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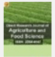

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Determination of the Design Parameters of Water Distribution System for Paddy Rice Irrigation: A Case Study

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ABSTRACT

The irrigation water distribution system ensures the transport of water through field ditches to the irrigated fields while the field application system assures the transport of water within the fields. Therefore, in the design of water distribution, irrigation water distribution design parameters must be determined. This includes rice irrigation water requirement, irrigation stream size, and canal hydraulic design. The study therefore involves the selection of Irrigation method, determination of rice irrigation water requirement and irrigation control structures that regulate the discharge in each irrigation canal and ensure that each plot receives the required quantity of water at the correct time. By comparing irrigation water requirement for the three water requirement stages: flushing flow rate of $0.0015m^3/s/ha$*, flooding water requirement of* $0.0064m^3/s/ha$ *and maintenance water requirement of* $0.0017m^3/s/ha$*, the unit irrigation stream size is found to be governed by the flooding water requirement. A minimum flow rate of* $0.007m^3/s/ha$ *was therefore considered adequate for unit irrigation. At 60% of the limiting opportunity time, the maximum allowable time to cover the basin with water is 7.32hr. This is used to obtain the minimum stream size of* $0.01\ m^3/s$ *required per 0.25 ha basin to achieve a plot irrigation efficiency of 80%. Natural ground slopes within the project area range from 0.3% to 0.6% resulting to two standard field layout patterns. The layout of flat land was adopted where the field shape is sufficiently regular and slope less than 0.4%.*

Keywords*: Irrigation; distribution; canal hydraulic design; flushing; efficiency; opportunity time*

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INTRODUCTION

Rice is one of the world's most important cereals providing nourishment for a greater number of people than any other grain and cultivated over a wide range of habitants extending from the equatorial tropics to higher altitude up to 40° N (Wang & Hagan 1981). It is a tropical and sub-tropical crop, hence the temperature of 25 – 37°C is ideal for the crop (FAO, 1978). Rice, especially the paddy type requires a constant and plentiful supply of water. Consequently, most varieties are adapted to flood culture. An annual rainfall of 900mm - 1200mm is required for good yield. However, some upland rice requires a rainfall of 50mm – 60mm over each running 10-day period, during a 3-4 month growing season (Leaky and Wills, 1977, Dastane, 1978). There are three phases in the irrigation of a rice farm: - flushing period during which the soil is wet to field capacity and puddled to about 2.5cm standing water to reduce its permeability just before sowing; flooding, during which the field is covered with water to some predetermine depth based on the agronomic practices and the maintenance water phase - to meet evapotranspiration requirements, field percolation and seepage loss thereby maintaining the flood (Wang & Hagan, 1981). The distribution system assures the transport of water through field ditches to the irrigated fields while the field application system assures the transport of water within the fields. Therefore, in the design of water distribution, irrigation water distribution design parameters must be determined. This includes rice irrigation water requirement, irrigation stream size, and canal hydraulic design.

METHODS AND MATERIALS

Study area

The study site is the fairly level swamp valley of Atayi stream which includes the flood plain of Iyioma and Mbuka, occupying about 16 hectares out of the 169.55 ha swamp field (Uche *et al.*,2023) located in Amaiyi Igbere in Abia State (Figure 1). It is a rainfall swamp that is flooded during the rainy season by run off from the surrounding uplands and rainfall on the swamp surface.

