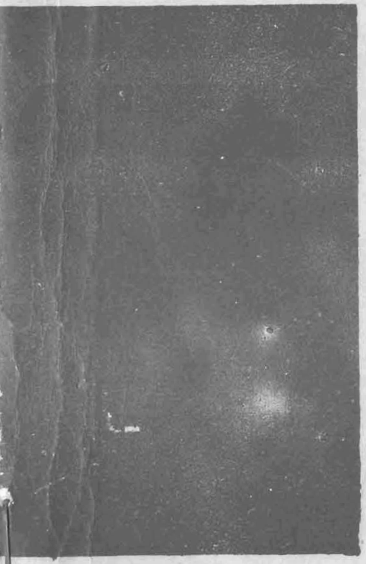
OBAFEMI AWOLOWO UNIVERSITY, ILE-IFE, NIGERIA

Inaugural Lecture Series 155



MAKING IT RAIN FOR HIGHER FARMER'S HARVEST

By

H. O. Fapohunda
Professor of Agricultural Engineering

OBAFEMI AWOLOWO UNIVERSITY PRESS LIMITED

H. O. Fapohunda
Professor of Agricultural Engineering

MAKING IT RAIN FOR HIGHER FARMER'S HARVEST

By

H. O. Fapohunda
Professor of Agricultural Engineering

An Inaugural Lecture Delivered at Oduduwa Hall, Obafemi Awolowo University, Ile-Ife on Tuesday, 14th May, 2002

Inaugural Lecture Series 155

Obafemi Awolowo University Press Limited, Ile-Ife, Nigeria.

ISSN 0189-7848

Printed by
Obafemi Awolowo University Press Limited,
Ile-Ife, Nigeria.

Introduction

Rain, a vital part of the hydrologic cycle, provides moisture necessary for plant and animal life. At an early point in the history of the preparation of the earth, *"God had not made it rain upon the earth"* but *"a mist would go up from the earth and it watered the entire surface of the ground."*(Genesis 2:5,6) The time referred to is evidently early on the third creative "day" before vegetation appeared. Obviously then, God is the source of the mist that would go up from the earth and watered the entire surface of the ground, a form of irrigation now often referred to as subsurface irrigation. It is also clear from the above Biblical quotation that before the existence of rain, God originated the first irrigation system. God did not stop at that, He also laid out and practiced the first surface irrigation system as evidenced from this quotation from the book of Genesis:

> *10 Now there was a river issuing out of E'den to water the garden, and from there it began to be parted and it became, as it were, four heads. 11 The first one's name is Pi'shon; it is the one encircling the entire land of Hav'i·lah,... ... 13 And the name of the second river is Gi'hon; it is the one encircling the entire land of Cush. 14 And the name of the third river is Hid'de·kel; it is the one going to the east of As·syr'i·a. And the fourth river is the Eu·phra'tes." (Genesis 2:10-11,13-14, New World Translation)*

The first instance in the Biblical record when rain is specifically mentioned as falling is in the account of the Flood. Then *"the floodgates of the heavens were opened,"* and *"the downpour upon the earth went on for forty days and forty nights,"* so says the Bible account at Genesis 7:11,12; 8:2.

Since these early accounts of rainfall and irrigation systems, man has only tried to mimic what God had originally instituted by developing various systems of irrigation for agricultural food production and other uses. In essence, irrigation is one of the oldest known agricultural technologies. Historically, civilizations have been dependent on the development of irrigated agriculture to provide the agrarian basis of a society and to enhance the security of the people. When the constraints of the complex soil-water-plant relationship were ignored either through ignorance or lack of planning, the productivity of irrigated agriculture declined. The ancient civilization of Mesopotamia flourished in the Tigris-Euphrates Valley 6000 years ago (Kang, 1972) and then floundered when the soil became saline due to poor irrigation practices and a lack of drainage. It has not recovered to this day.

When a reliable and suitable supply of water becomes available for agriculture it can result in vast improvements in agricultural production and assure economic returns to the grower. Effective agronomic practices must be included, such as fertilization and crop rotation. Soil reclamation and management, erosion control and drainage practices must be developed for the local conditions and applied rigorously. But water management, delivering water to the farms and on the farm itself, is the key to successful irrigation projects.

Irrigation, especially in arid areas of the world, has two primary objectives: (1) to supply the essential moisture for plant growth, which includes the transport of essential nutrients; and (2) to leach or dilute salts in the soil. Irrigation provides a number of side benefits, such as cooling the soil and the atmosphere to create a more favourable environment for plant growth. Irrigation supplements the supply of

water received from precipitation and other types of atmospheric water, floodwaters, and groundwater.

In view of the needs for irrigation—to increase food and fibre production with all the associated consequences to the stability of a society, as well as the potential for adverse environmental effects, the technology of irrigation is more complex than many nonprofessionals appreciate. It is important that the scope of irrigation engineering not be limited to diversion and conveyance systems, which has been the concern of the civil engineer, nor solely to the irrigated field, which has been the concern of agricultural engineers and agronomists. Thus, it is the "irrigation engineer" who attempts to integrate the delivery, farm, and drainage subsystems into a cohesive discipline.

Nature of Irrigation Systems

Irrigation involves the two broad categories of resources: natural (including physical and biological) and social. The physical resources include earth, air, energy and water. The biological resources include the plants and animals farmers grow plus the micro- and larger organisms that play essential and diverse roles in the food system. The social resources are also essential to irrigation and they include the capital for irrigated agricultural development, social institutions that help farmers do their job, human labour and skills, and the growing store of scientific and practical knowledge.

The anatomy of an irrigation scheme may consist of gigantic dams to impound and store water, large pumping plants and extensive canal or pipe systems to distribute water to the fields, and elaborate mechanized irrigation systems to apply the water to the land; or it may merely be a farm pond and a bucket. Thus, a functioning irrigation system, first of all, consists of an irrigator, his tools (requiring capital) and labour. An endless number of tradeoffs can be made between management, labour, capital and energy inputs; and through man's inventive genius numerous irrigation techniques have evolved.

The traditional method of irrigating by directing natural or controlled streams of water to the cropped area through basins or furrows is called gravity or flood irrigation. This method relies on the mental image in the mind of the irrigator plus his energy and skill in performing his art; the only tool involved may be a simple shovel-like implement. The irrigator's job requires deciding when and how much to irrigate (scheduling), planning how to move the water around plus physically coaxing it as uniformly as possible over the area being irrigated.

In contrast to the traditional irrigation system, there are completely automatic systems where the irrigator's job becomes when to punch the start and stop buttons (scheduling the irrigation); keeping energy supplied to the pump and drive systems; and servicing and maintaining the machinery and equipment. A professional service can be employed to make the scheduling decisions or the farmer can rely on moisture sensing instruments to turn the system on and off. Obviously, an irrigator with a mechanical system can handle a larger area, perhaps as much as 1000 times more, than an irrigator with a traditional system. Major advantages of mechanical systems over traditional systems include: ease of management; reduced labour requirements, less drudgery; less irrigation skill to operate efficiently, and more precise water application. Furthermore, mechanical systems can be made to operate effectively in sandy and hilly lands that are impractical to irrigate by traditional methods. Thus, through

innovative irrigation tools, the capacity to produce food could be expanded.

