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WATER REQUIREMENTS AND AGRICULTURE BENEFITS FOR THE SENEGAL RIVER BASIN

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ABSTRACT

Water Requirements and Agricultural Benefits
for the Senegal River Basin

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The purpose of this study was to develop a scheme for determining the water requirements and resulting agricultural benefits for irrigation development in the Senegal River Basin. In addition, management options and their social implications are discussed.

The agricultural benefits and water requirements for the entire basin were estimated using a computer model. The model uses a projected agricultural development rate for the basin, a farm budget which outlines the costs and resources, and basin wide seasonal crop water requirements.

For estimating the water requirements the Hargreaves methods for estimating evapotranspiration was used in conjunction with the FAO crop coefficients. To estimate the effective precipitation a probability analysis using a gamma distribution was used. A discussion of the potential for rainfed agriculture is presented based on the dependable precipitation with 75 percent probability of occurrence or exceedance.

For evaluating the crop yields, good expected yield are presented along with environmental requirements to obtain best results. Manage-

ment and technological factors to improve yields are also discussed. The interactions of water and fertility on crop yields are described and equations are presented that indicate how yields can be optimized.

A short discussion on the possible effects that a global atmospheric increase in carbon dioxide, CO_2, may have on future crop yields and water requirements is presented in Appendix A.

(111 pages)

CHAPTER I

INTRODUCTION

The Senegal River, approximately 1800 km long, is one of the largest rivers in Africa. The drainage basin contains approximately 290,000 km^2 in West Africa, between 10°30' and 17°30' north latitude and 7°00' and 16°30' west longitude (see Figure 1-1). It has three distinct regions, the upper basin, the valley, and the delta. The upper basin is the runoff source or water supply region, while the two lower regions are generally areas of net consumptive use. The highest point in the basin is 1372 meters above mean sea level. Channel gradients vary from a maximum of about 2 m per km in the headwater streams to less than 1 cm per km in the delta region.

Rainfall quantities vary considerably throughout the basin, ranging from an average of 2000 mm per year in the southern section to 250 mm per year in the northern portion. Isohyets of the basin are shown in Figure 1-1. At a particular location rainfall amounts also vary from season to season. Average rainfall quantities for the entire basin have been found to vary from one year to another by as much as 20 percent. Average monthly precipitation quantities are high during the rainy season, and are practically nil the rest of the year. In the south, rainfall occurs from April through November, whereas in the north this season is only the three months of July, August, and September. River flows, like precipitation quantities,

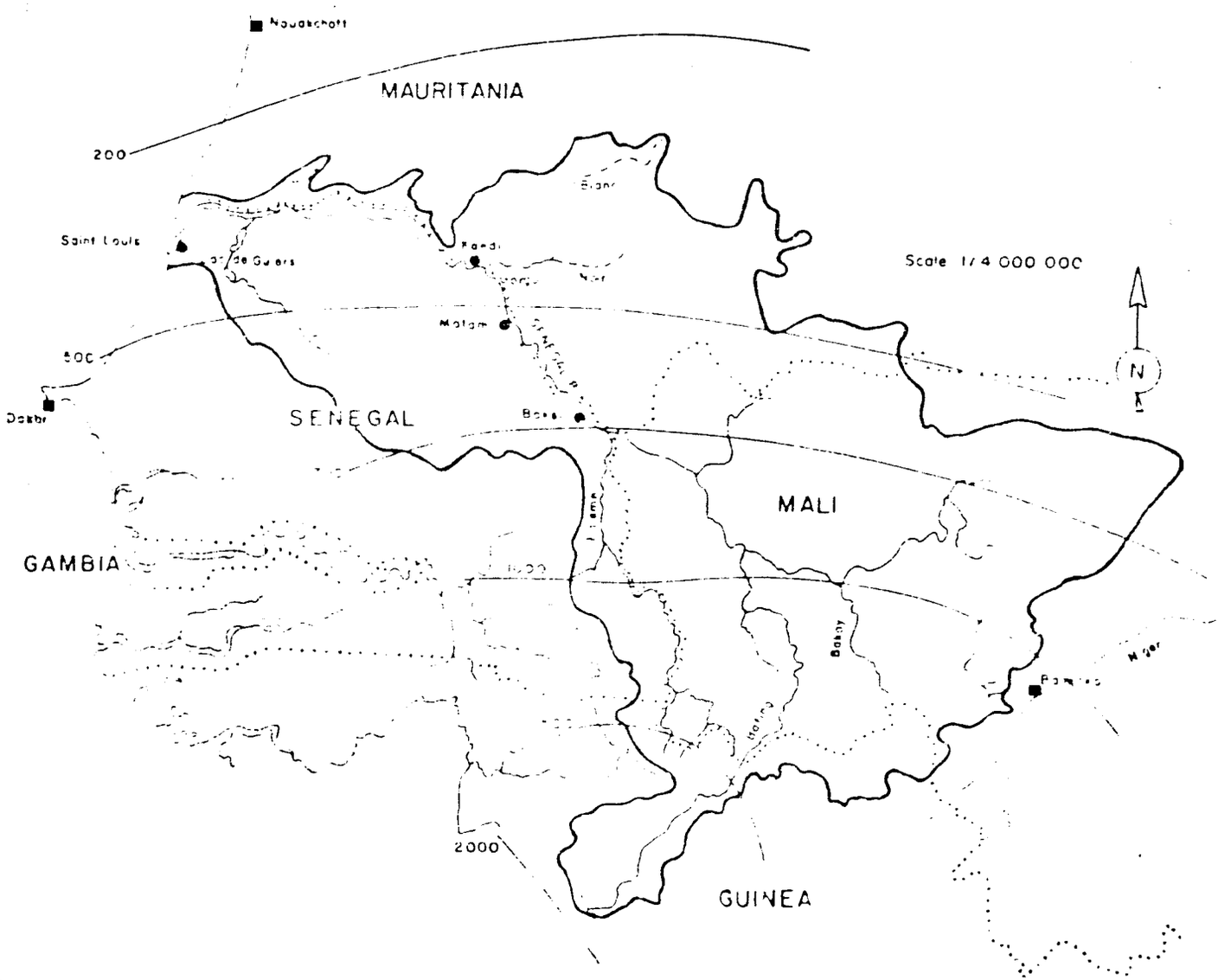

Figure 1.1. Map showing the location of the Senegal River Basin and isohyetal lines of average annual precipitation (in millimeters).

vary considerably both through the year and from one year to the next. The average annual discharge at Bakel is 771 m^3/s, while the 100-year peak flow at this location is 10,700 m^3/s. The average monthly discharge at Bakel is 3,423 m^3/s in September and 10 m^3/s in May.

Most of the cultivated lands lie in the valley and delta regions downstream from Bakel and comprise a total of approximately 120,000 ha of "recession" crops. These crops are grown on the river flood plains after the recession of high river flows each year. In addition, controlled irrigation is now being practiced on some small pilot projects in the valley and on an area of about 17,000 ha in the delta region. Of this total, 1,100 ha in Mauritania and 11,000 ha in Senegal are being irrigated by controlled surface flooding techniques and one crop is being produced each year. The remaining area of approximately 5,000 ha is in sugar cane, and is under fully controlled pumped irrigation in the Richard Toll area of Senegal.

With the construction of the Manantali Dam, two types of agricultural perimeters are being implemented, the large scale perimeter and the small scale perimeter. These two types of perimeters are characterized by Diallo (1980) as follows:

1. <u>Large scale irrigated perimeters</u>

    a. areas of 100 to 10,000 hectares;

    b. large pumping stations (more than 240 hp);

    c. heavy equipment (tractors, combines);

    d. large number of peasant workers;

    e. large number of extension agents and extension services.

The perimeter is divided into holdings of 0.5 to 3 hectares each and is fed by a feeder canal capable of irrigating ten hectares. This arrangement permits improved irrigation and use of large pumps. A mutual guarantee group of 15 to 20 farmers is put in charge of water distribution and maintenance of the feeder canals. The system requires a high capital investment with little peasant participation in its implementation.

2. Small scale village irrigated perimeters

a. small areas of 15 to 50 hectares with an average area of 20 hectares per perimeter;

b. one mutual guarantee group of farmers per village perimeter (15 to 20 farmers per groupement de producteurs);

c. one motor pump per perimeter;

d. one extension agent for two or three villages;

e. use of traditional tools.

This system requires a comparitively low capital investment with a large number of peasants participating in its implementation and operation.

Objective

The purpose of this study is to develop a methodology for estimating the irrigation water requirements and agricultural benefits associated with the proposed Senegal River development. The total agricultural benefit and irrigation water requirements will be used in an analysis for allocating project joint costs between services and determining the user fee for water. However, this cost allocation analysis is not presented in this report.

Procedure

1. Develop a model to calculate the agricultural benefits based upon a revenue minus cost analysis.

2. Determine and evaluate the agricultural economic data base to be used in the model.

3. Determine the irrigation water requirements

   a. Develop a model to calculate the potential evapotranspiration, ET_0.

   b. Determine the effective precipitation based upon a probability of occurrence or exceedance analysis.

CHAPTER II

WATER REQUIREMENTS

The water requirements for each crop are calculated on the basis of meeting the evapotranspiration rate, ET_{CROP}, of a disease-free crop, growing under optimal soil conditions with adequate water and fertility for a given environment.

The net irrigation water requirements of the crops are calculated using the field water balance.

$$I = ET_{CROP} - (P_e + G_e + W_b) \qquad (2\text{-}1)$$

in which

I = net irrigation requirement

ET_{CROP} = crop evapotranspiration

P_e = effective precipitation

G_e = groundwater contribution

W_b = initial soil moisture

For the Senegal River basin, the groundwater contribution is assumed negligible and the soil is assumed to be initially at wilting point (no initial soil moisture is available to the plants).

Estimating ET_{CROP}

The crop evapotranspiration ET_{CROP} is calcualted as follows:

$$ET_{CROP} = ET_o * K_c \qquad (2\text{-}2)$$

in which

ET_o = reference crop potential evapotranspiration

K_c = crop coefficient

ET_o is defined as "the rate of evapotranspiration from an extensive surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water" (Doorenbos and Pruitt 1977).

This definition though basically correct, needs some qualification and amplification. First, the type of grass is not specified. Cool season grasses such as bluegrass and Alta fescue grass can use up to 20 percent more water than warm season grasses (Borelli et al. 1981). Fritschen (1966) suggests that the small differences in water use by various plants may be explained, at least in part, by their physical properties such as albedo and roughness. Broad leaves are capable of extracting more energy from the air and hence have a higher rate of transpiration (Chang 1968). Secondly, the size of the field or the condition of the surrounding areas is not specified. In other words, no provision is made for the effect of advective energy (Chang 1968).

Methods of determining or estimating potential evapotranspiration fall into five categories (Chang 1968):

1. direct measurement, such as lysimeters,
2. empirical formulae using one or more common climatic factors,
3. the aerodynamic approach,
4. the energy budget approach, and
5. the use of evaporimeters

The selection of the method is based on the type of climatic data available, the cost, and the accuracy required in determining water needs. Tanner (1960) maintains that for day-to-day operation, agriculturists can use to advantage any method that is accurate to within 10 percent except for very specific purposes.

Direct measurement of the evapotranspiration rate with lysimeters is the most dependable but this procedure is costly. Aerodynamic and energy budget approaches require climatalogical data usually available only in first-order weather stations, and are generally quite complicated. The Hargreaves equation, an empirical equation, is one of the simplest to use and gives good results. It is written as follows:

$$ET_0 = 0.0075 \times RS \times TF \qquad (2\text{-}3)$$

in which

ET_0 = potential evapotranspiration for Alta fescue grass (mm)

RS = solar radiation at the surface (mm)

TF = mean temperature in degrees Fahrenheit (°F)

When comparisons were made between lysimeter data from Damien, Haiti and the following methods for estimating ET_0: Hargreaves, FAO modification of the Blaney-Criddle, FAO Radiation, FAO version of the Penman, and the Soil Conservation Service (SCS) version of the Blaney-

Criddle, the Hargreaves equation (Equation 2-3) was the method with the least variance (Hargreaves and Samani 1983). When comparing methods for estimating ET_0 using data from eight California locations, the order of preference of the methods evaluated based upon smallness of intercept, coefficient of determination, R^2, and standard deviation of ratios of measured to estimated values, was: Class A pan evaporation, Hargreaves, Jensen-Haise, and the Blaney-Criddle Method (Hargreaves and Samani 1982).

One weakness of Equation 2-3 above is the reliability of the solar radiation data. Solar radiation, RS, can, in fact, be measured directly with radiometers, but they are expensive and sometimes poorly calibrated. Hargreaves and Samani (1982) used the following equations to estimate RS:

$$RS = KT \times RA \times TD^{1/2} \quad \text{.....(2-4)}$$

$$RS = KS \times RA \times S^{1/2} \quad \text{.....(2-5)}$$

in which

KT = calibration coefficient

KS = calibration coefficient

RA = extraterrestrial radiation in the same units as RS

TD = difference between the mean maximum and mean minimum temperature

S = percentage of possible sunshine

The constants KT and KS were determined to be 0.16 and 0.07 respectively for the Senegal River basin. RS and RA are in the same units and TD in degrees Centigrade. The calculation of these constants is based on climatological data from four stations in the Senegal River basin: Richard-Toll, Guede, Kaedi, and Same (Rijks 1976). Values for RA can be determined from a table (Appendix C) or from a computer program based on latitude and the time of the year (Appendix D). Values of the percentage of possible sunshine, S, are based on measured insolation, SH, in hours and the day length, DL. Values of DL can be determined from a table (Appendix C) or from a computer program also based on latitude and the time of the year (Appendix D).

$$S = \frac{SH \times 100}{DL} \quad \text{.....(2-6)}$$

Slightly better results were obtained when estimating incident solar radiation, RS, from percentage of possible sunshine, S, than when estimating RS from temperature differences, TD.

$$RS = 0.16 \times RA \times (TD)^{1/2} \quad \text{.....(2-4a)}$$

$$RS = 0.07 \times RA \times (S)^{1/2} \quad \text{.....(2-5a)}$$

The relative error was approximately ± 15 percent and ± 10 percent for Equations 2-4a and 2-5a, respectively. The absolute error for Equations 2-4a and 2-5a was ± 45 langleys and ± 35 langleys, respectively.

Slightly improved results can be obtained by changing the exponent in Equation 2-5a to 0.6 from 0.5 and then adjusting the 0.07 coefficient. However, the square root function was left for simplicity. No significant improvements could be made on Equation 2-4a.

In addition to proven reliability and general application with little or no calibration, Equations 2-3 and 2-4 are simple and require only maximum and minimum temperatures. Once the potential evaporation of the reference crop is determined, it must be multiplied by the crop coefficient, K_c, of the desired crop to determine the potential evapotranspiration for that crop (Equation 2-2). Procedures for selecting appropriate values of K_c are given in the FAO Irrigation and Drainage Paper 24, "Crop Water Requirements" (Doorenbos and Pruitt 1977). It should be noted that both the ET_0 and K_c should be based upon the same reference crop. Table 2-1 presents a summary of K_c values and the approximate range in seasonal ET to be expected for various crops. If ET estimates are greater or less than those shown in Table 2-1, calculations should be reviewed carefully and efforts should be made to verify that conditions are significantly different to account for differences in the estimate.

Estimating Effective Precipitation (P_e)

When determining net irrigation water requirements, the amount of rain which enters the soil and becomes available for crop water use must be included since the crop water needs can be fully or partially met by rainfall. The portion of total precipitation that is effective that is, used by the plants depends largely on the quality and inten-

Table 2-1. Approximate range of seasonal K_c and ET_{CROP}

Crop	K_c	ET_{CROP} (mm)
Alfalfa	0.85 - 1.05	600 - 1500
Cotton	0.80 - 0.90	550 - 950
Maize	0.75 - 0.90	400 - 750
Rice	0.95 - 1.20	500 - 950
Sorghum	0.75 - 0.85	300 - 650
Sugarcane	0.85 - 1.05	1000 - 1500
Tomatoes	0.75 - 0.90	300 - 600
Wheat	0.80 - 0.90	400 - 600

Source: Crop Water Requirements (Doorenbos and Pruitt 1977).

sity of the rainfall and farm management practices. To determine a dependable level of rainfall, some type of probability analysis is necessary. Barger and Thom (1949), Miller and Weaver (1968), Essenwagner (1960), and Cry (1965) have shown that the best fit for precipitation probability is through the use of a gamma distribution. Friedman and Janes, as cited by Burchinal and Dickerson (1961), concluded that irregularities in precipitation probability curves obtained from the Kimball equation (Equation 2-7), based on 30 years of data, are smoothed by the gamma distribution.

$$F = \frac{m}{n+1} \quad \text{.....(2-7)}$$

in which

F = frequency

m = order number in the rank

n = total number of data points

Figure 2-1 shows a plot of the ranked precipitation data and the gamma distribution for August at the Matam climatological station.

Not all rainfall is effective in that it becomes available for use by crops. Portions may be lost due to surface runoff, evaporation, or deep percolation. Since only a portion of high intensity rain can enter and be stored in the crop root zone, its effectiveness is quite low. On the other hand, frequent light rains with full ground cover may be close to 100 percent effective. A simple method for estimating effective precipitation is presented in Table 2-2.

Table 2.2. Total versus effective monthly precipitation.

Total Monthly Precipitation (mm)	Monthly Rainfall Considered Effective: Part of Each 25-mm Increment %	(mm)	Accumulated Total (mm)
25	95	23.75	23.75
50	90	22.50	46.25
75	82	20.50	66.75
100	65	16.25	83.00
125	45	11.25	94.25
150	25	6.25	100.50
over 150	5	1.25	---

Source: U. S. Department of Agriculture, Agriculture Research Service, Technical Bulletin 1275.

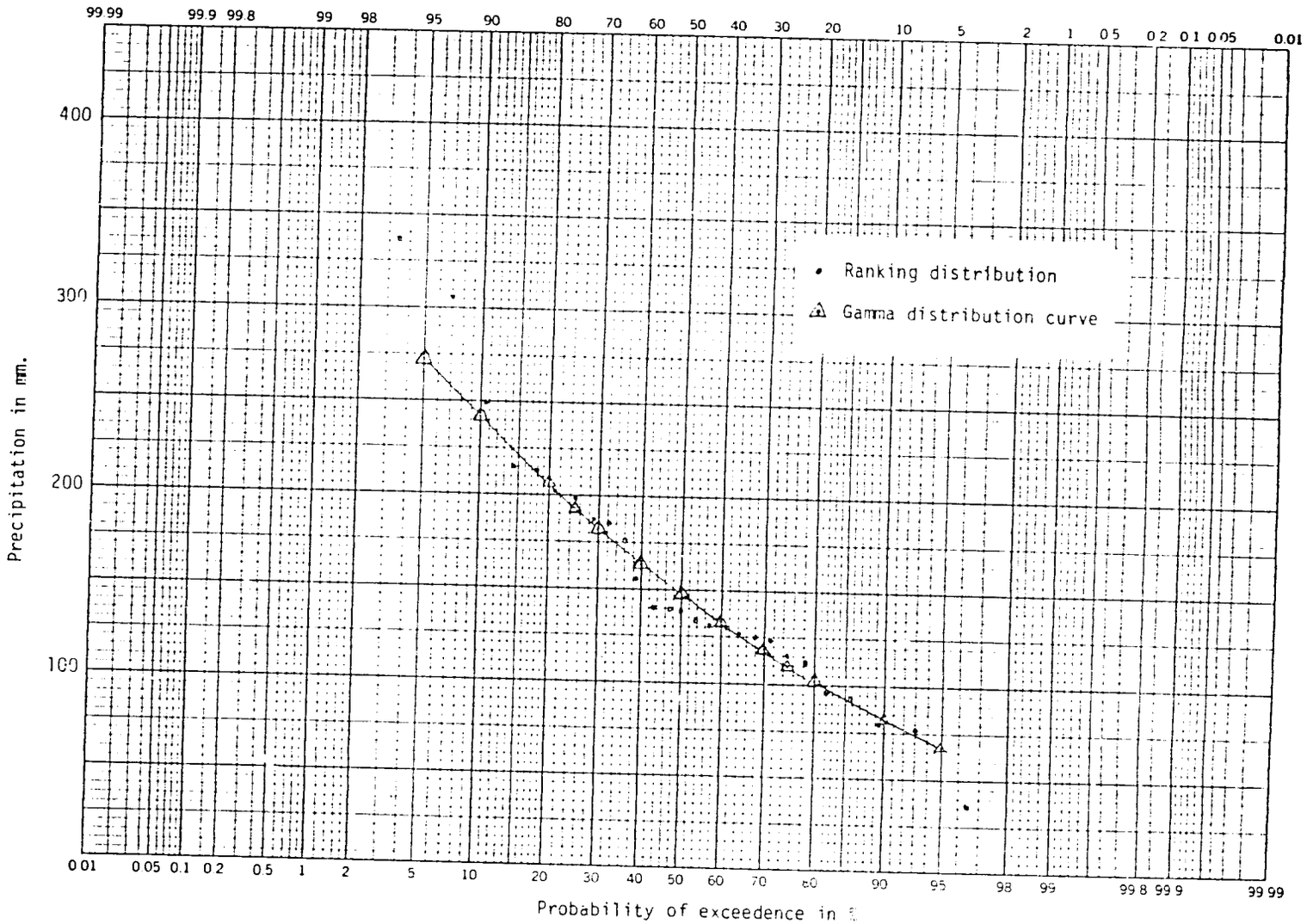

Figure 2-1. Ranking and gamma distribution curves for August at the Matam climatological station.

Hargreaves (1981) found that rainfall intensities or depth-duration amounts, D, vary approximately as the fourth root of the time, t, and the sixth root of the return period, T, for t from 0.5 to 96 hours and T from 5 to 100 years.

$$D = K \times t^{1/4} \times T^{1/6} \quad \text{.....(2-8)}$$

in which

K = calibration coefficient characteristic of the rainfall station being evaluated for a given month, usually the month of maximum rainfall.

t = rainfall duration (hours)

T = return period (years)

Hershfield (1961) found that maximum 24 hour rainfall averages 1.13 times observation day precipitation. A probability distribution of an annual series or a partial series of daily rainfall extreme events can be used to provide reasonable depth-duration amounts for time or duration periods and return periods within the limits given above.

Based on data from the United States and Central America the 10 year 24 hour rainfall, $P_{10,24}$, can be estimated from the 5 percent rainfall probability amount, P_{05}, (the monthly precipitation amount equalled or exceeded 5 percent of the time). The equation for precipitation in mm can be written:

$$P_{10,24} = 30 + 0.30 \times P_{05} \quad \text{.....(2-9)}$$

Although this equation is based upon United States and Central American data, it appears to have universal application.

