A FRAMEWORK FOR PERFORMANCE EVALUATION OF RIVER-LIFT IRRIGATION SCHEMES IN SUDAN[2]

by
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INTRODUCTION

The Government of Sudan is implementing an ambitious program of "*privatization of irrigated schemes*" in the entire country. At this stage,however, the activity is mainly confined to the transfer of some aspects of management from the public organizations to the farmers / tenants. Although the turnover process is being applied to all irrigated areas, but the main thrust remains on the river-lift pump schemes. For many of the small pump schemes along the White Nile, the Government has contracted its management role at the level of agricultural operations.

Even in the case of small pump schemes in the White Nile area, the responsibility for water lifting and supply still remains with the Ministry of Irrigation (MOI). At the next stage, it is an expressed intention of the Government to transfer its remaining management role to the private sector in the context of river-lift schemes. For the pump-schemes along the White Nile and Main Nile, the pilot testing of the idea is already underway.

In view of the pending donor-assisted pilot testing of the management turnover plan for irrigation facilities and control of irrigation supply to the farmers, it seems important to quantify its impact on the sustainability, effectiveness and performance of the schemes. For the policy makers, it will be very useful if the research efforts are focussed on providing information about the comparative performance of the river-lift schemes under private and public sector. It is this context in which *"A Framework for Performance Evaluation of River-lift Schemes in Sudan"* is proposed.

This framework intends to document the efficiencies of the pumping plants for lifting the river water and performance status of the irrigated schemes in the public and private sector. The resulting information is then used to drive indices for comparing the above referred management modes. The proposed evaluation is divided in the following four categories: (i) overall diesel powered pumping plants, (ii) functional status of water

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distribution, (iii) performance indicators, and (iv) indices for the comparison of management modes.

As the diesel powered pumping plants are not very common in the irrigated world, there is not enough information available about the evaluation of such systems. As almost all river-lift pumping plants in Sudan are diesel powered, there is need to outline a detailed procedure to determine the efficiencies of the pumping plants. In view of the above stated situation, the section about determining an overall efficiency of the plants is more like an elaborate outline which generally appears in manuals only.

EVALUATION

I. Overall Diesel Powered Pumping Plant Efficiency

Overall efficiency ($E_{overall}$) for an engine-driven pluming plant is defined as the ratio of output work to the input energy. Longenbaugh and Duke (1980) has described the efficiency as the product of the individual components of the pumping plant (turbine pumps) as:

$$E_{overall} = E_{pump} \times E_{gearhead} \times E_{driveshaft} \times E_{engine} \qquad (1)$$

For directly coupled centrifugal pumps, the authors have presented following relationship:

$$E_{overall} = E_{pump} \times E_{engine} \qquad (2)$$

The latter type of pumping plants are very commonly used along the White Nile and many similar small river-lift pump schemes in Sudan. As the current study in the White Nile area is aimed only to determine overall efficiencies of the engine powered pumping plants, the ratio can also be described as follows:

$$E_{overall} = \left[\frac{Output\ \ Work}{Input\ \ Energy}\right] \qquad (3)$$

Where the output work performed by a pump on the liquid is generally described as given below (Jain, 1987):

$$Output\ \ Work = \gamma \times Q \times H \times sg. \qquad (4)$$

In this case the gamma (γ) is the specific weight of water at 4° C i.e. weight per unit volume (1000 kg/m^3), Q is flow rate i.e.

volume per unit time (m^3/sec), H is head (m) and sg. stands for specific gravity of a selected liquid (ratio). Hence, the output work in SI units results as kgf-m/sec. As it is common to describe the input energy in kilo-joules per hour (kJ/h), the output work on water (liquid in this study) is also converted into the units as:

$$10^3 \left(\frac{kg}{m^3}\right) \times Q \left(\frac{m^3}{sec}\right) \times H\ (m) \times \frac{1\ kW}{101.98\ kg\text{-}m/sec} = 9.806 \times Q \times H\ (kW)$$

-------- (5)

or

$$9.806 \times Q \times H\ (kW) \times \frac{3.6 \times 10^3\ kJ}{1\ kWh} = 35301 \times Q \times H \left(\frac{kJ}{h}\right)$$

-------- (6)