Centre pivot systems are the most extensively used fully automatic irrigation tools and to me the most fascinating. They travel in a circle and irrigate large areas up to 1.6 kilometer in diameter covering up to 200 hectares. They can operate continuously without interruption or attention because the circular path has no end. Splinter (1976) nicely described the centre pivot irrigation as follows: A centre-pivot system consists of a row of sprinklers mounted on a pipe that is in turn supported over the crop by mobile towers. Water is pumped into the pipe from a source at the centre of the field, and the towers which, are mounted on wheels carry the pipe around the fixed pivot point. The rate at which the towers and pipe advance is set by the speed of the outer-most tower, and alignment devices at each inner tower detect any laggards and move each tower to line up with the one beyond it. Irrigation engineers tailor the centre pivot for a given site. A number of the centre pivot systems are in operation in the Kano River Irrigation Project.

Trickle irrigation is another ingenious innovation that can be fully automated and used under adverse land and water conditions. It is a low pressure system that applies water in small amounts, literally, drop by drop. The system consists of small diameter plastic tubing laid on the surface of the field alongside the plants. Water is delivered to the plants slowly but frequently from holes or special emitters located at appropriate points along the tubes. There are also more elaborate emitters, some of which have the ability to regulate their own discharge and/or automatically flush themselves. Since trickle irrigation slowly and frequently supplies precise amounts of water, the soil-water content in the plant root zone remains relatively constant; hence the plants grow without water stress in an environment of favourable moisture. This results in fast uniform growth and yield. Another advantage of trickle irrigation is its ability to make maximum beneficial use of available water. With trickle irrigation, the parts of the field that are between the rows of plants remain dry so that little water is lost to evaporation, runoff, wind drift, or deep percolation. Plants use as much water as with other methods, but with trickle irrigation, losses are minimized. The result is irrigation efficiencies from 80 to 95 percent as compared with 60 to 85 percent for sprinkle irrigation and 40 to 80 percent for surface irrigation.

Development of Irrigated Land

The development of irrigated lands has paralleled increases in world population. Shmueli (1973) estimated that less than 10 million hectares (ha) were irrigated in 1800 and about 40 million ha were irrigated in 1900. By 1950 the irrigated land had increased to about 160 million ha and in 1969 to about 200 million ha. The FAO of the UN (FAO, 1977) estimated that the total global irrigated area was 223 million hectares and that this would increase to about 273 million hectares by 1990. The FAO (1979) estimated irrigated agriculture to be only 13 percent of the global arable land, but the value of crop production is 34 percent of the world total. These data clearly indicate the role managing water resources (irrigation) plays in agricultural production today, as well as its future role.

The world population, on the other hand, was two billion in 1930 and by 1960, it had reached three billion. In 1976, it had doubled the 1930 level, reaching four billion. World population actually reached 6 billion in year 2000. The African population reached about 514

million in 1986 with Nigeria accounting for 17% of the total population. The population has since been growing at an average rate of 3 percent (FAO, 1987). More food and fibre would have to be provided. An estimated 86 million ha throughout the world now need improvement of both the main and on-farm systems for distributing and applying irrigation water. The FAO estimate for 1990 in the developing countries of Africa, Latin America, the Near East and Asia was 22 million ha of new irrigated land and 45 million ha would need improvement. The costs of making these improvements and developing new irrigated lands would naturally be high. FAO (1977) suggests that one way to decrease these costs is by developing national facilities and skills to reduce the dependence on imported expertise, equipment and materials.

The African Continent covers a total area of 2817 million hectares of which some 9 million hectares (0.032%) are irrigated. Over six million of these, or about 70 percent are located in four countries, namely: Egypt (2.7 million ha), Sudan (1.75 million ha), Madagascar (0.96 million ha), and Nigeria (0.85 million ha). It is not as if Africa does not know the contribution of irrigation to agricultural production. The report by FAO (1987) indicates that the total value of the 1979-80 agricultural production on 124 million hectares of cultivated land in 43 countries of Africa was US$ 36.851 billion (excluding fodder crops). The contribution of irrigation to the total production is given in Table 1 below:

Table 1: Total area under rainfed and irrigated agriculture and production values. (1979-80, 43 countries)

	Area (million ha)	% of cultivated area	Productive value (billion US$)	% of value
Rainfed* **	116	93.5	29.376	80
Irrigated*	8	6.5	7.475	20
Total cultivated area	124	100	36.851	100

*including natural flooding, **excluding fodder crops

Table 1 shows that the area under irrigation represents 6½% of the total cultivated area but 20% in terms of total production value. Also, the production value of an irrigated hectare is about 3½ times that of a rainfed hectare. Despite all the advantages of irrigation, Africa's and indeed, Nigeria's agriculture remains predominantly rainfed.

Irrigation Development in Nigeria

The first recorded survey of irrigation potential in Nigeria has been traced back to the early 1900's, when Colonel Collins, a military engineer, undertook work in the Sokoto-Rima and Zamfara valley systems (Nwa and Martins, 1982). The first Irrigation Division in Nigeria was established in 1949 in the Ministry of Agriculture of the then Northern Region. The activities of this Division were confined to small-scale irrigation schemes. The FAO Report (1965), commissioned by the Federal Government, which deals with the perspectives for agricultural development in Nigeria up to 1980 can be considered the watershed in water resources and irrigation development in the country. Also, the 1975-80 Third National Development Plan (Federal Republic of Nigeria, 1975) has brought a coherent irrigation development plan to Nigeria. The Federal Ministry

of Water Resources, which is responsible for irrigation development in the country, was established during this period.

It is noteworthy also that the setting up of the River Basin Development Authorities (RBDAs) between 1973 and 1976 was a milestone in the development of irrigation in Nigeria. It indicated the commitment of Government and formed the basis for organized irrigation development in the country. In 1976, the Federal Government divided the whole country into eleven 'River Basins.' Ten of these basins were established by Decree No. 25 of 15th June, 1976 while the 11th, the Niger Delta Basin Development Authority was established by Decree No. 37 of 3rd August, 1976. The continued existence of these River Basin Development Authorities was re-confirmed by Decree No. 87 of 28th September, 1979 (Federal Republic of Nigeria, 1979). Among the many functions of each Authority are:

(a) To undertake comprehensive development of both surface and underground water resources for multi-purpose use.

(b) To undertake schemes for the control of floods and erosion and for watershed management including afforestation.

(c) To construct and maintain dams, dykes, polders, wells, bore-holes, irrigation and drainage systems and other works necessary for the achievement of the Authority's functions under this section.

(d) To provide water from reservoirs and lakes under the control of the Authority for irrigation purposes to farmers and recognized associations as well as for urban water supply schemes for a fee to be determined by the Authority concerned, with the approval of the Commissioner.

With the establishment of the RBDAs, it is assumed clear that the importance of irrigation development for food and fibre production is no longer an issue in Nigeria. The issue, however, is how to sustain irrigated agriculture for the permanent benefit of the Nigerian population. So, it might be a desirable effort to look at the past and present performance of irrigation in Nigeria. By the end of December 1980, when the RBDAs were just about taking off, the area of land being irrigated in Nigeria was 30,706 hectares, excluding areas being irrigated by the shadoof, pump-hire and other small systems. Out of this area, 15,596 hectares was actually being irrigated by the RBDAs, the rest by the States. In a survey of the then six Northern States, it was found that a total of 5,540 ha were irrigated by the shadoof, 2,370 ha by small pumps and 8,150 ha by other means such as buckets, calabashes and blocking of small streams. In essence, the total land area under formal, informal and traditional irrigation in Nigeria by the end of 1980 was estimated to be 46,766 hectares (Nwa and Martins. 1982).

