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DISCHARGE AND MECHANICAL EFFICIENCY OF EGYPTIAN WATER-LIFTING WHEELS

By

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ABSTRACT

In irrigated areas where water is a limiting resource, evaluation of irrigation practices is important. In Egypt and neighboring areas, where waterwheels are used to lift the water from supply canals to field level, two important parameters in evaluating an irrigation system are the discharge per revolution and the mechanical efficiency of the waterwheel. Data on thirty-five spiral-shaped waterwheels from the Mansuriya and Kafr El-Sheikh regions of Egypt were used to develop a field procedure for calibrating the dischange per revolution relative to the percent of submergence of the wheel. Thus, the rate and quantity of water applied to a field could be determined using data on the number of revolutions and the change of submergence of the wheel over time. A typical discharge per revolution of a 3 m diameter wheel, lifting water 75 cm, was 600 liter/rev. In addition, a procedure was developed to determine the mechanical efficiency from field data. Data on eleven waterwheels from the Kafr El-Sheikh area were analyzed and indicated that a well-designed and maintained installation might be expected to have a mechanical efficiency of 45%.

37 pages 11 figures

ملخص

فى مناطق الرى ذات المورد المائى المحدود يعتبر تقييم طرق الرى المستخدمه بها امرا ضروريا .فى مصر وفى المناطق المجاوره لها والتى تستعمل بها الساقيه لرفع المياه من الترع الى الحقول يدخل عاملين اساسيين فى تقييم نظام الرى وهما التصرف للدوره الواحده والكفاءه الميكانيكيه للساقيه. وقد تم تجميع البيانات على عدد خمسه وثلاثون ساقيه فى منطقتى المنصوريه وكفر الشيخ بمصر وذلك لاستنتاج طريقه تستعمل فى الحقل لمعايرة التصرف للدورة الواحده بالنسبه للنسبه المئويه للعمق المغمور من عجلة الساقيه. وبهذا فانه يمكن حساب معدل وكمية المياه الداخله للحقل عن طريق استخدام البيانات الناتجه من عدد الدورات للساقيه ومقدار التغير فى العمق المغمور لعجلة الساقية بالنسبه للزمن ،وكمثال فقد وجد ان التصرف للدوره الواحده لعجلة ساقية قطرها ٣ متر وترفع المياه ٧٥ سم كان يساوى ٦٠٠ لتر / الدوره وبالاضافه الى هذا ،فانه تم استنتاج طريقه لحساب الكفاءه الميكانيكيه من البيانات الحقليه .

وقد تم تحليل البيانات لعدد ١١ ساقيه بمنطقة كفر الشيخ وقد اظهرت هذه التحاليل انه باستعمال سواقى مصممه جيدا وتحت صيانه جيده من المتوقع بانه تصل كفائتها الميكانيكيه الى ٤٥ ٪ .

٣٧ صفحه ١١ شكل

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Introduction

Many areas throughout the world lift water for irrigation purposes using a waterwheel. Various types of animal powered water-lifting wheels have been developed to meet local needs. A certain wheel used throughout Egypt relies on spiral channels to move the water toward an outlet at the center of the wheel. The top, front and right side views of a typical waterwheel installation are presented in Figure 1. Water from the supply canal passes through the inlet pipe to the reservoir where it is collected by the buckets of the turning wheel. As the wheel turns, the water is spiraled toward the outlet at the center. The configuration of the water within the operating wheel is indicated in Figure 2. The wheel discharges the water through the outlet flange into the exit channel. The outlet pipe carries the water under the elevated animal track to the field head ditch.

Power to lift the water is supplied to the vertical axis by a draft animal as it moves in a circular path. Forged bevel gears are commonly used to transmit power from the vertical axis turned by the animal to the horizontal axis of the wheel.

The discharge per revolution, q, from the waterwheel installation is important in irrigation analyses. From information on this parameter and the number of revolutions in a time period, the rate and total volume of water entering the field head ditch can be determined.