When C, a conversion factor, is taken as 35301 (with Q and H as defined above) the Eq. 4 results :

$$Output\ Work\ \left[\frac{kJ}{h}\right] = C \times Q \times H \qquad (7)$$

The input energy of a fuel can be calculated using the following relationship:

$$Input\ Energy\ \left[\frac{kJ}{h}\right] = FCR\ \left(\frac{l}{h}\right) \times EC\ \left(\frac{kJ}{l}\right) \qquad (8)$$

Where fuel consumption rate (FCR) is stated in liters per hour (l/h), and the energy content (EC) is defined in terms of kilo Joules per Liter (kJ/l). Longenbaugh and Duke (1980) have provided following energy contents for various fuels:

Fuel	Energy Contents		Fuel	Energy Contents	
Diesel	39020	(kJ/l)	Gasoline	34,560	(kJ/l)
Butane or Propane	26,340	(kJ/l)	Natural Gas	35,550 - 37,260 (kJ/m^3)	

For diesel fuel, Karassik et al.(1985) have also reported its energy contents being 4.4 MJ/kg. Depending on origin or percent and type of solvent, the specific gravity of diesel varies from 0.82 to 0.95. Comparison of the two above sources of energy contents of the fuel suggests that if an average value of specific gravity for diesel is taken as about 0.89, both converge to the similar values.

In many river-lift small and medium size pump schemes of Sudan are powered by diesel fuel. Using the diesel contents of diesel, the input energy (IE) becomes:

$$IE\ [\frac{kJ}{h}] = FCR\ (\frac{l}{h}) \times 39020\ (\frac{kJ}{l}) = 39020 \times FCR\ (kJ/h)$$

------- (9)

In order to determine overall efficiency ($E_{overall}$), Eqs. 7 and 9 are substituted in Eq. 3 to get

$$E_{overall} = \frac{35301 \times Q\ (\frac{m^3}{sec}) \times H\ (m)}{39020 \times FCR\ (\frac{l}{h})} \quad (10)$$

or

$$E_{overall} = \frac{0.905 \times Q\ (\frac{m^3}{sec}) \times H\ (m)}{FCR\ (\frac{l}{h})} = \quad (11)$$

Output work has already been derived in terms of kilo-watts as

$$Output\ Work\ (kW) = 9.806 \times Q\ (\frac{m^3}{sec}) \times H\ (m) \quad (12)$$

Similarly, input energy can also be expressed in kilo-watts. This can be dine by converting the energy content (EC) into kW-hrs / l as suggested by Purkey (1993):

$$EC_{diesel}\ (\frac{kJ}{l}) = 39020\ (\frac{kJ}{l}) \times 1000\ (\frac{J}{kJ}) \times 2.778\ (\frac{kW\text{-}h}{J})$$

------- (13)

or

$$EC_{diesel} = 39020\ (\frac{kJ}{l}) = 10.84\ (\frac{kW\text{-}h}{l}) \quad (14)$$

Substitution of Eq. 6 into Eq. 3C provides relationship for input energy. If the fuel is considered to be diesel, then the energy can be given as below:

$$[Input\ Energgy]_{diesel}\ (kW) = FCR\ (\frac{l}{h}) \times 10.84\ (\frac{kW\text{-}h}{l})$$

------- (15)

Finally, when the Eqs. 5 and 7 are filled in Eq. 3, an overall efficiency of a diesel powered pumping plant results or

$$E_{overall} = \frac{9.806 \times Q\,(\frac{m^3}{sec}) \times H\,(m)}{10.84 \times FCR\,(\frac{l}{h})} \qquad (16)$$

$$E_{overall} = \frac{0.905 \times Q\,(\frac{m^3}{sec}) \times H\,(m)}{FCR\,(\frac{l}{h})} \qquad (17)$$

which is exactly the same relationship as given by Eq. 11.

As the fuel consumption rate, FCR, is recorded in gallons per hour, appropriate conversion into liters per hour will be required. For imperial and U.S. gallons, the conversion factors are 4.546 and 3.785 respectively.

In order to determine an overall efficiency of diesel powered pumping plants, the use of Eq. 4 or 8 will require following measurements: (i) pumped flow rate, Q (m^3/sec), (ii) total head, H (m), and (iii) fuel consumption rate, FCR (liters / hour). Methodology applied for the measurements is briefly described below in the context of the White Nile river-lift pumping plants.