Musa (2001), in an overview of irrigation and drainage development in Nigeria, presented the current status and features of irrigated agriculture in Nigeria (Table 2). A quick look at Table 2 shows that the irrigated land area is 3.6% of the total crop coverage, implying that more than 96% of Nigeria's agriculture is rain-fed. As if this is not bad enough, only 15% of the irrigated area is under formal (modern) irrigation, while 71% is under traditional irrigation systems. (*See footenote to Table 2 for definitions of modern and traditional irrigations).* It is not as if government is unaware of the importance of irrigation development for food and fibre production. The Third National Development Plan (Federal Republic of Nigeria, 1975)

proposed to put about 2 million ha of land under formal irrigation during the 1980 - 85 development plan period and beyond.

Table 2. Features of Irrigated Agriculture in Nigeria

Total land area	98.3 million ha	-
Cultivable area	73 million ha	4% of total land area
Crop coverage	25 million ha	34% of cultivable area
Irrigated area	0.9 million ha	3.6% of crop coverage
Area under formal (modern) irrigation[1]	100,300 ha	15% of irrigated area
Area under informal irrigation	100,000 ha	14% of irrigated area
Traditional irrigation	755,000 ha	71% of irrigated area

[1]Irrigation practice in Nigeria are classified into three main categories: public irrigation projects which under government control (formal irrigation), farmer owned and operated irrigation projects (informal irrigation) which receives assistance of government in form of subsidies and training, and the residual fadamas (traditional irrigation) where no government aid is supplied. (Adapted from Musa, 2001)

But this was not to be since even the relatively small areas under formal irrigation were bedeviled by some problems including declining yields, groundwater and salinity problems, poor operation and maintenance, and low returns on investment, among others. In recent years, it has been recognized that the rate of expansion of the irrigated areas has been very slow and some of the identified problems and other issues affecting irrigation development have come under intense discussion. But, the question still remains: "Which way forward, Nigeria, in irrigation development?" Nwa (1991) in an attempt to find an answer to this question suggested as follows: *"To derive the full benefit from irrigated agriculture, it is recommended that Nigeria should establish and maintain a definite rate of expansion of its irrigated land until a reasonable area has been developed. The* *benefits from irrigation should be sustained for posterity through monitoring of projects, research, and open scientific debate and discussion."*

One of the duties of universities and research institutes is to carry out research and subject their findings to peer scrutiny and even to open scientific debate and discussion. Suffice to say that our University has not lagged behind in carrying out this duty. Nwa and Pradham (1993) identified six important areas requiring priority research attention in irrigation as: irrigation performance assessment, economics of irrigation, irrigation technology, institutional framework for irrigation development and management, environmental impact of irrigation, and sociology of irrigation. My research work in this University has largely been in one of these priority areas --irrigation technology and agricultural water management. Specifically, this involves evapo-transpiration modeling, water quality improvement for irrigation, crop seedling emergence as related to soil and water factors, developing crop yield-water use relations for some common Nigerian field crops (e.g., maize, cowpea, etc.), river basin irrigation (quantity and quality) modeling and computer-aided designs of irrigation systems.

Irrigation (On-Farm Water Management) Research at O.A.U.

The Department of Agricultural Engineering of this University started out as a sub-department of Plant Science in October 1968 and was finally established in 1971. At that time and in the 1970s, the Department concentrated its research activities on the development of farm power and machinery and produced such machines as the portable grain planter, cassava stem-cutting planter, cassava root digger and kenaf decorticator (Makanjuola, 1977). I can boldly say that I was part of this early development since my final year B.Sc.

project in June 1972 was 'A study of some of the physical properties of cassava in relation to mechanical harvesting" under the supervision of Professor G. A. Makanjuola. When I became a graduate assistant in the department in October 1972, my focus for further studies changed from agricultural mechanization to soil and water engineering, largely because of the influence of Dr. A. A. Abiodun, who was then the only lecturer in soil and water engineering area of research. When I came back to the department in July 1980 after a period of study leave, Dr. Abiodun had left leaving an expatriate, Mr. M. M. Hossain as the only permanent staff in soil and water engineering. There was no visible on-going research in this area too. What do I do? Where do I begin? Those were the questions agitating my mind.

Even though I had written and submitted one article in a reputable international journal back in the United States (Fapohunda and Hill, 1981), I still did not know where to start under the Nigerian situation staring me on the face. Then Professor M. O. Ogedengbe came calling, he must have probably seen my dilemma. 'What have I got in common with him? I thought.' I considered him an urban water supply and sanitary engineer, a civil engineer getting ready to start a new Civil Engineering Department. He then reminded me that as an Irrigation Engineer, I should also be concerned with the quality of irrigation water to apply to crops. I could not agree any less. He also knew that I was armed with a Salinity Conductivity Temperature (S-C-T) meter used on my Ph.D work. He then suggested a case study of Ona River in Ibadan involving an interplay of data collection, analysis and dialogue with officials of industries involved in dumping effluents into the river. This study (Ogedengbe et al., 1984) suggested a possible solution to pollution problems on our streams through voluntary action by industries and gentle persuasion by public-spirited individuals or groups. The officials showed active interest in an effort to clean up the stream. This single paper was an eye-opener, it showed me the way to conducting a simple, meaningful research at the inception of my research career. It proffered solutions to almost all my teething problems, and I wish to say "A Big Thank You" to Professor M. O. Ogedengbe.

Later, a similar study on water quality improvement for irrigation was conducted closer home. Mr. Adelakun, and an undergraduate student working under my supervision, evaluated the suitability of sewage effluents from Obafemi Awolowo University oxidation pond for irrigation purposes in dry, early-rainy and mid-rainy seasons. The results showed that the effluents were suitable for irrigation all the year round except that some management for salinity control would be needed in the dry season (Adekalu, et al., (1993). The effluents are best suited to crops with good salt tolerance and soils with unrestricted drainage.

i. Evapotranspiration Modeling

Most ET models are based on physical principles controlling evaporation and the conservation of mass and energy, and use daily climatic data. Knowledge of evapotranspiration (ET) is necessary in the development, management and utilization of water resources with particular reference to seasonal and peak water requirements for irrigation.

My work on potential evapotranspiration (ETp) was borne out of necessity. Early in my research work, I needed to determine evapotranspiration for use in the determination of water requirements of crops. Most of the existing models were developed in and for the temperate countries. Most of them are not predicting ETp accurately

well enough in the tropics and where they fairly do, the data requirements are many and varied. Sophisticated equipment, the type available only in top class agro-meteorological stations, are required for data collection. Such ETp models (like Penman, Jensen-Haise equations, etc.) require fast-speed computers to bring out results quickly. So, there was the need to develop a simple and accurate ETp model from existing models using local weather data.. The Blaney-Criddle equation (USDA-SCS, 1970) was found to be a good model for adjustment since in its original form, it is simple and has low data requirements (only air temperature and sunshine hours). But, it does not predict well in the hot, humid to arid tropical regions since it over-estimates ETp in the rainy season and under-estimates it in the dry season. From 1980 onward, several students were assigned different locations especially in southern Nigeria to collect meteorological data—temperature (maximum and minimum), relative humidity, wind speed, sunshine hours, rainfall, class A pan evaporation, etc.—in order to come up with an accurate ETp model for the Tropics. The result of these preliminary efforts resulted in the publication of the work by Fapohunda and Isedu (1984). We felt we had not yet arrived at the final model for determining potential evapotranspiration.

About this time, Duru (1984) published the Blaney-Morin-Nigeria evapotranspiration model based on Nigerian climatological data. The model had the problem of being cumbersome because it depended on estimating a radiation ratio that was somewhat difficult to come by at that time. The author later produced a table of radiation ratios based on latitude and time of the year. Meanwhile, a graduate student was assigned to harness all the available data and he extended his data collection coverage to the entire country. This effort resulted in the 'adjusted Blaney-Criddle' model (Fapohunda and Ude, 1992), which retains the simplicity and low data requirements of the original equation and predicts ETp with satisfactory accuracy. The equation has been found useful in the Tropics.

