MICROSYSTEMS IRRIGATION IN NIGER, WEST AFRICA

By W. Ray Norman[1] and Michael F. Walter[2]

ABSTRACT: Small-scale irrigation plays a crucial role in agricultural production in Niger, West Africa. Despite the prevalence of traditional irrigation microsystems (average size of about 0.1 ha), not much is known about water-management practices. This paper examines, over a range of lifting heads, the water-lifting and water-use characteristics of 84 manual lift microsystems and intensively investigates two manual systems and two motorized lift systems. An adaptation of the Thornthwaite-Mather procedure to predict recharge is used to model the soil moisture budget. Because of the size of microsystems, irrigation efficiency tends to be high. While pumps offer a significant labor-saving advantage over manual lifting devices, many pumps are not well matched to lifting head. This paper concludes that both manual and motorized lift technologies should continue to be employed in Niger, but that pumps must be better matched to lifting heads and to the particular labor constraints for field water distribution.

INTRODUCTION

The Republic of Niger is one of a number of countries in the Sahel region of West Africa that has placed increasing importance on small-scale irrigation development during the past decade. Over the years, the government has continued to support both national and donor-agency involvement in irrigation development, and views irrigation as one of the primary means of mitigating the effects of future droughts. Although the government maintains an interest in large schemes, the associated high development costs, difficulties involved in organizing large groups of farmers, heavy recurrent costs, and a desire to decentralize management have resulted in a renewed interest in the development of small, irrigated microsystems. The government interest in microsystems increased as a result of their successful use during the 1984 drought. In fact, the profitability of irrigated microsystem production has caused the government of Niger to make support for this activity a major policy priority in the post drought years. The Nigerien government and external donor agencies have focused on agricultural intensification as the principal means to achieve economic and nutritional stability and sustainable development. Thus, the role of irrigated agriculture, particularly small systems, is seen as one of several viable options for attaining sustainability; recent policy has therefore been to provide support and assistance to small-scale, microsystem irrigation wherever feasible within the country's agricultural sector.

Indigenous irrigated production using traditional methods has been practiced in the drought-prone Sahel region for several centuries (Barth 1857; Richardson 1853). This aspect of the region's agricultural history and practice represents a significant local resource base of knowledge and experience

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in small-scale water management for the region. Some of the most successful irrigation development programs worldwide are those that have been built upon proven, existent local experience, rather than attempting to replace it with overly complex technologies and management practices foreign to the local population. Those involved in the introduction of new technologies and management practices in the irrigation sector may thus do well to evaluate valuable local resources and examine means by which those may be integrated into their intervention strategies.

Surprisingly little substantial study has been made of traditional irrigation in the region; more particularly, few attempts have been made to examine water-management practices (Keller et al. 1987; Norman 1988; Moris and Thom 1990). This study is an attempt to partially fill the gap in what is known and understood about these practices by characterizing water-lifting technology and water use within irrigated microsystems of Niger.

This study was first initiated under the Water Management Synthesis II Project and was continued as part of the Niger Applied Agricultural Research Project (NAARP), both U.S. Agency for International Development (USAID)-funded initiatives. Activities under the NAARP were carried out as part of the research program of the Irrigation Section of the Institute National de Recherche Agronomique du Niger (INRAN).

OVERVIEW

Most irrigated microsystems in Niger are located within the country's agricultural zone situated in the southern third of the country. This zone receives a highly variable annual rainfall of 250–550 mm, with mean annual temperatures of approximately 25°–30°C. The area is characterized by an 8–9-month dry season, and a 3–4-month wet season in which rainfed millet and sorghum are the most common crops grown. While supplemental irrigation in microsystems is increasing in the wet season, it remains primarily a dry-season activity in which intensively cultivated, high-value crops are produced. As opposed to what is primarily staple-food crop production in the wet season, irrigated dry-season production (usually occurring between November and April) serves to generate cash income within the rural sector. Onion production for export is the most important irrigated cash crop.

There is considerable uncertainty as to the total amount of land under indigenous, traditionally irrigated production in Niger, and no official estimate exists. The uncertainty is compounded by a significant annual production fluctuation of the rainfed crops. Farmers respond by increasing or decreasing irrigated area to meet annual production needs. Since irrigated production in a microsystem is a very labor-intensive activity, farmers often limit irrigated production to that necessary to generate the extra cash essential to meet household needs for the remainder of that year (Norman 1988). Approximately 12,000 ha are found within government-administered irrigation schemes, while the area in traditional systems is 10,000–30,000 ha (Ferguson 1979; *Development* 1979; *Project* 1990). Irrigated microsystem cultivation takes place in small, privately held, individually or family-managed plots ranging in size 0.05–2.0 ha, with a mean of around 0.1 ha. These microsystems, therefore, constitute single-source (e.g., a hand-dug well), single-user water systems. Thus, the individual farmer has control over all irrigation activities. Most systems are found in broad alluvial valleys that are usually characterized by shallow water tables. Significant areas are also found along the Niger and Komadougou Rivers and among cuvettes (shallow depressions or nondraining basins) of the eastern portion of the country.

Most water sources are shallow wells, but water may also be drawn from a river or other surface sources. In most cases, water is lifted by hand, chadouf, animal traction, or with small gasoline-powered pumps. The principal crops grown under microsystem irrigation are onions, tomatoes, peppers, wheat, maize, carrots, lettuce, garlic, and potatoes. Onions represent over 75% of the national microsystem crop and about the same percentage of the total revenues from microsystem production.