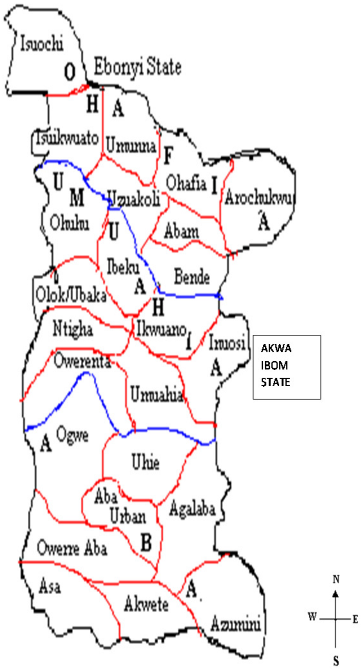

Figure 1: Study area

Selection of irrigation method

Surface irrigation system is indicated in the Igwu Rice Scheme which is contiguous to the project site (Appraisal of Rice Project Nigeria, 1974). The surface topography is such that land leveling costs are low (on the average ₦145000 per ha). The surface soils are predominantly sandy clay (72%) under laid at about 60cm depth by clay of low infiltration rate (10mm/hr.) (Uche *et a*l, 2023). Local experience, although limited is wholly with surface irrigation. Atayi Stream can be considered as an inexhaustible source of water for the foreseeable future. But for pumping cost, water supply to cover the basin is relatively free.

Rice irrigation water requirement (Wang & Hagan, 1981).

The irrigation water requirements were obtained as follows:

a) Flushing irrigation stream size using equation 1:

$$Q = \frac{AD_t}{8.64E_c[1-(1-\frac{PD_t}{D_s})^n]} \tag{1}$$

Where: Q = maximum discharge required (m^3/s),
A = total area to be irrigated (ha),
D_t = Field irrigation water requirement (m/dy),
E_c = Conveyance efficiency,
D_s = Land flushing water requirement (m),
B = Irrigation period, n = number of irrigation periods in each land

b) Flooding water requirement (equation 2)

$$Q_{fd} = \frac{(P_s + V_i/2 + F_f + L_p)}{6p} \tag{2}$$

where: Q_{fd} = flowrate into field during flooding (m^3/s)
Ps = water depth required to saturate the soil (mm),
Vi = vertical interval (mm),
F_f = depth of pond water (mm),
Lp = deep percolation loss during the time period (mm),
P = irrigation period (mm)

c) Maintenance water requirement was determined from equation 3

$$Q_{fm} = \frac{Lp}{6p} + \frac{E_{TP}}{8640} \tag{3}$$

where: Q_{fm} = flow rate for maintenance flood $m^3/s/ha$,
E_{TP} = peak consumptive use mm/day

Irrigation stream size

The present crop is rice. Swamp rice is proposed as this is the type presently grown in the vicinity. A basin form of irrigation must be adopted to ensure that flooding condition can be maintained on the rice field. The largest practical basin size would be adopted to reduce labour costs. However, this will be limited among other things by the requirement that for a plot efficiency of 80% to be attained the time required to cover the basin should not be more than 60% of the time required for the net application to enter the soil– opportunity time (Tn), (Jensen, 1980). Opportunity time Tn (min) is given by equation 4.

$$Tn = \left((Fc - C)/a \right)^{1/b} \qquad (4)$$

where: Fc = desired net application depth
c, a, and b are infiltration constant (Uche et al, 2023)
fc = 118.25
c = 0.2
a = 0.064
b = 1.14

A minimum stream size to meet this requirement is determined from equation 5:

$$Qt = F_nA \qquad (5)$$

Q = Stream size (L^3T^{-1})
T = time
F_n = net depth of application (L)
A = Area of basin (L^2)

$$Q = \frac{FnA}{t}$$

Irrigation layout

The size of the basin was determined by topographic and field shape considerations to bring into cultivation as much land as possible and to reduce leveling cost. Factors considered were stream size, irrigation water requirement and hour of watering. Figure 2 shows a topographic map of the project site. The layout of canals, drains and pipelines is designed after due consideration of the following general and often conflicting principles.