It was necessary to see how the 'adjusted Blaney-Criddle' equation compared with such models as the 'Blaney-Morin-Nigeria' equation (Duru, 1984), the FAO equation (Doorenbos and Pruitt, 1977) and others. Ten methods of estimating potential evapotranspiration (ETp) were compared with pan ETp method using monthly climatological data collected from agro-climatological stations distributed over four climatic regions of Nigeria. The temperature and humidity methods approximate pan ETp very well in the regions. An adjusted 'modified Blaney-Criddle' equation (Fapohunda, 1995) approximates best in three of the regions, while, the Blaney-Criddle equation (FAO version) performs best in the high plateaux. It appeared quite plausible at this moment to commence work on crop-yield water-use relations, but not until a closer look is taken on those factors affecting crop seedling emergence.

ii. Crop Emergence as related to Soils and Irrigation

The physical resistance of soil to the growing seedling is a considerable factor in crop production as it affects the establishment of a uniform crop stand of a desired density and subsequent plant development. Soil parameters known to influence mechanical impedance include texture, bulk density, and moisture content. It has also been found that method of soil watering during irrigation, the type of crop (monocot or dicot) also affect emergence. Soil strength appears to be a critical impedance factor that is commonly used to relate mechanical impedance to seedling emergence. Excessive surface crust strength often decreases or prevents emergence of crops. Soil strength is usually estimated by

measuring penetration resistance of soil to a probe or penetrometer. Sometimes, the modulus of rupture of soil briquets is used as a measure of soil strength.

The effect of soil compaction, which commonly results from cultural practices of crop production, on seedling emergence is noted through the changes in soil strength. Normally, soil strength and impedance of emerging seedlings increase with bulk density, the relationship is however not a simple one but depends on soil type and interactions of bulk density and soil water content. In the tropics, soils have predominantly weak structure that deteriorates rapidly as a result of cultivation or increased use of farm machinery in cultural operations. This physical condition enhances compaction and poor physical regimes that may mechanically resist seedling emergence. Mulches that cover part or the entire soil surface generally reduce crust strength. Mulches reduce evaporation and maintain higher water content at the soil surface. Higher water contents reduce crust strength of most soils.

We have made some modest contributions in the study of crop seedling emergence as affected by soil physical properties and methods of wetting. Fapohunda *et al.* (1985) established a relationship between soil strength and maize seedling emergence under exposure to different heat or drying duration. The study indicated that as soil strength increases, emergence decreases until it ceases at soil strengths of about 80 kPa. It also emphasized the type of water management practices (e.g., *mulching, wetting just before emergence, etc.*) that could be carried out to obtain good stands of maize at emergence. In general, this knowledge enhances suitable soil management aimed at limiting soil impedance and encouraging optimum crop production. Aina *et al.* (1985) found that the general relation of seedling emergence to bulk density and moisture suction was partially attributed to soil strength. The results of the study are useful in indicating what level of compaction and water suction can be expected to adversely affect seedling emergence in the soils commonly encountered under bush fallow and different stages of cultivation across south-western Nigeria. Fapohunda (1986) found that rapid wetting of soils by flooding resulted in strong crust formation, which, on drying, restricted seedling emergence; whereas, wetting by trickle or furrow method did not saturate the soil above the seed, and more seedlings emerged. The study further indicated that the type of crop and its mode of emergence are important factors for consideration in crop emergence.

iii. Crop Yield and Water-Use Relationships

The single most important factor that influence crop yields from one location to another, or from one year to the next, is moisture availability. A better understanding of how water influences yields are essential for maximizing yields through water management practices. The design of irrigation systems, land allocation, etc., depends on knowledge or estimate of the amount of water required to produce a given crop. Since agriculture in Nigeria is mostly rain-fed, there is dearth of data on water requirements and water use of a number of crops, which often become water-stressed resulting in low yields.

We have carried out most of our fieldwork on the subject of crop yield-water use relations, and sprinkler irrigation forms the basis of these studies. By definition, sprinkler irrigation is the application of water in a system that uses pressure energy to form and distribute "rainlike" droplets over the land surface. I have therefore chosen the topic of this lecture with this definition in mind. Two methods of determining crop yield - water use relationships with the sprinkler method have been

made popular in recent times. These are the point and line source sprinkler systems. These methods are adopted in order to obtain variable water use and crop yield data.

The point source sprinkler system consists of a single sprinkler, with 4.76-mm by 2.38-mm, 7° slotted nozzles, placed in the centre of a circular plot, 30 m in diameter (Figure 1). A control valve is connected on each lateral pipe and a riser keeps the sprinkler head well above the crop canopy.

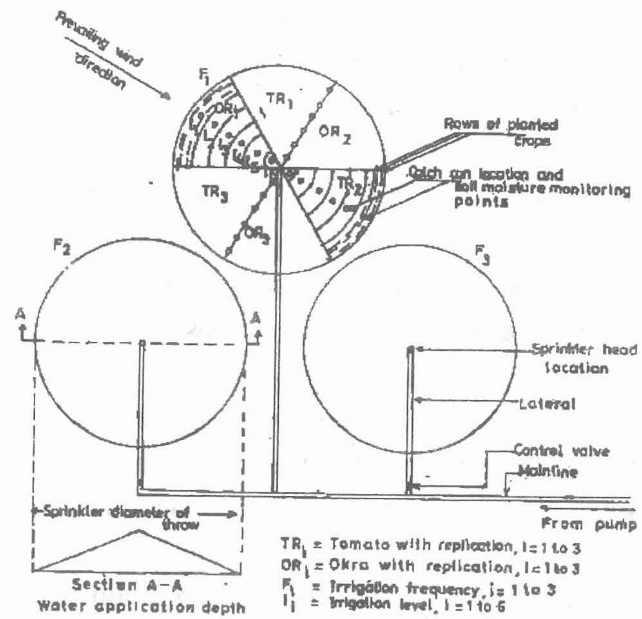


Fig. 1: Schematic diagram of the point source sprinkler system.

Operating pressure is maintained at 3-bar pressure at the sprinkler during irrigation and this produces a wetted radius of about 15-m and a cone-shaped water distribution pattern (section A-A). Two rows of catch cans for collecting rainfall and irrigation amounts are placed one parallel and the other perpendicular to the prevailing wind direction. The catch cans are located at equal distances away from the sprinkler on each of the four radial lines depending on the number of irrigation levels desired. The average value of four collector cans at the same distance from a sprinkler head is accumulated over the entire growing season to compute the irrigation depth constituting an irrigation level. In the set-up of Figure 1, there are six irrigation levels. Each circular plot is divided into r × c segments depending on the number of replicate (r) and crops (c) grown.

All cultural operations—cultivation, fertilizer application, weed, pest and disease control, etc.--are carried out on each circular plot. Harvested crop yields are measured per irrigation level and production functions of yield versus water use can be easily measured.

Fapohunda *et al.* (1984) used the point source sprinkler system to generate data of water use as related to cowpea and maize yields. The study shows that grain and dry matter yields increase with increases in water use up to a point where applied water matches the evapotranspiration values calculated from climatological data. Irrigating beyond this point, cowpea and maize yields are depressed by over-irrigation. The study thus pinpoints the amount of water to apply for optimum cowpea and maize production while other inputs are held at their optimum levels. Another study (Fapohunda, 1992) evaluated the effects of irrigation frequency and amount on yields of okra and

tomato. Okra produced the highest yield at the 4-day irrigation frequency while the highest tomato yields produced at the 4- and 8-day intervals were about the same. The point source sprinkler system was found to be a reliable and convenient method for generating crop yield-water use data.