The mechanical efficiency of this waterwheel method of lifting water is also of interest. The mechanical efficiency, eff, can be used to evaluate modifications and improved designs. Efficiency is one of the important parameters used in comparative analyses between this and other methods of lifting water. The objectives of this study were to develop

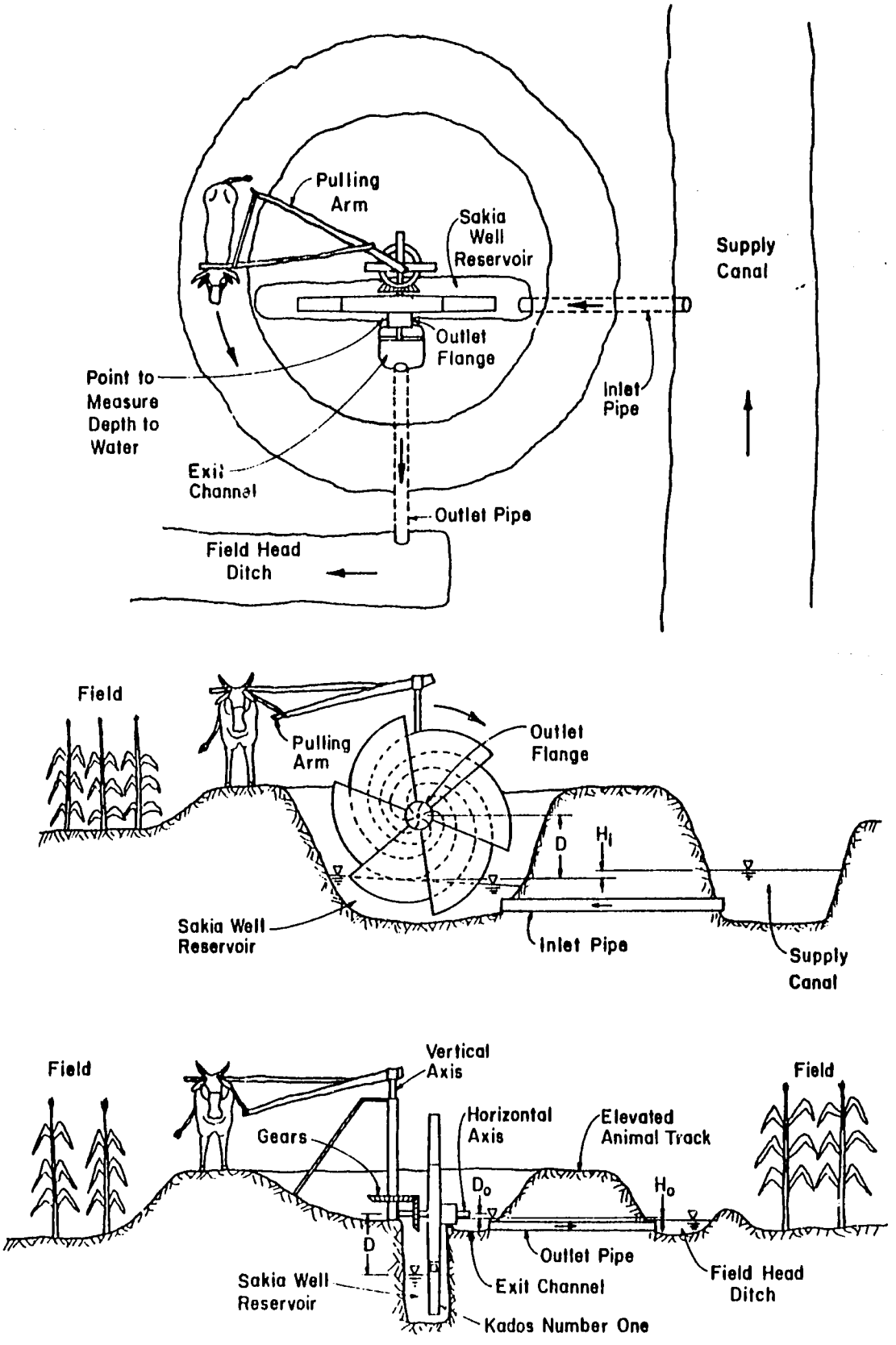

Figure 1. (a) top, (b) front, and (c) right side views of a typical Egyptian waterwheel installation.