The principal tradition water-lifting methods used in Niger are also found in other areas across the Sahel. These are described as follows:

1. Direct manual lifting with a small half-gourd by the irrigator, standing at water level and throwing water up to the irrigation channel. This method is used most often in cuvettes and depressions with residual surface storage left over from the wet season, primarily in the eastern portion of the country and to a lesser extent along the Niger River Valley in the east. Typical lifting heights are 1–2 m.
2. Direct manual lifting from the ground surface with a small *puisette* (a half-gourd, or *bailer*, attached to the end of a short rope). This method is used most frequently with open wells in the south central portion of the country, and is the most commonly practiced manual method. Typical lifting heights range 1.5–6.0 m.
3. The manually operated chadouf (a counter-weighted balance equipped with a rope and half-gourd). The chadouf is found in the south-central and eastern portions of Niger. The lift is generally 4.5–7.5 m.
4. The animal traction *dallou* system found in the Aïr plateau in the north. This method utilizes animal traction (usually an ox) and a locally fabricated wood frame and pulley system to lift a large, flexible leather bucket at depths ranging 7–12 m.

Each of these traditional methods is well adapted to the typical lifts that exist in the areas in which they are found. For example, due to physical constraints a manually operated counterweight (the chadouf) is impractical at depths greater than 8.0 m, and requires more work per unit volume of water lifted than a simple puisette at depths less than 3.5 m. Similarly, operation of a dallou system at depths greater than 13 m requires excessively long periods between lifts, thus making it difficult to maintain continuous channel flow necessary for field water distribution. At shallower depths of less than 6.0 m, the ox begins to spend increasingly more time in turning around between pulls (lifts) than time spent actually pulling. This may also explain why past attempts to introduce traditional lifting technologies in new areas within the country have not met with particular success.

Manually powered water lifting is done by one individual in a rhythmic dip-and-lift manner producing flow rates of about 0.5 l/s (lps). The locally obtained half-gourd serves as an excellent bailer due to its low cost ($2.00 or less), its durability (three to four years if well maintained), its light weight (less than 1 kg when wet), and its semispherical shape, which negates the need to tip and empty the vessel with each lift. The combination of the weight of a full gourd and its momentum as it is lifted out and away from the mouth of the well causes it to roll on its side in a self-emptying motion at the moment it comes in contact with the ground at the field channel entrance.

Since the early 1980s, water lifting with small, 2.5–5.0 hp portable gasoline-powered centrifugal pump sets has become an increasingly common phenomenon in irrigated microsystems. With the availability of these pump sets (from neighboring Nigeria, primarily), many farmers who have the necessary capital have been switching to this form of lifting. As recently as the late 1970s and early 1980s, the number of chadouf systems along the Komadougou basin in the eastern portion of the country numbered in the thousands, but today hardly one chadouf for every 50–100 motor pumps can be found in the area. Most of these small pump sets, however, are not well matched to the lifting and the delivery conditions found locally, and are usually throttled down to produce average discharges of 1–2 lps. Most pump sets are used at suction lifts of 2–7 m. Optional fuel efficiency within this lifting range generally occurs at operating speeds that deliver 5–8 lps. Related factors are discussed later in this article. Nevertheless, they represent a significant reduction in labor costs for water delivery to those who can afford them. Increasingly, projects sponsored by the government or nongovernment organizations may be found in different parts of the country that provide these small pump sets on credit to farmers.

Open wells are by far the most common water source for microsystem irrigation. Each microsystem may have one or more well, stabilized in the traditional manner with local wood and straw materials or stabilized with concrete rings provided through government or donor-agency programs. Most commonly, open wells have a diameter of 1–2 m. Most traditional wells tend to have a storage depth of only 0.5–1.0 m, while the less common concrete-lined wells are found with storage depths of 1.5–3.0 m. Wells stabilized in the traditional manner tend to have available storage depth limitations and usually have to be reinforced several times during the course of the season. When the water table drops, the interior sides of the well collapse.

Many of the open wells must also be redug each season. The concrete wells, though a much costlier investment, maintain a better storage volume and are virtually maintenance free. Withdrawal from wells that have low storage volumes and/or low recharge rates often results in frequent depletion during the course of the day. Individual well yield may vary from one dry season to the next depending on the amount and timing of the rainfall during the preceding wet season. It is not uncommon for the water table to drop by as much as 2 m in the course of the season. As recharge rates in the wells drop correspondingly, farmers may either extend the depth of their wells or dig an extra well or two. When the latter is done the farmer may rotate from well to well as each is depleted during withdrawal from irrigation, leaving time for the previous one to recharge before returning to it. When motorized pump sets are used, they are carried from one well to another. Thus, the farmer can keep up a fairly continuous irrigation without having to wait at intervals for his well to recharge.

Water is delivered to small basins through a network of small earthen channels. Generally there is a principal field channel running radially away from the water source delivering water to any number of smaller, secondary channels running perpendicular to the main channel. These secondary channels deliver water directly to small rectangular basins of 1.5–3.0 m^2 each. From its source, water is delivered directly into the head of the primary field channel. The head of this channel is usually lined with straw, which serves at least two purposes. The first is to reduce splash and erosion at the point where water is emptied into the channel. Secondly, in the case of manual lift systems, the material serves as a buffer to reduce the surge of each half-gourd of water emptied, thus serving to maintain reasonably constant flows throughout the dip-and-lift procedure.