(1) The need to make use of the existing ridges and depression and the avoidance of watering against the natural slope.
(2) The need to convey water in channels within the allowable slope.
(3) The adoption of regular layout incorporating standard basin size of 0.25 ha
(4) To bring into command the maximum possible area
(5) To limit the use of canal structures

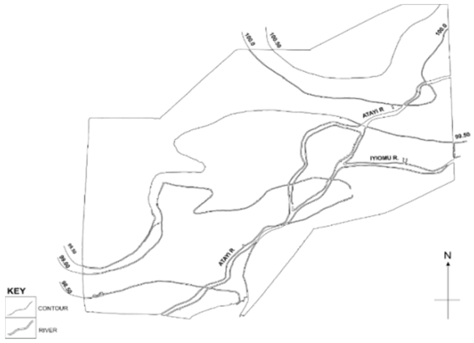

Figure 2: Topographic map of study site

(6) The need for the shortest length of pipelines
(7) The need to divide the area into manageable commands each served by a canal and
(8) The need to limit canal meandering.

Canal hydraulic design

Canals (Figure 3) were designed so that their boundaries are stable in order that maintenance costs are kept to a minimum. The cross sections selected (Figure 4) are to carry the necessary amount of water and require the least amount of excavation and earth haulage during construction. Therefore, the underlying principle in canal design for the project field is safety and economy. The canals in the Igwu Rice Scheme were designed on the bases of Manning's equation (equation 6). (Majumdar, 2015)

$$Q = \frac{1.5}{n} AP^{2/3} S^{1/2} \qquad (6)$$

$$Q = \frac{S^{1/2} \left(bd + 1.5d^2\right) 2/3}{n \; (b + 3.6d) \; 2/3}$$

Where:
Q = Flowrate $m^{3/s}$
n = Manning channel roughness coefficient
A = Area of waterway (m^2)
b = Surface width of water in the channel (m)
d = The water depth of channel
R = Hydraulic radius (A/P) (m)
P = Wetted Perimeter (m)
S = Hydraulic gradient = ratio of vertical to horizontal (S.S)

Unlined channels are proposed for the project as is presently in operation at the Igwu Scheme. The value of

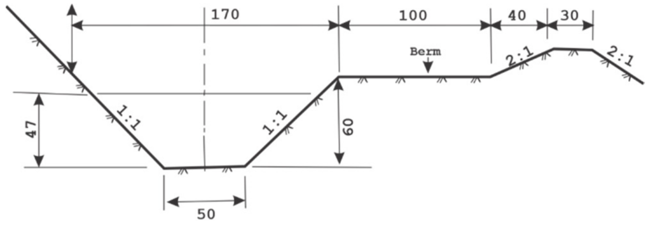

Figure 3: Main Canal

n used in the design ranged from 0.020 – 0.025. Observation in the Igwu Scheme indicates that the canals are functioning satisfactorily.

Cross paddy irrigation

A paddy bund spillway will be required to convey water in cases where paddy fields do not have direct access to farm ditch. The bund opening required for the irrigation water flow B_O was obtained from equation 7:

$$Bo = \frac{SDt}{8.64 C_d H^{3/2}} \qquad (7)$$

Where Bo = bund opening
S = allowance for settlement/rotational interval (dys) = 7dy
H = water head above the spillway (m)
Dt = maintenance water requirement (m/dy)
C_d = discharge coefficient (ratio of the actual discharge to the ideal discharge.

$$H = D - F_b - h \qquad (8)$$

where

H = the maximum water head was obtained from equation 8:
D = height of the paddy bund (m)
Fb = freeboard allowance (m)
h = spillway sill height from the paddy soil surface (m)

The freeboard deals with unanticipated events that a canal may encounter such as water surface vibration, and its size is assessed by the discharge. Discharge coefficient C_d which is the ratio of the actual discharge to the ideal discharge was given by equation 9 :

$$C_d = \sqrt{\frac{2g}{2}}\left(\frac{K^2-1}{K^2}\right)\left(\frac{(h+H)^{1/2}}{K(h+H)} - H\right)\frac{1}{2} \qquad (9)$$

where
K = a constant (1.8)
D = 500m
Dt = 15mm/dy
Fb = 0.4(d – h) = 0.4 (400 – 150) = 100m
h = 150mm