Crop production surfaces as influenced by water and fertility levels are needed for many analyses to relate economic return to soil and water management practices. Accurate water control is necessary to produce the numerous water levels required to generate the desired production surface. The line source sprinkler system has been used to achieve this high degree of water control. The system consists of a single line of sprinklers down the centre of the test plot. The system produces a water application pattern which is uniform along the length of the plot and continuously but uniformly variable across the plot. Figure 2 shows a schematic layout of the line source sprinkler plot design. Adding more sprinklers can increase the length of the plot. However, the width of the plot is governed by the wetted diameters of the sprinklers. To obtain the "line source" effect, sprinklers should be spaced as closely as practicable on the water supply line with the spacing not exceeding 25% of the wetted diameter. Furthermore, the individual sprinklers should produce a triangular shaped profile when operated in low winds at the design pressure.

By this arrangement, the maximum rate of water application occurs nearest to the sprinkler line and reduces approximately linearly to zero at about 15-m laterally from the supply line.

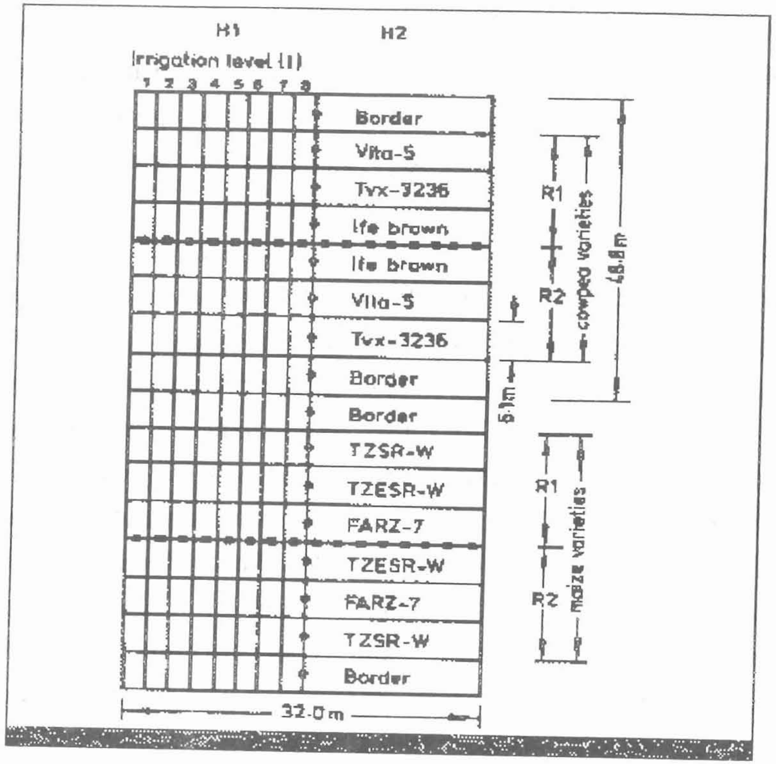


Fig. 2. Schematic diagram of the line source sprinkler irrigated test plot. (From Fapohunda, 1985)

Crop rows are usually laid parallel to the supply line on both sides and a number of rows (2 – 4) constitute an irrigation level depending on the standard spacing of the test crop. The number of irrigation levels on either side of the supply line depends on the width of each level and the wetted radius of the sprinklers. By applying a fertility variable along a plot (at right angles to the water variable), the system offers a convenient means for developing crop production function data which relate crop yield responses to water, fertilizer and water-fertilizer interactions. These functions are useful to engineers, economists, agronomists and planners who want to know or estimate the amount of water and probably, fertilizer required to produce a given crop.

Fapohunda (1985) used sixteen sprinklers in a line source experiment to generate maize and cowpea grain and dry matter yields under different irrigation regimes. The study shows that there are significant differences in maize and cowpea cultivars as to their yield responses to varying levels of water application. More general, transferable functions are developed for grain and dry matter yields of maize and cowpea in relation to water use. Fapohunda and Hossain (1990) took an in-depth look into the effects of water-fertilizer interactions on maize grain and dry matter yields. The study showed that even with high fertilization and optimum amounts of other growth inputs, maize yields could still be depressed if water (soil moisture) is inadequate. Maize response surfaces were generated which are useful for computing maize yields as functions of water and fertilizer inputs. A similar study (Fapohunda and Adekalu, 1995) evaluated cowpea yield response to water and fertilizer. Figures 3 and 4 show sample outputs from these studies. Figure 3 indicates the relative grain yield of maize (left) and relative dry matter (right) as influenced by relative ET (one variable), thus producing linear relationships. Figure 4 shows cowpea seed yield (left) and dry matter yield (right) as influenced by fertilizer and applied water (two variables), thus showing cowpea yield response surfaces to these variables. Production functions are presented in graphic and algebraic forms in terms of relative yield and relative net or gross water applications. The use of relative rather than absolute values offers a simple way of presenting data from different locations and years in a uniform manner and making them comparable and probably transferable. The maximum value of each parameter--yield, water or fertilizer applied--in each experiment was considered as 100% and all other values are related to this. Other contributions using the line source sprinkler irrigator include Aina and Fapohunda (1986), and Akinyemiju et al. (1990).

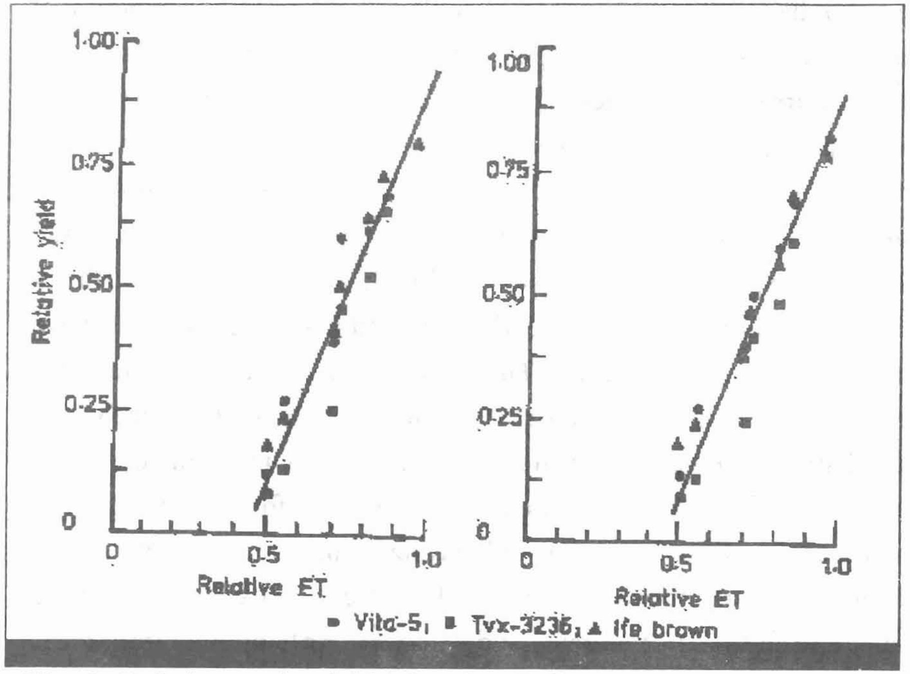


Fig. 3. Relative grain yield of maize (left) and relative dry matter (right) as influenced by relative ET (one variable). (From Fapohunda, 1985)