During actual irrigation, an adult generally does the water lifting while a second person, often a child, diverts the flow of water into individual basins by hand, or with the use of a small hoe. Because basins and channels are laid out in a systematic way and flow rates are low, water distribution can be mastered by youths of five to seven years of age. When a pump set is in use only one person is required to manage the system.

In off-peak periods the entire plot is usually irrigated every two to four days, with more typical three- and four-day cycles taking two days to complete one full irrigation of the plot. During peak use periods irrigation may occur as frequently as every day. Farmers may be at their plots six to 10 hours when irrigating the entire crop, with about four to six hours of this as actual pumping time. On manual lift plots, typical depths applied in the basins during each irrigation are on the order of 1–2 cm, while those with pump sets usually apply depths on the order of 1.5–3.0 cm.

All maintenance of the system is done by the farmer usually during the course of the day as needs arise. These efforts largely consist of fixing small breaches in the channels, reinforcing the sides of the traditionally stabilized wells, and removing collapsed sand material from the well bottom to maintain acceptable storage depths. Routine maintenance is also kept up on the pump sets, with minor repairs usually done by the owner. For larger repairs beyond the capability of the owner, there is usually a repairman in the local community who specializes in small-pump repair. However, since the availability of parts is limited in the country, time lag and costs involved in obtaining them (usually from Nigeria) can cause serious setbacks.

STUDY SITES

A total of 84 microsystems using manual water-lifting methods were selected at sites throughout the country in an effort to extensively examine water-lifting characteristics over a range of lifting heads.

Additionally, four microsystems in the Tarka Valley and the Maradi Goulbi in the south-central portion of the country were selected for intensive study. Within the Tarka Valley, two microsystems using a puisette and a

TABLE 1. Characteristics of Four Microsystems Selected for Intensive Study

Year and location (1)	Size (ha) (2)	Water source (3)	Water-lifting method (4)	Average lift (m) (5)	Crop (6)
88/89—Tarka Valley	0.17	one concrete open well	2.5 hp motorized gasoline pump set	2.9	onions
88/89—Tarka Valley	0.13	two traditional open wells	manual (puisette)	2.0	onions
89/90—Maradi Goulbi	0.06	one concrete open well	3.5 hp motorized gasoline pump set	6.1	onions
89/90—Maradi Goulbi	0.08	one traditional open well	manual (chadouf)	5.8	onions, carrots, lettuce

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motorized pump set were selected, while a chadouf system and a second motorized pump-set system were selected in the Maradi Goulbi. The primary difference between the regional sites is the depth to the water table; approximately 1.5–2.5 m and 5.0–6.0 m for the Tarka and Maradi regions, respectively. Soils within the microsystems tend to be fairly uniform, primarily consisting of clay loams and sandy-clay loams. Table 1 details characteristics of each site.

METHODOLOGY

In the survey of 84 microsystems, measurements were taken of the static and dynamic lifting heads, lifting frequencies, lift volumes, and sustained flow rates.

Each of the four microsystems selected for intensive study was monitored on a daily basis throughout one entire cropping cycle during the dry season. This was done by assigning a full-time field assistant at each site who was charged with monitoring all irrigation-related activities, as they occurred in the period between field preparation to end-of-season harvest. Data retrieved during this activity include irrigation delivery rates and volumes, static and dynamic pumping heads, field channel seepage losses, electrical conductivity of irrigation water, soil moisture, pan evaporation, crop root development, cropping areas, and crop yields.

All starting and stopping times of water lifting (or pumping) were monitored throughout each day of irrigation. The frequency of lifts over a three-minute period was recorded for the manual lift systems every 15 min. On 30-min intervals, the field assistant would measure the weight of three randomly selected half-gourds (the puisette or bailer). With pump sets, a small cutthroat flume was placed at the head of the principal field channel with flows recorded at 30-min intervals. By necessity, the process by which field assistants monitored these daily activities had to be as discrete as possible in order to assure uninterrupted activity of the farmer. To help maintain as natural as environment as possible for the farmer, the field assistant would usually make his observations from a significant distance. The only interruption necessary was to weigh the water-filled bailer.

Depth to the water table was measured each day before withdrawal began from the well. The pumping head was then measured at the onset and end of each lifting session. Seepage losses in field channels were measured by ponding of selected sections and measuring the subsequent water decline within each. From these measurements a rate per unit length of channel for each system was estimated. Electrical conductivity of irrigation water was monitored in all systems. The salt content of the water in the Tarka Valley microsystems was high enough (1.2 mmhos/cm) to affect crops if not managed. Interviews with farmers in areas with irrigation water having significant salinity levels indicated their understanding of the effects of poor water quality on yields. However, depending on seasonal labor constraints or other related factors (such as produce market value for a given season) farmers, from season to season, may choose not to invest the time or labor necessary to provide full leaching of salts, rather accepting a loss in yield. Irrigation during the following wet season, when water tables are higher and water quality is good, may then serve to leach any salts accumulated during the previous dry season. Water quality was relatively good within the Maradi Goulbi microsystems. The development of the crop root zone was measured on 10-day intervals. Pan evaporation was measured with a class A pan placed on each site.