Irrigation control structures

The discharge in each irrigation canal must be controlled to ensure that each plot receives the required quantity of water at the correct time. If discharges were not controlled water would be wasted, the canal damaged and production drops. For the project, water will be pumped out of the river into stilling wells from where it will be conveyed and distributed by main channel and distributaries respectively and thence by way of pipes inlets into the fields. Watering will be for twelve hours each day with pumping commencing an hour before irrigation is due to start to fill up channels.

RESULT AND DISCUSSION

Rice irrigation water requirement

Therefore $Tn = \left(\frac{118.25 - 0.2}{0.064}\right)\frac{1}{1.14}$
= 12.2 hrs.

Where Tn = Opportunity Time

At limiting time of 60% of opportunity time Tn the maximum allowable time to cover the basin with water is therefore
= 0.6 × 12.2
= 7.32hr

By comparing irrigation water requirement for the three steps: flushing flow rate of 0.0015m3/s/ha, flooding water requirement of 0.0064m3/s/ha and maintenance water requirement of 0.0017m3/s/ha, it was obvious that the unit irrigation stream size is governed by the flooding water requirement. A minimum flow rate of 0.007m3/s/ha was therefore considered adequate for unit irrigation. Table 1 shows the cropping calendar water requirement for the various periods in production. Table 1 indicates that the highest water need occurs during the flooding periods (Jan 30 – Feb 12, 28 days for dry crop and July 23 to August 5, 21 days for the wet crop). The land soaking period which allows for the wet cropping has been shortened because of the usual April rain which is expected to reduce soil irrigation water needs hence, shorter time needed to saturate the soil. A comparison of the irrigation water demand from the Atayi stream and the flow rate available in the stream (Uche 2023), shows that

Table 1: Cropping calendar and water requirement.

Activities	Period	Water Demand m^3/s
Dry season		
Land soaking	Oct 15 to Nov. 13	0.029
Maintenance	Nov. 14 to Jan 29	0.024
Flooding	Jan 30 to Feb 12	0.024
Harvesting	Feb 8 to Mar 13	0.159
Wet season		
Land Soaking	May 1 to May 20	0.026
Maintenance	May 2 to July 22	0.023
Flooding	July 23 to Aug 5	0.159

the Atayi stream would remain an inexhaustible source of water for the project in the fore-see-able future (Table 2).

Table 2: Atayi stream flow and water requirements (Uche et al., 2023)

Period	Available Flow rate at Atayi (m^3/s)	Required flood in the project (m^3/s)	Excess (m^3/s)
February	1.5	0.2	1.3
July	2.5	0.2	2.3

Irrigation stream size

Opportunity time of 12.2 h. is obtained from equation 4 in section 2. With limiting time of 60% of opportunity time, the maximum allowable time to cover the basin with water is therefore: 0.6 × 12.2 = 7.32hr. This is used to determine the minimum stream size. of 0.01 m^3/s required per 0.25 ha basin to achieve a plot irrigation efficiency of 80% (using equation 5). For a basin size of 0.25 ha.

$$Q = \frac{.11825 \times 2500}{7.32 \times 3600}$$

$$= 0.01\ m^3/s$$

Canal hydraulic design

As the natural ground slope in the project area are in some instances steeper than 0.9% a maximum slope of 0.2% has been allowed with check drops at appropriate intervals for 258m canal run (18% of total length) after due consideration of available earth material for the necessary fill work (Table 3). Another 0.2% bed slope was allowed for 208m canal length (14%) while the rest about 995m (68%) canal length have been designed to 0.1% bed slope (USDA, 1978). The resulting effect of designing to 0.1% natural ground bed slope is the meandering of canal D (450m) which would however be constructed to a minimum permissible canal radius given by equation 10.