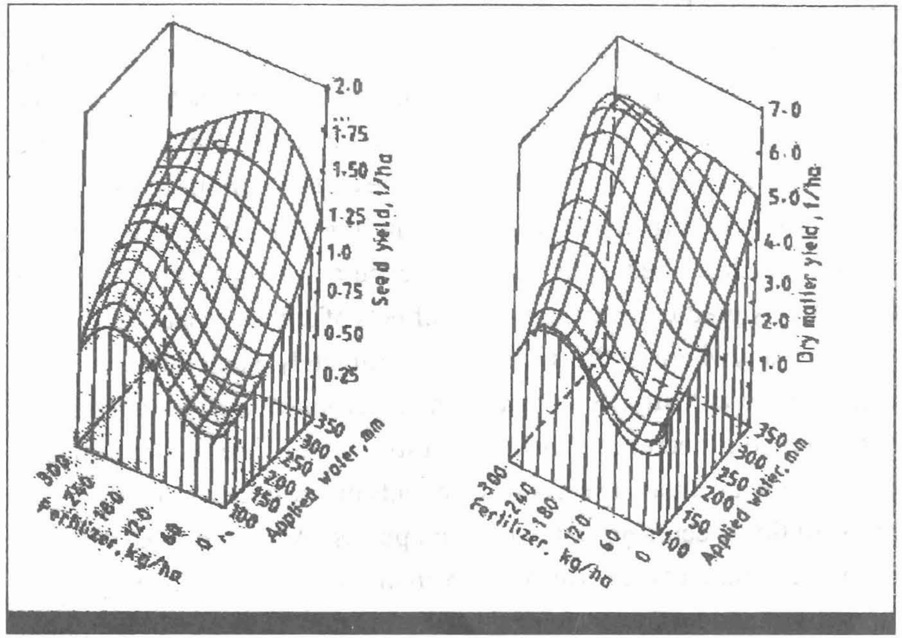


Fig. 4. Cowpea seed yield (left) and dry matter yield (right) as influenced by fertilizer and applied water (two variables). (From Fapohunda and Adekalu, 1995)

Because many of the production functions are site specific and the analyses are statistical in nature, recent research efforts have been directed towards better physically-oriented, simple models to predict crop yields from crop, soil, and climatic data. This has led to crop yield simulations on the computer using the results of field studies carried out earlier. More importantly, when my field activity was suddenly put on hold due to a physical disability, I had to look elsewhere to continue my research work. Fortunately, my prior knowledge in computer programming and simulations became readily useful.

iv. River Basin Irrigation Modeling

The increasing use of water for irrigation, industry, and municipal water supplies has led to an increasing need for careful planning for the usable water resources. Efficiency in water use requires skilled planning and careful management of water. Efficient use considerations in a dynamic system such as a river basin implies that the physical and economic systems be described with sufficient accuracy to quantitatively and qualitatively predict the system-wide effects of depletions resulting from water use anywhere in the system. Unfortunately, such depletions for irrigation and industry concentrates and adds non-degradable substances that produce a decrease of water quality. Thus, in every hydrologic system, each upstream use has some effects on the quantity, quality, and timing of flow occurring at downstream points. An accurate assessment of the net benefits of various upstream changes or management alternatives can lead to increased use and better efficiency of available water resources within the basin. An appropriate description of a water resource system, therefore, includes the hydrologic, salinity and economic flows systems, and those functions that relate them.

River basin hydrologic and salinity flow systems were usually analyzed independently. Fapohunda and Hill (1981) combined the two flow systems with an economic system to form a single working model that can predict management effects of sequential water use in a river basin. Figure 5 presents a schematic diagram of how the hydrologic-economic and salinity-economic systems are linked together by crop production and crop salt tolerance functions, respectively. The connecting links of the flow systems in an agricultural enterprise are dependent upon such factors as water availability (supply), water requirements (demand), and salinity levels of irrigation water and soil solution, crop salt tolerance level, and production per unit of water consumed. Other factors affecting production in agriculture—capital, labour, crop variety,

weather, soil type and fertility, etc.—are assumed kept at their optimum levels in the model.

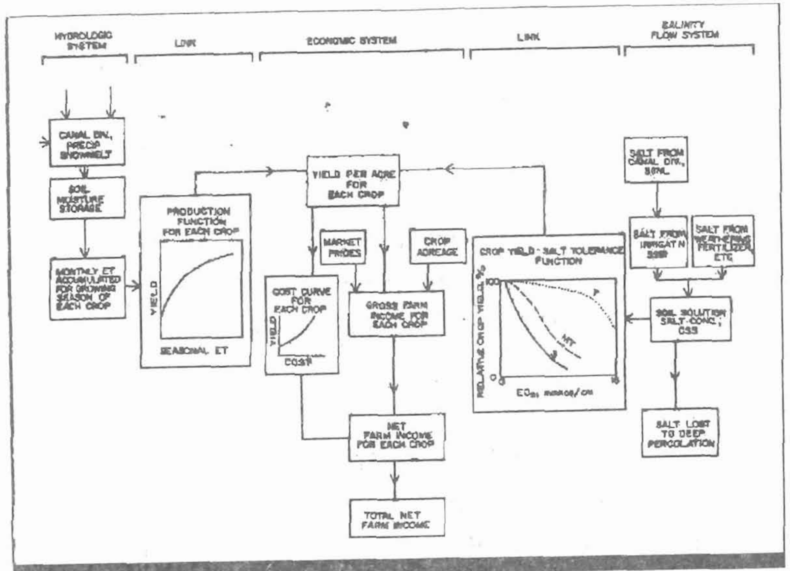


Fig. 5. Production function as link between hydrologic-economic systems and crop salt tolerance function as link between salinity-economic systems [From Fapohunda and Hill, 1981]

The model of Fapohunda and Hill (1981) on river basin hydro-salinity-economic modeling formed the basis for further work. Fapohunda (1981) reviewed and appraised the hydrologic models employed in the planning and development of water resource projects in Nigeria, and suggested a more detailed and comprehensive computer simulation model to appropriately describe the various complex processes within a river basin. Fapohunda (1990) in his study of an economic simulation of agricultural water use within a river basin, found that the amount of water available for plant use and its associated quality level are some of the critical factors determining crop growth and yield. This study defines the relationship of water and its quality to crop yield. It uses the concept of marginal values to evaluate irrigation water for competitive uses among agricultural sub-users within a river basin. The study provides an approach for an efficient allocation of water to specific cropping patterns through an economic simulation process. Alatise and Fapohunda (1999) incorporated an optimally allocated crop area into the model of Fapohunda and Hill (1981) using a linear programming package. The modified model was tested on Osun river basin as a case study. The management options tried showed that crop yield decreased substantially with a decrease in water supply, while increasing crop area did not result in any increase in yield. However, increase in salt concentration gave a remarkable decrease in crop yield.

v. Computer-Aided Irrigation Systems Design

Our latest efforts have been directed at the computer-aided designs of trickle, sprinkler and surface irrigation systems. In the past, a lot of time was usually spent on hand computations of different parameters involved in these designs. Some of these calculations were often tedious, rigorous and repetitious. However, the analysis and solution of the problems in irrigation and drainage have advanced at an increased rate since the advent of the high-speed electronic computers. The growing sophistication of computing machinery has not only made possible the rapid and accurate calculations of the complex parameters, it has also been a catalytic factor in the evolution of several mathematical theories and methods developed in the field of water resources in recent times. However, a computer would carry out instructions and give accurate results only if it has been programmed to do so.