Based upon data from the United States values of $P_{10,24}$ can also be estimated from the 30 year maximum monthly precipitation, PMX, in mm.

$$P_{10,24} = 22 + 0.30 \times PMX \qquad (2\text{-}10)$$

The correlation coefficient, R^2, was 84 percent, with 46 degres of freedom.

Example

Estimating depth-duration. If the length of record is 9 years and the maximum day rainfall observed during the 9 years was 200 mm, then for the 24 hour 10 year return period rainfall, the maximum amount would be 226 mm (200 mm x 1.13). Equation 2-8 would becomes:

$$226 = K \times 24^{1/4} \times 10^{1/6}$$

$$K = 70$$

$$D = 70 \times t^{1/4} \times T^{1/6}$$

If the P_{05} is known from a gamma distribution analysis, the value of K can be determined from Equations 2-8 and 2-9.

$$K = \frac{30 + 0.30 \times P_{05}}{3.25} \qquad (2\text{-}11)$$

Once having a value of K, the probable rainfall depth-duration amounts for durations from 0.5 to 96 hours and for return periods from 5 to 100 years can be estimated for a given location.

Total Irrigation Water Requirements

In addition to meeting the net irrigation water requirements, water may be required for leaching accumulated salts from the crop roots zones and to compensate for water loses during conveyance and application. Thus, the total irrigation water requirement is calculated as follows:

$$V = \frac{10}{E_p} \sum_{i=1}^{NCROP} \left[\frac{A \times I}{I - LR}\right]_i \quad \text{.....(2-12)}$$

in which

V	= total irrigation water requirements (m^3)
E_p	= project irrigation efficiency (fraction)
A	= area under a given crop, i, (ha)
I	= net water requirements of a given crop (mm)
LR	= leaching requirements (fraction)
NCROP	= number of irrigated crops

The factor 10 which appears in the above equation is due to the conversion to V in m^3 (Doorenbos and Pruitt 1977).

Leaching requirements

The amount of water required for adequate leaching of the soil depends on the salt tolerance of the crop and on local conditions. These include the amount of soluable salts present in the soil, soil

type (texture), quality of irrigation water, ET rates, rainfall amounts and distribution, irrigation methods and practices, depth of groundwater, and drainage practices. Procedures for estimating the leaching requirements are presented in FAO-ID 29 and the ASCE-CU Report (Ayers and Westcot 1976; and Jensen 1974). Salinity problems and control plus salt tolerance of agricultural crops are discussed in detail in Chapter 5 of "Design and Operation of Farm Irrigation Systems" (Jensen 1980).

Irrigation efficiencies

After calculating the net irrigation water requirements and the leaching requirements, the project irrigation efficiency must be estimated to determine the gross irrigation water requirements. Project efficiency is normally subdivided into three categories:

Conveyance efficiency (Ec): ratio between water received at the inlet to a block of fields and that released at the project headworks.

Field canal efficiency (Eb): ratio between water received at the field inlet and that received at the inlet of the block of fields.

Field application efficiency (Ea): ratio between water directly available to the crop and that received at the field inlet.

Project efficiency (Ep): ratio between water made directly available to the crop and that released at headworks. The product of the component terms expressed as ratios.

$$E_p = E_c \times E_b \times E_a \quad \text{.....(2-13)}$$

Efficiencies are hard to determine accurately and change with time. Water efficiencies can be low due to uncontrollable situations such as fluctuations in climate (drought and floods), inadequacy of the water supply when needed, and the lack of flexibility in the management of an agricultural enterprise.

The primary problem in determining irrigation efficiencies is the inaccuracy of the data. First, there is the problem of accuracy in water measurements. A reasonable level of accuracy in water flow measurement is plus or minus 5 to 10 percent, depending on the types of mesuring devices being used (U. S. Dept. of the Interior et al. 1979).

Second, there is a problem of computing crop water requirements, ET_{CROP}. However, the calculation of the crop water requirement is probably more accurate than the measurement of water onto the field. Causes of low irrigation efficiencies basically fall under three categories: physical factors, management factors, and institutional and social factors. The physical factors which cause conveyance losses can be attributed to: permeable canals; obsolete, inadequate, or improperly maintained facilities; and excessive vegetative growth. The soil characteristics on the farm and irrigation method greatly influences the field application efficiency, E_a.

Management factors include lack of trained personnel, lack of soil moisture data and improper timing of irrigation, lack of adequate flow measurements, incorrect application amounts, and lack of adequate facilities to control water. Simple improvements such as using surge flow techniques when surface irrigating could improve the application uniformity and efficiency (Bishop et al. 1981).

Institutional and social factors include: social attitudes as related to land use, financial capabilities, water prices, environmental conflicts existing water laws, and traditional agricultural practices. Table 2-3 gives some indicative efficiencies from well designed schemes in operation for some years and based mainly on a comprehensive ICID/ILRI survey and USDA and US(SCS) sources (Bos and Nugteren 1974). Additional helpful information on the topic of crop water use is found in the various references listed in Appendix E.

Table 2-3. Conveyance (Ec), field canal (Eb), distribution (Ed) and field application efficiency (Ea).

			ICID/ILRI
Conveyance Efficiency (Ec)			
Continuous supply with no substantial change in flow			0.9
Rotational supply in projects of 3 000 - 7 000 ha and rotation areas of 70 - 300 ha, with effective management			0.8
Rotational supply in large schemes (> 10 000 ha) and small schemes (< 1 000 ha) with respective problematic communication and less effective management:			
based on predetermined schedule			0.7
based on advance request			0.65
Field Canal Efficiency (Eb)			
Blocks larger than 20 ha:	unlined		0.8
	lined or piped		0.9
Blocks up to 20 ha:	unlined		0.7
	lined or piped		0.8
Distribution Efficiency (Ed = Ec.Eb)			
Average for rotational supply with management and communication adequate			0.65
sufficient			0.55
insufficient			0.40
poor			0.30
Field Application Efficiency (Ea)	USDA	US(SCS)	
Surface methods			
light soils	0.55		
medium soils	0.70		
heavy soils	0.60		
graded border		0.60 - 0.75	0.53
basin and level border		0.60 - 0.80	0.58
contour ditch		0.50 - 0.55	
furrow		0.55 - 0.70	0.57
corrugation		0.50 - 0.70	
Subsurface		up to 0.80	
Sprinkler, hot dry climate		0.60	
moderate climate		0.70	0.67
humid and cool		0.80	
Rice			0.32

Source: Crop Water Requirements (Doorenbos and Pruitt 1977).

These references are not cited in the text of this thesis but were examined as part of the literature review process.

Method of Irrigation

Selection of an irrigation method needs to be made at an early date by evaluating the technical, economic, and social feasibility. The advantage of one method over another is largely determined by the adequacy with which the crop water requirements are met. Surface irrigation methods are generally the least costly to install, and where conditions are suitable there is little reason for considering other irrigation methods.

Different methods of irrigation imply different rates of water application. When comparing the various methods in terms of water efficiency in meeting crop demand such differences should be recognized. The apparent superiority of one method over another may merely be the result of too much or too little water being applied. There may be no fault in the actual method of irrigation, only in the management (Doorenbos and Pruitt 1977).

When selecting the irrigation method, the following items need to be considered:

- system costs (including operation, maintenance, and labor costs)
- climate
- soil types
- water quantity and quality
- topography
- crop selection

- crop marketability
- legal aspects

A good discussion on the above topics can be found on pages 129-132 of "Irrigation Design and Practice" by Withers and Vipond (1980).

The calculation of the irrigation water requirements for each crop in the Senegal River Basin is shown in Table 5-2. When determining the irrigation water requirements for the entire Senegal River Basin a 60 percent project efficiency was assumed for each crop in Table 4-4. The assumed 60 percent project efficiency is considered to be realistic for surface irrigation in the Matam irrigation perimeter (Bechtel 1976), and representative for the entire Senegal River Basin (Groupement Manantali 1979). Surface irrigation is the method of irrigation most widely used in the Senegal River Basin.

CHAPTER III

AGRICULTURAL YIELDS

Management and Technology

When using the Agricultural Benefits model, AGBEN, presented in Chapter 4 for management purposes, it is important to know (1) the characteristics of a well managed system, (2) achievable yield levels for each crop, and (3) the water requirements for these yields. Table 3-1 gives values in days to crop maturity, potential yield, fertilizer requirements, and water requirements for several crops suitable to the Senegal River Basin. A comprehensive analysis on the suitability of different crops in Africa is presented by FAO (1978). Adams (1953) gives the environmental requirements for best results for cotton, sorghum, rice, tomatoes, and wheat as follows:

Cotton

Soil - Silt loam or fine sandy loam texture; four feet or more in depth; free from alkali or other injurious salts, with a pH of 5.5 to 8.0 (optimum pH is 7.0 to 8.0); friable; fertile; easily tilled; retentive of moisture.

Climate - Warm and mild during the planting and growing season; free from extremes between day and night temperature; hot summers; freedom from unseasonable rains during the ripening and picking season; and a frost-free period of from 7 to 9 months with minimum temperatures unlikely to drop much below 60°F for any period of time.

Table 3-1. Crop requirements.

Crop	Total growing period (days)	Potential yield (ton/ha)	Fertilizer requirements (kg/ha)			Water requirements (mm/growing period)
			N	P	K	
Alfalfa	100-365	15	0-40	55-65	75-100	800-1600
Cotton	150-180	3-4	100-180	20-60	50-80	700-1300
Groundnut	90-140	3-4	10-20	15-40	25-40	500-700
Maize	100-140+	6-8	100-200	50-80	60-100	500-800
Rice	90-150	6-8	100-150	20-40	80-120	350-700
Sorghum	100-140+	3.5-5	100-180	20-45	35-80	450-650
Soybean	100-130	2.5-3.5	10-20	15-30	25-60	450-700
Sugar cane	270-365	100-150	100-200	20-90	125-160	1500-2500
Tomato	90-140	45-65	100-150	65-110	160-240	400-600
Wheat	100-130	4-6	100-150	35-45	25-50	450-650

Source: Yield Response to Water (Doorenbos and Kassam 1979).

Topography - Level land permitting proper handling of irrigation water is essential since the crop is invariably grown under irrigation.

Sorghum

Soil - Loam or sandy loam soil, 3 feet or more in depth, fairly well supplied with organic matter and plant foods; relatively tolerant to periodic water logging; with a pH of 6 to 8.

Climate - Warm to hot sunny weather, free from frosts, cold nights, and high humidity; does best under conditions of high temperatures, low humidity, and warm nights. A rain free harvest time is essential. Not well adapted to the cool coast or high mountain climates. Will stand maximum temperatures of over 100 degrees Fahrenheit.

Topography - Areas adapted by reason of soil and climate to the production of milo tend to have inadequate rainfall so that irrigation is generally required. Hence, land sufficiently level to permit proper use of irrigation facilities and water is essential.

Rice

Soil - Loam soil two to four feet in depth, underlain with impervious layers to reduce percolation losses; although rice will withstand some alkali, freedom from injurious salts is desirable, with a pH of 5.5 to 6.0. Freedom from serious rice weeds.

Climate - Warm to hot sunny weather during a growing period of 6 to 7 months; free of fogs or other high humidity; free from rains at harvest time. Minimum and maximum temepratures are about 60°F and 100°F, respectively.

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Topography - Since rice is raised in ponds of standing water, very level topography is essential, especially within checks, since the level should not vary more than 2 or 3 inches within a check.

Tomatoes

Soil - Light loam or fine sandy loam, free from injurious salts, with a pH of 5 to 7, fertile but not too rich in organic matter or plant foods (since over-richness may force vine growth instead of encouraging fruiting); depth four feet or more; of good moisture-holding capacity.

Climate - Warm but not excessively hot, sunny growing season of 4 to 6 months; freedom from frosts, cold spells, sudden changes from day to night temperatures, and high humidity. Minimum and maximum temperatures should not fall much below 60°F nor rise much above 90°F.

Topography - Irrigated crops require land sufficiently level so that irrigation can be conducted both efficiently and economically.

Wheat

Acceptable environmental conditions for wheat are relatively broad. However, the more desirable soils are fertile silt loams, 2 or more feet in depth, not subject to standing water during the rainy season, well supplied with organic matter. and free from injurious salts; with a pH of 6 to 8. The more desirable climatic conditions consist of mild, sunny, fairly cool, but not cold weather, for a growing season of 4 to 7 months, with minimum temperatures of about 40°F and maximum of about 70°F. During maturing somewhat warmer temperatures are required, viz., up to 85°F to 90°F. Freedom from unseasonal rains and shattering winds are essential for best results.

It is important to determine not only the crop requirements for maximum yields, but also what are the probable effects of technological and managerial improvements on yields. It is expected that during the early years of the project, yields will be relatively low and that they will gradually increase as farmers become accustomed to irrigated agriculture. Figure 3-1 shows the historical trends in the yield of rice in Japan and of wheat in England. Present yields in other countries are also indicated, but should not be taken as a reflection of their agricultural sophistication. For example, the yields of wheat in Canada reflects the more adverse environment in which the crop is grown. Table 3-2 illustrates the increases in yields for various crops over a period of 26 years. Thus, if only one constant yield value is used when running the model to estimate the agricultural benefits for a 50 year period, the agricultural benefits may be grossly underestimated.

Fertility and Crop Yields

A knowledge of water and fertility is also necessary for optimizing yields. If water availability to the plant is too low, fertilizer application may actually depress yields while with adequate water, response to fertilizer may result in large increases in production (Cusack 1983).

Yield data from Heady and Hexem (1978) for several U.S. states and from Shalhevet (1976) for Israel are shown on Figure 3-2 as isoquants of yield with seasonal ET on one axis and fertility on the

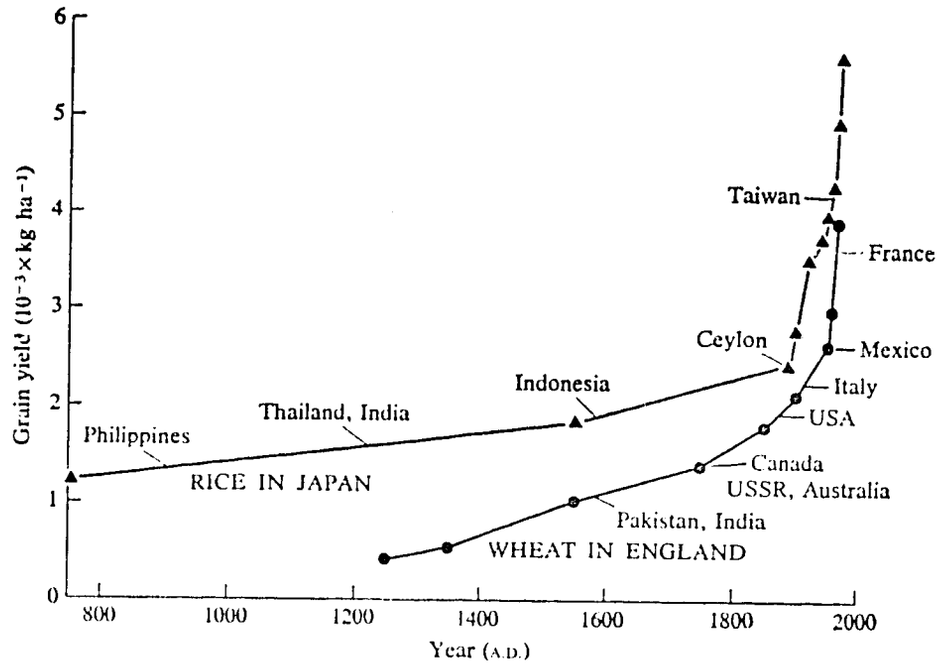

Figure 3-1. Historical trends in the grain yield of rice in Japan and of wheat in England compared with 1968 yields of wheat and rice in several countries. Source: Crop Physiology (Evans 1978)

Table 3-2. Yield increases over time.

Crop	1953 (T/ha)[1]	1979 (T/ha)[2]	% Increase
Cotton	2.3	3.4 - 5.0	48 - 117
Sorghum	2.8	3.5 - 5.0	25 - 79
Rice	4 5	5 - 7	11 - 56
Tomatoes	16.9	55 - 75	225 - 344
Wheat	2.3	4 - 6	74 - 161

[1]Farm Management Crop Manual (Adams 1953).
[2]Yield Response to Water (Doorenbos and Kassam 1979).

fertility on the other. The equation, derived from these experimental data, for optimizing yields in terms of applied nitrogen, N and seasonal evapotranspiration, ET (Cusack 1983) is:

$$N = 0.32\ ET \quad \text{.....} (3\text{-}1)$$

Similar equations have been calculated for other crops based on data from Heady and Hexem (1978) and are as follows:

For Cotton:	$N = 0.10\ ET_{crop}$
Wheat:	$N = 0.12\ ET_{crop}$
Sugar Beets	$N = 0.15\ ET_{crop}$

in which

N = optimum application of nitrogen (kg/ha)

ET_{crop} = seasonal evapotranspiration (mm)

Economically, additional fertilizer should be applied until its marginal physical product is reduced to the ratio of marginal benefit (increased yields) to marginal cost (additional cost of fertilizer). However, it should be noted that fertilizer application needs proper management to prevent toxic buildups in the soil. Figure 3-3 shows a typical relationship between nitrogen application and yield increases. Such curves can easily be used to determine the optimum amount of nitrogen fertilizer application.

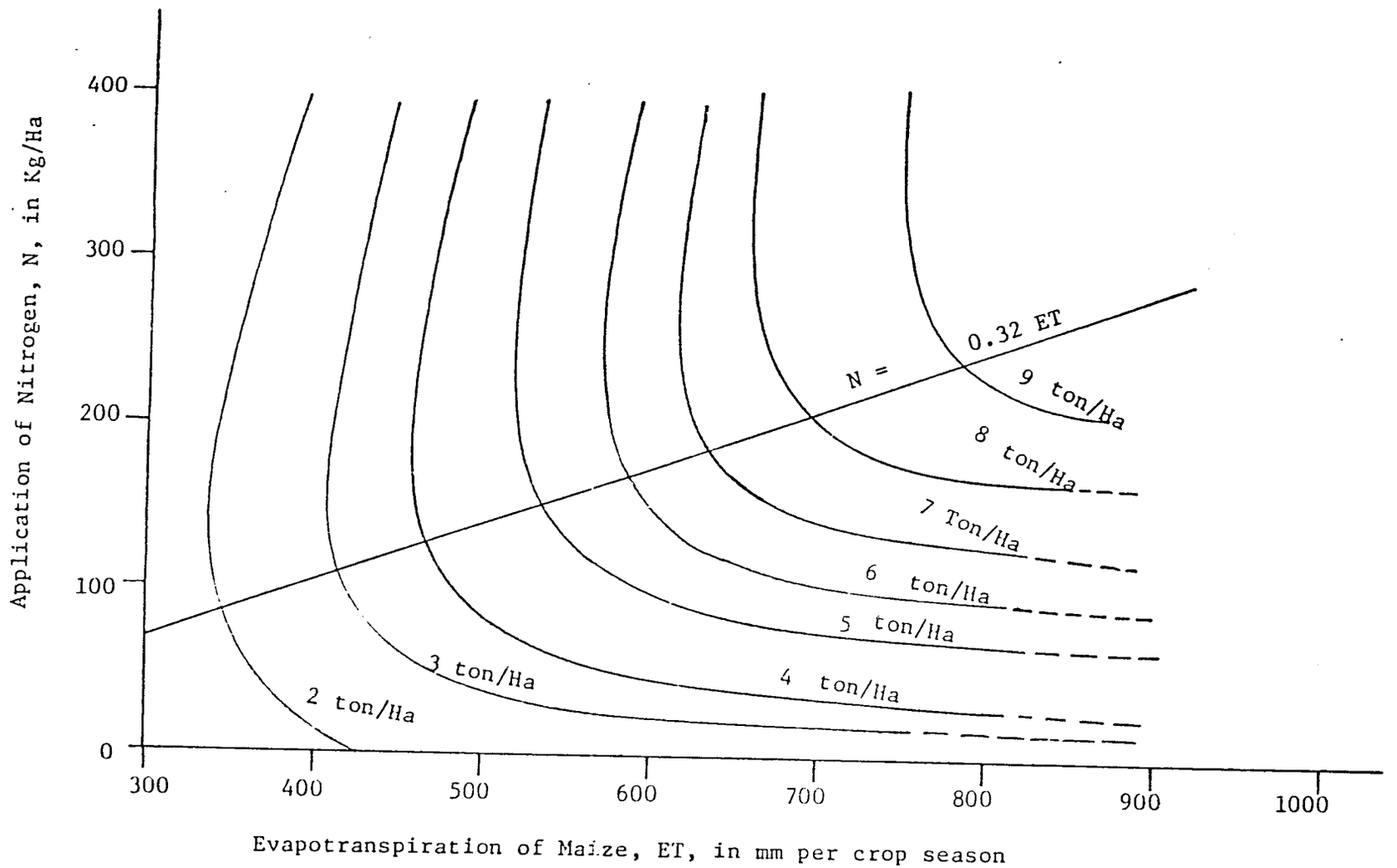

Figure 3-2. Isoquants of maize production. Source: Agroclimatic Information for Development (Cusack 1983).