$$r = 70Q^{1/2} \qquad (10)$$

where;
r = minimum radius (A)
Q = discharge (m^3/s)

$$r = 70\ (0.051 \times 35.314)^{1/2}$$
$$= 93.94ft$$
$$28.63m \approx 30m$$

To avoid the possibility of instability outside bank of the curve. The maximum permissible velocity allowable with the sandy clay which will form the channel boundaries was estimated at about 75cm/s (Booher, 1974). Canal design (Figure 4) for the project has been based upon the manning equation with n value of 0.025 and side slope of 1.5:1 to suit the type of soil (Majumdar, 2015).

The design capacity criteria for the various canal were obtained from the formula (equation 11)

$$Q = \frac{A\ d\ g}{360\ \mathrm{PhEc}} \qquad (11)$$

Where = flow rate into the entire canal (3/5)
A = area of field (ha)
dn = gross application depth
P = irrigation period
H = number of irrigation hours per irrigation day
Ec = conveyance efficiency

The tree board or canal bank top level above water level to accommodate inadequate design friction coefficient, sediment, vegetative growth, wave action and anticipated short term flows in excess or normal flow has been based upon equation 12.

$$Fb = 0.67 + 0.25\ Q^{1/3} \qquad (12)$$

Where Fb = free board (A)
Q = discharge (cum/s)

The design criteria are summarized in Table 3 and displayed in Figure 4

Cross paddy irrigation

From equation 8: H = 0.4 - 0.10 - 0.15 = 0.15m

Hence

$$Cd = \sqrt{\frac{2x9.81}{2}}\left(\frac{(1.8)^2-1}{1.8^2}\right)\left(\frac{0.15+0.15}{1.8(0.15+0.15)} - 0.15\right)^{\frac{1}{2}}$$

Therefore, from equation 7:

$$Bo = \frac{7 \times 0.015}{8.64 \times 1.0715 \times (.15)^{1.5}}$$

$$= 0.195\ m/ha/dy.$$

A paddy bund spillway will be required to convey water

Table 3: Canal Hydraulic Design Parameters.

Desc description	Area Ha	Discharge (m^3/s)	Bed slope %	Bed width (m)	Water depth (m)	Total depth (m)	Length (m)
MAINS							
A	1.44	0.020	0.1	0.25	0.15	0.40	225
B	1.48	0.020	0.2	0.25	0.10	0.35	65
C	2.95	0.035	0.1	0.30	0.15	0.45	77
E	4.58	0.051	0.1	0.45	0.20	0.50	450
Distributaries							
A1	0.72	0.18	0.2	0.15	0.075	0.35	50
A2	0.40	0.015	0.2	0.15	0.075	0.325	30
B1	0.39	0.015	0.2	0.15	0.075	0.325	30
B2	0.47	0.016	0.1	0.25	0.10	0.35	125
C1	1.95	0.035	0.2	0.40	0.15	0.45	100
D1	0.75	0.018	0.2	0.15	0.075	0.35	70
D2	1.75	0.020	0.1	0.25	0.15	0.45	118
D3	1.64	0.0185	0.2	0.25	0.15	0.45	105
Total	10.45						