We have, therefore, taken advantage of the existence of electronic computers to make our modest contributions in cost comparisons of different sprinkler irrigation systems (Osunbitan and Fapohunda, 1998), in the development of a computer algorithm for the solid set/set-move sprinkler irrigation system (Osunbitan and Fapohunda, 2000a), modeling of pressure variation along the lateral of a center pivot irrigation system (Osunbitan and Fapohunda, 2000b), and computer-aided sprinkler pipe size selection based on pressure and economic criteria (Osunbitan and Fapohunda, 2000c),. Over the years, a number of undergraduate students have developed computer programs that help in the designs of trickle and surface irrigation systems, design of vegetated waterways for erosion control and safe removal of runoff water from irrigated lands. We have also developed a computer package for land leveling calculations for regular and irregular fields. The package determines the equation for the plane of best-fit, estimates the earthwork volumes and cut-fill ratio for the field using the four-point method. These programs are available on request from our department.

Holistic Thinking and Irrigation Technologies

In recent times, one often hears of "appropriate technology," "sustainable irrigation," etc. and depending on your field of endeavour, these appellations have no bound. In essence, the selection and appropriateness of irrigation technologies are usually in view but seldom in clear focus because the question of appropriateness involves many fields of thought such as faith, philosophy, economics, finance, politics, history, expediency, science and engineering. Others have even talked of small-scale, intermediate or large-scale irrigation technologies. My concern is that in using these terms, we stand the risk of limiting our perspectives and understanding of what irrigation technology is all about. The question of what is or is not appropriate varies from country to country or even from region to region while the scale of the technology is a third variable. It is important, therefore, to spend time to think about our country or region and assimilate its standards and culture, in order to identify what really is appropriate.

The various irrigation systems have evolved in such a manner that the social, political, and management needs of each type of system have been taken for granted. Whatever the system, the primary function of irrigation is to provide water to the root zone in proper quantities at appropriate times, the crux of this deceptively simple statement is the words "proper" and "appropriate." The objective, however, is to utilize available water resources effectively for crop production without detriment to other social or economic goals. Whereas irrigation principles may be reasonably understood and universally applicable, their use is strongly specific to the situation. Generally, the use must match the physical, social and economic factors on the farm and also find a compromise among objectives within a societal framework. Sometimes, technological and management options are at hand; at other times, innovative or new methods must be devised.

Historically, irrigation project development throughout the world has seldom produced the returns envisioned by planners. This is especially true with projects in developing countries involving peasant farmers; and one often hears that the projects and farm irrigation systems were properly selected and beautifully designed; but the "people" failed to make them work. In short, one is hard-pressed to find many projects that come close to reaching the projected time schedule. This problem arises in part, at least, from the belief that a good physical irrigation system is synonymous with good irrigation, when it is very easy to have poor or essentially no irrigation with a good system, and it is even

possible to have good irrigation with a poor system. Thus, this confusion between the physical irrigation system and the activity of irrigation leads to the disappointing results in irrigation project implementation. Often, the activity of irrigation is taken too much for granted once the physical system has been developed. Whereas, what we need to do is to develop irrigation techniques that are congruent with existing levels of technology and farmer practices. For example, where labour intensive agriculture is practiced, it may not be appropriate to replace the irrigator with machines, and in such cases, planners must select irrigation techniques which have a reasonable chance of being productive without abruptly replacing labour with capital intensive machinery. In addition, the training needed for successful operation and maintenance of the system must be incorporated into the development procedure.

In order to achieve these results, the social context within which development is to occur has to be taken into account. Adams, et al. (1979) suggests that the best way to do this is to involve the farmers in the planning process. This can promote project success in several ways. First, it provides the developers with better insight into peasant agricultural needs and concerns. At the same time, it allows planners to tap the knowledge the farmers have developed through many years of experience in the project area. It is true that Nigeria's experience in modern irrigation technology is relatively recent, what is being preached is that project planning must start with and carry along the "people" who would be the end users. People's involvement can also increase their commitment to new practices, and finally, it can be used to create sufficient understanding of the project for peasant farmers to make further improvement as needed.

Much of the technology that is being promoted to improve the effectiveness of irrigation throughout the world was instigated in the developed nations. This technology reflects the energy and monetary economics as well as the type of people in the areas where it originated. Often alternate technologies, which would be better suited for developing nations like Nigeria, have been bypassed, rejected, or are too little advertised and known; and sometimes, it may be advantageous to mix simple technology with more advanced ones. For example, where the main task is to irrigate efficiently groups of tiny (0.04 to 0.4 ha) farms supplied from small rain catchment reservoirs or farm ponds, the alternate and appropriate irrigation technology appears to be simple hose-fed sprinklers operating at low pressure, the type used for kitchen gardens and home lawns in advanced countries. But, such systems are seldom recommended and, in fact, most designers are not even aware of them as possibilities for farm use. Also, the type of mixed technology being advocated is a hand-move sprinkler system using conventional equipment but moved in a circular centre-pivot fashion around the source of water supply such as a well or a dug-out pond.

Finally, I believe that engineering is not the fundamental problem underlying irrigation development in a country like ours. Engineering principles are the same the world over and can, with some modifications, be transferred from developed to less-developed countries. Rather, the problem is to engender a transformation in the farmer, in his expectations and motivations, in the agricultural production process in all its aspects—techniques and inputs—and in the institutional framework at the village and regional level.

Concluding Remarks

Presently, our irrigation systems may be performing below expectation, there may be a lot of factors militating against an acceptable measure of success in the operation of large- and small-scale irrigation systems. But we cannot abandon irrigation since it has its advantages. We need to look inward at our culture, our level of technology and farmer practices, and design appropriate, sustainable irrigation system that meets our needs.

With optimistic vision, I see the sun is slowly rising, bringing a brighter tomorrow; and though the progress is painfully slow and fraught with many problems, I sense a feeble but relentless momentum toward an all-year round possibility of "Making It Rain For Higher Farmer's Harvest" technologically.

Mr. Vice-Chancellor, ladies and gentlemen, may I please crave for your indulgence to express my inner feelings and gratitude. First and foremost I wish to thank my Creator, Jehovah God, who has made it possible for me to be before you today. A few years back, I thought I had reached the end of the road. But today, I am happy to be here to give an inaugural lecture on my academic pursuits over the years. To God be the glory.

It is pertinent also to acknowledge here with gratitude that research funds were granted by the University, through the University Research Committee (URC), to carry out most of my work on crop-yield and water-use relationships. The British Council also provided funds for my last outing outside Nigeria under an exchange programme between Obafemi Awolowo University and the University of Newcastle Upon Tyne, U.K., I wish to thank them for the privilege.

Finally, I wish to thank the Vice-Chancellor, Principal Officers, staff and students of the Department of Agricultural Engineering, the entire medical personnel of Obafemi Awolowo University Teaching Hospital Complex and the Health Centre, who till date are still monitoring my health condition. The support that this entire community has given me cannot be forgotten and is gratefully acknowledged.

Mr. Vice-Chancellor, ladies and gentlemen, thank you for listening and God bless.

References

Adams, N., Keller, J. and Spillman, B. M. (1979). "Peasant involvement in on-farm irrigationdevelopment," Proceedings, ASCE Specialty Conference, Blacksburg, Virginia, July 26-28, pp. 813-826.

Adekalu, K. O., Fapohunda, H. O., Bamgboye, O. A. and Ogunsina, B. S. (1993) "Evaluating seasonal variation of oxidation pond effluent for irrigation purposes." *Nigerian Journal of Water Resources,* Vol. 1, No. 2, pp. 44-52.