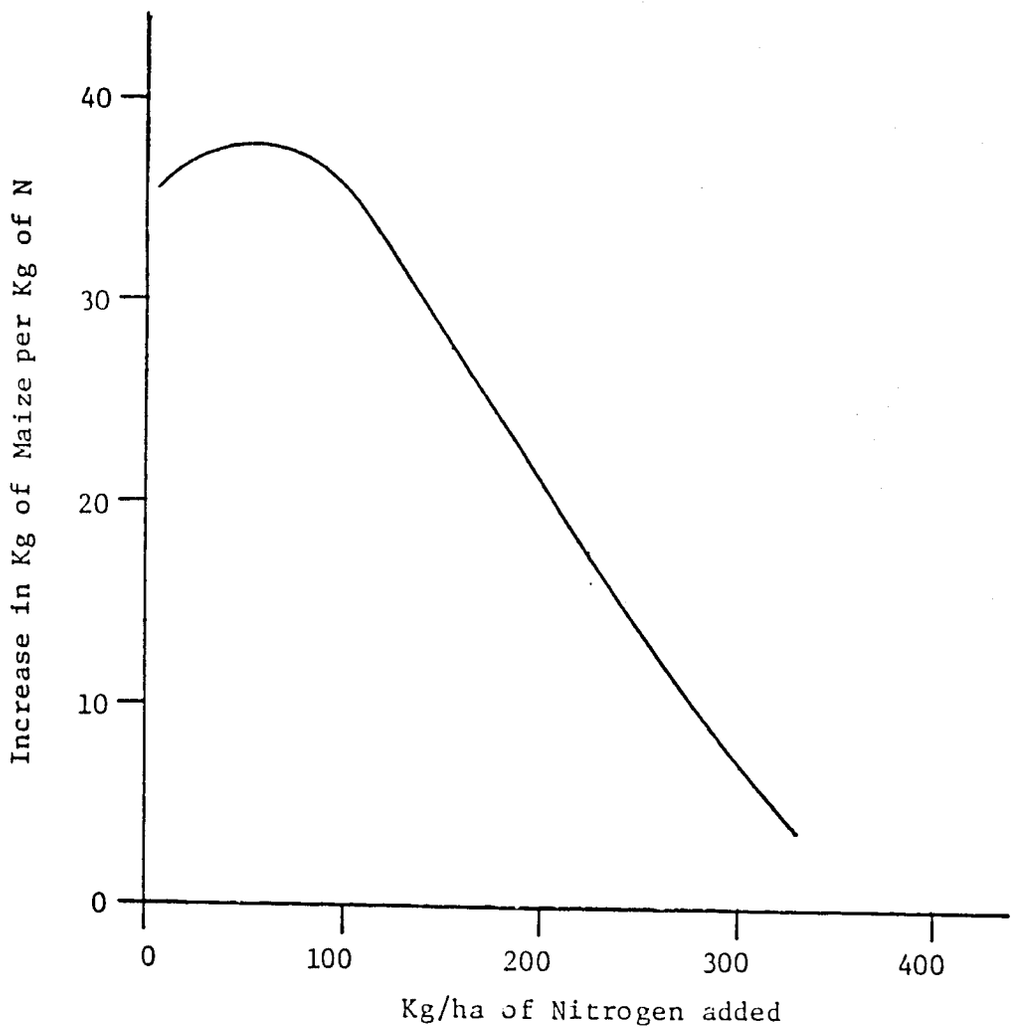

Figure 3-3. Increase in yield of maize per Kg of nitrogen added at various rates of application of N. Water was adequate at all levels of N application. Based on data from Israel. Source: Agroclimatic Information for Development (Cusack 1983).

CHAPTER IV

AGRICULTURAL BENEFITS MODEL

For the purpose of determining the agricultural benefits and water requirements for the Senegal River Basin development project, an agricultural benefit model, AGBEN, was written using FORTRAN programming. A flow chart of the model is presented as Figure 4-1. A description of each component shown in the flowchart is presented later in this chapter, along with a description of the input data and how they were calculated, the algorithms used in the model, and sample outputs.

In the model, all monetary values for the three countries, Mali, Mauritania, and Senegal, are expressed in 1979 CFA F, with U.S. $1.00 being assumed to equal 245 CFA F. Inflation is not considered because all prices and costs are assumed to inflate at the same rate.

Input Data for the Agricultural Benefit Model (AGBEN)

The running of AGBEN requires two separate data tables, the Agricultural Economic Sector Data, AGTAB.PRE, and the Agricultural Area Data, AREA.DAT. In addition to these two data tables, some data are entered interactively on the computer terminal when running the program.

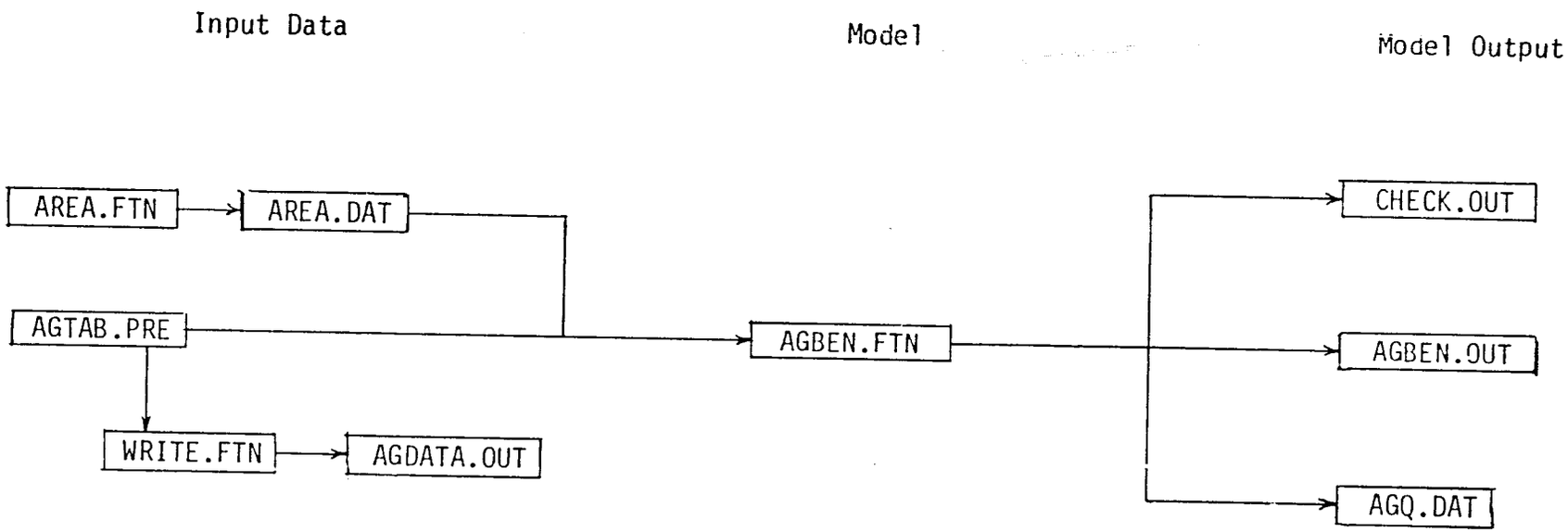

Figure 4-1. Flowchart of the model which determines the agricultural benefits and water requirements for the Senegal River Basin development project.

The agricultural economic sector data (AGTAB.PRE)

Agricultural benefits equal the additional net income from irrigated agriculture above that obtained by traditional recession and dry-land farming. Calculation of these benefits depends upon accurate representation of the costs and revenues to the agricultural sector. These data were obtained from existing farm budgets for representative irrigated perimeters and traditional agriculture. Information for the existing farm budgets was taken from the Groupement Manantali Report (1979), Annex 4. The budget for each farm crop is calculated on a per hectare basis, and the agricultural benefits are calculated from the proportions which each crop makes up of the theoretical (average) hectare. However, the numerical estimates of revenues and costs are somewhat outdated.

Production costs. To update the production costs for all crops, all production costs were increased by the same proportion that rice production costs increased from values shown by the Groupement Manantali Report (1979) to 1980 values reported by SAED for the Lampsar, Dagna, and Nianga perimeters. The 1980 rice production costs as shown in Report 5 (Bowles et al. 1981) are:

Large perimeters	
Rainy season	109,480 CFA F/ha
Dry season	120,428 CFA F/ha
Small perimeters	
Rainy season	69,800 CFA F/ha
Dry season	89,800 CFA F/ha

These costs were then reduced by 10 percent to reflect 1979 costs.

The costs of production include seed, fertilizer, insecticides, and the maintenance and operational costs of the farm equipment or of the draft animals. The production costs basin-wide are assumed to be constant for both large and small perimeters.

Fixed costs. The fixed costs associated with the development of the new irrigated lands are based on the estimates in the Groupement Manantali Report (1979) Annex 4: Agriculture, p. 123). These estimates were then revised using estimates made by SAED, SONADER, and the Malian agricultural engineering Directorate. These updated costs are shown in Report 5 (Bowles et al. 1981) as follows:

Mali	2,000,000 CFA F/ha
Mauritania	
large perimeters	3,000,000 CFA F/ha
small perimeters	1,000,000 CFA F/ha
Senegal	
large perimeters	2,750,000 CFA F/ha
small perimeters	1,000,000 CFA F/ha

For the basin as a whole, the weighted average is in the order of 2,800,000 CFA F/ha. The fixed cost for developing new irrigated lands is thus assumed to be 2,800,000 CFA F/ha with an additional fixed cost of 760,000 CFA F/ha for pumping equipment every five years. The initial fixed cost of 3,560,000 CFA F/ha (2,800,000 + 760,000) is assumed for each new hectare developed, with another 760,000 CFA F/ha for pumping equipment added every five years thereafter. These estimates do not include taxes, thus net primary returns to agriculture include income received by the government through taxes leveed on the agricultural sector.

Theoretical hectare. The theoretical hectare represents the allocation of the agricultural area for each crop in the wet and dry season as a percentage of the total agricultural area.

Table 4-1. Wet and dry season crop as a percentage of the total agricultural area in the Senegal River Basin.

Crop	Wet Season (June-October)	Dry Season (November-May)
Rice	30.6 %	16.3 %
Wheat	--	23.0
Maize	16.5	16.7
Sorghum	28.6	16.7
Niebe	--	5.8
Cotton	3.0	--
Tomatoes	--	3.5
Sugar cane	3.4	3.4
Forage	14.5	14.5

Source: Groupment Manantali Report (1979), Annex 4.

It is assumed that:

- 100 percent of the area is cultivated in the wet season.

- 75 percent of the area planted in rice, wheat, maize, sorghum, and niebe are cultivated in the dry season. Values in Table 4-2 for these crops reflect this reduction.

- Sugar cane is cultivated 80 percent of the time (4 out of 5 years). Thus, the value of 3.4 for sugar cane in Table 4-1 becomes 2.7 in Table 4-2.

Table 4-2. Composition of the irrigated theoretical hectare.

Crop	Wet Season (June-October)	Dry Season (November-May)
Rice	30.6 %	12.2 %
Wheat	--	17.3
Maize	16.5	12.5
Sorghum	28.6	12.5
Niebe	--	4.3
Cotton	3.0	--
Tomato	--	3.5
Sugar Cane	2.7	2.7
Forage	14.5	14.5
Total	95.9 %	79.5 %

Yields from animal husbandry

The yields shown in Table 4-4 for the livestock products are artificially increased by dividing the yields shown in Table 4-3 by the percentage of the theoretical hectares in forage. This accounts for the use of the by-products from crop production as forage for animal husbandry. The yields shown in Table 4-3 represent those for cattle, sheep, and goats all co-existing simultaneously using the available forage from crop by-products and irrigated pastures. This implies that the yields shown in Table 4-3 are those for the entire agricultural area under irrigation. Thus by artificially increasing the yields for the livestock products on irrigated pastures, the added livestock production using the forage from crop by-products is accounted for. For example, the revenues from goat milk, product 25, in year 50 would be:

(83 CFA F/l) x (73 l/ha) x (269,805 ha) = 1.63 billion CFA F

This is equivalent to using Equation 4-2 with the artificially increased yields and the cropping pattern for forage.

(83 CFA F/l) x (3040 l/ha) x (269,805 ha) x (.024)
= 1.63 billion CFA F

Table 4.3 Livestock products per theoretical hectare.

	Wet Season			Dry Season			
Yields	Cattle	Sheep	Goats	Cattle	Sheep	Goats	Total
Milk (l)	97.8	99.1	73.0	26.2	26.5	19.6	342.2
Meat (kg)	41.4	20.1	10.5	11.1	5.4	2.8	91.3

Source: Groupement Manantali Report

Table 4-4 indicates the revenues and costs by crop for irrigated agriculture. World price is in (1979) CFA F/metric ton and yields are in metric tons per hectare, except for the livestock products (cattle, sheep, and goat milk and meat), which are in CFA F/liter and liters/ha and CFA F/kilogram and kilograms/ha, respectively. Production costs per hectare of crop are listed for both small and large perimeters. The entire production costs for livestock are allocated to the production of meat and none to the production of milk. The cropping pattern indicates the fraction of the theoretical hectare planted to

Table 4-4. Agricultural economic sector data table.

PRODUCT	WORLD PRICE	YIELDS (T/HA) IRRIG.	FLOODED	RECESSION	RAINFED	PRODUCTION COSTS LARGE PER.	%	SMALL PER.	%	CROPPING PATTERN (%) AREA	FLOODED	RECESSSION	RAINFED	WATER REQ.
RICE WET	76270.	4.000	0.0000	0.0000	0.0000	99527.	0.7	63440.	0.3	0.306	0.000	0.000	0.000	1.79
RICE DRY	76270.	3.500	0.0000	0.0000	0.0000	109480.	0.7	81631.	0.3	0.122	0.000	0.000	0.000	2.03
TOMATO W	21180.	0.000	0.0000	0.0000	0.0000	0.	0.0	0.	0.0	0.000	0.000	0.000	0.000	0.00
TOMATO D	21180.	54.000	0.0000	0.0000	0.0000	259065.	0.7	203185.	0.3	0.035	0.000	0.000	0.000	0.98
WHEAT W	109465.	0.000	0.0000	0.0000	0.0000	0.	0.0	0.	0.0	0.000	0.000	0.000	0.000	0.00
WHEAT D	109465.	3.500	0.0000	0.0000	0.0000	222955.	0.7	105229.	0.3	0.173	0.000	0.000	0.000	0.88
NIEBE W	63540.	0.000	0.0000	0.1750	0.0875	0.	0.0	0.	0.0	0.000	0.000	0.025	0.025	0.00
NIEBE D	63540.	0.875	0.1750	0.0000	0.0000	78157.	0.7	45604.	0.3	0.043	0.025	0.000	0.000	1.18
S.CANE W	6038.	0.000	0.0000	0.0000	0.0000	184825.	0.7	72248.	0.3	0.027	0.000	0.000	0.000	1.20
S.CANE D	6038.	100.000	0.0000	0.0000	0.0000	201415.	0.7	93859.	0.3	0.027	0.000	0.000	0.000	1.96
SORGHM W	71925.	3.500	0.0000	0.3750	0.1875	71724.	0.7	37554.	0.3	0.286	0.000	0.255	0.255	0.64
SORGHM D	71925.	3.500	0.3750	0.0000	0.0000	78169.	0.7	45604.	0.3	0.125	0.255	0.000	0.000	0.93
MAIZE W	73230.	4.000	0.0000	0.3750	0.1875	78503.	0.7	43676.	0.3	0.165	0.000	0.053	0.053	0.74
MAIZE D	73230.	4.000	0.3750	0.0000	0.0000	85544.	0.7	54193.	0.3	0.125	0.053	0.000	0.000	0.88
COTTON W	69156.	3.000	0.0000	0.0000	0.0000	71724.	1.0	0.	0.0	0.030	0.000	0.000	0.000	0.97
COTTON D	69156.	0.000	0.0000	0.0000	0.0000	0.	0.0	0.	0.0	0.000	0.000	0.000	0.000	0.00
C.MILK W	83.	4075.000	0.0000	0.0000	0.0000	0.	0.0	0.	0.0	0.024	0.000	0.000	0.000	0.00
C.MILK D	83.	1100.000	0.0000	0.0000	0.0000	0.	0.0	0.	0.0	0.024	0.000	0.000	0.000	0.00
C.MEAT W	500.	1725.000	0.0000	0.0000	0.0000	121287.	0.7	72612.	0.3	0.024	0.000	0.000	0.000	1.20
C.MEAT D	500.	460.000	0.0000	0.0000	0.0000	132166.	0.7	92847.	0.3	0.024	0.000	0.000	0.000	1.96
S.MILK W	83.	4130.000	0.0000	0.0000	0.0000	0.	0.0	0.	0.0	0.024	0.000	0.000	0.000	0.00
S.MILK D	83.	1100.000	0.0000	0.0000	0.0000	0.	0.0	0.	0.0	0.024	0.000	0.000	0.000	0.00
S.MEAT W	700.	840.000	0.0000	0.0000	0.0000	121287.	0.7	72612.	0.3	0.024	0.000	0.000	0.000	1.20
S.MEAT D	700.	225.000	0.0000	0.0000	0.0000	132166.	0.7	92847.	0.3	0.024	0.000	0.000	0.000	1.96
G.MILK W	83.	3040.000	0.0000	0.0000	0.0000	0.	0.0	0.	0.0	0.024	0.000	0.000	0.000	0.00
G.MILK D	83.	820.000	0.0000	0.0000	0.0000	0.	0.0	0.	0.0	0.024	0.000	0.000	0.000	0.00
G.MEAT W	700.	440.000	0.0000	0.0000	0.0000	121287.	0.7	72612.	0.3	0.024	0.000	0.000	0.000	1.20
G.MEAT D	700.	120.000	0.0000	0.0000	0.0000	132166.	0.7	92847.	0.3	0.024	0.000	0.000	0.000	1.96

Table 4-4. Continued.

Notes:

1. W and D in the product column represent wet and dry seasons, respectively. C., S., and G. are for cattle, sheep, and goats, respectively.
2. World prices are based on values from Groupement Manantali Report (1979) Annex 4 p. 120 and updated by the Council of OMVS Ministers in Nouakchott in March 1980.
3. Crop yields are from Groupement Manantali Report (1979) Annex 4, p. 120. Milk and meat products yields were discussed earlier in this report.
4. Yields for the entire Senegal River Basin are treated as equal although this is probably not true.
5. Yields for artificially flooded, recession, and rainfed agricultural area are based on a personal communique, Dr. Ba, Agriculture, OMVS, October 1979.
6. Sugar cane is an annual crop harvested in the dry season.
7. Total production costs for livestock are allocated to meat and none to milk.
8. Assumed equal distribution of the forage area between the six livestock products.
9. The cropping pattern for artifically flooded, recession, and rainfed agricultural areas are based on a personal communique, Dr. Ba, Agriculture, OMVS, October 1979.
10. Water requirements are adjusted to allow for irrigation system losses assuming an overall irrigation efficiency of 60 percent (the combined conveyance and application efficiency factor). They are assumed to be the same for small and large perimeters in the entire Senegal River Basin.

each crop in each season, for irrigated, artificial flood, recession, and rainfed production. The final column indicates the water requirement (consumptive use) for each season that crop is grown. The ratio of area in large and small perimeters has been assumed to be 2 to 1, or 67 and 33 percent of the theoretical hectare, respectively.

The Agricultural Area Data (AREA.DAT)

The Agricultural Area Data (Table 4-5) is based upon the assumption of a basin wide average development rate of 4000 ha/yr through 1984, and 5000 ha/year thereafter. This table consists of the year, the agricultural development rate (RATE), the irrigated area (AI), the area of recession agriculture displaced (ARD), the area of dry-farm agriculture displaced (ADD), and the area artifically flooded (AF), and the irrigted area in each country expressed as a percentage of the total irrigated area in the basin, AI. All values are end-of-year totals.

Since agricultural costs and revenues are assumed identical for all countries, it was not necessary to separate out agricultural areas by countries nor to distinguish between land in the delta and in the valley for benefit calculations. However, agricultural development by country was needed in order to allocate irrigation water costs.

The initial proportion of agricultural area development for Mali, Mauritania, and Senegal are 0.1666, 0.3436, and 0.4898, respectively (Bowles et al. 1980, Table 9, p. 24). These proportions are maintained until Mali develops its potential of 23,437 hectares. The development rates for Mauritania to Senegal is held at 1:1.425 after Mali develops its potential.

Table 4-5. Agricultural areas data table.

YEAR	RATE	AI	ARD	ADD	AF	MALI	MAUR	SENE
1980	0.	28805.	0.	0.	0.	0.0094	0.1842	0.8065
1981	4000.	32805.	4000.	0.	0.	0.0285	0.2036	0.7678
1982	4000.	36805.	8000.	0.	0.	0.0435	0.2188	0.7376
1983	4000.	40805.	12000.	0.	0.	0.0556	0.2311	0.7133
1984	4000.	44805.	16000.	0.	0.	0.0655	0.2411	0.6934
1985	5000.	49805.	21000.	0.	0.	0.0757	0.2514	0.6729
1986	5000.	54805.	26000.	0.	0.	0.0840	0.2598	0.6562
1987	5000.	59805.	31000.	0.	0.	0.0909	0.2668	0.6423
1988	5000.	64805.	36000.	0.	0.	0.0967	0.2727	0.6306
1989	5000.	69805.	41000.	0.	20195.	0.1017	0.2778	0.6205
1990	5000.	74805.	46000.	0.	15195.	0.1061	0.2822	0.6117
1991	5000.	79805.	51000.	0.	10195.	0.1099	0.2861	0.6041
1992	5000.	84805.	56000.	0.	5195.	0.1132	0.2894	0.5974
1993	5000.	89805.	61000.	0.	195.	0.1162	0.2925	0.5914
1994	5000.	94805.	66000.	0.	0.	0.1188	0.2952	0.5860
1995	5000.	99805	71000.	0.	0.	0.1212	0.2976	0.5812
1996	5000.	104805.	76000.	0.	0.	0.1234	0.2998	0.5768
1997	5000.	109805.	81000.	0.	0.	0.1254	0.3016	0.5729
1998	5000.	114805.	86000.	0.	0.	0.1272	0.3036	0.5693
1999	5000.	119805.	91000.	0.	0.	0.1288	0.3053	0.5659
2000	5000.	124805.	96000.	0.	0.	0.1303	0.3068	0.5629
2001	5000.	129805.	101000.	0.	0.	0.1317	0.3082	0.5601
2002	5000.	134805.	106000.	0.	0.	0.1330	0.3095	0.5575
2003	5000.	139805.	108633.	2367.	0.	0.1342	0.3108	0.5550
2004	5000.	144805.	108633.	7367.	0.	0.1353	0.3119	0.5528
2005	5000.	149805.	108633.	12367.	0.	0.1364	0.3129	0.5507
2006	5000.	154805.	108633.	17367.	0.	0.1373	0.3139	0.5487
2007	5000.	159805.	108633.	22367.	0.	0.1383	0.3149	0.5469
2008	5000.	164805.	108633.	27367.	0.	0.1391	0.3157	0.5451
2009	5000.	169805.	108633.	32367.	0.	0.1380	0.3173	0.5446
2010	5000.	174805.	108633.	37367.	0.	0.1341	0.3201	0.5459
2011	5000.	179805.	108633.	42367.	0.	0.1303	0.3226	0.5470
2012	5000.	184805.	108633.	47367.	0.	0.1268	0.3251	0.5481
2013	5000.	189805.	108633.	52367.	0.	0.1235	0.3274	0.5491
2014	5000.	194805.	108633.	57367.	0.	0.1203	0.3296	0.5501
2015	5000.	199805.	108633.	62367.	0.	0.1173	0.3316	0.5511
2016	5000.	204805.	108633.	67367.	0.	0.1144	0.3336	0.5520
2017	5000.	209805.	108633.	72367.	0.	0.1117	0.3355	0.5528
2018	5000.	214805.	108633.	75000.	0.	0.1091	0.3373	0.5536
2019	5000.	219805.	108633.	75000.	0.	0.1066	0.3390	0.5544
2020	5000.	224805.	108633.	75000.	0.	0.1043	0.3406	0.5551
2021	5000.	229805.	108633.	75000.	0.	0.1020	0.3422	0.5558
2022	5000.	234805.	108633.	75000.	0.	0.0998	0.3437	0.5565
2023	5000.	239805.	108633.	75000.	0.	0.0977	0.3451	0.5571
2024	5000.	244805.	108633.	75000.	0.	0.0957	0.3465	0.5578
2025	5000.	249805.	108633.	75000.	0.	0.0938	0.3478	0.5584
2026	5000.	254805.	108633.	75000.	0.	0.0920	0.3491	0.5589
2027	5000.	259805.	108633.	75000.	0.	0.0902	0.3503	0.5595
2028	5000.	264805.	108633.	75000.	0.	0.0885	0.3515	0.5600
2029	5000.	269805.	108633.	75000.	0.	0.0869	0.3526	0.5605
2030	5000.	274805.	108633.	75000.	0.	0.0853	0.3537	0.5610

In the Senegal River basin, there were 270 ha, 5305 ha, and 23,230 ha under irrigation in Mali, Mauritania, and Senegal, respectively, in 1980. The total initial (1980) irrigated area is, therefore, 28,805 hectares. These initial areas are based on Les Amenagements Hydroagricoles dans le Bassin du Fleuve Senegal, Report ER/PC/79-12 (OMVS 1979) for Mauritania and Senegal and the Groupement Manantali Report (1979) Annex 4, for Mali (with the 1981-1984 development rate assumed for 1980). The total area expected to be irrigated from the Diama and Manantali dams combined is 375,000 hectares of which 315,000 ha is from the Manantali Dam and 60,000 ha from the Diama Dam.