SOIL MOISTURE BUDGET

A soil moisture budgeting model was employed to evaluate water use and to estimate plant evapotranspiration. The model is an adaptation of the physically based Thornthwaite-Mather procedure to predict recharge, and is described by Steenhuis and Van der Molen (1986) and Thornthwaite and Mather (1957). An application of this procedure to conditions in Niger is described by Norman (1988). In this procedure available soil moisture status in the active root zone is dependent on the accumulated potential water loss. Accumulated potential water loss is incremented by the difference of potential evapotranspiration (PET) and the sum of the irrigation application and precipitation ($Ig + Pi$), for days that PET is in excess of moisture added ($Ig + Pi$). In this case available soil moisture storage in the active root zone may be expressed as

$$ST_t = ST_f \cdot \exp\left(-\frac{A_t}{ST_f}\right) \quad \ldots\ldots (1)$$

where ST_t = available moisture in the root zone at time t (cm); ST_f = available moisture in the root zone at field capacity (cm); and A_t = accumulated potential water loss at time t (cm).

When PET is less than the moisture added ($Ig + Pi$), soil moisture storage is incremented by the difference between those two values, where

$$ST_t = ST_{t-\Delta t} + (Pi + Ig) - \text{PET} \quad \ldots\ldots (2)$$

If the resultant moisture content at time t does not reach field capacity (ST_f) then there is no recharge to the ground water (Rch; i.e., seepage below the root zone) and A_t may be given as

$$A_t = -ST_f \cdot \ln\left[\frac{(ST_{t-\Delta t} + (Ig + Pi) - \text{PET})}{ST_f}\right] \quad \ldots\ldots (3)$$

If the resultant moisture content (2) is on the other hand in excess of field capacity (ST_f) the ST_t is assigned a value equal to ST_f, A_t is set equal to zero, and recharge (Rch) is given as

$$Rch_t = -(ST_f - ST_{t-\Delta t}) + (Ig + Pi) - \text{PET} \quad \ldots\ldots (4)$$

Actual evapotranspiration (ETA) may then be derived from a mass balance of the soil moisture budget components. ETA is then estimated as

$$\text{ETA}_t = (ST_{t-\Delta t} + Ig + Pi) - ST_t - Rch_t \quad \ldots\ldots (5)$$

Onions were the only crops grown in three of the four microsystems studied. In the chadouf microsystem in which three crops were irrigated, exact irrigation applications to each crop were difficult to determine. However, since relative crop areas were known, mean root zone depth and change (across the plot) was generated from a weighted basis for each crop.

Ten-day averages of pan evaporation were adjusted to estimate PET for the budget. Charoy (1971) obtained PET estimates from lysimeter studies in the Maradi Goulbi, and found that PET for the dry-season period (November–March) could be approximated from pan evaporation by applying a factor of 0.8.

IRRIGATION EFFICIENCY

Available water supply and the respective demand for that water constitute two principal factors considered in irrigation water-use evaluation. However, little can be surmised in regard to the performance of water-use practices when each variable is examined individually. Classically, these two terms are combined to provide the standard irrigation efficiency measure. For the purposes of this study, efficiency (EFF) is defined as the ratio of actual crop water demand to irrigation supply and is expressed as

$$\mathrm{EFF} = \left[\frac{(\mathrm{ETA} + s_a - \mathrm{Stor})}{(Ig + Pe)}\right] \cdot 100\% \quad \text{(6)}$$

where ETA = actual crop evapotranspiration (cm); s_a = observed seepage losses (cm); Stor = change in root zone moisture storage before and after cropping cycle (cm); Ig = total irrigation supply (cm); and Pe = effective precipitation (cm).

Seepage or uncontrolled losses were included in the demand component, as well as actual crop water consumption. Within the microsystems, EFF primarily reflects the water-management practices of the individual farmer, and since surface drainage was essentially nonexistent the EFF value reflects primarily losses incurred from deep percolation of excess water below the root zone.

This ratio of actual crop demand to supply (EFF) should not be confused with the ratio in which the demand component is based on a theoretical or design value for crop water needs. Typically, because crops have a response function and not a set water requirement, a design limit or requirement is set for the purpose of establishing some upper boundary on the crop water demand. Generally, a maximum evapotranspiration value ("$\mathrm{ET}_{\mathrm{max}}$") is used to establish this demand and is typically obtained by applying crop coefficients to PET for various stages of crop development. Design demand values are frequently used in system planning, but may be less useful in measuring irrigation performance, particularly in the cases where farmers may view optimal production at evapotranspiration rates below design crop demand (Norman 1988).

RESULTS AND ANALYSIS

A summary of characteristics of water lifting and delivery for each of the four microsystems is given in Table 2. Flow rates, which are averaged over the entire season, indicate that the farmers using pump sets generally operate at delivery rates double that of manual lift systems. Delivery rates do not vary significantly with differences in lift between the 2 pump-set systems nor between the two manual lift systems. The range of delivery rates for each day of irrigation within the four microsystems is shown in Table 2.