(i) Flow Rate, Q (m^3/sec)

In the field, there are not very many options available for measuring the flow rates of the White Nile river-lift pumps. Three techniques used are given as follows:

A. **Purdue Trajectory method:** This flow measuring procedure is used in cases where the delivery pipe is not submerged and water is discharged in the air making a trajectory. This method requires a delivery pipe to full and horizontal. Accuracy of such measurements is stated to be 90-100 percent (Colt Industries, 1973). Following equation determines the flow rate (Bos, 1989):

$$Q = \frac{C_d\ \Pi\ D_p^2}{4} \sqrt{g\ \frac{X^2}{2\ Y}} \qquad (18)$$

where: Q = m^3/sec, C_d = coefficient of discharge taken as 1.10, D_p = diameter of pipe (m), g = acceleration due gravity (9.81 m / sec^2, and X (m) & Y (m) represent coordinates of the trajectory.

B. **Velocity - Area Methods:** The flow rate passing a point in an open channel can be estimated by multiplying the cross-sectional area of the flow section perpendicular to the direction of flow and average velocity. Following three velocity-area methods will be considered for determining the rate of water pumped in different schemes:

1. Current Meters: Flow is estimated with current meter when a delivery pipe is submerged and there is no flow measuring device or structure installed. With current meter, velocity of flow is estimated. For example, a propeller type current meter being used by IIMI-Sudan in the White Nile schemes has the following calibrated equation (it may differ from for unit to other) an average velocity (V) at selected point:

$$V = 0.2281\ n + 0.023 \quad for\ n \leq 0.67 \qquad (19)$$

and

$$V = 0.2475\ n + 0.01 \quad for\ n \geq 0.67 \qquad (20)$$

where: n = revolutions per second measured at a selected depth from the water surface along a vertical.

Once the average velocities for different selected verticals are determined as per equations given above, the total flow rate then become a simple summation of the products of different subsection areas and respective average velocities. If A_i (m^2) and V_i (m/sec) are average area and velocity of an ith vertical (total verticals being n) channel cross-section, the discharge can be computed by the following equation:

$$Q = \sum_{i=1}^{i=n} (A_i \ V_i) \qquad (21)$$

As the current meter measures velocity at a point only, there are different ways to select such a point or points to have good estimate of the respective average velocity in a selected vertical. Generally, there are two practical methods used for the measurement: (1) two point method, and (2) six-tenth depth method (PRC Engineering / CHECCHI, 1987). The two-point method is applied to measure velocity in a vertical at 0.2 and 0.8 of the depth from the water surface. The mean of the two measurements gives an average velocity of at the vertical representing a subsection of a channel or stream. This method is applied where flow depths are 0.6 m or more.

For the flow depths less than 0.6 m, six-tenth depth method gives fairly satisfactory results. In the latter case, velocity is measured at 0.6 of the depth from the water surface for the shallow flows.

2. Float Method: This method is not as accurate to estimate average velocity as is done with current meter. But, on the other hand, it is less time consuming. The accuracy can be improved if the method is applied in prismatic section of an open channel and better determination of a constant factor in the following equation:

$$Q = f \times X\text{-}Section\ Area \times Float\ Velocity \quad (22)$$

where "f" is the constant factor which can be determined by the vertical velocity curve method of current metering.

Electro-magnetic Flow Meters: These meters are also used to estimate average velocity at the end of a delivery pipe of a pump. As they are calibrated to give direct velocity at point, in many pump manufacturing firms use these devices for developing H-Q relationships.

L-Tube Method: This technique can be used to estimate average velocity for a cross-section of a flowing pipe and in fact it is a slight modification in the application of the Pitot method. In this case, just at the exit of a delivery pipe of a pump a small diameter L-shaped tube can be used to determine velocity at a line perpendicular to flow. These velocities can then be averaged and multiplied with the cross-sectional area to determine discharge.

This method does not require static head measurements as the points of measurement proposed are exposed to atmospheric pressure. The L-tube can be fabricated locally and it appears to be relatively more practical under field conditions. Tests conducted in the field indicate results being satisfactory. However, the exact accuracy level has yet to be determined under controlled laboratory conditions.