At the end of 1980 the potential areas of recession farming and dry farming to be displaced are 108,633 ha and 75,000 ha, respectively. It is assumed that each hectare of new irrigated area will first displace a hectare of recession farming until recession farming is totally displaced. Then each hectare of new irrigated area will displace a hectare of dry farming until the 75,000 ha are displaced. After that, irrigation expansion will open new land to cultivation.

The artificial flood described by Senegal Consult (1970) is assumed to commence in 1989 when the Manantali Dam is completed and is to continue until the total irrigated area reaches 90,000 hectares, the estimate of the area available for the artificial flood (Groupement Manantali Report (1979), Annex 4, p. 82). This flood will enable "recession" agriculture to continue until it is replaced by irrigated agriculture.

Area program (AREA.FTN)

The FORTRAN program AREA.FTN can be used to generate the agricultural area data table, AREA.DAT, based on the assumptions presented above. Although this program generates the agricultural area data table, AREA.DAT, it should be noted that this table can be generated by hand or changes can be made in the future to reflect current conditions.

The program itself is basically an accounting procedure. It totals the area developed and the artificially flooded area, plus it determines the areas of recession and dry-farmed agriculture displaced. It also determines the percentage of area irrigated in each country as a fraction of the total irrigated area.

Interactive input data

The AGBEN model can be operated with an existing data base already entered into the program and consistent with Reports 4 and 5 of the Senegal River Cost Allocation Study (Bowles et al. 1980, 1981). If the user wishes to use other data, he can respond to the interaction prompts presented by the programs. The data to be entered interactively and their default values for the Agricultural Benefits Model, AGBEN, and the agricultural area program, AREA.FTN are as follows:

For AGBEN.FTN.

1. The development cost per new hectare (CFA F/ha). (Default = 3,560,000 CFA F/ha) (2,800,000 + 760,000).

2. The pump replacement cost (CFA F/ha). (Default = 760,000 CFA F/ha).

3. The effective life of the pump in years (the time to pump replacement). (Default = 5 years).

4. The project life in years. (Default = 50 years).

5. The discount rate in decimal form. (Default = 0.05).

For AREA.FTN.

1. The "new" development rate (ha/yr). (Default = 5000 ha/yr) (The initial development rate is 4000 ha/yr).

2. The time when the "new" development rate starts (years). (Default = 4 years).

3. The time to artificial flood (years). (Default = 9 years).

4. The initial proportion to Mali, Mauritania, and Senegal of area development in decimal form. (Default = 0.1666, 0.3436, and 0.4898, respectively).

5. The maximum number of hectares which can be developed in Mali (ha). (Default = 23,437 ha).

6. The proportion to Mauritania and Senegal of area development after the potential development in Mali has been achieved, in decimal form. (Default = 0.4125 and 0.5875, respectively).

7. The initial irrigated area in Mali, Mauritania, and Senegal (ha). (Default = 270, 5305, and 23,230; respectively).

8. The total initial irrigated area (ha). (The summation of the above areas). (Default = 28,805 ha).

Entering the base data. It is likely that as irrigated area increases, added information will provide a basis for improving the existing data base. If the user wishes to alter the data from the base data files, changes must be made to the data files themselves. The Agriculture Economic Sector data file, AGTAB.PRE is free

formated. Each row consists of the following: the row number corresponding to a crop each season as shown in Table 4-4, the (1979) world price, yields from irrigated agriculture, yields from area artifically flooded agriculture, yields from recession agriculture, yields from rainfed agriculture, production costs for large perimeters, the percent of a theoretical hectare in large perimeters for that crop, production cost for small perimeters, the percent of a theoretical hectare in small perimeters for that crop (the complement of the percent in large perimeters), the percent of a theoretical hectare for each of the following irrigated areas: artifically flooded areas, recession agricultural areas, and rainfed agricultural areas; and the crop water requirements, in that order.

The Agricultural Economic Sector data file AGTAB.PRE is difficult to read in its free formated form. For this reason, the WRITE program was written to rewrite the AGTAB.PRE data file in a more readable form, AGDATA.OUT (Table 4-4). However, the user must remember that the AGTAB.PRE data file is the one used by the Agricultural Benefit Model, AGBEN, and changes to the data base must be made to the AGTAB.PRE file and not to the AGDATA.OUT file.

The format for the Agricultural Areas Data table, AREA.DAT, (Table 4-5) is I10, F12.0, F11.0, F11.0, F11.0 F11.0, and F10.0 for the year, agricultural development rate, irrigated areas, area of recession agriculture displaced, area of rainfed agriculture displaced, and area artifically flooded, respectively. Note that the year is an interger number while all the rest are real.

Algorithms of the Agricultural Benefit Model (AGBEN)

For the purpose of project justification and allocating the joint costs of the Manantali dam, the agricultural benefits are the net primary returns to the land irrigated. The annual benefits for each crop are estimated for the 315,000 ha assigned to the Manantali dam as:

$$AGBEN = RI + RF - RRL - RDL - FC - VC \quad \text{.....(4-1)}$$

in which

AGBEN = agricultural benefits

RI = revenues from irrigated areas

RF = revenues from artifically flooded areas

RRL = lost revenues from recession agricultural areas

RDL = lost revenue from rainfed agricultural areas

FC = fixed costs (land development plus pump replacement)

VC = variable costs (production costs)

All values are expressed in 1979 CFA F.

Agriculture revenues

The annual revenues from the irrigated area for each product are calculated as follows:

$$RI = WP * \dot{Y} * (AI * CP) \quad \text{.....(4-2)}$$

in which

RI = revenue from the irrigated area (CFA F)

WP = world price (CFA F/metric ton)

Y = yield from irrigated agriculture (metric ton/ha)

AI = irrigated area (ha)

CP = irrigated area cropping pattern (theoretical hectare) (fraction)

Irrigated area is the number of hectares available at the beginning of that cropping year. The annual revenues from the area artificially flooded (RF) are calculated in the same manner but using the values corresponding to the artificially flooded area (AF).

Value of displaced production

The value of displaced production is the revenue lost due to the displacement of recession and rainfed agricultural areas (RRL and RDL, respectively). It is calcualted in the same manner as revenue in Equation 4-2 above, except that AI is replaced with the agricultural area displaced. The displaced area is that area previously farmed by recession (ARD) or rainfed agriculture (ADD) at the beginning of the cropping year. Note that, irrigated agricultural areas being developed cannot be used for recession or rainfed agriculture.

No difference is made between crops sold for cash and crops consumed by the farmers. Thus, for the latter, the value imputed to traditional production consumed on the farm uses the world price as an opportunity cost.

Non-project costs

Fixed costs. The annual fixed costs consist of development costs for new agricultural areas and the costs for pump replacements. They are calculated as follows:

$$TFC = (C_1 * R) + (C_3 * AI) \quad \text{.....(4-3)}$$

in which

TFC = total annual fixed cost (CFA F)

C_1 = development cost per new hectare (CFA F/ha)

R = agricultural development rate (ha/yr)

C_3 = annualized pump replacement cost (CFA F/ha/yr)

AI = area of irrigated agriculture at the beginning of the year (ha)

The pump replacement costs are annualized over the expected life of the pump.

$$C_3 = C_2 * SFF \quad \text{.....(4-4)}$$

in which

C_2 = pump costs (CFA F/ha)

SFF = sinking fund factor

$$SFF = \frac{r}{(1 + r)^n - 1} \quad \text{.....(4-5)}$$

in which

r = discount rate in decimal form

n = number of years to pump replacement

To determine the fixed cost for each crop (FC) the above total fixed cost, TFC, is multiplied by the cropping pattern factor (that crop's proportion of the theoretical hectare). The cropping pattern factor is automatically adjusted within the AGBEN program to insure

that 100 percent of the total fixed costs are proportionately distributed among all the products shown in Table 4-4.

Variable costs. The annual variable costs for each crop (VC) consist of the sum of the production costs for the large and small perimeters. They are calculated as follows:

$$VC = [(PC_L * P_L) + (PC_S * P_S)] * AI * CP \quad \text{.....(4-6)}$$

in which

VC = variable costs (CFA F/ha)

PC_L = production costs for large perimeters (CFA F/ha)

P_L = percent of area in large perimeters (fraction)

PC_S = production costs for small perimeters (CFA F/ha)

P_S = percent of area in small perimeters (fraction)

AI = area of irrigated agriculture at the beginning of the year (ha)

CP = cropping pattern (theoretical hectare) (fraction)

The present value of the agricultural benefits is calculated as follows:

$$SUMB = \sum_{t=1}^{NYEAR} DISF_t * TAGBEN_t \quad \text{.....(4-7)}$$

in which

SUMB = discounted total project agricultural benefit (CFA F)

NYEAR = project life in years

$DISF_t$ = discount factor in the tth year

$TAGBEN_t$ = total yearly agricultural benefits (CFA F/yr)

$$DISF_t = \frac{1}{(1 + r)^{t-1}} \quad \text{.....(4-8)}$$

in which

r = discount rate in decimal form

t = time in years

Water requirements

The total irrigation water requirements, TWR, for the entire basin is the summation of the water requirement for each product, WR, and is calculated as follows:

$$TWR = \sum_{i=1}^{NCROP} WR * CP * (AI * 10000) \quad \text{.....(4-9)}$$

in which

TWR = total irrigation water requirements (m^3)

WR = crop water requirement (m/season)

CP = cropping pattern (theoretical hectare) for each season

AI = area of irrigation agriculture at the beginning of the year (ha)

NCROP = number of products or crops produced

To determine the irrigation water requirements for each country, the total irrigation water requirement, TWR, is multiplied by the ratio of the area developed in each country to the total area developed in the basin. The calculation of the irrigation water requirements for each crop is presented in Table 5.2.

Output from the Agricultural Benefit Model AGBEN

The results from running the AGBEN consist of three output files: CHECK.OUT, AGBEN.OUT, and AGQ.DAT.

CHECK.OUT (Table 4-6) tabulates the individual product benefits and water requirements for each year specified by the user. The output is in nine columns which are listed as follows:

the product number, (I);

revenue generated from irrigated agriculture, (RI);

revenue generated from areas artifically flooded, (RF);

revenue lost from recession agriculture, (RRL);

revenue lost from rainfed agriculture, (RDL);

fixed costs, (FC);

variable (production) costs, (VC);

water requirements, (WR); and

product benefits, (AGBEN) in that order.

The last row shows the column totals for the specified year, K.

AGBEN.OUT (Table 4-7) indicates total water requirements and agricultural benefits by year. The first column is the year, the second the total yearly agricultural water requirements, and the third the total yearly agricultural benefits. Total project water requirements and agricultural benefits are discounted to 1980. The discounted project water requirements are used to calculate user fees on a consistent basis. User fees are calculated to repay the discounted project costs over the project life.

The AGQ.DAT (Table 4-8) output gives the yearly agricultural water requirements for each of the three countries, Mali, Mauritania,

and Senegal plus their total for each year. A discussion of the results from the AGBEN program are presented in Chapter 5.

Table 4-6. Individual product benefits and water requirements.

I	RI	RF	RRL	RDL	FC	VC	WR	AGBEN
1	2.52E+10	0.00E-01	0.00E-01	0.00E-01	9.59E+09	7.23E+09	1.48E+09	8.36E+09
2	8.79E+09	0.00E-01	0.00E-01	0.00E-01	3.82E+09	3.50E+09	6.68E+08	1.66E+09
3	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01
4	1.08E+10	0.00E-01	0.00E-01	0.00E-01	1.10E+09	2.27E+09	9.25E+07	7.43E+09
5	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01
6	1.79E+10	0.00E-01	0.00E-01	0.00E-01	5.42E+09	8.59E+09	4.11E+08	3.87E+09
7	0.00E-01	0.00E-01	3.02E+07	1.04E+07	0.00E-01	0.00E-01	0.00E-01	-4.06E+07
8	6.45E+08	0.00E-01	0.00E-01	0.00E-01	1.35E+09	7.82E+08	1.37E+08	-1.48E+09
9	0.00E-01	0.00E-01	0.00E-01	0.00E-01	8.46E+08	1.08E+09	8.74E+07	-1.92E+09
10	4.40E+09	0.00E-01	0.00E-01	0.00E-01	8.46E+08	1.21E+09	1.43E+08	2.34E+09
11	1.94E+10	0.00E-01	7.47E+08	2.58E+08	8.96E+09	4.66E+09	4.94E+08	4.79E+09
12	8.49E+09	0.00E-01	0.00E-01	0.00E-01	3.92E+09	2.27E+09	3.14E+08	2.30E+09
13	1.30E+10	0.00E-01	1.59E+08	5.49E+07	5.17E+09	2.98E+09	3.29E+08	4.67E+09
14	9.88E+09	0.00E-01	0.00E-01	0.00E-01	3.92E+09	2.54E+09	2.97E+08	3.43E+09
15	1.68E+09	0.00E-01	0.00E-01	0.00E-01	9.40E+08	5.81E+08	7.85E+07	1.59E+08
16	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01	0.00E-01
17	2.19E+09	0.00E-01	0.00E-01	0.00E-01	7.52E+08	0.00E-01	0.00E-01	1.44E+09
18	5.91E+08	0.00E-01	0.00E-01	0.00E-01	7.52E+08	0.00E-01	0.00E-01	-1.61E+08
19	5.58E+09	0.00E-01	0.00E-01	0.00E-01	7.52E+08	6.81E+08	7.77E+07	4.15E+09
20	1.49E+09	0.00E-01	0.00E-01	0.00E-01	7.52E+08	7.72E+08	1.27E+08	-3.47E+07
21	2.22E+09	0.00E-01	0.00E-01	0.00E-01	7.52E+08	0.00E-01	0.00E-01	1.47E+09
22	5.91E+08	0.00E-01	0.00E-01	0.00E-01	7.52E+08	0.00E-01	0.00E-01	-1.61E+08
23	3.81E+09	0.00E-01	0.00E-01	0.00E-01	7.52E+08	6.81E+08	7.77E+07	2.37E+09
24	1.02E+09	0.00E-01	0.00E-01	0.00E-01	7.52E+08	7.72E+08	1.27E+08	-5.04E+08
25	1.63E+09	0.00E-01	0.00E-01	0.00E-01	7.52E+08	0.00E-01	0.00E-01	8.82E+08
26	4.41E+08	0.00E-01	0.00E-01	0.00E-01	7.52E+08	0.00E-01	0.00E-01	-3.11E+08
27	1.99E+09	0.00E-01	0.00E-01	0.00E-01	7.52E+08	6.81E+08	7.77E+07	5.61E+08
28	5.44E+08	0.00E-01	0.00E-01	0.00E-01	7.52E+08	7.72E+08	1.27E+08	-9.80E+08
K	TRI	TRF	TRRL	TRDL	TFC	TVC	TWR	TAGBEN
50	1.42E+11	0.00E-01	9.36E+08	3.23E+08	5.49E+10	4.19E+10	5.14E+09	4.43E+10

Table 4-7. Total water requirements and agricultural benefits.

YEAR	TWR	TAGBEN
1980	5.49E+08	-7.51E+09
1981	6.25E+08	-6.61E+09
1982	7.02E+08	-5.70E+09
1983	7.78E+08	-4.80E+09
1984	8.54E+08	-7.46E+09
1985	9.49E+08	-6.33E+09
1986	1.04E+09	-5.20E+09
1987	1.14E+09	-4.07E+09
1988	1.24E+09	-2.94E+09
1989	1.33E+09	-1.63E+09
1990	1.43E+09	-5.45E+08
1991	1.52E+09	5.43E+08
1992	1.62E+09	1.63E+09
1993	1.71E+09	2.72E+09
1994	1.81E+09	3.85E+09
1995	1.90E+09	4.98E+09
1996	2.00E+09	6.11E+09
1997	2.09E+09	7.24E+09
1998	2.19E+09	8.37E+09
1999	2.28E+09	9.50E+09
2000	2.38E+09	1.06E+10
2001	2.47E+09	1.18E+10
2002	2.57E+09	1.29E+10
2003	2.66E+09	1.41E+10
2004	2.76E+09	1.52E+10
2005	2.86E+09	1.64E+10
2006	2.95E+09	1.75E+10
2007	3.05E+09	1.87E+10
2008	3.14E+09	1.98E+10
2009	3.24E+09	2.10E+10
2010	3.33E+09	2.21E+10
2011	3.43E+09	2.33E+10
2012	3.52E+09	2.44E+10
2013	3.62E+09	2.56E+10
2014	3.71E+09	2.67E+10
2015	3.81E+09	2.79E+10
2016	3.90E+09	2.90E+10
2017	4.00E+09	3.02E+10
2018	4.09E+09	3.14E+10
2019	4.19E+09	3.25E+10
2020	4.28E+09	3.37E+10
2021	4.38E+09	3.49E+10
2022	4.48E+09	3.61E+10
2023	4.57E+09	3.72E+10
2024	4.67E+09	3.84E+10
2025	4.76E+09	3.96E+10
2026	4.86E+09	4.08E+10
2027	4.95E+09	4.19E+10
2028	5.05E+09	4.31E+10
2029	5.14E+09	4.43E+10

DISCOUNTED TOTAL PROJECT AGRICULTURAL BENEFITS = 1.1743392E+11
DISCOUNTED TOTAL PROJECT WATER REQUIREMENTS = 3.7054169E+10
THE DISCOUNT RATE = 0.05

Table 4-8. Yearly irrigation water requirements by country.

MALI	MAURITANIA	SENEGAL	TOTAL	YEAR
1.5647E+07	1.1178E+08	4.2154E+08	5.4903E+08	1980
2.7199E+07	1.3681E+08	4.6120E+08	6.2527E+08	1981
3.9004E+07	1.6212E+08	5.0039E+08	7.0151E+08	1982
5.0942E+07	1.8751E+08	5.3929E+08	7.7775E+08	1983
6.4647E+07	2.1469E+08	5.7465E+08	8.5399E+08	1984
7.9740E+07	2.4663E+08	6.2292E+08	9.4929E+08	1985
9.4953E+07	2.7870E+08	6.7094E+08	1.0446E+09	1986
1.1023E+08	3.1085E+08	7.1881E+08	1.1399E+09	1987
1.2562E+08	3.4314E+08	7.6644E+08	1.2352E+09	1988
1.4116E+08	3.7546E+08	8.1386E+08	1.3305E+09	1989
1.5669E+08	4.0792E+08	8.6132E+08	1.4258E+09	1990
1.7219E+08	4.4020E+08	9.0870E+08	1.5211E+09	1991
1.8782E+08	4.7279E+08	9.5593E+08	1.6164E+09	1992
2.0335E+08	5.0529E+08	1.0031E+09	1.7117E+09	1993
2.1901E+08	5.3776E+08	1.0502E+09	1.8070E+09	1994
2.3474E+08	5.7031E+08	1.0972E+09	1.9023E+09	1995
2.5050E+08	6.0287E+08	1.1444E+09	1.9976E+09	1996
2.6622E+08	6.3540E+08	1.1915E+09	2.0929E+09	1997
2.8184E+08	6.6806E+08	1.2383E+09	2.1882E+09	1998
2.9754E+08	7.0058E+08	1.2854E+09	2.2835E+09	1999
3.1329E+08	7.3314E+08	1.3324E+09	2.3788E+09	2000
3.2905E+08	7.6573E+08	1.3793E+09	2.4741E+09	2001
3.4481E+08	7.9857E+08	1.4260E+09	2.5694E+09	2002
3.6053E+08	8.3112E+08	1.4730E+09	2.6647E+09	2003
3.7646E+08	8.6360E+08	1.5199E+09	2.7600E+09	2004
3.9203E+08	8.9628E+08	1.5667E+09	2.8553E+09	2005
4.0807E+08	9.2914E+08	1.6137E+09	2.9506E+09	2006
4.2368E+08	9.6159E+08	1.6603E+09	3.0459E+09	2007
4.3349E+08	9.9670E+08	1.7107E+09	3.1412E+09	2008
4.3401E+08	1.0360E+09	1.7668E+09	3.2365E+09	2009
4.3413E+08	1.0748E+09	1.8225E+09	3.3318E+09	2010
4.3456E+08	1.1142E+09	1.8784E+09	3.4271E+09	2011
4.3502E+08	1.1532E+09	1.9342E+09	3.5224E+09	2012
4.3521E+08	1.1924E+09	1.9901E+09	3.6177E+09	2013
4.3554E+08	1.2312E+09	2.0462E+09	3.7130E+09	2014
4.3567E+08	1.2705E+09	2.1022E+09	3.8083E+09	2015
4.3603E+08	1.3097E+09	2.1579E+09	3.9036E+09	2016
4.3628E+08	1.3488E+09	2.2138E+09	3.9989E+09	2017
4.3644E+08	1.3879E+09	2.2698E+09	4.0942E+09	2018
4.3697E+08	1.4269E+09	2.3256E+09	4.1895E+09	2019
4.3705E+08	1.4663E+09	2.3815E+09	4.2848E+09	2020
4.3713E+08	1.5054E+09	2.4375E+09	4.3801E+09	2021
4.3725E+08	1.5445E+09	2.4932E+09	4.4754E+09	2022
4.3742E+08	1.5838E+09	2.5495E+09	4.5707E+09	2023
4.3767E+08	1.6228E+09	2.6055E+09	4.6660E+09	2024
4.3804E+08	1.6622E+09	2.6611E+09	4.7613E+09	2025
4.3807E+08	1.7013E+09	2.7173E+09	4.8566E+09	2026
4.3824E+08	1.7406E+09	2.7731E+09	4.9519E+09	2027
4.3860E+08	1.7796E+09	2.8290E+09	5.0472E+09	2028
4.3866E+08	1.8189E+09	2.8849E+09	5.1425E+09	2029
1.5568E+10	4.5656E+10	7.9348E+10	1.4057E+11	TOTALS

CHAPTER V

RESULTS AND DISCUSSIONS

Agricultural Benefits

The discounted total agricultural benefits, determined by the agricultural benefit model, AGBEN, using the input data presented in Chapter 4 and a 50 year project life, is 117.44 billion CFA F. (245 CFA F = U. S. $1.00). This figure is given by Table 4-7. Table 4-7 also indicates that 11 years are required for the project to achieve positive net agricultural benefits. Year 1991 is the first year that the revenues from agricultural production and animal husbandry are sufficient to pay off the initial development costs for new lands, plus yearly maintenance, and production costs.