Delivery rates for 84 manual systems over a range of lifting heads are given in Fig. 1. Delivery rates tend to decrease exponentially as the lifting head increases. Figs. 2 and 3 depict the relationship of lift volume and lift frequency to the lifting head. No relationship was found between volume and lifting head. An average volume of water per lift was about 7.4 kg. The frequency of lifts does vary with lifting head. For manual systems, the relationship between delivery rates and lifting heads tends to be governed by relative lifting frequency and not by the volume per lift. The result is that flow rates are less stable when lifting occurs from greater depths because

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TABLE 2. Characteristics of Water Lifting and Delivery for Farm Microsystems Studied

Microsystems (1)	Dynamic lift average (m), range (m) (2)	Flow rate average (lps), range (lps) (3)	Pumping or labor time (1,000 h/ha) (4)	Seepage losses (% irrigation volume) (5)	Average irrigation frequency (days) (6)
Tarka Valley pump set (2.5)	2.9, 2.2–3.6	1.8, 1.2–2.3	1.8	10.0	3.2
Tarka Valley manual lift (puisette)	2.3, 1.8–2.8	0.6, 0.4–1.0	3.0	15.0	3.3
Maradi Goulbi pump set (3.5 hp)	5.9, 5.7–6.1	2.0, 1.5–2.5	0.6	5.0	5.5
Maradi Goulbi manual lift (chadouf)	5.7, 5.2–6.3	0.6, 0.5–0.6	2.5	15.0	3.2

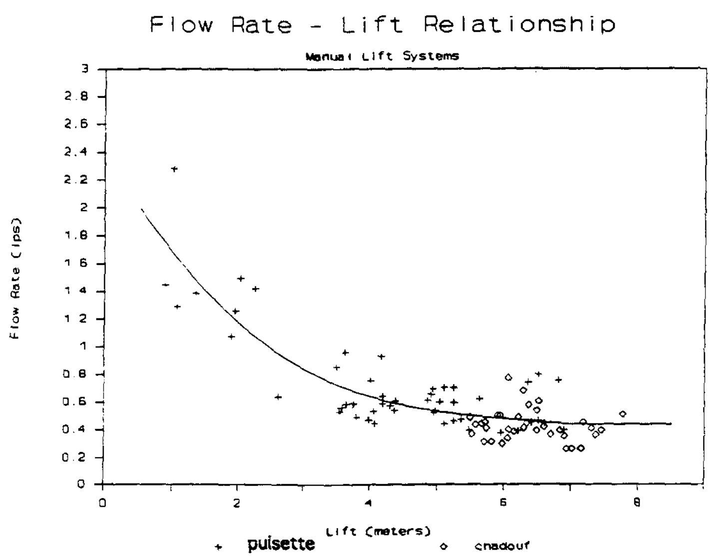

FIG. 1. Flow Rate versus Lifting Head among Manual Systems

the time between lifts is greater as the lifting head increases. While maintaining a similar lift frequency but reducing lift volumes at greater lifting heads may serve to stabilize flows, it is likely that a higher percent in overall seepage losses would be incurred. The proportion of water lost to seepage was found to decrease with increasing flow rates.

Seepage losses in the earthen channel networks were found to be ap-

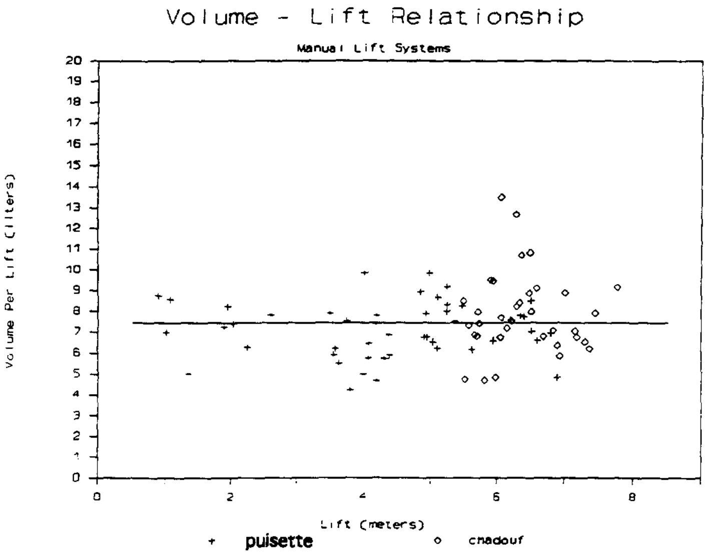

FIG. 2. Volume versus Lifting Head among Manual Systems

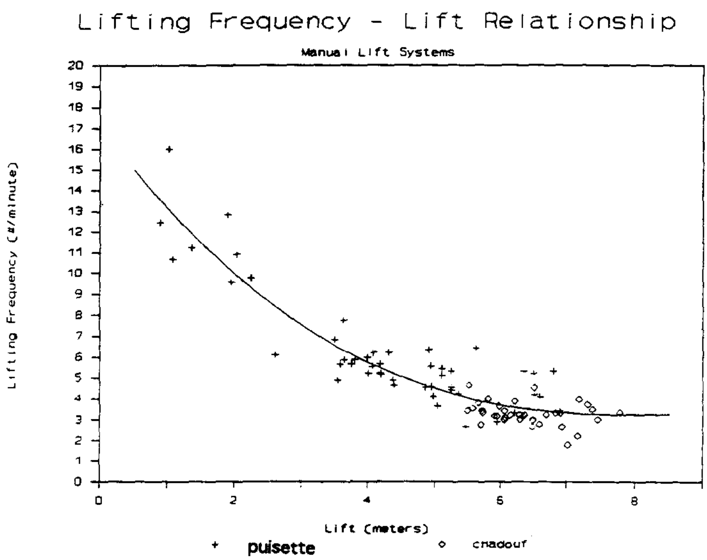

FIG. 3. Lifting Frequency versus Lifting Head among Manual Systems

proximately 0.005 lps/m of channel length and were similar at all sites, i.e., between 5% and 15% as indicated in Table 2. Because pumps produce a higher delivery rate, overall seepage losses were less than when manual lift methods were used.