C. **Weir Flow Measurement:** In some schemes along the White Nile, discharge measuring devices are installed. These are mainly rectangular weir structures attached to discharge boxes. In such cases, the measurements are easier to make and they are relatively more accurate. Bos (1989) has presented following discharge equation for a rectangular sharp-crested weir:

$$Q = C_e \frac{2}{3} \sqrt{2g}\ b\, h_1^{1.5} \quad (23)$$

where: C_e = effective discharge coefficient as determined according a table given in Appendix 1,
b = full width (m) of a fully contracted weir,

h_1 = head (m) over the crest of a fully contracted weir, and
Q = flow rate (m^3/sec).

D. **Vane Flow-meter Measurements:** In order to determine performance of water distribution at different levels of the irrigation systems of the selected White Nile pump schemes, Vane Flow-meter is used. For estimating discharge, this device measures either the deflection of or the restoring moment on a flat plate (Ali, 1993). Flow is directed through horizontal pipe / (s) and the meter is placed at a rectangular groove through which vane is lowered into the flowing water causing deflection. To determine moment (M), weights are applied to the meter to secure vane-equilibrium. As suggested by the Weller (1986), for the pipe of one meter in length and 0.35 m in diameter, following discharge relationship is used:

$$Q = \frac{0.693\sqrt{M}}{1000} \qquad (24)$$

where: Q = Flow rate (m^3/sec), and
M = Moment (g-cm).

E. **Volume Method for Water measurement:** This is a simple but relatively accurate method for measuring small irrigation systems. By using a container with known capacity and a stop watch, the flow rate can be determined by the relationship:

$$Q\ (L/\text{sec}) = \frac{\text{Volume of Container, liters}}{\text{Filling time, seconds}} \qquad (25)$$

This method can easily be applied for measuring flows of small river lift pumps (10-12.5 cm delivery pipe size). These pumps are very common in the private sector scheme in the White Nile area. For many cases, already described trajectory method can be used. However, where delivery pipe is submerged in a conveyance channel, the referred method can not be applied. In such cases also, the delivery pipe can be connected a plastic pipe to divert water to a container.

F. **Flow Estimation Using Manning's Equation:** The application of the method is suggested because of many culvert-pipes are found partly full and provide a circular open channel flow conditions. The flow rate can be estimated by the equation given below:

$$Q\ (m^3/\text{sec}) = \frac{A\ R^{\frac{2}{3}}\ S^{\frac{1}{2}}}{n} \qquad (26)$$

Where:
A (m^2) is the flow area of a partly full pipe and can be

calculated using following relationship:

$$A\ (m^2) = 0.125\ [\ \theta - \sin\theta\ ]\ D^2 \qquad (27)$$

R (m) is the hydraulic radius and for the partly full pipes is determined as follows:

$$R\ (m) = 0.25\ [\frac{\theta - \sin\theta}{\theta}]\ D \qquad (28)$$

S (m/m) is the water slope and n is the roughness coefficient.

(ii) Total Head, H (m)

The total head in meters is defined as the head against which a pump must work when pumping a liquid (water). Mathematically it can be described as

$$H\ (m) = H_{delivery}\ (m) - H_{suction}\ (m) \qquad (29)$$

where $H_{delivery}$ = total delivery head in meters, and
$H_{suction}$ = total suction head in meters.

Note: $H_{suction}$ is taken negative when water is lifted below the center line of a pump and positive otherwise.

A. **Total Delivery Head, $H_{delivery}$:** This head is measured in meters and it is the sum total of static discharge head and friction head in the discharge system as given below:

$$H_{delivery} = h_{sd} + h_{fd} \qquad 30)$$

where h_{sd} = static discharge head in meters is the vertical distance from the pump datum to the water surface in the discharge basin if delivery pipe is submerged, or to the center line of the delivery pipe if it is not submerged.

h_{fd} = friction discharge head in meters is the head needed to overcome friction in the pipe, valves, fittings, turns, exit losses etc. in the discharge system.

B. **Total Suction Head, $H_{suction}$:** The total suction head in meter is the sum total of the static suction head or lift and the friction suction head in the suction system presented as follows:

$$H_{suction} = - h_{sl} - h_{fs} \qquad (31)$$

where h_{sl} = static suction head or lift in meters is the vertical difference in elevation between the pump datum

and surface of water in suction bay when pump is running.
h_{fs} = friction suction head in meters needed to overcome friction in pipe, valves, fittings, turns, entrance losses etc. in the suction system.

Note: Friction heads in the discharge and suction systems can be estimated by referring to any pump handbooks or relevant hydraulic books.