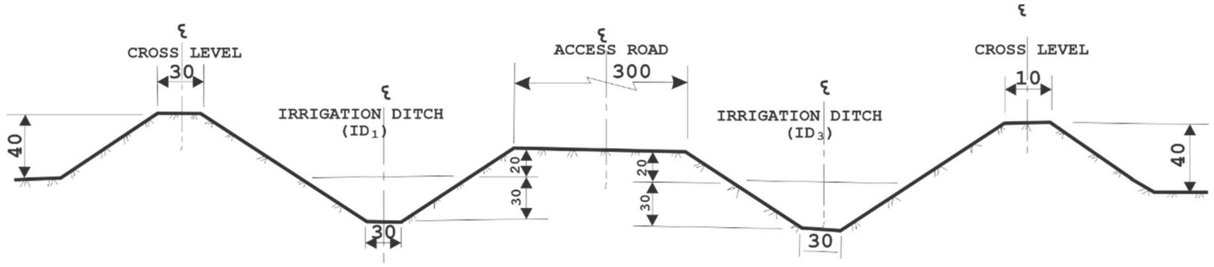

Figure 4: Irrigation ditch cross section

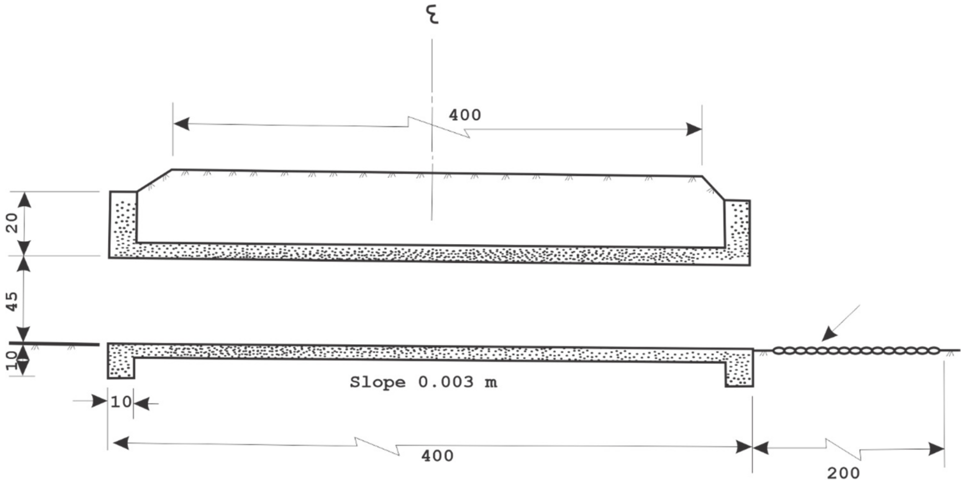

Figure 5: The water control structure comprises of stilling wells

amounting to 0.195 m/ha/dy in cases where paddy fields do not have direct access to farm ditch as calculated from the cross-bund irrigation water flow B_O in equation 7.

Irrigation control structures

The water control structure comprises of stilling wells (Figure 5) at pump line outlets to dissipate excess head, adjustable weir at the main canal head, control regulators on the main canal equipped with stop logs, turn out structures at the distributary head designed to regulate discharge and head regulators on the distributaries. Flow from distributaries canal to field would be controlled by field inlet pipe regulators. The structure would consist of a head operated stop gate and discharge box. The gate would be used to regulate the flow and would be opened and closed according to field water level. The discharge box would ensure that the discharge of the structure was controlled by water level in the distributary and the gate opening.