Table 4-6 gives the breakdown of the revenues, costs, water requirements, and net benefits for each product in both the wet and dry seasons in the 50th year. The numbers in the first column of Table 4-6 correspond directly with the products listed under "PRODUCT", the first column in Table 4-4.

Table 5-1 shows the number of years that it takes for each product to become economically profitable, the cropping pattern (the percentage of the theoretical hectare over which that product is produced) for each season, and the number of years required for the annual crops to achieve a positive net annual benefit. The number of

Table 5-1. Number of years to positive benefits for each product.

Crop	Wet Season	Cropping Pattern (%)	Dry Season	Cropping Pattern (%)	(+) Net Annual
Rice	11	30.6	20	12.2	
Tomato	NA	0.0	1	3.5	
Wheat	NA	0.0	13	17.3	
Nicb-	NA	0.0	--	4.3	
Sugar Cane	NA	2.7	NA	2.7	27
Sorghum	18	28.6	16	12.5	
Maize	11	16.5	11	12.5	
Cotton	32	3.0	NA	0.0	
Livestock					
Cattle	NA	4.8	NA	4.8	3
Sheep	NA	4.8	NA	4.8	9
Goats	NA	4.8	NA	4.8	43
TOTAL		95.8		79.4	

years that it takes for each product to become economically profitable was determined by examining the CHECK.OUT output file for each year. The total fixed cost for each hectare developed is carried proportionately by the crops produced on a theoretical hectare. Therefore, if a portion of the theoretical hectare is idle such as in the dry season, the crops produced will carry the cost burden. As shown in Table 5-1, 95.8 percent and 79.4 percent of the theoretical hectare is cropped in the wet and dry seasons, respectively. This means that 55 percent of the total fixed cost is carried by the crops grown during the wet season.

If the total cropping pattern in the dry season was increased to 95.8 percent, that of the wet season, the time that it takes for each product to achieve positive net benefits would be reduced by approximately 20 percent. In other words, rice in the dry season would have positive net benefits in year 16.

Although niebe (cowpea) does not show a positive benefit within the 50 year lifespan of the project, it has other secondary benefits which justify its production. Niebe has a high nutritional value, 23 to 25 percent protein; produces high quality of forage, 30 t/ha; and increases the nitrogen levels in the soil, thus providing indirect benefits to both livestock and other crops.

The reason why sorghum takes longer to reach positive net benefits in the wet season is that during the wet season there are revenues lost due to the displaced production of sorghum on areas which are normally farmed by recession or dry farm agriculture.

Animal husbandry as it is shown produces approximately 15.5 percent of the total agricultural benefits. However, the production of goats in the future, will most likely be substituted with cattle or sheep production, which are more profitable.

Small versus large perimeters

By changing the ratio of areas in large and small perimeters from 2:1 to 1:1, and leaving everything else in the AGTAB.PRE data file the same, the discounted total agricultural benefit is calculated to be 141.87 billion CFA F, a 20.8 percent increase.

The yields for large and small perimeters will also most likely be different. Diallo (1980) reports that rice yields in Senegal from

large perimeters are lower than those from small perimeters. He explains that agriculture on large perimeters is often only a sideline activity for many of the laborers who are civil servants, merchants, herdsmen, or artisans. These people are often absent from their plot for days or weeks. Thus, much of the work such as weeding is often neglected. In small perimeters there is so much labor input involved, since everything is done by hand, that it is impossible for an outsider to own a plot.

Diallo (1980) also reports that the investment cost for large perimeters is several times higher than for small perimeters. High investment costs per hectare are attributed to the fact that companies engaged in constructing the irrigated perimeters are disinterested in lower costs. There is little competition among such companies and an absence of systematic research for solutions capable of reducing the unit price.

If high revenues and benefits are to be expected from large perimeters, strong leadership and good management is needed to expel outsiders who are not fully engaged in agriculture, to produce high yielding varieties using the available technology, to apply optimum water and fertilizer amounts, and to reduce construction, operating, and administration costs.

Irrigation Water Requirements

The yearly irrigation water requirements and the discounted total project (50 years) water requirements are presented in Table 4-7. The seasonal water requirements for each product are shown in Table 5-2. The methodology used to determine the irrigation water requirements is

Table 5-2. Crop water requirements.

	Rice		Tomato		Wheat		Niebe		Sugar Cane		Sorghum		Maize		Cotton		Forage	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Monthly ET_o																		
Jan		129		129		129		129		129		129		129				129
Feb		151		151		151		151		151		151		151				151
Mar		179		179		179		179		179		179		179				179
Apr		196		196				196		196		196						196
May		203								203								203
June									192				192		192		192	
July	186								186		186		186		186		186	
Aug	171								171		171		171		171		171	
Sept	173								173		173		173		173		173	
Oct	167								167		167				167		167	
Nov	132									132								132
Dec						129		129		129				129				129
Seasonal ET_o	829	858		655		588		784	889	1119	697	655	722	588	890		889	1119
Seasonal K_c	1.20	1.20		0.90		0.90		0.90	1.05	1.05	0.85	0.85	0.90	0.90	0.90		1.05	1.05
ET_{crop}	995	1030		590		529		706	933	1175	592	557	650	529	800		933	1175
P_e**	207	0		0		0		0	215	0	207	0	208	0	215		215	0
I	1788*	2030*		590		529		706	718	1175	385	557	442	529	585		718	1175
Efficiency																		
60%	N/A	N/A		983		882		1176	1197	1958	642	928	736	882	975		1197	1958
75%	N/A	N/A		786		706		941	958	1567	513	743	590	702	780		958	1567

*Includes 1000 mm of water for soaking, filling, and percolation losses.
**Based on rainfall with a 50 percent probability of occurrence or exceedence.

presented in Chapter 2. The seasonal water requirement shown in Table 4-4 assumes an irrigation efficiency of 60 percent. The reason for using the 60 percent efficiency is described in Chapter 2.

Potential evapotranspiration.

The monthly potential evapotranspiration values equivalent to those for Alta fescue grass as a reference crop, ET_0, are presented in Table 5-3. The calculation of ET_0 is based on measured radiation data from the climatological stations at Richard-Toll, Guede, Kaedi, and Same. Since radiation values, RS, do not vary significantly within the Senegal River Basin, the monthly RS values for each of the four stations were averaged, thereby giving monthly radiation estimates for the entire basin. These values are presented in Table 5-3.

Table 5-3. RS, ET_0, actual and effective precipitation for the Senegal River Basin.

Month	RS (cal/cm^2)	ET_0 (mm)	Actual Precip. (mm)	Effective Precip. (mm)
Jan	425	129	0	0
Feb	505	151	0	0
Mar	550	179	0	0
Apr	585	196	0	0
May	580	203	0	0
June	560	192	8	8
July	550	186	54	50
Aug	510	171	96	80
Sept	520	173	80	70
Oct	485	167	7	7
Nov	420	132	0	0
Dec	410	129	0	0
Ann	6100	2008	245	215

Monthly rainfall amounts in mm for different probability levels of occurrance or exceedance, mean monthly precipitation, mean monthly temperatures in °C, and the monthly potential evapotranspiration in mm for Alta fescue grass, ET_0 (shown as ETP), for the climatological stations at Saint-Louis, Rosso, Podor, Matam, and Kayes are presented in Appendix B.

Effective precipitation, Pe.

Values for the actual and effective precipitation to be expected in the Senegal River Basin are also presented in Table 5-3. The actual precipitation is defined as the amount of rainfall with a 50 percent probability of occurrence or exceedance based upon a gamma distribution. The 50 percent probability level is used for planning and determining the user fee because it represents the long-term average. The actual precipitation for the entire Senegal River Basin is based upon the rainfall pattern downstream from Matam. This is the drier portion of the basin and includes 70 percent of the area proposed for agricultural development. The rainfall pattern for this region was determined by taking the average of the actual monthly precipitation for the Saint Louis, Rosso, Podor, Matam, and Kayes climatological stations. If future users would prefer to use a different probability of occurrence or exceedance to determine the actual precipitation, rainfall amounts for a full range of probabilities are presented for five climatological stations in Appendix B.

The effective precipitation was calculated using Table 2-2. Further refinements can be made in estimating the effective precipita-

tion by considering such factors as: soil type, rainfall intensity (depth-duration amounts), ground cover, and management factors such as the use of broad beds and furrows on flat slopes, incorporating plant residues into the soil, and tillage practices.

Further refinements in the calculation of the effective precipitation is not warranted in this analysis because of the broad nature of the actual precipitation and water requirements. Further refinement should, however, be considered when detailed planning is carried out for the large irrigated perimeters.

Rainfall depth-duration amounts.

Estimates for rainfall depth-duration amounts with a 10 year return period and a 24, 1, and 1/2 hour rainfall duration and with a 5 year return period, 1/2 hours rainfall duration ($P_{10,24}$, $P_{10,1}$, $P_{10,0.5}$, and $P_{5,0.5}$, respectively) are presented in Table 5-4. These estimates were calculated using Equation 2-7. The calibration coefficients, K, for Equation 2-8 are also presented in Table 5-4 for each station and month shown. These calibration coefficients, K, were determined using Equation 2-11 and the P_{05} values presented in Appendix B. For those stations with 30 years of record, K was also evaluated using the 30 year maximum monthly precipitation, PMX. and Equations 2-8 and 2-10.

Knowledge about the depth-duration amounts is useful for determining the effective precipitation and suitable management practices. The rainfall quantity, which is actually effective, is largely dependent on the rate at which the rainfall infiltrates into the soil. The infiltration rate depends on many factors such as soil

type, initial moisture content, management practices, and rainfall intensity (depth-duration amounts). The $P_{10,24}$, is useful in determining the need for drainage, while $P_{10,1}$, $P_{10,0.5}$, and $P_{5,0.5}$) are useful to determine the desirable soil conservation practices.

The $P_{5,0.5}$ estimates shown in Table 5-4 are significantly above the maximum infiltration rate of the soil. This indicates that significant runoff will occur. If slopes are significant soil erosion can also be expected to be significant.

Rainfall agriculture.

Of the 375,000 hectares of agricultural land to be developed in the Senegal River Basin, 70 percent lies downstream from Matam. The potential for rainfed agriculture in this region is quite limited, since there is only one month or less of dependable rainfall which is adequate for crop production. Dependable rainfall is defined as the rainfall amount with a 75 percent statistical probability of occurrence or exceedance. In this report the gamma distribution was used for the frequency analysis.

Upstream from Matam the potential for rainfed agriculture is higher, since this portion of the basin has three months or more of dependable rainfall which is adequate for crop production. A detailed analysis of the length of the dependable rainy season for rainfed agriculture is given by Hargreaves (1981).

Table 5-4. Maximum monthly precipitation measured (P_{max}) and depth-duration amounts.

Station	Years of Period	P_{max} (mm)	Month & Year	$P_{0.5}$ (mm)	K (Eq. 2-8)	$P_{10,24}$ (mm)	$P_{10,1}$ (mm)	$P_{10,0.5}$ (mm)	$P_{5,0.5}$ (mm)
Saint Louis	30	280	Aug. '58	235	31.8	103	47	39	35
Rosso	24	199	Aug. '58	270	29.5	96	43	36	32
Podor	29	315	Sep. '56	233	33.3	108	49	41	37
		291	Aug. '58	204	30.9	100	45	38	34
Matan	30	336	Aug. '58	273	36.0	117	53	44	40
Kayes	39	402	Aug. '59	442	50.0	163	73	62	55

CHAPTER VI

SUMMARY AND RECOMMENDATIONS

The purpose of the study was to develop a methodology for estimating the irrigation water requirements and agricultural benefits associated with the Senegal River development. In presenting this methodology, an example run was made using an existing data base to determine the agricultural benefits and water requirements for the entire Senegal River Basin. This sample run can be used in an analysis for allocating the project joint costs between service sectors and determining the user fee for water. It should be noted, however, that another powerful application of the model presented is its use for managing and operating irrigation perimeters. With this in mind, the following recommendations presented fall into two categories: (1) recommendations on how to improve on the estimation of the agricultural benefits and irrigation water requirements in the Senegal River Basin, and (2) recommendations on what needs to be done to optimize the agricultural benefits and water use.

Recommendations

To improve on the estimation of the agricultural benefits and irrigation water requirements, the following recommendations are made:

1. That more radiation data, RS, be evaluated basin-wide. If RS is not measured directly, it can be estimated from percent sunshine or temperature difference using the procedure outlined in Chapter 2.

2. That the Senegal River Basin be subdivided into a minimum of three regions to determine the irrigation water requirements. These regions should consist of the following areas: Podor, Matam, and Kayes.

3. That this model be used to evaluate the agricultural benefits and irrigation water requirements for each country, the valley and delta regions, and large irrigation perimeters.

To optimize the agricultural benefits and water use the following recommendations are made:

1. That a study be conducted to determine the optimum rainfall probability level of occurrence to be used in determining the irrigation water requirements. In other words, what is the allowable risk? This study should include crop production function analyses to evaluate the reduction of yields due to water shortages. The 75 percent level is generally a good level to use for design purposes.

2. That a comprehensive water management program be established to do the following:

a. Determine the irrigation water requirements for each perimeter using the methodology presented in this report or another comparable method.

b. Select the method of irrigation for each crop based upon the recommendations of a qualified consultant.

c. Determine the irrigation schedule which best matches the multiple needs.

d. Measure the amounts of irrigation water applied.

e. Determine the water use efficiency and uniformity.

f. Determine the optimum amount of fertilizer to be applied.

g. Develop a program for evaluating the production costs and yield for large and small perimeters.

3. That a sensitivity analysis be conducted on the parameters presented in Table 4-4 to help determine goals and methods for increasing the positive net benefits.

4. That an optimization scheme be developed to determine which products should be produced and in what proportions to maximize benefits and satisfy social and political goals.

5. That an economic comparison be made between large and small perimeters to determine which would be more cost effective.

6. That some form of contract competition be set up for the construction of large perimeters to try and keep development costs down.

7. That purchase of project equipment include training and maintenance contracts.

SELECTED REFERENCES

Adams, R. L. 1953. Farm management crop manual. University of California Press, Berkeley, California.

Allen, L. H. 1979. Potential for carbon dioxide enrichment. In modification of the aerial environments of crops, B. J. Barfield and J. F. Gerber (eds.), Monograph No. 2, American Society of Agricultural Engineers, St. Joseph, Mich., p. 500-519.

Ayers, R.S., and D. W. Westcot. 1976. Water quality for agriculture. FAO Irrigation and Drainage. Paper 29, FAO, Rome.

Barger, G. L. and H. C. S. Thom. 1949. Evaluation of drought hazard. Agronomy Journal 41:519-526.

Bechtel Overseas Corporation. 1976. Development of irrigated agriculture at Matam, Senegal: Feasibility study for United States Agency for International Development.

Bishop, A. Alvin, Wynn R. Walker, Neil L. Allen, and Gregory J. Poole. 1981. Furrow advance rates under surge flow systems. Journal of the Irrigation and Drainage Division, Proceeding of the Am. Soc. Civ. Eng. p. 257-264.

Bollman, F. and G. Hellyer. 1974. The economic consequences of projected temperature changes in climatically sensitive wheat growing areas of the Canadian prairie. Development and Resources Corporation, Sacramento, California.

Borelli, John, Larry O. Pochop, William R. Kneebone, Ian L. Pepper, Robert E. Danielson, William E. Hart, and Victor B. Youngner. 1981. Blaney-Criddle coefficients for western turf grasses. Journal of the Irrigation and Drainage Division, ASCE, Proc. Paper 16749, Vol. 107, No. IR4, pp. 333-341.

Bos, M. G. and J. Nugteren. 1974. On irrigation efficiencies. Publication 19. International Institute for Land Reclamation and Improvements.

Bowles, David S., J. Paul Riley, Jay C. Anderson, and John E. Keith. 1980. Some further cost allocation studies for the Senegal River Development Program: Report 4. Utah Water Research Laboratory. Utah State University, Logan, Utah.

Bowles, David S., J. Paul Riley, Jay C. Anderson, and John E. Keith. 1981. Some further cost allocation studies for the Senegal River Development Program: Report 5. Utah Water Research Laboratory. Utah State University, Logan, Utah.

Burchinal, J. C. and W. H. Dickerson. 1961. Rainfall probability and its applications. West Virginia University Agricultural Experiment Station Bulletin 454T.

Chang, Jen-Hu. 1968. Climate and agriculture. Aldine Publishing Company, Chicago.

Cry, George W. 1965. Estimation of precipitation probabilities. Fourth Army Conference on Trophical Meteorology Proceedings, May 6-7, 1965, Miami Beach, Florida.

Cusack, David F. ed. 1983. Agroclimate information for development: Reviving the Green Revolution. Westview Press, Inc., Boulder, Colorado.

Diallo, Mamadou Dian. 1980. Comparative analysis of capital intensive and labor intensive rice irrigated perimeters in the Senegal River Valley. Master's thesis, Dept. of Agricultural Economics, Michigan State University.

Doorenbos J., and A. H. Kassam. 1979. FAO irrigation and drainage paper 33: Yield response to water. FAO, Rome.

Doorenbos J. and W. O. Pruitt. 1977. FAO irrigtion and drainage paper 24: Crop water requirements. FAO, Rome.

Essenwagner, Oskar. 1960. Frequency distribution of precipitation, physics of precipitation. Geophysical Monograph No. 5, American Geophysical Monograph No. 5, American Geophysical Union No. 746:14-25.

Evans, L. T. (ed.) 1978. Crop physiology. Cambridge University Press, New York.

FAO (Food and Agriculture Organization of the United Nations). 1978. Report on the agro-ecological zones project, Vol. 1. Methodology and results for Africa. FAO, Rome.

Fritschen, L. J. 1966. Evapotranspiration rates of field crops determined by the Bowen ratio method. Agronomy Journal, 58:339-42.

Groupement Manantali Report. 1979. Etude D'execution du barrage et de l'usine hydroelectrique de Manantali Annex 4: Agriculture. Soned, Dakar.

Hargreaves, G. H. 1981. Simplified method for rainfall intensities. Journal of the Irrigation and Drainage Division, Proceedings of the American Society of Civil Engineers, ASCE, Vol 107, No. IR3, September, pp. 281-288.

Hargreaves, G. H. and Z. A. Samani. 1982. Estimating potential evapotranspiration. Journal of the Irrigation and Drainage Division, Proceedings of the ASCE, Vol. 108, No. IR3, September, pp. 223-230.

Hargreaves, G. H. and Z. A. Samani. 1983. Evapotranspiration comparisons for Haiti, Paper submitted to the Irrigation and Drainage Division, American Society of Civil Engineers for publication in the Proceedings.

Heady, Earl O. and Roger W. Hexem. 1978. Water production functions for irrigated agriculture. Iowa State University Press, Ames, Iowa.

Hersfield, D. M. 1961. Rainfall frequency atlas of the United States for durations from 30 minutes to 24 hours and return periods of from 1 to 100 years. Technical Paper No. 40, U. S. Weather Bureau.

Jensen, M.E. (Ed.) 1974. Consumptive use of water and irrigation water requirements. Rep. Tech. Com. on Irrigation Water Requirements, American Society of Civil Engineers, Irrigation Drainage Division.

Jensen, M.E. (Ed.) 1980. Design and operation of farm irrigation systems. American Society of Agricultural Engineers, St. Joseph, Michigan.

Kellogg, William W. and Robert Schware. 1981. Climate change and society. Westview Press, Boulder, Colorado.

Miller, Marvin E. and C. R. Weaver. 1968. Monthly and annual precipitation probabilities for climatic divisions of Ohio. Ohio Research and Development Center Research Bulletin 1005:1-11.

OMVS (Organisation pour la Mise en Valeur du Fleuve Senegal). 1979. Les amenagements hydroagricoles dans le Bassin du Senegal. Dakar, Senegal.

Rijks, D. A. 1976. Developpement de la recherche agronomique dans le Bassin du Fleuve Senegal, Agrometeorogie, UNDP, FAO, Rome.

Senegal-Consult. 1970. Feasibility survey for the regulation of the Senegal River. Volume 1B: Summary Rport. Zurich, Switzerland.

Shalhevet. 1976. Irrigation of field and orchard crops under semi-arid conditions. International Irrigation Information Center, IIC Publ. No. 1, Ottawa, Canada.

Tanner, C. B. 1960. A simple aero-heat budget method for determining daily evapotranspiration. Transactions, Seventh International Congress of Soil Science. Madison, Wisconsin.

U. S. Department of Agriculture, Agriculture Research Service. 1962. Technical Bulletin 1275: Consumptive use and water requirements. U. S. Government Printing Office, Washington, D. C.

U. S. Department of Energy. 1979. Workshop on environmental and societal consequences of a possible CO_2 - induced climate change. Annapolis, Maryland, 2-6 April, U. S. Department of Energy, Washington, D. C.