(iii) Fuel Consumption Rate, FCR (liters / hour)

This piece of information is generally available from the record of the pump operators. In the White Nile area, the fuel consumption rates are recorded as gallons of diesel per hour which can easily be converted into liters per hours. In order to ensure the reliability of the data, direct measurement of the rate is desirable. This can easily be done by filling the fuel tank and operating the pump for say two to three hours. Refilling the tank after the test should provide the required rate quite accurately.

II. Functional Status of Water Distribution System

Functional status of the water distribution will be documented as proposed by Purkey (1992):

System	*Poor*	*Fair*	*Good*
Main Intake	- covered with water hyacinth - sloughing and eroding banks - much debris	- Few water hyacinth - small rills on banks - little debris	- no water hyacinth - stable banks - no debris
Conveyance Network	- heavy degree of siltation - deep dike erosion - many weeds	- moderate degree of siltation - superficial dike erosion - few weeds	- small degree of siltation - minimal dike erosion - no weeds
Division Structure	- leaking heavily - heavy degree of siltation - many weeds	- slow leaks - moderate degree of siltation - few weeds	- no leaks - small degree of siltation - no weeds
Farm Inlet Structures	- many breaches in field dike - heavy soil erosion at inlet	- few breaches in field dike - mild soil erosion at inlet	- no breaches in field dike - light soil erosion at inlet

As the water distribution system in the area is managed by more than one agency or group, the above visual method can help to compare the management performance of each agency or group. However, it simply provides qualitative information only.

III. Indices for Physical System Performance

For the evaluation of the White Nile pumping schemes, the performance indicators are divided into three categories: (II.A) fuel consumption of the diesel powered pumping plants, (II.B) maintenance of pumps, and (II.C) water supply in the project area. This information then can be used to compare the performance of different schemes under different management modes being tried in the project area.

III. A Performance Indicators for Fuel Consumption

Fuel consumption can be considered a useful indicator for many diesel powered pumping plants under the control of the Ministry of Irrigation (MOI) supplying water to the small irrigated schemes under different management modes. The Ministry keeps records of fuel consumption in gallons per hour for each and every river-lift pump in the area. These consumption rates are then used for providing diesel to the field and estimating future fuel needs of the project. In order to determine the ***Actual Fuel Consumption Status, AFCS,*** ratio between actual and reported fuel (diesel) consumption rates, following index will be utilized:

$$AFCS = \frac{Actual\ Fuel\ Consumption\ per\ Hour}{Reported\ Fuel\ Consumption\ per\ Hour} \qquad (32)$$

As compared to many gravity flow systems in Sudan, the cost of pumped water particularly with diesel powered plants is expected to be very high. There is some adjustments made in water charges for all MOI operated schemes. However, the adjustments may not reflect the extra cost associated with the lifting of water. In order to compare the expected cost recovery and cost incurred only for the supply of diesel per unit area may reveal the actual cost recovery status (CRS), for the pump schemes. This indicator (CRS) can be presented as follows:

$$CRS = \frac{Fuel\ Cost\ Per\ Unit\ Area\ Per\ Crop}{Cost\ Recovery\ Per\ Unit\ Area\ Per\ Crop} \qquad (33)$$

III. B Performance Indicators for Pump operations

It is important to note that water indenting procedure for the pumping schemes is different than the one followed in the large gravity-fed systems of Sudan. Instead of the volume of water, as is the latter case, indents are placed in terms of daily hours of pump operation. Depending upon the availability of fuel (diesel), oil and spare parts; condition of individual pumps, maintenance status, interest and incentives for the pump-operators, accountability mechanisms built in the system, and many similar factors will determine the level of response to the daily indented hours. Although the records of the relevant department in the White Nile area show almost 100% demand met in the field, it will be useful to document if the generally reported excellent performance is a reality or myth. In order to measure such performance, Daily Pump Operation Ratio (DPOR) can be defined as

$$DPOR = \frac{Reported\ Daily\ Pump\ Operating\ Hours}{Actual\ Daily\ Pump\ Operating\ Hours} \qquad (34)$$

III. C Performance Indicators for Maintenance

As there are different modes of management being tried on the agriculture side of the schemes, it is hypothesize that they may influence the time taken for the repair and maintenance (R & M) of the pumping plants. The lift-pumps are still operated by the Ministry of Irrigation but the indirect impact of the managing parties on the receiving end for the R & M of plant can be quantified by the following ***Repair Maintenance Ratio (RMR)***:

$$RMR = \left[\frac{Repair + Maintenace\ Hours}{Indented\ /\ Planned\ hours}\right]_{Period_i} \qquad (35)$$

