'Amenagement du Territoire, Projet U.S. AID/Remote Sensing Institute-South Dakota State University No. 685-0233*, Republique du Senegal, Ministere de l'Interieur, Dakar.

Mohan, S. and Keskar, J. B. (1991). "Optimization of Multipurpose Reservoir System Operation", *Water Resources Bulletin* 27(4):621-629.

Nair, P. K. R., and P. K. Khanna (1975). 'Potassium dynamics in the soil-plant system of tropical plantation systems". In G. S. Sekhon [ed.] *Potassium in Soils and Crops.* Potash Res. Inst. of India, New Delhi. pp. 415-432.

Ndiaye, Mbalo (1993) personal communication.

Newton, Alex (1988). *West Africa - A Travel Survival Kit*, Lonely Planet Publications, Victoria, Australia.

Ominade, Bade (1990). *The IMF, The World Bank and African Debt, Vol. II. The Social and Political Impacts*, Institute for African Alternatives, New York

Organisation Pour la Mise en Valeur du Fleuve Senegal (1980). *Assessment of the Environmental Effects of Proposed Developments in the Senegal River Basin*, Synthesis-Final Report, OMVS, Dakar.

ORSTOM (1992). *Banque de Donnees Hydrologique du Fleuve Senegal*, OMVS/ORSTOM, Dakar.

Palutikoff, J. P., J. M. Lough and G. Farmer (1981) "Senegal River Runoff", *Nature*, 293:p.414.

Platon, Pierre (1981). "The Development of the Senegal River", *Marches Tropicaux et Mediterraneens*, 17th April 1981.

Potworowski, Andre (1990). "A Taste of Salt", *IDRC Reports* 18(4), p.10.

Rao, A. R., S. G. Rao and R. L. Kashyap. (1985). "Stochastic Analysis of Time-Aggregated

Hydrologic Data, *Water Resources Bulletin* 21(4):663-675.

Reid, Walter V. C. (1989). "Sustainable Development - Lessons from Success", *Environment*, 31(4), pp. 8-12.

Richards, P. (1986). *Coping with Hunger*, Allen and Unwin, London.

Riedacker, Arthur and Benjamin Dessus (1991). *Increasing Productivity of Agricultural Land and Forest Plantations to Slow Down the Increase of the Greenhouse Effect.* EEC 6th European Conference on Biomass for Energy, Industry and Environment, Athens.

Riley, Paul J., Jay C. Anderson, A. Bruce Bishop, David S. Bowles and John E. Keith (1978). *Cost Allocation Alternatives for the Senegal River Development Program*, Water Resource Planning Series UWRL/P-78/06, College of Engineering, Utah State University, Logan, Utah.

Salunke, V. B. (1983). *Pani Panchayatt, Dividing Line between Poverty and Prosperity*, Gram Gourav Pratishthan, Shetkarinagar-Khalad Taluka-Purandhar District: Pune, Maharashtra, India.

SAED (1985). *Les amenagements hydro-agricoles et la gestion de l'eau a la SAED*, Societe Nationale d'Ammenagement et Exploitation des Terres du Delta du Fleuve Senegal, Ministere du Development Rural, Republique du Senegal, Dakar.

SAED (1986). *Methodologie Pour la Conception et la Realisation des Perimetres Villageois*, Societe Nationale d'Ammenagement et Exploitation des Terres du Delta du Fleuve Senegal, Ministere du Development Rural, Republique du Senegal, Dakar.

Salewicz, K. A. (1991). "Management of Large International Rivers-Practical Experience from a Research Perspective" in *Hydrology for the Management of Large River Basins* (Proceedings of the Vienna Symposium, August 1991). IAHS Publ. no. 201, 1991.

Salewicz, K. A. and D. P. Loucks (1990) "Development and Application of an Interactive Decision Support System for River Management - Some Experiences at IIASA", in S. Simonovic (ed.) *Water Resource Systems Application*, Dept. of Civil Engineering Univ. of Manitoba, Winnipeg, Canada.

Savic, D. A., D. H. Burn, and Z. Zrinji (1989) "A Comparison of Streamflow Generation Models for Reservoir Capacity-Yield Analysis", *Water Resources Bulletin* 25(5):977-983.

Scudder, Thayer (1988). *The African Experience with River Basin Development: Achievement to Date, the Role of Institutions and Strategies for the Future*, Institute for Development Anthropology Cooperative Agreement on Settlement and Resource Systems Analysis, Worcester, Mass.

Scudder, Thayer (1989). River Basin Projects in Africa", *Environment* 31(2):4-9,27-32.

Seck, Sidy M. (1991). "Sur la Dynamique de l'irrigation dans la vallee du fleuve" in Bernard Crousse, Paul Mathieu, Sidy, M. Seck, eds., *La Vallee du Fleuve Senegal*, Karthala, Paris.

Seck, Mousse (1991). *Programme Intensification Agricole et Nouveaux Systemes de Production*, ENDA-Syspro, Dakar.

Seck, Mousse (1992). *Environnement et Systemes de Production: Une Prospective pour le Sahel*, ENDA-Syspro, Dakar.

Seck, Mousse, Phillipe Engelhard and Taoufik B. Abdallah (1992). "Beyond the Agricultural Crisis in the Sahel" in A. M. Lykke, K. Tybrik and A. Jorgenson, eds., *Sustainable Development in the Sahel*, AAU Reports 29. Aarhus University Press, Denmark.

Seck, Mousse and Thiemo Seck (1993). Personal Communication.

Sene, Ibrahima (1992). "Agriculture Senegalaise: diagnostic et perspectives", *Afrique Espoir* 9, pp. 20-22.

Senghor, D. (1985). *Environnement et Developpement: Les Degradations du Millieu Sahelien*, ENDA-Syspro, Dakar.

Simonovic, S. (1989). "Application of Water Resources Systems Concept to the Formulation of a Water Master Plan", *Water International*, 14 pp. 37-50

Sircoulon, J. (1990). *Impact possible des changements climatiques a venir sur les ressources en eau des regions arides et semi-arides*. World Climate Programme. WCAP-12, WMO/TD No. 380.

Taylor, T. A. (1977). "les associations culturales, moyen de lutte contre les parasites en Afrique Tropicale", *Environnement Africain*, November 1977, ENDA, Dakar.

TAMS (1985). *Senegal River Basin Irrigation Review*, Tippet Abbot, McCarthy and Stratton Engineering/USAID, Dakar.

Tucker, C. J., C. Van Praet, E. Boerwinkle and A. Gaston (1984). "Satellite Remote Sensing of Total Herbaceous Biomass Production in the Senegalese Sahel: 1980-1984", *Remote Sensing of the Environment* 17, pp.233-249.

USAID (1984). *Bakel Irrigation Project Mid-term Evaluation*, USAID/OMVS, Dakar.

Valencia, R. and J. C. Shaake (1973). "Disaggregation Processes in Stochastic Hydrology", *Water Resources Research* 9:580-585.

Vlachos, E. (1986). *The Challenges of Transboundary River Basins, Paper presented at the*

Workshop on Management of International River Conflicts, September 22-25, Laxenburg, Austria.

WARDA/Wageningen Agricultural University (1985). *Recherche sur la gestion de l'eau dans les perimetres irrigues villageois de la vallee du fleuve Senegal.* Phase Preliminaire. Rapport de synthese.

William, Philip, (1989). "Adapting Water Resources Management to Global Climate Change", *Climate Change* 15, pp. 83-93.

Yeh, H. (1985). "Reservoir Management and Operations Models: A State of the Art Review", Water Resour. Res. 21(12):1797-1818.