U. S. Department of the Interior, Department of Agriculture, and the Environmental Protection Agency. 1979. Irrigation water use and management.

Withers, Bruce and Stanley Vipond. 1980. Irrigation: Design and practice. 2nd Ed. Cornell University Press, Itheca, New York.

APPENDICES

Appendix A

The Greenhouse Effect

Many climatologist now believe that future climates will vary significantly from todays climate. The principal reason being the steady increase of carbon dioxide in our atmosphere, produced largely through fossil fuel use and possibly through deforestation. This long term increase is shown in Figure A-1. This so called "greenhouse effect" is projected to produce a global warming. If so, major alternations of regional rainfall and temperature, patterns may be expected in the next 50 years.

Average global increase of surface temperature for a doubling of carbon dioxide will probably be between 1.5°C and 4.5°C. Generally, a 1°C rise in average summertime temperature at middle latitudes increases the average growing season by roughly ten days. But as Bollman and Hellyer (1974) have shown, this depends on seasonal durations. Another benefit to crop production is that an increase in carbon dioxide levels is known to enhance photosynthesis and plant growth.

This climate change will also shift rainfall patterns. Currently many developing countries in the semiarid parts of the subtropics are expected to experience a general increase of precipitation and soil moisture, as shown in Figure A-2.

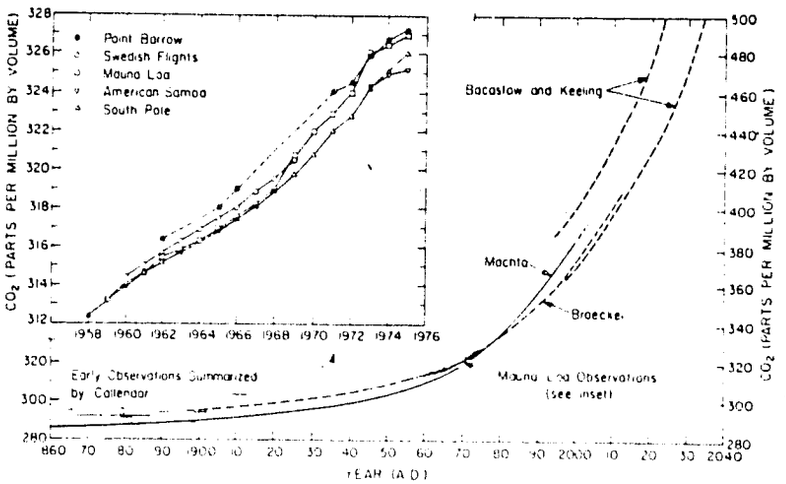

Figure A-1. The long term rise in atmospheric carbon dioxide content starting at the time of the Industrial Revolution and continuing into the next century (Source: Climate Change and Society (Kellogg and Schware 1981)).

This increase in carbon dioxide may turn out to be quite beneficial to crop production. It is known that increased carbon dioxide can for many plant species (U. S. Department of Energy 1979):

- increase average net photosynthesis
- change leaf area and leaf structure
- change canopy shape
- change the pattern of photosynthetic allocation
- increase water use efficiency
- increase tolerances to toxic atmospheric gases
- change root/shoot ratios
- change flowering dates and increase number of flowers produced per individual plant
- increase number and size of fruits and number of seeds produced per plant
- affect germination of some species

Allen (1979) demonstrated that greenhouse grown vegetables with added carbon dioxide have increased yields by at least 20 percent.

Thus, over the next 50 years, plants are expected to experience an increase in water use efficiency, be more tolerant to water stress, and increase yield as atmospheric carbon dioxide increases. With plants becoming more water efficient and rainfall expected to increase in the future, the feasibility of rainfed agriculture should be seriously examined.

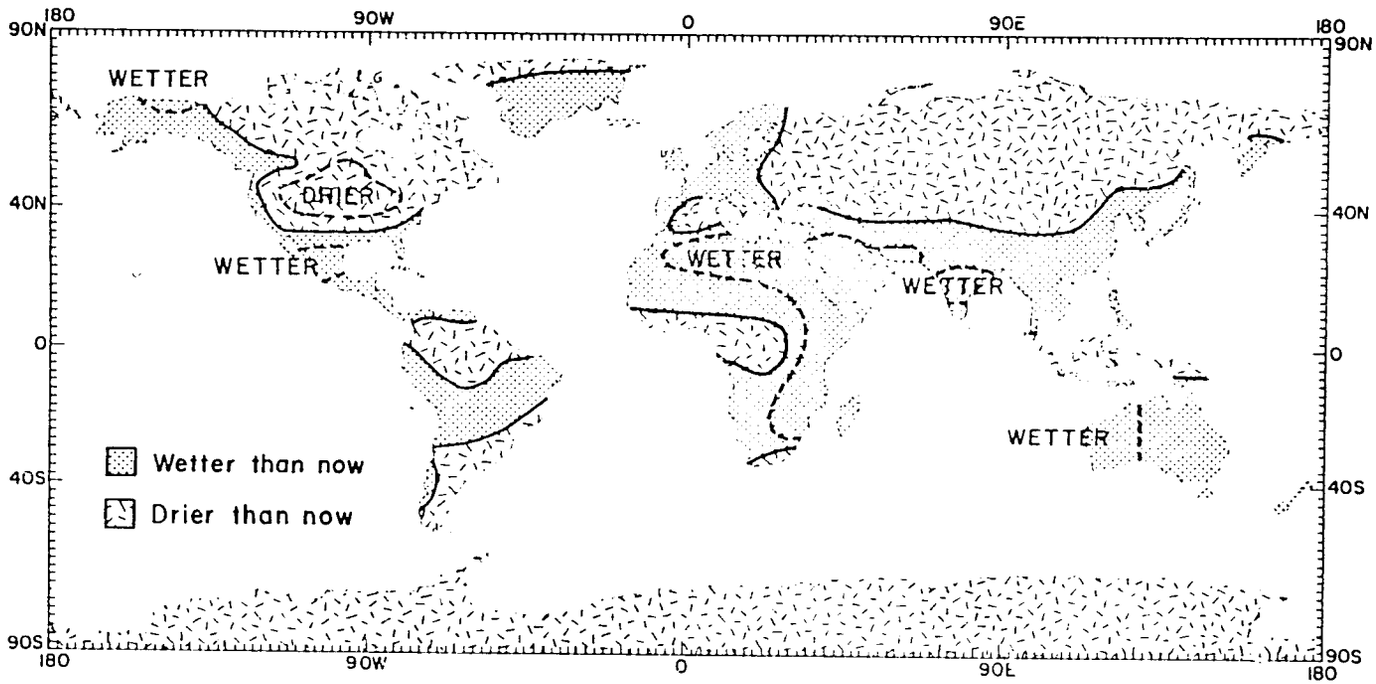

Figure A-2. Example of a scenario of possible soil moisture patterns on a warmer earth. Source: Climate and Society (Kellogg and Schware 1981).

Appendix B

Monthly Rainfall Amounts as a Function of Probability

Monthly rainfall amounts for different probability levels of occurrence or exceedance based on a gamma distribution, mean monthly temperatures, and monthly ET_0 values. For the following stations:

Saint Louis

Rosso

Podor

Matam

Kayes

STATION SAINT LOUIS LAT 16 6 LONG 16 30 ELEV 4.0 M 30 YEARS

PROB	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
95.	0.	0.	0.	0.	0.	0.	1.	23.	32.	0.	0.	0.	142.
90.	0.	0.	0.	0.	0.	0.	3.	33.	42.	0.	0.	0.	168.
80.	0.	0.	0.	0.	0.	0.	7.	48.	55.	0.	0.	0.	204.
75.	0.	0.	0.	0.	0.	0.	10.	55.	61.	1.	0.	0.	219.
70.	0.	0.	0.	0.	0.	0.	13.	62.	67.	2.	0.	0.	233.
60.	0.	0.	0.	0.	0.	0.	20.	76.	78.	4.	0.	0.	260.
50.	0.	0.	0.	0.	0.	1.	29.	91.	89.	9.	0.	0.	287.
40.	0.	0.	0.	0.	0.	2.	40.	108.	101.	18.	0.	1.	316.
30.	1.	1.	0.	0.	0.	5.	54.	128.	116.	32.	1.	1.	349.
25.	1.	1.	0.	0.	0.	7.	64.	140.	124.	43.	1.	2.	368.
20.	2.	2.	0.	0.	1.	10.	75.	154.	134.	58.	1.	3.	390.
10.	5.	4.	1.	0.	2.	22.	112.	196.	163.	113.	3.	7.	452.
5.	8.	8.	1.	1.	3.	38.	150.	235.	190.	176.	5.	13.	508.
MEAN	2.	1.	0.	0.	1.	7.	46.	105.	97.	38.	1.	2.	301.
TEMP	24.7	23.0	23.2	23.1	23.4	25.6	27.0	27.8	28.0	27.6	25.7	23.0	25.2
ETP	130.	138.	162.	166.	172.	169.	178.	167.	166.	158.	127.	120.	1853.

STATION ROSSO LAT 16 30 LONG 15 48 ELEV 6.0 M 24 YEARS

PROB	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
95.	0.	0.	0.	0.	0.	0.	8.	10.	14.	0.	0.	0.	111.
90.	0.	0.	0.	0.	0.	0.	13.	17.	21.	0.	0.	0.	135.
80.	0.	0.	0.	0.	0.	0.	20.	29.	33.	0.	0.	0.	167.
75.	0.	0.	0.	0.	0.	0.	23.	35.	38.	1.	0.	0.	181.
70.	0.	0.	0.	0.	0.	0.	26.	40.	44.	1.	0.	0.	194.
60.	0.	0.	0.	0.	0.	1.	33.	53.	55.	3.	0.	0.	219.
50.	0.	0.	0.	0.	0.	2.	41.	67.	68.	6.	0.	0.	244.
40.	0.	0.	0.	0.	0.	4.	50.	83.	82.	12.	0.	1.	271.
30.	1.	1.	0.	0.	1.	8.	60.	104.	99.	21.	1.	2.	302.
25.	1.	2.	0.	0.	1.	11.	66.	116.	110.	28.	1.	3.	321.
20.	2.	2.	0.	0.	1.	14.	74.	131.	122.	38.	2.	4.	342.
10.	4.	5.	0.	0.	3.	28.	97.	176.	160.	73.	4.	10.	401.
5.	7.	9.	0.	0.	5.	44.	118.	220.	195.	113.	8.	18.	456.
MEAN	1.	2.	0.	0.	1.	10.	49.	85.	81.	25.	2.	3.	259.
TEMP	22.9	27.6	26.5	27.7	29.1	30.0	28.9	29.1	29.3	29.3	26.7	23.0	27.5
ETP	124.	155.	176.	186.	196.	187.	185.	173.	171.	165.	130.	120.	1967.

STATION PODOR LAT 16 36 LONG 14 54 ELEV 7.0 M 29 YEARS

PROB	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
95.	0.	0.	0.	0.	0.	0.	5.	20.	9.	0.	0.	0.	118.
90.	0.	0.	0.	0.	0.	0.	8.	28.	15.	0.	0.	0.	144.
80.	0.	0.	0.	0.	0.	0.	16.	41.	27.	0.	0.	0.	180.
75.	0.	0.	0.	0.	0.	1.	19.	47.	33.	0.	0.	0.	195.
70.	0.	0.	0.	0.	0.	1.	23.	53.	39.	1.	0.	0.	209.
60.	0.	0.	0.	0.	0.	3.	31.	65.	52.	2.	0.	0.	237.
50.	0.	0.	0.	0.	0.	6.	40.	78.	67.	5.	0.	0.	265.
40.	0.	1.	0.	0.	0.	10.	51.	93.	84.	10.	0.	0.	295.
30.	1.	1.	0.	0.	0.	16.	65.	110.	106.	20.	1.	1.	330.
25.	1.	2.	0.	0.	1.	21.	74.	121.	119.	28.	1.	2.	351.
20.	1.	3.	0.	0.	1.	27.	84.	133.	135.	38.	2.	3.	375.
10.	3.	8.	1.	0.	2.	47.	116.	170.	185.	78.	4.	7.	442.
5.	5.	14.	1.	1.	4.	71.	147.	204.	233.	125.	7.	12.	503.
MEAN	1.	3.	0.	0.	1.	17.	53.	91.	87.	26.	1.	2.	282.
TEMP	23.1	28.2	27.6	32.3	31.9	32.4	30.8	29.9	30.1	30.3	27.9	31.9	29.7
ETP	125.	157.	180.	205.	208.	197.	193.	176.	174.	169.	134.	147.	2064.

STATION MATAM LAT 15 36 LONG 13 18 ELEV 17.0 M 30 YEARS

PROB	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
95.	0.	0.	0.	0.	0.	1.	40.	68.	29.	0.	0.	0.	243.
90.	0.	0.	0.	0.	0.	3.	50.	82.	39.	0.	0.	0.	279.
80.	0.	0.	0.	0.	0.	6.	66.	102.	55.	0.	0.	0.	326.
75.	0.	0.	0.	0.	0.	8.	72.	110.	62.	1.	0.	0.	345.
70.	0.	0.	0.	0.	0.	10.	78.	118.	68.	1.	0.	0.	363.
60.	0.	0.	0.	0.	0.	15.	91.	133.	82.	3.	0.	0.	397.
50.	0.	0.	0.	0.	0.	21.	104.	148.	96.	7.	0.	0.	430.
40.	0.	0.	0.	0.	1.	28.	117.	164.	112.	13.	1.	0.	465.
30.	0.	1.	0.	1.	2.	38.	133.	182.	131.	22.	2.	0.	505.
25.	0.	2.	0.	1.	3.	44.	143.	193.	142.	29.	3.	1.	529.
20.	0.	3.	0.	2.	4.	52.	154.	206.	155.	39.	5.	1.	555.
10.	1.	6.	0.	4.	8.	75.	186.	241.	193.	72.	12.	2.	629.
5.	2.	11.	0.	8.	12.	99.	215.	273.	229.	110.	21.	3.	694.
MEAN	0.	2.	0.	1.	3.	32.	112.	156.	108.	25.	4.	1.	444.
TEMP	26.5	25.9	29.0	34.2	33.8	35.9	30.2	28.8	34.0	32.5	27.8	26.8	30.5
ETP	135.	149.	185.	213.	217.	211.	191.	172.	189.	177.	134.	132.	2104.

STATION KAYES LAT 14 24 LONG 11 24 ELEV 47.0 M 39 YEARS

PROB	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
95.	0.	0.	0.	0.	0.	35.	102.	78.	72.	1.	0.	0.	502.
90.	0.	0.	0.	0.	0.	44.	116.	99.	86.	2.	0.	0.	546.
80.	0.	0.	0.	0.	0.	56.	134.	131.	107.	6.	0.	0.	603.
75.	0.	0.	0.	0.	1.	61.	141.	144.	115.	9.	0.	0.	626.
70.	0.	0.	0.	0.	1.	66.	148.	157.	123.	12.	0.	0.	647.
60.	0.	0.	0.	0.	2.	76.	162.	183.	139.	18.	0.	0.	686.
50.	0.	0.	0.	0.	4.	86.	175.	209.	154.	27.	0.	0.	723.
40.	0.	0.	0.	1.	8.	97.	188.	238.	171.	38.	1.	0.	762.
30.	0.	0.	0.	2.	13.	109.	204.	271.	190.	53.	2.	1.	806.
25.	0.	0.	0.	4.	17.	117.	213.	291.	201.	63.	3.	1.	830.
20.	0.	1.	0.	6.	22.	125.	223.	314.	214.	75.	5.	1.	858.
10.	1.	1.	0.	15.	40.	149.	251.	381.	251.	115.	12.	3.	935.
5.	1.	2.	0.	28.	61.	172.	276.	442.	284.	155.	21.	5.	1002.
MEAN	0.	0.	0.	5.	14.	92.	180.	228.	163.	46.	4.	1.	734.
TEMP	25.1	27.9	30.8	33.7	35.2	32.1	28.6	27.4	27.9	29.3	28.4	25.4	29.3
ETP	131.	156.	193.	211.	223.	196.	184.	166.	166.	165.	135.	127.	2053.

Appendix C

Tables

Table C-1. Extraterrestrial radiation.

Latitude	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
					Northern Hemisphere							
50°	3.8	6.1	9.4	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2
48	4.3	6.6	9.8	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7
46	4.9	7.1	10.2	13.3	16.0	17.2	16.6	14.5	11.5	8.3	5.5	4.3
44	5.3	7.6	10.6	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7
42	5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2
40	6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7
38	6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	6.1
36	7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6
34	7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2
32	8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8
30	8.8	10.7	13.1	15.2	16.5	17.0	16.8	15.7	13.9	11.6	9.5	8.3
28	9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8
26	9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3
24	10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7
22	10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2
20	11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7
18	11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1
16	12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6
14	12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0
12	12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5
10	13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9
8	13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3
6	13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7
4	14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1
2	14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4
0	15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8

Source: Crop Water Requirements (Doorenbos and Pruitt 1977)

Table C-2. Mean daily maximum duration of bright sunshine hours.

Northern Lats	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Southern Lats	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	April	May	June
50°	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48°	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46°	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44°	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42°	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.9	11.1	9.8	9.1
40°	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35°	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30°	10.4	11.1	12.0	12.9	13.6	14.0	13.9	13.2	12.4	11.5	10.6	10.2
25°	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20°	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15°	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10°	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5°	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0°	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1

Source: Crop Water Requirement (Doorenbos and Pruitt 1977)