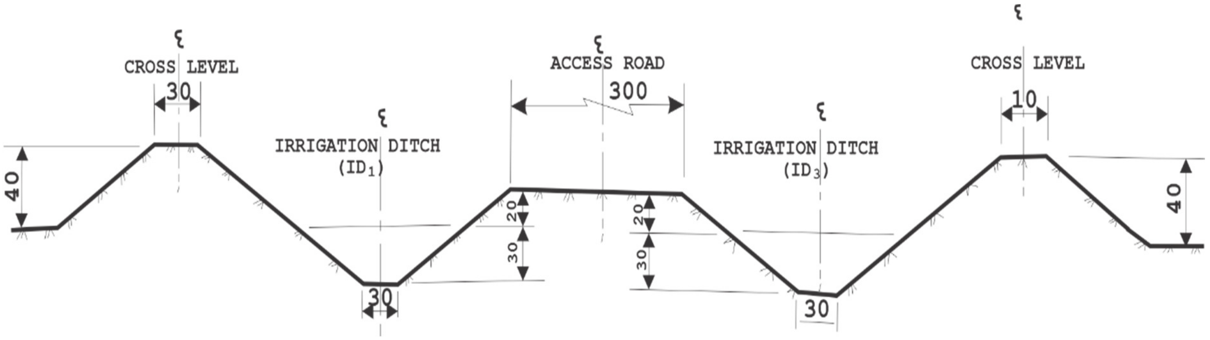

Figure 6: Diagrammatic representation of structure

The head discharge of distributary canal would be controlled by the turn-out-pipe taken from a main channel immediately upstream from a main cross regulator. Stop gates would be used to control the flow while open flow meters are used to measure the amount of water diverted. The propeller flow meters are portable and one can be used for several distributaries while operating effectively in limited water head. The cheapest means of providing such control is by means of vertical hand operated lifting gate. The function of the main canal cross regulators is purely to control the upstream level in the main channel. The head discharge of main channel would be controlled by adjustable wires of from the stilling wall into which water is delivered from the pumping station. Energy dissipaters will be required to dissipate excess kinetic energy possessed by the water coming from the pump line- to avoid canal damage. Due to limitations of hydraulic jump involved in the use of stilling pools the impact type energy dissipaters which direct the water into an obstruction that diverts the flow was considered. Baffle outlet and stilling wall types were studied and the later adopted due to limitation in the Froude number of the system discharge to enable the use of the former. The head to be dissipated by the sleeve valve is the pressure in excess of total static head resulting from the elevation differences of the various discharging points. With well CpW the head to be dissipated was obtained as 5.2m while the line Bp with BpW –stilling well would require about 4.49m head to be dissipated. Table4 summarizes the specification for the various structures while figure 6 is diagrammatic representation. The irrigation control system proposed is unsophisticated, relying on manual rather than automatic control. The reasons for recommending such a system are:

1) Initial capital investment is minimal
2) Maintenance is simplified.

Description of irrigation system

Canal discharges together with areas served are given on (Table 4). The system was designed in accordance with the criteria already discussed. A longitudinal section with full details for the main canals is shown in (Figure 6). The area will be supplied from the confluence of the Atayi and Iyioma streams by way of an intake pipe, pump, and delivery pipes. In all cases water will be discharged into stilling well located at the main canal head ditch from where it will be delivered by the main channels, distributary canal and unit conduits to the project fields. Main A will water the area between the Atayi stream and the southeastern boundary designated AF through the distributary canal A1 and A2 and inlet pipes. The area is generally steep (0.6%) and irregular with probable high developmental cost. At present it is not cultivated but grows wild cocoa yam. Main B runs a distance of about 190m watering fields on either side of the Iyioma stream amounting to 1.48 ha and crosses the Iyioma by over chute at chainage 35. A lot of filling work will be required to bring it to a bed slope 0.2%. The general slope in the area commanded by the channel is about 0.4% irregular and contour leveed to reduce leveling work and reduce un-irrigable land. Earth materials are readily available for its construction from the higher elevations. The main supplies a channel (B1) can irrigate about 1.09 ha directly while running a bed slope of 0.1% after chainage 65. Presently the lower portion of the field (B1) is marshy and with good drainage would be put into cultivation in future. The main finally empties into an outfall drain.

The area north of the pump station is served by main C and distributary C1. The field is relatively regular in shape and occupies over 2.90 ha, with about 0.3% natural ground slope. It is irrigated by the level basin method, served by an outfall drain on the eastern boundary and collector drain on the west while the distributary C1 empties directly into the Atayi stream.

Main D serves three distributaries D1, D2, and D3 and covers a distance of 450m while watering over 4.58 ha fields. It forms the western boundary of the irrigable area demarcating it from the project site office. This area is generally regular in shape and gently sloping and enjoys a mixture of flat basin and contour levee irrigation.