For each level of water distribution system, following measure of maintenance performance,MP, (Bos et al, 1993) can be used:

$$MP = \frac{Number\ of\ functioning\ Structures}{Total\ Number\ ofStructures} \qquad (36)$$

III. D Performance Indicators for Water Distribution

The soils in the area are heavy montmorillonite type of clays. They develop large cracks on drying. The infiltration rates are very low and most of the water absorption occurs through the cracks during the advance phase only. Due to the nature of soils, infiltration characteristics may not change in the season. This implies that the amount of water stored in the root zone comes same each time. So, to deal with increased crop water needs the frequency of irrigation is increased (at least according to the books).

In the above stated context, the issues of adequacy, equity and reliability of water supply can be evaluated in simple way. Molden and gates (1990) have dealt with the matter by using ratios of supplies delivered and supplies required. In this paper, the ratio will be based on number of irrigations delivered and planned. Mathematical treat will be taken same.

1. Parameter for Adequacy:

A fundamental objective of the irrigation systems in Sudan is to deliver water according to crop water requirement. Like many gravity irrigation system, it is difficult to apply exact measured amount of water needed. Generally, the adequacy level in such cases is determined by comparing the number of irrigations supplied to the number of planned irrigations. Hence, for selected irrigated scheme or level of system the adequacy can be quantified as follows:

$$P_A = 1 - \left[\frac{1}{T} \sum_{T=1}^{T=n} \left(\frac{1}{R} \sum_{R=1}^{R=M} P_a \right) \right] \qquad \text{------------ (37)}$$

where

$$P_a = \frac{NOI_s}{NOI_p} \quad if\ NOI_s \leq NOI_p \qquad (38)$$

and

$$P_a = 1 \quad otherwise \qquad (39)$$

In the above equations the notations NOI_s and NOI_p represent number of irrigations secured / supplied and number of irrigations planned / recommended respectively. These relationships also indicate that NOI_s and NOI_p are considered for different locations (M) within a region R, and for finite times (N) within a period T.

As Eq. () is a slightly modified version of a relationship proposed by Molden and Gates (1990) for adequacy, standard of performance based on the values P_A is adjusted accordingly. The tentative performance standard as proposed by the referred authors is translated for the modified equation as follows: (i) the adequacy level is good if P_A falls between 0 and 0.1, (ii) fair for the value of P_A is within 0.11 and 0.20, and (iii) unsatisfactory if the resulting P_A is more than 0.2.

2. Parameter for Reliability / Dependability:

The parameter for reliability / dependability indicates the uniformity of quantity delivered to quantity required / planned. This quantity can be expressed either amount of water or number of irrigations. If quantity is taken in term of number of irrigations, the time span will spread over different irrigation seasons and the index will express reliability in the defined dimension of time. In such case, the parameter can be defined as under:

$$P_D = \frac{1}{R} \sum_{R=1}^{R=m} CV_T \left(\frac{NOI_s}{NOI_p} \right) \tag{40}$$

where $CV_T(NOI_s/NOI_p)$ is the temporal coefficient of variation, the ratio of standard deviation to the mean, of the ratio NOI_s/NOI_p for one discrete location within a region R. If the region R has M locations, the P_D, the parameter of reliability, is an average of the temporal coefficients of all locations.

In order to evaluate the irrigation performance in terms of reliable / dependable water distribution, the standard proposed by Molden and Gates (1990) is opted. It suggests that reliability of irrigation supplies will be good, fair and unsatisfactory if the calculated P_D values fall within 0.0 - 0.1, 0.11 - 0.20, and more than o.20 respectively.

3. Parameter for Equity of Water Distribution:

As defined by Mohammed (1987), the equity in water distribution is the ability of a system to deliver water uniformly. When water delivery is expressed in terms of the number of irrigations, following parameter for equity, similar to one suggested by Molden and Gates (1990) and Kuper and Kijne (1993) but with some adjustments, can be defined:

$$P_E = \frac{1}{T} \sum_{T=1}^{T=n} CV_R \left(\frac{NOI_s}{NOI_p} \right) \tag{41}$$

In the above equation, $CV_R(NOI_s/NOI_p)$ is the spatial coefficient of variation, the ratio of standard deviation to the mean, for a specific time over a region R with M locations. If a period T contains N times, the parameter of equity, P_E, is an average of the spatial coefficients of variation of all times.