Microsystem cultivation is a labor-intensive activity. In much larger, government-sponsored irrigation schemes farmers generally devote less than 350 hours per irrigated ha for field water distribution. Among the microsystems studied, labor allocation is three to five times greater for pump-set systems and seven to nine times greater for manual lift systems. Moving from a manual lift technology to pump-set use represents a significant labor savings for the farmer since he can simultaneously irrigate at a higher flow rate and reduce labor. A pump set also alleviates the need for two people required for manual lift microsystems. Most manual lift systems operate at delivery rates of 0.3–1.0 lps, while most farmers operate their pump sets at around 2 lps. Field interviews indicated that most farmers who moved from manual to pump-set lifting invested their extra freed labor into increased microsystem size and production, rather than in other, nonirrigated related activities.

The average delivery rates for most pump sets used among microsystems are well below optimal pumping efficiency, which according to manufacturer's specifications is around 3.5–4.0 lps for the suction heads most often incurred in the study area. Two factors appear to be the principal reasons for this action by the farmers. First, a great majority of the wells on which these pump sets are used do not have a yield equal to the pump's capacity, thus pumping at optimal design flow rates would increase the frequency of starting and stopping as a result of having to wait for the well to recharge after each depletion. Some farmers are able to reduce this constraint somewhat by using two wells and moving the pump between them, while one recharges and the other is used. Second, farmers indicate that there is an upper limit above which they are unwilling to run their pumps due to field problems incurred with higher flow rates. The first of these is that field delivery rates that exceed 2 lps generally require more than one person to manage field water distribution. Second, there is the concern of earthen field channels and basins needing frequent repairs or being washed out altogether due to higher flow rates.

Table 2 indicates that irrigation frequency on average is usually three days, with the exception of the pump-set system in the Maradi Goulbi. Field observations of other pump-set systems indicated a general tendency for intervals between irrigations to be greater than those systems using manual lift.

Figs. 4(*a–d*) depict the available soil moisture regimes for each microsystem as generated by the soil moisture budget model, according to irrigations observed in the field. In Figs. 4(*a–d*), maximum potential soil moisture is depicted by the upper solid line, and progresses over time in a stepwise manner due to incremental increases in the root zone values used as input to the budget model. Actual changes over time of potential soil moisture occur gradually with the day-to-day advance of the root zone and not in the incremental stages depicted in the figures. Available soil moisture was never depleted during any of the cropping cycles, following the first irrigation. Both microsystems in the Tarka Valley [Figs. 4(*a* and *b*)] did encounter brief soil moisture depletion for a period of one to three days, between transplanting and the first irrigation of the season. The lower irrigation frequency of the Maradi Goulbi pump-set system (average of 5.5 days) is evident in Fig. 4(*c*), when compared with the others. Farmers tend to maintain available soil moisture reserves at the upper limit. The farmer irrigating in the microsystem depicted in Fig. 4(*b*) never allows for soil moisture depletion following his first irrigation, but tends to maintain only minimum irrigation necessary until after day 60, after which peak crop water demand is encountered. Crop yields are given in Table 3. The onion yields for the system in Fig. 4(*b*) was 40% less than that for the other similar Tarka Valley

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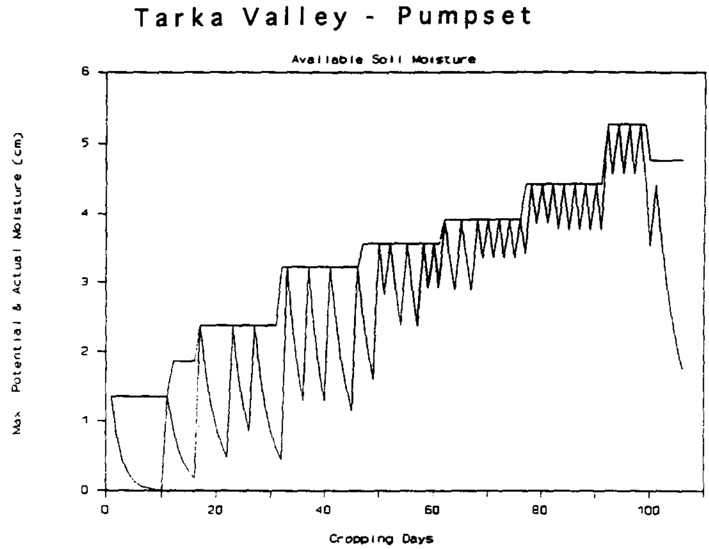

FIG. 4(*a*). Tarka Valley Motor Pump-Set System: Available Soil Moisture in Root Zone (Upper Line Is Maximum Potential)