Appendix D

Computer Programs

1. AGBEN - Program to determine the agricultural benefits and water requirements for the Senegal River Basin.

2. AREA - Program to determine the agricultural areas.

3. WRITE - Program to rewrite the AGTAB.PRE file in a more readable form.

4. RA - Program to calculate the extraterrestrial radiation in Langleys and the day length

5. GAMMA - Program to calculate the rainfall probability of occurrence or exceedence based upon a gamma distribution

6. HAR - Subroutine called by GAMMA, which is used to calculate ET_0 using the Hargreaves method.

AGBEN

```
C     THIS MAIN PROGRAM IS TO CALCULATE AG. BENEFITS AND WATER REQUIREMENTS
C     THIS PROGRAM WRITEN BY GEORGE LEO HARGREAVES 1982
C     THIS PROGRAM REQUIRES SPECIAL INSTRUCTIONS TO LINK
      DIMENSION TAB(28,15),RI(28),RF(28),RRL(28),RDL(28),VC(28),WR(28)
      DIMENSION AGBEN(28),FC(28)
      DIMENSION LTITLE(2),NTITLE(80),HEAD(80)
      OPEN(UNIT=2,NAME='AREA.DAT',TYPE='OLD')
      OPEN(UNIT=3,NAME='AGTAB.PRE',TYPE='OLD')
      OPEN(UNIT=4,NAME='AGBEN.OUT',TYPE='NEW',CARRIAGECONTROL='LIST')
      OPEN(UNIT=1,NAME='CHECK.OUT',TYPE='NEW')
      OPEN(UNIT=7,NAME='AGQ.DAT',TYPE='NEW',CARRIAGECONTROL='LIST')


CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     PARAMETER DEFINTIONS
C
C     ******ALL MONITARY VALUES ARE IN F.CFA*******
C     ADD    = AREA OF DRY FARM DISPLACED
C     AF     = AREA ARTIFICIALLY FLOODED
C     AFM1   = AREA ARTIFICIALLY FLOODED IN THE PREVIOUS YEAR
C     AGBEN  = AGRICULTURAL BENEFITS
C     AI     = IRRIGATED AREA
C     AIM1   = IRRIGATED AREA IN THE PREVIOUS YEAR
C     ARD    = AREA OF RECESSION AGRICULTURE DISPLACED
C     C1     = DEVELOPMENT COSTS PER NEW HECTAR IN F.CFA
C     C2     = COSTS FOR PUMPS IN F.CFA
C     C3     = ANNUAL REPLACEMENT COSTS PER HECTAR IN F.CF
C     CP     = CROPPING PATTERN FRACTION
C     DISF   = DISCOUNT FACTOR
C     FC     = FIXED COSTS
C     I      = ARRAY COUNTER FOR EACH PRODUCT OR CROP
C     IOUT   = VARIABLE CONTROLING INDIVIDUAL PRODUCT OUTPUT
C     KCHECK= NUMBER OF YEARS BETWEEN YEARLY OUTPUTS
C     LT     = NUMBER OF LINES IN HEADING
C     N      = PUMP LIFE OR TIME TO PUMP REPLACEMENT
C     NCOL   = NUMBER OF COLUMNS IN OUTPUT READ BY THE REVENUE PROGRAM
C     NPROD  = NUMBER OF PRODUCTS PER YEAR
C     NYEAR  = PROJECT LIFE IN YEARS
C     PCMAL  = PROPORTION OF TOTAL AREA IN MALI
C     PCMAU  = PROPORTION  OF TOTAL AREA IN MAURITANIA
C     PCSEN  = PROPORTION  OF TOTAL AREA IN SENEGAL
C     R1     = AGRICULTURAL DEVELOPMENT RATE
C     RATE   = DISCOUNT RATE IN DECIMAL FORM
C     RDL    = LOST REVENUES FROM DRY FARM AREAS
C     RF     = REVENUES FROM ARTIFICIALLY FLOODED AREAS
C     RI     = REVENUES FROM IRRIGATED AREAS
C     RRL    = LOST REVENUES FROM RECESSION AGRICULTURAL AREAS
C     SFF    = SINKING FUND FACTOR
C     SUMB   = DISCOUNTED TOTAL PROJECT AGRICULTURAL BENEFITS IN F.CFA
C     SUMQ   = DISCOUNTED TOTAL PROJECT WATER REQUIREMENTS IN CUBIC METERS
C     VC     = VARIABLE COSTS
C     WR     = WATER REQUIREMENTS IN CUBIC METERS
C     WRMAL  = WATER REQUIREMENT FOR MALI

C     WRMAU  = WATER REQUIREMENT FOR MAURITANIA
C     WRSEN  = WATER REQUIREMENT FOR SENEGAL
C
C     IF THE PARAMETER BEGINS WITH A "T" IT REFERS TO A YEARLY TOTAL
C       (example: TRI=YEARLY TOTAL REVENUES FROM IRRIGATED AREAS)
C       YTFC=YEARLY TOTAL FIXED COST
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
C       INITIALIZE VALUES
        CP=0.
        SUMB=0.
        SUMQ=0.

          TWRMAL=0.0
          TWRMAU=0.0
          TWRSEN=0.0
C*************************************************************************
C         PARAMETERS ENTERED INTERACTIVELY

        WRITE(5,*)'DO YOU WANT INDIVIDUAL PRODUCT BENEFITS? (Y/N)'
        READ(5,1003)IOUT
        IF(IOUT.EQ.'N')GO TO 10
          WRITE(5,*)'ENTER NUMBER OF YEARS BETWEEN YEARLY OUTPUTS'
          READ(5,*)KCHECK
   10   CONTINUE

        WRITE(5,*)'IS THE DEVELOPMENT COST PER NEW HECTAR =3560000 F.CFA?
     *    (Y/N)'
        READ(5,1003)NTEST
        C1=2800000.+760000.
        IF(NTEST.EQ.'Y')GO TO 11
          WRITE(5,*)'ENTER THE DEVELOPMENT COST PER NEW HECTAR IN F.CFA
     *    (C1)'
          READ(5,*)C1
   11   CONTINUE

        WRITE(5,*)'IS THE REPLACEMENT COSTS FOR PUMPS =760000 F.CFA?
     *    (Y/N)'
        READ(5,1003)NTEST
        C2=760000.
        IF(NTEST.EQ.'Y')GO TO 12
          WRITE(5,*)'ENTER THE REPLACEMENT COSTS IN F.CFA (C2)'
          READ(5,*)C2
   12   CONTINUE

        WRITE(5,*)'IS THE TIME TO PUMP REPLACEMENT =5 YEARS? (Y/N)'
        READ(5,1003)NTEST
        N=5
        IF(NTEST.EQ.'Y')GO TO 13
          WRITE(5,*)'ENTER THE TIME TO PUMP REPLACEMENT IN YEARS (N)'
          READ(5,*)N
   13   CONTINUE

        WRITE(5,*)'IS THE PROJECT LIFE =50 YEARS? (Y/N)'

        READ(5,1003)NTEST
        NYEAR=50
        IF(NTEST.EQ.'Y')GO TO 14
          WRITE(5,*)'ENTER THE PROJECT LIFE IN YEARS (NYEAR)'
          READ(5,*)NYEAR
   14   CONTINUE

        WRITE(5,*)'IS THE DISCOUNT RATE IN DECIMAL FORM=0.05? (Y/N)'
        READ(5,1003)NTEST
        RATE=.05
        IF(NTEST.EQ.'Y')GO TO 15
          WRITE(5,*)'ENTER THE DISCOUNT RATE IN DECIMAL FORM (RATE)'
          READ(5,*)RATE
   15   CONTINUE

 1003   FORMAT(A1)
C*************************************************************************
```

```
C-----------------------------------------------------------------------
C        PRINT OUT THE HEADINGS FOR THE AGQ.DAT DATA TABLE
      READ(2,*)LTITLE(2)
        READ(3,*)LTITLE(1),NPROD
        LT=LTITLE(2)+LTITLE(1)+6
        LT4=LTITLE(2)+LTITLE(1)+5
        NCOL=3
        WRITE(7,2001)LT,NYEAR,NCOL
        WRITE(7,2015)
        WRITE(7,*)'AGQ.DAT OUTPUT FROM AGBEN USED IN REVENUE'
        WRITE(4,*)LT4,NYEAR
        WRITE(4,2015)
        WRITE(4,*)'OUTPUT FROM AGBEN '
 2001   FORMAT(3I4,'  NUMBER OF LINES IN TITLE,YEARS,COLUMNS READ BY
     * REVENUE.FTN')
C     ACCOUNT FOR THE AREA DATA TABLE TITLE

        DO 60 I60=1,LTITLE(2)
      READ(2,1001)HEAD
        WRITE(7,1001)HEAD
        WRITE(4,1000)HEAD
60      CONTINUE
 1000   FORMAT(1X,80A1)
 1001 FORMAT(80A1)

C     ACCOUNT FOR THE AG. ECONOMIC SECTOR DATA TABLE TITLE
        DO 61 I61=1,LTITLE(1)
      READ(3,1002)NTITLE
        WRITE(7,1002)NTITLE
        WRITE(4,1000)NTITLE
61      CONTINUE
C
C                PRINT OUT VALUES OF OPTIONS ENTERED INTERACTIVELY
        WRITE(4,*)'VALUE OF OPTIONS ENTERED INTERACTIVELY ARE'
        WRITE(7,*)'VALUE OF OPTIONS ENTERED INTERACTIVELY ARE'
        WRITE(4,2000)C1,C2,N,RATE
        WRITE(7,2000)C1,C2,N,RATE
2000    FORMAT(' DEVELOPMENT COST ',F9.0,' REPLACEMENT COST ',F9.0,
     *  'TIME TO PUMP REPLACEMENT',I5,' DISCOUNT RATE ',F5.3)
        WRITE(7,2002)
        WRITE(7,2030)
 2002   FORMAT(2X,'YEARLY WATER REQUIREMENTS')
 2030   FORMAT(8X,'MALI',7X,'MAURITANIA',5X,'SENEGAL',8X,'TOTAL',7X,
     *  'YEAR')
C-----------------------------------------------------------------------
 1002 FORMAT(80A1)
C       PRINT OUTPUT HEADINGS FOR AGBEN.OUT
        WRITE (4,1004)
 1004   FORMAT(1X,'YEAR',9X,'TWR',11X,'TAGBEN')


C       IF YEARLY PRODUCTS WANTED PRINT OUTPUT HEADINGS FOR CHECK.OUT
          IF(IOUT.EQ.1)GO TO 75
          IF((MOD(K,KCHECK).NE.0).AND.(K.NE.1))GO TO 75
            WRITE(1,1005)
 1005       FORMAT(2X,'I',5X,'RI',7X,'RF',6X,'RRL',6X,'RDL',6X,
     *        'FC',6X,'VC',8X,'WR',6X,'AGBEN')
   75     CONTINUE

C     CALCULATE FIXED COSTS FOR PUMP REPLACEMENTS
      SFF=RATE/(((1.+RATE)**N)-1.)
      C3=C2*SFF
```

```
      READ(3,*)((TAB(I,J),J=1,15),I=1,NPROD)
C     CALCULATE ALLOCATED FIXED COSTS
      DO 100 I=1,NPROD
        CP=CP+TAB(I,11)
 100  CONTINUE

      READ(2,1006)R1,AI,ARD,ADD,AF,PCMAL,PCMAU,PCSEN

      DO 150 K=1,NYEAR
        KYEAR=1979+K
        AIM1=AI
        AFM1=AF

        READ(2,1006)R1,AI,ARD,ADD,AF,PCMAL,PCMAU,PCSEN
 1006   FORMAT(10X,F12.0,3F11.0,F10.0,2X,3(F6.4,1X))
C       INITIALIZE TOTAL YEARLY VALUES
        TRI=0
        TRF=0
        TRRL=0
        TRDL=0
        TVC=0
        TWR=0
        TAGBEN=0
        YTFC=0

C       CALCULATE TOTAL FIXED COSTS FOR IRRIGATED AREA
        TFC=C1*R1+C3*AIM1

        DO 200 I=1,NPROD
C         CALCULATE THE FIXED COSTS PER PRODUCT
          FC(I)=TFC*TAB(I,11)/CP

C         CALCULATE VARIABLE COST
          VC(I)=(TAB(I,7)*TAB(I,8)+TAB(I,9)*TAB(I,10))*TAB(I,11)*AIM1

C         CALCULATE REVENUES

C         REVENUE FROM IRRIGATION
          RI(I)=TAB(I,2)*TAB(I,3)*TAB(I,11)*AIM1
C         REVENUE FROM ARTIFICIAL FLOODING
          RF(I)=TAB(I,2)*TAB(I,4)*TAB(I,12)*AFM1
C         LOST REVENUE FROM RECESSION
          RRL(I)=TAB(I,2)*TAB(I,5)*TAB(I,13)*ARD
C         LOST REVENUE FROM DRY FARMING
          RDL(I)=TAB(I,2)*TAB(I,6)*TAB(I,14)*ADD

C         CALCULATE WATER REQUIREMENTS (*10000 TO GET CUBIC METERS)
          WR(I)=TAB(I,15)*TAB(I,11)*AIM1*10000.

C         CALCULATE AGRICULTURAL BENEFITS
          AGBEN(I)=RI(I)+RF(I)-FC(I)-VC(I)-RRL(I)-RDL(I)

C         CALCULATE YEARLY TOTALS
          TRI=TRI+RI(I)
          TRF=TRF+RF(I)
          TRRL=TRRL+RRL(I)
          TRDL=TRDL+RDL(I)
          YTFC=YTFC+FC(I)
          TVC=TVC+VC(I)
          TWR=TWR+WR(I)
          TAGBEN=TAGBEN+AGBEN(I)
```

```
          IF(IOUT.EQ.1)GO TO 200
          IF((MOD(K,KCHECK).NE.0).AND.(K.NE.1))GO TO 200
            WRITE(1,1)I,RI(I),RF(I),RRL(I),RDL(I),FC(I),VC(I),
     *      WR(I),AGBEN(I)
    1       FORMAT(I3,1P7E9.2,1PE10.2)
  200     CONTINUE
          IF(IOUT.EQ.1)GO TO 300
          IF((MOD(K,KCHECK).NE.0).AND.(K.NE.1))GO TO 300
            WRITE(1,1007)
 1007       FORMAT(2X,'K',4X,'TRI',6X,'TRF',6X,'TRRL',5X,'TRDL',
     *      5X,'TFC',6X,'TVC',6X,'TWR',4X,'TAGBEN')
            WRITE(1,2)K,TRI,TRF,TRRL,TRDL,YTFC,TVC,TWR,TAGBEN
    2       FORMAT(I3,1P8E9.2,/)
  300     CONTINUE
          WRITE(4,3)KYEAR,TWR,TAGBEN
    3     FORMAT(1X,I4,1P2E15.2)
          DISF=1./((1.+RATE)**(K-1))
          SUMQ=SUMQ+DISF*TWR
          SUMB=SUMB+DISF*TAGBEN

          WRMAL=TWR*PCMAL
          WRMAU=TWR*PCMAU
          WRSEN=TWR*PCSEN
          WRITE(7,2003)WRMAL,WRMAU,WRSEN,TWR,KYEAR
          TWRMAL=TWRMAL+WRMAL
          TWRMAU=TWRMAU+WRMAU
          TWRSEN=TWRSEN+WRSEN
          TOTTWR=TOTTWR+TWR
 2003     FORMAT(1X,1P4E14.4,I8)
  150   CONTINUE
          WRITE(7,2103)TWRMAL,TWRMAU,TWRSEN,TOTTWR
2103      FORMAT(/,' SUM '1PE10.4,1P3E14.4)
        WRITE(4,2005)SUMB
        WRITE(4,2004)SUMQ
        WRITE(4,2006)RATE
          WRITE(4,2015)
 2004 FORMAT(G15.8,' = DISCOUNTED TOTAL PROJECT',
     * ' WATER REQUIREMENTS')
 2005 FORMAT(/,G15.8,' = DISCOUNTED TOTAL PROJECT',
     *' AGRICULTURAL BENEFITS')
 2006 FORMAT(2X,'THE DISCOUNT RATE=',F4.2)
 2015   FORMAT(' ****************************************************',
     * '*********************************')
        CLOSE(UNIT=1,DISP='KEEP')
        CLOSE(UNIT=2,DISP='KEEP')
        CLOSE(UNIT=3,DISP='KEEP')
        CLOSE(UNIT=4,DISP='KEEP')
        CLOSE(UNIT=7,DISP='KEEP')
        STOP
        END
```

AREA

```
C     PROGRAM TO CALCULATE AGRICULTURAL AREAS
C     THIS PROGRAM WRITEN BY GEORGE LEO HARGREAVES 1982
      INTEGER T
      OPEN(UNIT=1,NAME='AREA.DAT',TYPE='NEW',CARRIAGECONTROL='LIST')

CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C         VARIABLE DEFINITIONS
C         *******ALL AREAS ARE IN HECTARS***********
C         AD=AREA OF DRY FARMING
C         ADD=AREA OF DRY FARM DISPLACED
C         AF=AREA ARTIFICIALLY FLOODED
C         AFMAX=MAXIMUM POTENTIAL AREA FOR  ARTIFICIAL FLOOD
C         AI=IRRIGATED AREA
C         AII=INITIAL IRRIGATED AREA
C         AIMAX=MAXIMUM IRRIGATED AREA
C         AR=AREA OF RECESSION AGRICULTURAL
C         ARD=AREA OF RECESSION AGRICULTURE DISPLACED
C         R1=INITIAL DEVELOPMENT RATE
C         R2=NEW DEVELOPMENT RATE
C         T=YEARLY COUNTER
C         TF=TIME TO WHEN  ARTIFICIAL FLOODING BEGINS (IN YEARS)
C         TNEW=TIME TO WHEN NEW DEVELOPMENT RATE STARTS (IN YEARS)
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

C     INITIALIZE PARAMETERS (EXCEPT FOR R1 WHICH IS INITIALIZED LATER)
      T=0
      AI=0.
      AII=28805.
      AIMAX=315000.
      AR=108633.
      AD=75000.
      AFMAX=90000.

C*********************************************************************
C     PARAMETERS INITIALIZED INTERACTIVELY

      WRITE(5,*)'IS THE NEW DEVELOPMENT RATE=5000. ha./yr? (Y/N)'
      READ(5,10)NTEST
      R2=5000.
      IF(NTEST.EQ.'Y')GO TO 20
        WRITE(5,*)'ENTER THE NEW DEVELOPMENT RATE IN ha./yr (R2)'
        READ(5,*)R2
        IF(R2.EQ.5000.)GO TO 20
   20 CONTINUE

      WRITE(5,*)'IS THE TIME TO NEW DEVELOPMENT RATE= 4 YEARS? (Y/N)'
      READ(5,10)NTEST
      TNEW=4
      IF(NTEST.EQ.'Y')GO TO 21
        WRITE(5,*)'ENTER THE NUMBER OF YEARS BEFORE NEW DEVELOPMENT'
        WRITE(5,*)'RATE IS EFFECTIVE (TNEW)'
        READ(5,*)TNEW
   21 CONTINUE

      WRITE(5,*)'IS THE TIME TO ARTIFICIAL FLOOD= 9 YEARS? (Y/N)'
      READ(5,10)NTEST
      TF=9
      IF(NTEST.EQ.'Y')GO TO 22
        WRITE(5,*)'ENTER NUMBER OF YEARS BEFORE FLOODING BEGINS (TF)'
        READ(5,*)TF
   22 CONTINUE

   10 FORMAT(A1)
C*****************************************************************
```

```
C
C  INITIALIZATION OF VALUES USED TO SEPARATE IRRIGATED AREAS BETWEEN COUNTRIES
C                 VARIABLE CODE USED
C       VARIABLES BEGINING WITH R ARE PROPORTION  OF AREA DEVELOPED IN EACH
C       COUNTRY
C       R1 IS THE AREA DEVELOPFD IN A GIVEN YEAR
C       THUS AREA DEVELOPED EACH YEAR IN MALI = RMALII * R1
C       R VARIABLES ENDING IN I ARE INITIAL PROPORTION
C       R VARIABLES ENDING IN F ARE FINAL PROPORTION (VALUES AFTER
C       THE MAXIMUM NUMBER OF HA HAS BEEN DEVELOPED IN MALI)
C       TOTMAL = THE MAXIMUM NUMBER OF HA THAT CAN BE DEVELOPED IN MALI
C       VARIABLES BEGINING WITH A ARE AREA VARIABLES
C       VARIABLES BEGINING WITH PC ARE THE PROPORTION VARIABLES(THE
C       PROPORTION OF THE TOTAL AREA IRRIGATED IN A GIVEN COUNTRY
C       VARIABLES ENDING WITH T ARE TEMPORARY STORAGE VARIABLES
        RMALII=.1666
        RMAURI=.3436
        RSENEI=.4898
        RMALIF=0.0
        RMAURF=.4125
        RSENEF=.5875
        TOTMAL=23437.
        AMALI=270.
        AMAUR=5305.
        ASENE=23230.
        RMALI=RMALII
        RMAUR=RMAURI
        RSENE=RSENEI
C                         CHECK WITH USER ON SEPARATION BETWEEN COUNTRIES
        WRITE(5,2020)RMALII,RMAURI,RSENEI,TOTMAL,RMAURF,RSENEF,
     *AMALI,AMAUR,ASENE,AII
2020    FORMAT(1X,'IN REPORT 4 AND REPORT 5 THE FOLLOWING ',
     *' PROPORTIONS WERE USED',/,' TO SEPARATE TOTAL AREA DEVELOPED',
     *1X,'EACH YEAR BETWEEN THE 3 COUNTRIES',/,1X,
     *'PROPORTION TO MALI ',F6.4,' PROPORTION TO MAUR ',F6.4
     *,/,1X,'PROPORTION TO SENEGAL ',F6.4,/,1X,
     *'AFTER ',F7.0,' HA HAS BEEN DEVELOPED IN MALI THE ',/,
     *' PROPORTION TO MAUR ',F6.4,' PROPORTION TO SENEGAL ',F6.4,/
     *,1X,'THE INITIAL AREAS IRRIGATED ARE',/,
     *1X,'MALI = ',F7.0,' MAURITANIA = ',F7.0,' SENEGAL ',F7.0,
     *' TOTAL = ',F8.0,/
     *,1X,'ARE THESE VALUES TO BE USED FOR THIS MODEL RUN (Y/N)')
        READ(5,10)OK
        IF(OK.EQ.'Y')GO TO 23
        WRITE(5,*)'ENTER VALUES IN DECIMAL FORM 50% = 0.50'
        WRITE(5,*)'ENTER NEW PROPORTION'
        WRITE(5,*)'FIRST INITIAL PROPORTION TO MALI'
        READ(5,*)RMALII
        WRITE(5,*)'ENTER INITAL PROPORTION TO MAUR'
        READ(5,*)RMAURI
        WRITE(5,*)'ENTER INITAL PROPORTION TO SENEGAL'
        READ(5,*)RSENEI
        WRITE(5,*)'ENTER MAXIMUM NUMBER OF HA POSSIBLE FOR MALI'
        READ(5,*)TOTMAL
        WRITE(5,*)'ENTER FINAL PROPORTION TO MAUR'
        READ(5,*)RMAURF
        WRITE(5,*)'ENTER FINAL PROPORTION TO SENEGAL'
        READ(5,*)RSENEF
        WRITE(5,*)'ENTER INITIAL AREAS IRRIGATED'
        WRITE(5,*)'ENTER AREA FOR MALI'
        READ(5,*)AMALI
        WRITE(5,*)'ENTER AREA FOR MAURITANIA'
        READ(5,*)AMAUR
        WRITE(5,*)'ENTER AREA FOR SENEGAL'
        READ(5,*)ASENE
        WRITE(5,*)'ENTER TOTAL INITIAL AREA IRRIGATED'
        READ(5,*)AII
23      CONTINUE
```

```
C                PRINT OUT THE NUMBER OF LINES IN THE TITLE HEADING
        WRITE(1,*)'14'
C     PRINT OUTPUT HEADINGS
        WRITE(1,2015)
        WRITE(1,*)'OUTPUT FROM AREA.FTN USED AS INPUT FOR AGBEN'
        WRITE(1,*)'VALUES OF OPTIONS USED FOR THIS RUN ARE'
        WRITE(1,2004)R2,TNEW
        WRITE(1,2005)TF
        WRITE(1,2030)RMALII,RMAURI,RSENEI,TOTMAL,RMAURF,RSENEF
     *,AMALI,AMAUR,ASENE
        WRITE(1,2015)
      WRITE(1,2000)
      WRITE(1,2001)
        WRITE(1,2015)
 2000 FORMAT(20X,'AGRICULTURAL AREAS DATA TABLE')
 2001 FORMAT(6X,'YEAR',7X,'RATE',8X,'AI',8X,'ARD',8X,'ADD',8X,'AF'
     *,2X,'    MALI    MAUR    SENE')
 2004 FORMAT('NEW DEVELOPMENT RATE',F8.0,'TIME TO NEW DEVELOPMENT RATE',
     *F5.0)
 2005   FORMAT(' NUMBER OF YEARS BEFORE THE FLOOD',F5.0)
 2015   FORMAT('              ')
 2030   FORMAT(' THE FOLLOWING VALUES WERE USED TO DISTRIBUTE'
     *,' HA DEVELOPED BETWEEN COUNTRIES',/,1X,
     *' INITIAL  MALI = ',F5.4,' MAUR ',F5.4,' SENEGAL ',F5.4,
     */,' TOTAL POSSIBLE HA IN MALI = ',F7.0,
     */,' FINIAL  MAUR ',F5.4, ' SENEGAL ',F5.4,
     */,' INITIAL AREAS MALI ',F7.0,' MAUR ',F7.0,' SENEGAL ',F7.0)
C*****************************************************************************
       DO 100 K=1980,2030
         IF(K.NE.1980)GO TO 200
           R1=0.
           AI=AII
           ARD=0.
           ADD=0.
           AF=0.
           GO TO 500
  200    CONTINUE

C        INITIALIZE THE DEVELOPMENT RATE
         R1=4000.
         IF(T.GT.TNEW)R1=R2

C        IRRIGATED AREA
         AI=AI+R1
         IF(AI.GE.AIMAX)AI=AIMAX

C        RECESSION AREA DISPLACED
         ARD=AI-AII
         IF(ARD.LT.AR)GOTO 300
           ARD=AR

C          DRY FARM AREA DISPLACED
           ADD=AI-ARD-AII
           IF(ADD.GT.AD)ADD=AD
  300    CONTINUE

C        ARTIFICIAL FLOOD AREA
         IF(T.LT.TF)GOTO 400
         IF(AI.GE.AFMAX)GOTO 400
         AF=AFMAX-AI
         GOTO 500
  400    AF=0
  500    CONTINUE
```

```
C               DISTRIBUTE THE AREA DEVELOPED IN A GIVEN YEAR
C               BETWEEN THE 3 COUNTRIES
C       FIRST CHECK TO SEE IF MALI IS AT MAXIMUM
C       IF AT MAXIMUM CHANGE PROPORTIONS
        R1T=R1
        AMALIT=AMALI+R1T*RMALI
        IF(AMALIT.LT.TOTMAL)GO TO 50
        XADD=TOTMAL-AMALI
        AMALI=TOTMAL
        RMALI=0.0
        RMAUR=RMAURF
        RSENE=RSENEF
        R1T=R1-XADD
50      CONTINUE
        AMALI=AMALI+R1T*RMALI
        AMAUR=AMAUR+R1T*RMAUR
        ASENE=ASENE+R1T*RSENE
C               CALCULATE THE PROPORTION OF TOTAL AREA IRRIGATED
C               IN EACH COUNTRY
        PCMAL=AMALI/AI
        PCMAU=AMAUR/AI
        PCSEN=ASENE/AI
        WRITE(1,2003)K,R1,AI,ARD,ADD,AF,PCMAL,PCMAU,PCSEN
 2003   FORMAT(I10,F12.0,3F11.0,F10.0,2X,3(F6.4,1X))
        T=T+1
  100 CONTINUE
        WRITE(1,2010)
 2010   FORMAT(' ***********************************************************',
     * '************************************')
      CLOSE(UNIT=1,DISP='KEEP')
      STOP
      END
```