It is obvious from the definition of parameter of equity that P_E values closer to zero indicate a higher degree of equity in irrigation supplies to the farmers of a region R. Again after Molden and Gates (1990) the boundaries between good, fair and unsatisfactory performance are based on the values of P_E being 0.1 and 0.2.

IV. Indices for the Comparison of Management Modes

VI. A Comparative Indices Fuel (diesel) & Oil Consumption

1. **Comparative Index for Diesel Consumption (CIDC):** This index is suggested to compare diesel consumption per unit cropped area in case of the private and public river lift pumping plants along the White Nile. Considering the higher capacity of the pumping plants and larger size of the river-lift irrigation schemes in the public sector, it seems logical to expect fuel (diesel in the context of Sudan) consumption per cropped lesser for public pumps as compared to private pumps. However, for many complications associated with management mode opted may change the situation in the field. In order to verify the hypothesis, the *comparative index for diesel consumption*, CIDC, is defined as follows:

$$\frac{[\textit{Diesel Consumption / Cropped Area}]_{\textit{Private}}}{[\textit{Diesel Consumption / Cropped Area}]_{\textit{Public}}} \qquad (42)$$

2. **Comparative Index for Oil Consumption (CIOC):** The need to test the index is also based for similar reasons as stated above. Like the CIDC, the *comparative index for oil consumption* (CIOC) is ratio of oil use per unit cropped area by the private and public operated pumping plants. The index is described below:

$$\frac{[\textit{Oil Consumption / Cropped Area}]_{\textit{Private}}}{[\textit{Oil Consumption / Cropped Area}]_{\textit{Public}}} \qquad (43)$$

VI. B Comparative Indices for Repair, Maintenance & Operation

1. **Comparative Index for Maintenance Cost (CIMC):** In spite of the possible advantage resulting from the economy of scale, it is not a very definite that the maintenance cost per unit cropped area for the public pumping plants is lesser than the one incurred for the contemporary small river lift pumps in the private sector. In order to document the relationship between the both cases, following *comparative index for maintenance cost*, CIMC, is proposed:

$$\frac{[\textit{Maintenance Cost / Cropped Area}]_{\textit{Private}}}{[\textit{Maintenance Cost / Cropped Area}]_{\textit{Public}}} \qquad (44)$$

2. **Comparative Index for Repair and Maintenance Ratios (CIRMR):** The *repair and maintenance ratio*, RMR, defines the relationship between time taken for repair and maintenance as compared to the indented

or planned time for the operation of the river-lift pumps. The *comparative index for repair and maintenance ratios*, CIRMR, provides comparison of the RMRs under the private and public managements. In reality, the index is indented to identify one of the two management modes which is more responsive for the repair and maintenance of the lift pumping plants. The comparative index is described as under:

$$\left[\frac{RMR_{Private}}{RPR_{Public}}\right] Period_i \tag{45}$$

3. Comparative Index for Major Breakdowns (CIB_{Major}): This ratio for the two management modes is based on number of major breakdowns during a selected period or season. It is intended to depict indirectly the capacity of the private or public managements to avoid major breakdowns by attending repair and maintenance problems in a timely manner. The ratio is presented as:

$$\frac{[Number\ of\ Major\ Breakdowns\ /\ Season]_{Private}}{[Number\ of\ Major\ Breakdowns\ /\ Season]_{Public}} \tag{46}$$

4. Comparative Index for Minor Breakdowns (CIB_{Minor}): This index is similar to the one suggested for major breakdowns. The selection of minor breakdowns is to explain occurrence of major breakdowns in any one of the management modes. Underlying assumption in this case is that if minor breakdowns are confronted promptly when they are detected, many major breakdowns can be avoided. This is also an indirect measure to compare the degree to which each management looks after its pumping plants. The *comparative index for minor breakdowns* is defined below:

$$\frac{[Number\ of\ Minor\ Breakdowns\ /\ Season]_{Private}}{[Number\ of\ Minor\ Breakdowns\ /\ Season]_{Public}} \tag{47}$$