Aina, P.O., and Fapohunda, H. O. (1986). "Root distribution and water uptake patterns of maize cultivars field-grown under differential irrigation", *Plant and Soil* 94:257 - 265.

Aina, P. O., Fapohunda, H. O and Idowu, J. (1985). "Compaction and moisture suction effects on soil strength and crop emergence", *Ife Journal of Agriculture,* Vol. 7, Nos.1 & 2, pp.16-25.

Akinyemiju, O. A., Fapohunda, H. O. and Adegoroye, A. S. (1990). "Performance and yield of cowpea (Vigna unguiculata L. Walp) subjected to imposed water deficit." *Ife Journal of Agriculture,* Vol. 12, Nos. 1 & 2, pp. 60-68.

Alatise, M. O. and Fapohunda, H.O. (1999) "Hydro-Salinity Modeling for Optimum Crop Yield—A Study of Osun River Basin." *Journal of Applied Sciences* (Nigeria), Vol. 2, No. 2, pp. 539-555.

Doorenbos, J. and Pruitt, W. O. (1977). Guidelines for prediction of crop water requirements, *FAO* Irrigation and Drainage Paper No. 24, FAO, Rome, 144 pp.

Duru, J.O. (1984). Blaney-Morin-Nigeria evapotranspiration model, *Journal of Hydrology,* 70: 71-83.

Fapohunda, H. O. (1981) "Hydrologic models employed in the planning and development of water resource projects in Nigeria", presented at the International Conference on Agricultural Engineering and Agro-Industries in Asia, Nov. 10 - 13, Bangkok, Thailand.

Fapohunda, HO. (1985). "A study of maize and cowpea yield response to irrigation with line source sprinkler system", *International Journal for Development Technology,* Vol. 3, pp. 131 - 143.

Fapohunda, H. O. (1986). "Crop emergence as affected by soils and irrigation", *Plant and Soil* 92:201-208.

Fapohunda, H.O. (1990). "Economic simulation of agricultural water use within a river basin." *Nigerian Journal of Engineering and Technology*, Vol. 9(1): 41-52.

Fapohunda, H. O. (1992). "Irrigation frequency and amount for okra and tomato using a point source sprinkler system." *Scientia Horticulturae*. 49(1-2): 25-31.

Fapohunda, H. O. (1995) "Comparison of potential evapotranspiration calculation methods in a humid to semi-arid tropical region". *Nigerian Journal of Agricultural Engineering and Technology* (In press).

Fapohunda, H. O and Adekalu, K. O. (1995) "Cowpea yield response to fertilizer and water." *Discovery and Innovation*, Vol. 7, No. 1, pp. 61 - 67.

Fapohunda, H. O. and Hill, R. W. (1981). "River basin hydro-salinity-economic modeling." J. of the Irrigation and Drainage Div., ASCE, Vol. 107, No. IR1, Proceeding Paper 16145, pp.55-69.

Fapohunda, H. O. and Hossain, M. M. (1990) "Water and fertilizer inter-relations with irrigated maize." *Agricultural Water Management*, 18: 49-61.

Fapohunda, H. O. and Isedu, A. "An evapotranspiration model based on tropical climatological data", presented at the ASAE 1984 Summer Meeting, June 24-27, Knoxville, Tennessee.

Fapohunda, H. O. and Ude I. C. (1992) "Estimating potential evapotranspiration from tropical climatological data." *The Nigerian Engineer*, Vol. 27, No. 1, pp. 23-29.

Fapohunda, H. O., Aina, P. O. and Hossain, M. M. (1984). "Water use-yield relations for cowpea and maize," *Agricultural Water Management*, 9:219 - 224.

Fapohunda, H. O., Kemper, W. D. and Heermann, D. F. (1985). "Effect of drying on soil strength and corn emergence", *Irrigation Science*, 6(3): 149 - 158.

Federal Republic of Nigeria (1975) *"Third National Development Plan."* Vol. 1, Lagos.

Federal Republic of Nigeria (1979) *"Official Gazette,"* Vol. 66, No. 48, Lagos.

Food and Agriculture Organization of the UN (FAO). (1965). "Agricultural development in Nigeria,"1964-80, *F.A.O.*, Rome

Food and Agriculture Organization of the UN (FAO). (1977). *"Water for agriculture."* FAO of the UN Water Conference, Mar del Plata, March, 26 p.

Food and Agriculture Organization of the UN (FAO). (1979). *"The on-farm use of water."* Commission on agriculture, 5th Session, 22 p.

Food and Agriculture Organization of the UN (FAO). (1987). *"Consultation on irrigation in Africa."* FAO Irrigation and Drainage Paper No. 42, Rome.

Hossain, M. M. and Fapohunda, H. O. (1985) *"Maize production surface at varying levels of water and fertilizer,"* presented at the ASAE Winter Meeting, Dec. 17 - 20, Chicago, Illinois.

Kang, S. T. (1972). *"Irrigation in ancient Mesopotamia."* Water Resources Bull. 8(3):619-624.

Makanjuola, G. A. (1977). *"Agricultural mechanisation in Nigeria*: The prospects and promises. Inaugural Lecture, Series 25. University of Ife Press, Ile-Ife, Nigeria.

Musa, I. K. (2001). *"Challenges and opportunities for sustainable irrigation development in Nigeria."* Proceedings of the International Conference of the Nigerian Institution of Agricultural Engineers, Vol.23, pp 13-22, Enugu.

Nwa, E. U. (1991) "Irrigation in Nigeria: some contemporary issues." *Nigerian Journal of Water Resources*, Vol.1, No. 1, pp. 1-8.

Nwa, E. U. and Martins, B (1982) "Irrigation development in Nigeria." Proc. of Fourth Afro-Asian Regional Conference of International Commission on Irrigation and Drainage, Lagos, Nigeria, Vol. I (Publ. 101): 1-18.

Nwa, E. U. and Pradham, P. (Editors) (1993). "Irrigation research priorities for Nigeria." Proc. Of a National Seminar held at the University of Ilorin, Nigeria, International Irrigation Management Institute, April 20-23.

Ogedengbe, M.O., Fapohunda, H.O. and Gotau, M.B. (1984). "Studies on a selected industrial effluent and the receiving stream", *International Journal of Environmental Studies,* Vol. 23, pp. 229-234.

Osunbitan, J. A. and Fapohunda, H. O. (1998) "Cost comparison of different sprinkler irrigation systems." Proc. Annual Conference of the N.S.A.E., Vol 20, pp. 142-149.

Osunbitan, J. A. and Fapohunda, H. O. (2000a) "Development of a computer algorithm for the solid set/set move sprinkler irrigation system." *Journal of Agricultural Engineering & Technology,* Vol. 8, pp. 26-36.

Osunbitan, J. A. and Fapohunda, H.O. (2000b) "Modeling pressure variation along the lateral of center pivot irrigation system." *FUTAJEET,* Vol. 2, No. 2, pp. 29-34.

Osunbitan, J. A. and Fapohunda, H. O. (2000c) "Computer-aided sprinkler pipe size selection based on pressure and economic criteria." *Technovation* (In press).

Shmueli, E. (1973). "Efficient utilization of water in irrigation." In: *Arid Zone Irrigation,* D. Yaron, E. Danfours and Y. Vaadis (Ed.), Springer-Verlag, New York.

Splinter, W. E. (1976). 'Centre-pivot irrigation," *Scientific American* 234:90-99.

United States Dept. of Agriculture, Soil Conservation Service (USDA-SCS). (1970). *Irrigation water requirements, Technical Release* No. 21, Washington, D.C., 88 pp.