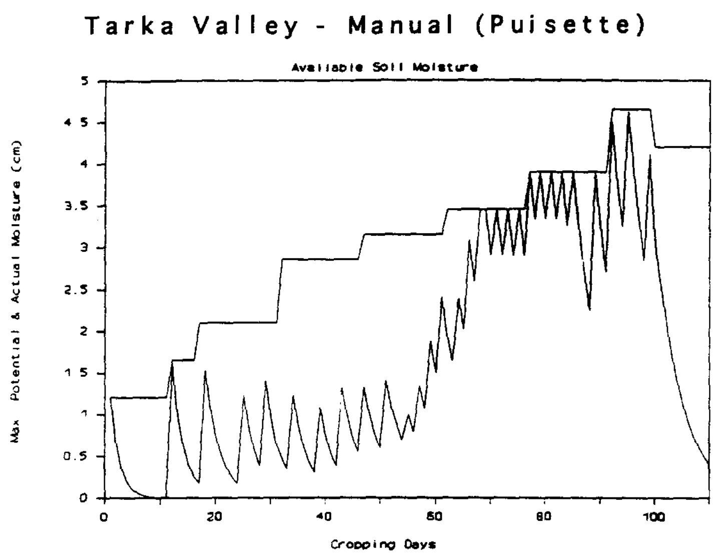

FIG. 4*b*). Tarka Valley Manual (Puisette) System: Available Soil Moisture in Root Zone (Upper Line Is Maximum Potential)

system. Factors other than water stress could have also accounted for the low yields. Table 3 also indicates that onion yields can be exceptionally high in the region. Farmers in the Tarka Valley and other parts of south-central Niger have been cultivating onions (known as *violet de Galmi*) for at least two centuries, and their onions are well known throughout West Africa.

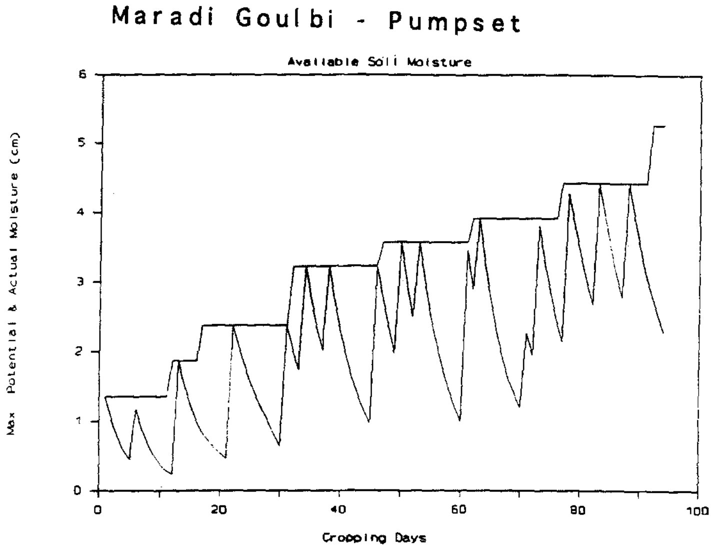

FIG. 4(c). Maradi Goulbi Motor Pump-Set System: Available Soil Moisture in Root Zone (Upper Line Is Maximum Potential)

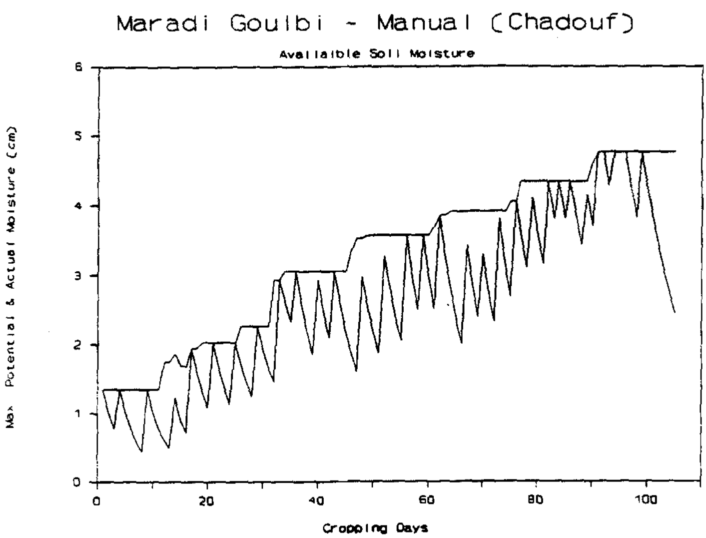

FIG. 4(*d*). Maradi Goulbi Manual (Chadouf) System: Available Soil Moisture in Root Zone (Upper Line Is Maximum Potential)

Most of these are exported to coastal cities such as Lome, Cotonou, and Abidjan. Some are then exported from these port cities to destinations as far away as Europe. The variety of onions grown in the Maradi Goulbi are of a smaller, lower-yielding variety known as *blanc de Soumarana*. Yield variances among similar varieties may be affected by fertilizer use and disease, as well as irrigation applications.