The field is also served by a major access road connecting the pumping house and the site office. The area is well drained by natural depression which has been incorporated into the layout. Development cost would be high because of the high leveling requirement for some plots served by distributary D2, but with the small sized basin the cost will not be too high to upset the overall cost – benefit ratio. Where field is irrigated directly from main, flexible tubes would be used to tap water into the field. Table 4 is summary of the water distribution system envisaged. Inlet pipes include those required for cross paddy irrigation which reduces both labour need and number of irrigation ditches. +Available discharge is only 0.052 m ^{3}/s emphasizing the advantage of rotational irrigation.

Table 4: Land system and area served.

COMMAND	**Gross Area Served (ha)**	**Distributary served No.**	**Field Inlet Pipes No**	**Total Discharge m$^{3/s}$**
AF	1.44	2	5	0.016
BF	1.48	1	7	0.017
CF	2.95	1	9	0.035
DF	4.58	3	20	0.051
TOTAL	10.45	7	41	0.119$^+$

Canal construction and maintenance

Canals could be constructed manually using lorries and shovel because of the small cross section involved. However, where possible, mechanical ditches which can be adjusted to about 0.15 bed width would be used. Where required by the natural ground level as for B, A2, A1, C1, D1, D3, B1 (32% total canal length) ribbon of fill material compacted at 20m layers would be placed before formation of the channel. Material for such fills is readily available from the higher un-irrigable areas. If extra material is required to form canal embarkments it will be obtained from material executed from open drains or the high land borrow areas. The berms (small banks) would be 50cm wide to provide access for the field inspection. Finishing off will be by graders. Good maintenance of canal and structures is prerequisite for the efficient operation of project. The yearlong growing season proposed requires that maintenance be an ongoing process to keep the entire irrigation and drainage system in operating conditions year-round. Regular inspection and maintenance will be there for required. Channels shall be kept in good condition by the removal of aquatic weeds, any deposited sediment or material washed from the banks by rainfall which is left losses through increased seepage evaporation and transpiration.

Aquatic weeds will grow in channels with revolution less than 60cm/s and water depth of less than 0.6m, further decreasing the velocity and consequent increase in sedimentation. Although aquatic growth is killed by intermittent canal operations as is proposed such an operation encourage other weed and grass development.

It is therefore expected that weed growth will be extensive in the channel. Weed can be removed by chemicals (Propanil, 2,4D Amine) but this is not recommended in the early stages of the project since the weeds will assist in stabilizing the channel. Small weed can therefore be removed by hands.

It is anticipated that pumped water would contain only minimal amount of silt which would be satisfactorily removed by the design gradient energy and hence no extensive siltation will occur.

In the early stages before growth of weeds and grass develops canal banks will be liable to gullying from rainfall and material carried into the canal section will have to be removed. For such clearance shovel and other pick instrument would be employed. Apart from the maintenance of already discussed facilitates the project access road and inspection roads as well as field levees will require to be maintained in good condition. Also structures with control gates will require regular inspection. Spare for pumping plant and gates should be stocked against breakdown.

Conclusion

The study set out to determine the design parameters of paddy rice irrigation water distribution system. This includes rice irrigation water requirement, irrigation stream size, and canal hydraulic design. A minimum flow rate of 0.007m3/s/ha was considered adequate for unit irrigation with the highest water need occurring during the flooding periods (Jan 30 – Feb 12, 28 days for dry crop and July 23 to August 5, 21 days for the wet crop). The Canal design for the project is based upon the manning equation with n value of 0.025 and side slope of 1.5:1 to suit the type of soil. The design criteria are calculated and presented in the work. However, energy dissipaters will be required to dissipate excess kinetic energy possessed by the water coming from the pump line- to avoid canal damage. Good maintenance of canal and structures is prerequisite for the efficient operation of project. The yearlong growing season proposed requires that maintenance be an ongoing process to keep the entire irrigation and drainage system in operating conditions year-round. Regular inspection and maintenance water distribution systems are therefore imperative.

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