5. Comparative Index for Repair Time - Major Breakdowns ($CITB_{Major}$): The above two indices are to show that if a management provides proper and on-time repair and maintenance its pumping plants, breakdowns can be minimized. This and next indices are indented to look at the capacity of each management mode, private and public, which attends the breakdowns once they happened. For the major breakdown, the comparative index is described:

$$\frac{[Av.\ Time\ Taken\ /\ Major\ Breakdown]_{Private}}{[Av.\ Time\ Taken\ /\ Major\ Breakdown]_{Public}} \tag{48}$$

6. Comparative Index for Repair Time - Minor Breakdowns ($CITB_{Minor}$): It is related to average time taken in fixing minor breakdowns. The reason to include the index is that procedural complications may effect the promptness of a managing agency, group or individuals for attending even minor breakdowns. Readily availability of spare parts may also be one factor in this context. Like for major breakdowns, the *comparative index of time taken for minor breakdowns* is given as follows:

$$\frac{[Av.\ Time\ Taken\ /\ Minor\ Breakdown]_{Private}}{[Av.\ Time\ Taken\ /\ Minor\ Breakdown]_{Public}} \qquad (49)$$

7. Comparative Index for Pump Operation (CIPO): The measure is aimed at the two management modes in providing effective repair and maintenance of pumping plants which result into seasonal longevity in the hours of operations per cropped area. Because of differences in discharge rates, the index does not necessarily mean one management mode is better than other, it just shows the usefulness of timely repair and maintenance activities. The comparative index good only if the availability of spare parts and fuel is not serious constraint. The ratio is described as:

$$\frac{[Operation\ Hours\ /\ Season\ /\ Cropped\ Area]_{Private}}{[Operation\ Hours\ /\ Season\ /\ Cropped\ Area]_{Public}} \qquad (50)$$

VI.C Comparative Indices for Irrigation Water Supplies

1. Comparative Index for Pump Discharge (CIPD): This index is intended to compare the water supply capacities of systems under public and private management modes on unit cropped area basis. This should help to identify under or over-capacity status under each management at water supply level. The comparative index for pump discharge is defined as under:

$$\frac{[Pump\ Discharge\ /\ Cropped\ Area]_{Private}}{[Pump\ Discharge\ /\ Cropped\ Area]_{Public}} \qquad (51)$$

2. Comparative Index for Irrigation Time (CIIT): This measure is aimed to see if irrigation management practices under each mode differ or not. Underlying assumption in this case is that one management mode may do better in applying water efficiently by say adjusting stream size per unit width, leveling of fields, paying more attention at the time of irrigation etc.

$$\frac{[Av.\ Irrigation\ Time\ /\ Unit\ Area]_{Private}}{[Av.\ Irrigation\ Time\ /\ Unit\ Area]_{Public}} \qquad (52)$$

VI. D Comparative Indices for Cost Recovery

1. **Comparative Index for Water Charges (CIWC):** This indicator is proposed to compare price water paid by the farmers who do not own a lift-pump in the private sector and water charges assessed by the Ministry of Irrigation for the farmers / tenants served by public lift pumps. The comparison is expected to show the scope and willingness of the farmers to pay extra if the water supply can be made available at a time and quantity required.

$$\frac{[Water\ Charges\ /\ Feddan\ /\ Crop]_{Private}}{[Water\ Charges\ /\ Feddan\ /\ Crop]_{Public}} \qquad (53)$$

VI. E Comparative Indices for Crop Production

1. **Comparative Index for Crop Yields (CICY):** The comparative ratio is intended to compare crop yields per unit area under two selected management modes for water supply. Although there may be many other factors which effect yields, timely availability of required water supply is considered to have very significant direct and indirect influence on crop yields. The Comparative Index for Crop Yield, CICY, is defined as under:

$$\frac{[\ Crop\ \ Yield\ \ /\ \ Feddan]_{Private}}{[Crop\ \ Yield\ \ /\ \ Feddan\ ]_{Public}} \qquad (54)$$

2. **Comparative Index for Crop Profitability (CICP):** In most cases, the ultimate objective of trying different management practices under different modes is to improve profitability of farmers. In order to compare net profit per unit area per crop for private and public water supply modes can be described by a ratio, CICP, as follows:

$$\frac{[Crop_i\ Profitability\ /\ Feddan]_{Private}}{[Crop_i\ Profitability\ /\ Feddan]_{Public}} \qquad (55)$$

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