WRITE

```
C     THIS PROGRAM WRITES OUT THE AG. ECONOMIC SECTOR DATA TABLE
C     THIS PROGRAM WRITEN BY GEORGE LEO HARGREAVES 1982
      DIMENSION NTITLE(80)
      REAL*8 NAME(28)
      DATA NAME/'RICE WET','RICE DRY','TOMATO W','TOMATO D',
     * 'WHEAT  W','WHEAT  D','NIEBE  W','NIEBE  D','S.CANE W',
     * 'S.CANE D','SORGHM W','SORGHM D','MAIZE  W','MAIZE  D',
     * 'COTTON W','COTTON D','C.MILK W','C.MILK D','C.MEAT W',
     * 'C.MEAT D','S.MILK W','S.MILK D','S.MEAT W','S.MEAT D',
     * 'G.MILK W','G.MILK D','G.MEAT W','G.MEAT D'/
      OPEN(UNIT=1,NAME='AGTAB.PRE',TYPE='OLD')
      OPEN(UNIT=2,NAME='AGDATA.OUT',TYPE='NEW')

C     ACCOUNT FOR THE TABLE TITLE AND WRITE IT OUT
      READ(1,*)LTITLE
        DO 67 I67=1,LTITLE
         READ(1,1001)NTITLE
      WRITE(2,2001)NTITLE
 67     CONTINUE
 1001 FORMAT(80A1)
 2001 FORMAT(80A1,/)

C     PRINT OUT COLUMN HEADINGS
      WRITE(2,2002)
 2002 FORMAT(30X,'YIELDS (t/ha)',15X,'PRODUCTION COSTS',
     * 13X,'CROPPING PATTERN (%)')

      WRITE(2,2003)
 2003 FORMAT('+',10X,'WORLD',3X,'_____________________________________',2X,
     *  '_____________ _____________',2X,
     *  '_____________________________')

      WRITE(2,2004)
 2004 FORMAT(2X,'PRODUCT',2X,'PRICE',3X,'IRRIG.',2X,
     * 'FLOODED',2X,'RECESSION',2X,'RAINFED',2X,'LARGE PER.',2X,
     * '%',2X,'SMALL PER.',2X,'%',2X,'AREA',2X,'FLOODED',2X,
     * 'RECESSSION',2X,'RAINFED',2X,'WATER REQ.')

      WRITE(2,2005)
 2005 FORMAT('+','_____________________________________________________
     *_____________________________________________________________
     *_____________',/)

      DO 100 I=1,14
        READ(1,*)K,B,C,D,E,F,G,H,O,P,Q,R,S,T,U
        WRITE(2,2006)NAME(K),B,C,D,E,F,G,H,O,P,Q,R,S,T,U
 2006   FORMAT(1X,A8,F8.0,F9.3,F8.4,2F10.4,F10.0,F6.1,F10.0,F5.1,F6.3,
     *   F7.3,F11.3,F11.3,F9.2)
        READ(1,*)K,B,C,D,E,F,G,H,O,P,Q,R,S,T,U
        WRITE(2,2007)NAME(K),B,C,D,E,F,G,H,O,P,Q,R,S,T,U
 2007   FORMAT(1X,A8,F8.0,F9.3,F8.4,2F10.4,F10.0,F6.1,F10.0,F5.1,F6.3,
     *  F7.3,F11.3,F11.3,F9.2,/)
 100 CONTINUE
      CLOSE(UNIT=1,DISP='KEEP')
      CLOSE(UNIT=2,DISP='KEEP')
      STOP
      END
```

RA

```
C       CALCULATE EXTERRESTIAL RADIATION IN LANGLEYS AND DAY LENGHT
        OPEN(UNIT=4,NAME='RA',STATUS='NEW')
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C       PARAMETER DEFINITIONS
C       D=JULIAN DATE (JANUARY 1 = 1)
C       DECL=DECLINATION (ANGLE OF THE SUN) IN DEGREES
C       DER=DECLINATION (ANGLE OF THE SUN) IN RADIANS
C       DL=DAY LENGTH IN HOURS (SUNRISE TO SUNSET)
C       ES=DISTANCE OF THE SUN TO THE EARTH DIVIDED BY THE MEAN DISTANCE
C       RLD=EXTRATERRESTIAL RADIATION IN LANGLEYS PER DAY
C       XLA=LATITUDE OF THE STATION IN DEGREES (MINUTES IN DECIMAL FORM)†
C       XLR=LATITUDE IN RADIANS
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
        WRITE(5,2001)
 2001   FORMAT(2X,'ENTER LATITUDE OF STATION IN DEGREES (XLA)')
        READ(5,*)XLA
        XLR=XLA/57.2958
C       INITIALIZE PARAMETER
        D=0
        DO 100 I=1,365
        D=D+1.
        Y=COS(.0172142*(D+192.))
        DER=.40876*Y
        DECL=57.2958*DER
        ES=1.00028+.03269*Y
        Z=-TAN(XLR)*TAN(DER)
        IF(Z) 44,43,42
   42    OM=ATAN(SQRT(1.0-Z*Z)/ABS(Z))
        DL=OM/.1309
        GO TO 45
   43    OM=1.5708
        DL=12.
        GO TO 45
   44    OM=ATAN(SQRT(1.0-Z*Z)/ABS(Z))
        DL=24.-(OM/.1309)
   45   CONTINUE
        RLD=120.*(DL*SIN(XLR)*SIN(DER)+7.639*COS(DER)*COS(XLR)*SIN(OM))/ES
        WRITE(4,2000)D,RLD,DL
 2000   FORMAT(3F10.2)
  100   CONTINUE
        STOP
        END
```

GAMMA

103

```
C       THIS PROGRAM CALCULATES THE RAINFALL PROBABILITY OF OCCURRENCE
C       BY CALCULATING THE GAMMA DISTRIBUTION OF PRECIPITATION ON A
C       MONTHLY BASIS, THE GAMMA PARAMETERS ARE CALCULATED WITH THE
C       USE OF MAXIMUM LIKELIHOOD ESTIMATORS.  THE GAMMA FUNCION IS
C       EVALUATED WITH THE USE OF A SUBROUTINE IN VAX CALLED GAMMA
C       WHICH IS A PART OF THE PACK IMSL.
C       THE SUBROUTINE HAR WHICH IS CALLED IN THIS PROGRAM IS TO
C       CALCULATE THE ETP USING THE HARGREAVES EQUATION.
C       Z ARRAY IS THE PARAMETERS FOR THE NORMAL DISTRIBUTION
C       PFREQ IS THE PROBABILITY LEVELS
C       AV IS THE MONTHLY AND YEARLY AVERAGE RAINFALL
C       PREC IS THE MONTHLY PRECIPITATION IN TENTHS OF MM
        DOUBLE PRECISION RPIE,GAMMA1
        CHARACTER FILE*12,NAME*30
        REAL  PREC(100,13),Z(6),PFREQ(13),AV(13),RPAR(13),
     *  AMBA(13),GAMMAP(13),RUN1(13),RUNPP(13,14),
     *  NAME1(14),NAME2(3),TEMP(100,13),AVT(13),ETP(13)
C*********************************************************************
C       ENTER STATION NAME AND DATA
        WRITE(5,'(2X, ''ENTER STATION NAME '',$)')
        READ(5,'(A)')NAME
        WRITE(5,'(2X, ''ENTER STATION LATITUDE (DEGREE,MINUTES) '',$)')
        READ(5,*)LD,LDM
        WRITE(5,'(2X, ''ENTER STATION LONGITUDE (DEGREE,MINUTES) '',$)')
        READ(5,*)LG,LGM
        WRITE(5,'(2X, ''ENTER STATION ELEVATION IN METERS '',$)')
        READ(5,*)ELEV
        WRITE(5,'(2X, ''ENTER NUMBER OF YEARS OF DATA '',$)')
        READ(5,*)NYEARS
        WRITE(5,'(2X, ''ENTER NAME OF TEMP & PRECIP FILE DATA '',$)')
        READ(5,'(A)')FILE
C *******************************************************************
        OPEN(UNIT=1,FILE=FILE,STATUS='OLD')
        OPEN(UNIT=2,FILE=NAME,STATUS='NEW')
C     ******* INITIALIZE THE DATA***********
        DATA NAME1/'PROB','JAN','FEB','MAR','APR','MAY','JUN','JUL',
     *  'AUG','SEP','OCT','NOV','DEC','ANN'/
        DATA NAME2/'MEAN','TEMP','ETP'/
        DATA Z/1.64485,1.28155,.84162,.67449,.5344,.25300/
        DATA PFREQ/5.,10.,20.,25.,30.,40.,50.,60.,70.,75.,80.,90.,95./
        DATA NFREQ/13/
C       READ MONTHLY TEMPERATURE & PRECIPITATION DATA
        DO 1 I=1,NYEARS
        DO 21 J=1,12
          READ(1,1002) TEMP(I,J),PREC(I,J)
  21    CONTINUE
  1     CONTINUE
 1002   FORMAT(14X,2F10.1)
C  ******************************************************************
        FN=NYEARS
        NPH=NFREQ/2.
        NPRBP=NFREQ+1
C       CALCULATE THE AVERAGE MONTHLY PRECIPITATION
```

104

```
      DO 2 J=1,12
        SUM=0.0
        COUNT=0.0
C     IDENTIFY MISSING DATA AND CALCULATE MONTHLY AVERAGES
      DO 3 I=1,NYEARS
        IF(PREC(I,J).EQ.200000.) PREC(I,J)=-1.0
        IF(PREC(I,J).GE.0.0) SUM=SUM+PREC(I,J)
        IF(PREC(I,J).GE.0.0) COUNT=COUNT+1
 3    CONTINUE
      AV(J)=SUM/COUNT
 2    CONTINUE
      IF(J.LE.12)GOTO 11
C     CALCULATE THE AVERAGE ANNUAL PRECIPITATION
      DO 4 I=1,NYEARS
      DO 5 J=1,12
        IF(PREC(I,J).LT.0.0) PREC(I,J)=AV(J)
 5    CONTINUE
 4    CONTINUE
      DO 6 I=1,NYEARS
        SUM=0.0
        DO 7 J=1,12
          SUM=SUM+PREC(I,J)
 7      CONTINUE
        PREC(I,13)=SUM
        SUM2=SUM2+SUM
 6    CONTINUE
      AV(13)=SUM2/NYEARS
 11   CONTINUE
C     BEGINING OF LOOP TO CALCULATE THE MONTHLY DISTIBUTION
      DO 180 J=1,13
      IF(AV(J).LT..01) AV(J)=.001
      SX2=(PREC(1,J)-AV(J))*(PREC(1,J)-AV(J))
      ALSX=ALOG(PREC(1,J)+.001)
 15   DO 10 I=2,NYEARS
        IF(PREC(I,J).LT.0) GOTO 10
        SX2=SX2+(PREC(I,J)-AV(J))*(PREC(I,J)-AV(J))
        ALSX=ALSX+ALOG(PREC(I,J)+.001)
 10   CONTINUE
      ALXBAR=ALOG(AV(J)+.001)
      ALXBAR=ALXBAR-ALSX/FN
C     MAXIMUM LIKELIHOOD ESTIMATOR FOR THE GAMMA ARE CALCULATED
      RPAR(J)=1./(4.*ALXBAR)*(1+SQRT(1.+4.*ALXBAR/3.))
      AMBA(J)=RPAR(J)/AV(J)
      RPAR1=RPAR(J)-1.
      IF(RPAR(J).LE.0) RPAR(J)=+.001
C     SAMPLE STANDARD DEVIATION STD1 CALCULATED
      STD1=SQRT(SX2/(FN-1.))
C     FOR VALUES OF RPAR GREATER THAN 85 THE DISTRIB IS ASSUMED NORMAL
      IF(RPAR(J).GE.85) GO TO 150
      GAMMAP(J)=GAMMA(RPAR(J))
      GAMMAP(J)=ALOG(ABS(GAMMAP(J)))
      GAMMA1=GAMMAP(J)
C     LOOP TO CALCULATE A PRECIP VALUE FOR A GIVEN PROBABILTY
```

```
      DO 140 N=1,13
      NEST=0
      TEST=.0001
      DEST=.0004
      XO=RPAR1
      IF(RPAR(J)-1.0)30,20,20
 20   IF(XO)40,40,50
 30   XO=.0001
      GO TO 50
 40   XO=.01
 50   Z1=2.0
      NEST=NEST+1
      T1=XO/(RPAR1+Z1)
      S=T1+1.0
C     LOOP TO CALCULATE S IN THE NEWTON APPROXIMATION
      DO 70 L=1,100
      Z1=Z1+1.0
      T1=(T1*XO)/(RPAR1+Z1)
 60   S=S+T1
      IF(T1-TEST)80,80,70
 70   CONTINUE
 80   DL=PFREQ(N)/100
      IF(DL)120,90,90
 90   RPIE=XO
C     FOR VALUES OF XO GREATER THAN 86 GO TO NORMAL DISTRIBUTION
      IF(XO.GT.86.0) GO TO 150
      RPIE=DEXP(GAMMA1-(RPAR1*DLOG(RPIE)))
      X1=XO-(XO/RPAR(J))*S+(DL*RPIE*EXP(XO))
      DX=X1-XO
 100  XO=X1
      IF(XO)120,130,110
 110  IF(ABS(DX).LE.DEST) GO TO 130
      IF(NEST.LE.100) GO TO 50
 120  X1=0.0
C     THE VALUES OF PRECIPITAION IS CALCULATED FOR PROB. LEVEL
 130  RUN1(N)=X1/AMBA(J)
 140  CONTINUE
      GO TO 170
C     LOOP TO CALCULATE A NORMAL DISTRIBUTION
 150  DO 160 K=1,NPH
      FACD=STD1*Z(K)
      RUN1(K)=AV(J)-FACD
      RUN1(NPRBP-K)=AV(J)+FACD
      IF(RUN1(K).LT.0) RUN1(K)=0.0
 160  IF(RUN1(NPRBP+1).LT.0) RUN1(NPRBP+1)=0.0
      RUN1(NPH+1)=AV(J)
 170  CONTINUE
      DO 180 N=1,13
 180  RUNPP(N,J)=RUN1(N)
      CALL HAR(ETP,TEMP,NYEARS,AVT)
C *********** FORMATS TO WRITE DOWN THE VALUES******
      WRITE(2,310)NAME,LD,LDM,LG,LGM,ELEV,NYEARS
 310  FORMAT(1X,'STATION ',A12,' LAT',2I3,'   LONG',2I3,
```

```
     *  '   ELEV',F7.1,' M',I5,' YEARS')
        WRITE(2,510)
        WRITE(2,500)
        WRITE(2,320) (NAME1(J),J=1,14)
        WRITE(2,500)
320     FORMAT(3X,14A6)
        DO 330 N=1,13
          N1=14-N
          IF(MOD(N,5).EQ.0) WRITE(2,510)
          WRITE(2,340) PFREQ(N1),(RUNPP(N,J),J=1,13)
340       FORMAT(3X,14F6.0)
330     CONTINUE
        WRITE(2,510)
        WRITE(2,400) NAME2(1),(AV(J),J=1,13)

        WRITE(2,400) NAME2(2),(AVT(J),J=1,13)
        WRITE(2,400) NAME2(3),(ETP(J),J=1,13)
400     FORMAT(3X,A6,13F6.0)
        WRITE(2,500)
500     FORMAT(3X,84(1H*))
510     FORMAT(3X,84(1H ))
        STOP
        END
```

HAR

```
      SUBROUTINE HAR(ETP,TEMP,NYEARS,AVT)
C     THIS SUBROUTINE ESTIMATES ETP USING THE HARGREAVES FORMULA
C     DM=NUMBER OF DAYS IN A MONTH
C     ETP=POTENTIAL EVAPOTRANSPIRATION IN MM/MONTH
C     RMM=RS EXPRESSED IN EQUIVALENT MM/MONTH OF WATER EVAPORATION
C     RS=RADIATION AT THE EARTH'S SURFACE IN LANGLEYS/DAY
C     TF=TEMPERATURE IN DEGREES FAHRENHEIT
      DIMENSION ETP(13),TEMP(100,13),DM(12),RS(12),AVT(12)
      DATA RS/425.,505.,550.,585.,580.,560.,550.,510.,520.,
     *  485.,420.,410./
      DATA DM/31,29,31,30,31,30,31,31,30,31,30,31/
C     CALCULATE THE AVERAGE MONTHLY TEMPERATURE
      DO 10 J=1,12
        SUMT=0.0
        COUNTT=0.0
C     IF TEMP=990 DATA IS MISSING
      DO 20 I=1,NYEARS
      IF(TEMP(I,J).NE.990) THEN
        SUMT=SUMT+TEMP(I,J)
        COUNTT=COUNTT+1
      END IF
 20   CONTINUE
      AVT(J)=SUMT/COUNTT
 10   CONTINUE
C     CALCULATE DAY LENGTH & ETP FOR EACH MONTH
      DO 13 J=1,12
C     CALCULATE EQUIVELENT MM OF EVAPORATION BASED OF LATENT HEAT
      RMM=DM(J)*10.*RS(J)/(595.9-.55*AVT(J))
      TF=1.8*AVT(J)+32
      ETP(J)=.0075*RMM*TF
 13   CONTINUE
      DO 14 J=1,12
        SUM=SUM+ETP(J)
        TSUM=TSUM+AVT(J)
 14   CONTINUE
      ETP(13)=SUM
      AVT(13)=TSUM/12.
      RETURN
      END
```

Appendix E

Bibliography

Bolivian - Utah State/USAID Study Team. 1972. Irrigation analysis for selected crops. Santa Cruz, Bolivia. Utah State University, Logan, Utah.

Chow, Ven Te, editor-in-chief. 1964. Handbook of Applied Hydrology. McGraw-Hill, New York.

Dastane, N. G. 1974. FAO Irrigation and Drainage Paper 25: Effective Rainfall. FAO Rome.

Dunne, Thomas and Luna B. Leopold. 1978. Water in Environmental Planning. W. H. Freeman and Company, San Francisco.

FAO (Organization des Nations Unies pour L'Alimentation et L'Agriculture). 1979. Rapport sur le projet relatif aux zones agro-ecologiques, Vol. 1. Methodologie et resultats pour L'Afrique. Fao, Rome.

Gupta, S. C. and W. E. Larson. 1979. Estimating soil water retention characteristics from particle size distribution, organic matter persent, and bulk density. Water Resources Research, Vol. 15, No. 6, p. 1633-1635.

Haan, Charles T. 1979. Statistical methods in hydrology. Iowa State University Press, Ames, Iowa.

Hardee, James E. 1971. Analysis of Colombian precipitation to estimate irrigation requirements. Department of Agricultural and Irrigation Engineering, Utah State University, Logan, Utah.

Hargreaves, G. H. 1977. World water for agriculture (climate, precipitation probabilities and adequacies for rainfed agriculture). Utah State University, Logan, Utah.

Hargreaves, G. H. 1981a. Water requirements and man-induced climate change. Journal of the Irrigation and Drainage Div., Proceedings of the ASCE, Vol. 107, No. IR3, Sept. pp. 247-255.

Hargreaves, G. H. 1982a. Dependable precipitation and potential yields for Senegal: A practical guide for rainfed agriculture. International Irrigation Center. Utah State University, Logan, Utah.

Hargreaves, G. H. 1982b. Blaney-Criddle coefficients for Western Turf Grasses, Journal of the Irrigation and Drainage Division, Proceedings of Vol. 108, No. IR4, December, pp. 277-279.

Hargreaves, George H. and G. Leo Hargreaves. 1982. Irrigation scheduling and water management: A paper for the USCID ninth technical conference. Utah State University, Logan, Utah.

International Rice Research Institute. 1978. Irrigation policy and management in Southeast Asiz. Los Banos, Philippines.

James D. W. and R. K. Stutler (eds). 1982. On-farm water management research and demonstration in a tropical wet/dry climate. Research Bulletin No. 1, International irrigation Center, Utah State University, Logan, Utah.

James, L. Douglas and Robert R. Lee. 1971. Economics of water resources planning. McGraw-Hill, New York.

Jean, Frank C. and John E. Weaver. 1924. Root behavior and crop yield under irrigation. Carnegie Institution of Washington, Washington, D. C.

Litzenberger, Samual C., ed. 1974. Guide for field crops in the tropics and subtropics. Office of Agriculture Technical Assistance Bureau Agency for International Development Washington, D. C.

Ministere de la Cooperatation Republique Francaise. 1974. Memento de l'Agronome: Techniques rurales in Afrique. Ministere de la Cooperation. Paris, France.

Riley, J. Paul, Jay C. Andersen, A. Bruce Bishop, David S. Bowles, and John E. Keith. 1978. Cost allocation alternatives for the Senegal River Development Program. Utah Water Research Laboratory, Utah State University, Logan, Utah.

Sir Alexander Gibb and Partners. 1978. Global evaluation of the regional development programme (Global Study). Consulting Engineers, London.

Sogreah, Ingenieurs Conseils. 1972. Etude hydro-agricole du Bassin du Fleuve Senegal. Schema de principe detaille, casier pilote de Nianga, Frenoble, France.

Stern, Peter H. 1979. Small scale irrigation. International Irrigation Information Center. Ottawa, Canada.

Stewart, J. I, R. M. Hagan, W. O. Pruitt, R. J. Hanks, J. P. Riley, R. E. Danielson, W. T. Franklin, and E B. Jackson. 1977. Optimizing crop production through control of water and salinity levels in the soil. Utah Water Research Laboratory, Utah State University, Logan, Utah.

Vanegas, Jaime. 1977. Irrigation requirements for Peru from minimum data. Master's thesis, Dept. of Agricultural and Irrigation Engineering, Utan State University, Logan, Utah.

Vicente-Chandler, Jose, Ruben Caro-Costas, Robert W. Pearson, Fernando Abruna, Jacinto Figarella, and Servando Silva. 1964. The intensive management of tropical forages in Puerto Rico. University of Puerto Rico. Agricultural Experimental Station, Rio Piedras, puerto Rico.