TABLE 3. Summary of Microsystem Crops with Respective Season Length, Area, and Yield

Microsystem (1)	Crop (2)	Season (days) (3)	Area (ha) (4)	Yield (T/ha) (5)
Tarka Valley (pump)	onion	106	0.17	85
Tarka Valley (puisette)	onion	110	0.13	49
Maradi Goulbi (pump)	onion	94	0.06	16
Maradi Goulbi (chadouf)	onion	90	0.04	16
Maradi Goulbi (chadouf)	carrot	91	0.03	19
Maradi Goulbi (chadouf)	lettuce	65	0.01	25
Maradi Goulbi (chadouf)	all	—	0.08	—

TABLE 4. Microsystem Water-Use Characteristics

Microsystem (1)	Crop (2)	Irrigation (mm) (3)	S_a (mm) (4)	*Stor* (mm) (5)	*Rch* (mm) (6)	*ETA* (mm) (7)	ET_{max} (mm) (8)	EFF (%) (9)
Tarka Valley (pump)	onion	1,145	114	4	433	590	624	61
Tarka Valley (puisette)	onion	662	99	−8	95	471	653	87
Maradi Goulbi (pump)	onion	459	23	9	93	344	506	78
Maradi Goulbi (chadouf)	onion	—	—	—	—	—	478	—
Maradi Goulbi (chadouf)	carrot	—	—	—	—	—	543	—
Maradi Goulbi (chadouf)	lettuce	—	—	—	—	—	350	—
Maradi Goulbi (chadouf)	all	523	79	9	93	343	480	79

Water-use performance indicators and their components are given in Table 4 for the four microsystems. Irrigation efficiency (EEF) as described in (6) ranges 60–90%. Of the four, the two manual systems have marginally higher efficiencies than the pump-set systems. It is understandable that water would be managed more efficiently in the manual lift systems because the labor investment for lifting water is much higher than the cost of fuel for the pump (see Table 2).

When the demand-to-supply ratio is determined from a design demand (based on crop coefficients applied to PET and estimated leaching requirements) the ratio tends to be much higher (ranging approximately 0.90–1.20 among the four microsystems studied) than the EFF values found in Table 4. Although labor constraints may account to some degree for instances where this ratio exceeds 1.0, it has been previously suggested that this may well be a reflection of farmers' perceptions of maximum productivity occurring somewhere below design crop demand (ET_{max}). Consistently higher values of the design demand/supply ratio to the actual demand/supply ratio (EFF) are indicative of a relative failure of crops to transpire at maximum design ET rates (ET_{max}). Since available soil moisture depletions between

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the first irrigation and the end of the season were never observed with any of the crops (both in the field and in the budget model), the consistency of this differential may be linked to the occurrence of midday stomatal closure—which is related to the percentage of available moisture in the active crop root zone. This may occur when the capacity for plant moisture uptake from the soil is apparently exceeded by transpiration demands induced by excessive solar radiation and high air temperatures. The physiological result is temporary stomatal closure until transpirational demand drops to a point equal to what the plant is capable of removing from soil moisture reserves (Wenkert 1983; Hsiao and Bradford 1983; Robins et al. 1974). This phenomenon may thus account for actual evapotranspiration (ETA) rates, which tend to be lower than those estimated by classical methods, which are typically based on potential ET rates.

In general, irrigation efficiencies (EFF) among the systems studied are high. This is particularly true when compared with similar efficiencies of larger and newer, government-sponsored schemes in the country that may operate at efficiencies about 55% percent (Norman 1988). One of the principal advantages of these smaller microsystems, and one that may account to a larger degree for their high operational efficiencies, is that of complete farmer control of both the amount and timing of irrigations. The certainty of full control over water-management practices provides the farmer with the incentives necessary to take the risks required for the successful, intensified, and diversified irrigated production found within Niger's microsystems. Farmers in these systems have the flexibility to adapt seasonal production to individual household needs. They are better able to take advantage of the market by timing their planting and harvest to coincide with preferable markets. The introduction of large systems in the country have introduced a new management requirement previously not encountered in the irrigation subsector; that of single-source systems having multiple users. Farmers owning parcels in large schemes are generally locked into an inflexible, monocrop system, where decisions on crop types, season dates, and the amount and timing of irrigations are corporate decisions and not ones made by the individual.

CONCLUSIONS

Traditional water-lifting technologies appear to be well adapted to local physical conditions that govern access to water. However, these methods tend to be exceedingly labor-intensive. The search for, and the development of, new water-lifting technologies for small-scale irrigation should be careful not to: (1) Provide flows so low that the seepage losses in channels would be prohibitively high; or (2) provide flows that are too high and thus that are erosive or that require more than one person for field water distribution. A change from manual lift systems to small pump sets represents a significant reduction of overall costs to the microsystem farmer. Pump sets need to be sought that are better matched to the lifting heads found among most Nigerien microsystems and that are better matched to labor constraints facing farmers for field water distribution.

The efficiencies at which water is managed in microsystems tend to be high, although the labor requirement for lifting and field water distribution is high. Microsystem farmers display an understanding of the water-management practices that they employ. Much of their success seems to be linked to the high degree of control that they exercise over water management and other cultivation practices within their systems. Endeavors at

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developing the irrigation subsector would thus do well to make attempts to assure to the degree possible, farmer control over water-management practices within his parcel.

Efforts are presently being made throughout Sahelian West Africa by national governments and donor agencies to assist countries in attaining economic and nutritional sustainability through agricultural intensification. Few agricultural practices in the Sahel are more intensive than those found among microsystems. The characterization of the management practices among the microsystems of indigenous origin highlights the potential profitability of integrating this valuable local resource into intervention strategies for the development of the irrigation subsector.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A_t = accumulated potential water loss at time t;
Ig = irrigation application;
Pe = effective precipitation;

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Pi = precipitation;
Rch = recharge to ground water;
s_a = observed seepage losses;
ST_f = available moisture in root zone at field capacity; and
ST_t = available moisture in the root zone at time t.