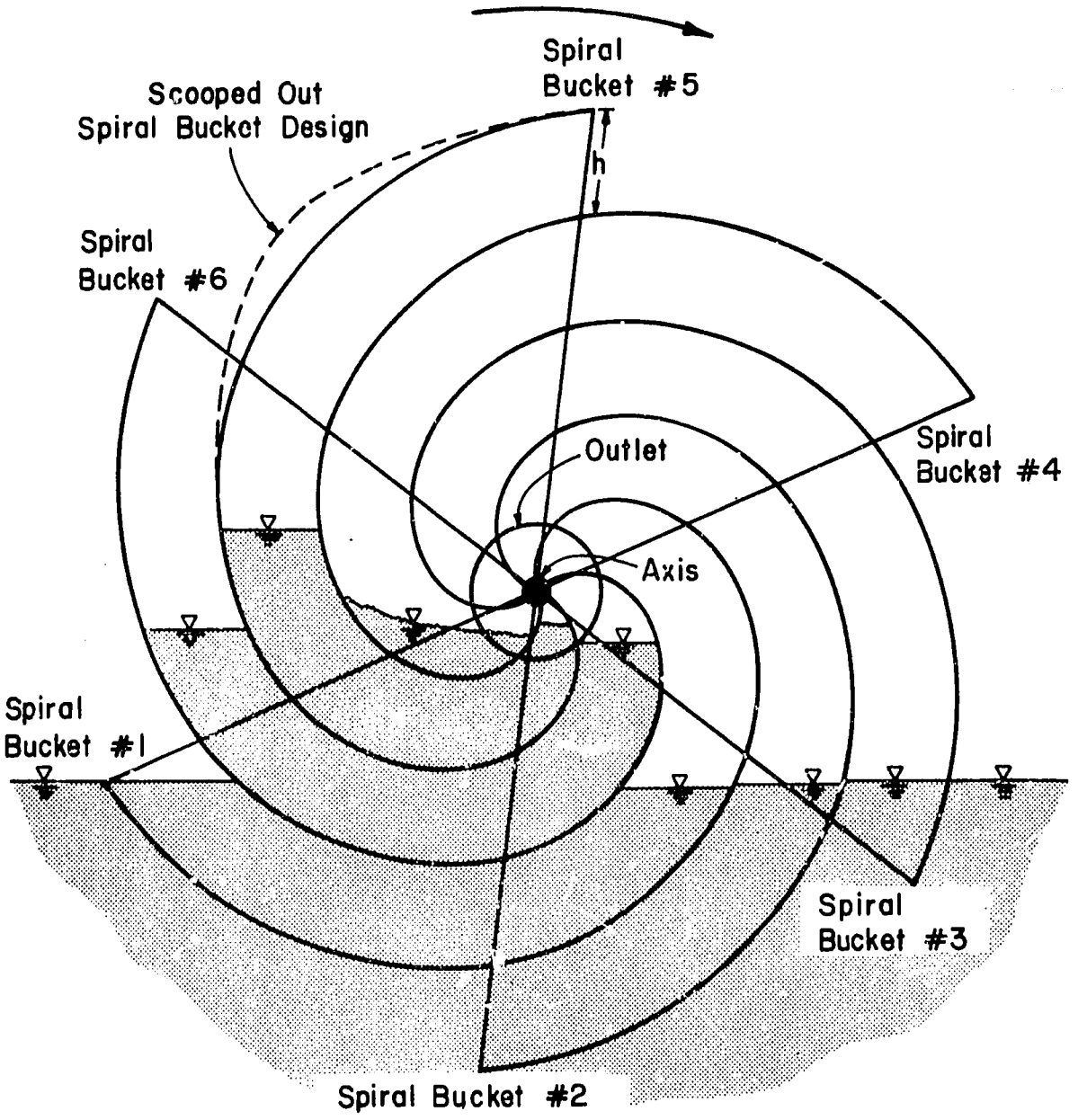

Figure 2. The water distribtuion within an operating wheel.

field procedures which could be used to calibrate an installation with respect to both discharge per revolution and mechanical efficiency (Slack, 1982).

Discharge per Revolution -- Experimental Development

Kool (1979) offered a technique for estimating the discharge per revolution of a waterwheel. This method was evaluated using the percent submergence of the waterwheel defined as:

$$S = \left(\frac{R-D}{R}\right) 100$$

where,

R = waterwheel radius, measured from the waterwheel axis to the lip of a bucket (L).

D = depth to water from the waterwheel axis (L).

A comparison of the field data with the values predicted by Kool's method showed that this method did not accurately predict the characteristic curve of discharge per revolution, q, vs. the percent submergence, S (Figure 3). A better method was needed.

Elberry's study of waterwheels indicated that at speeds less than 12 rpm, dynamic effects were negligible (Elberry, 1975). That is to say, under animal power the quantity of water collected in each bucket is not effected by the speed of rotation and is equal to the quantity collected under quasi-static conditions. This suggested that a method of determining the quantity of water picked up in a single spiral bucket of the waterwheel at a given submergence could be used to determine the dischange per revolution. A waterwheel measuring device (Figure 4) was developed to determine the submerged area, A, of a bucket. It established an x, y coordinate system from which measurements could be made. The submerged area was approximated using the measured dimensions shown in Figure 5. In most installations there are significant backflow losses as water is lost back to the reservoir. These losses are due either to

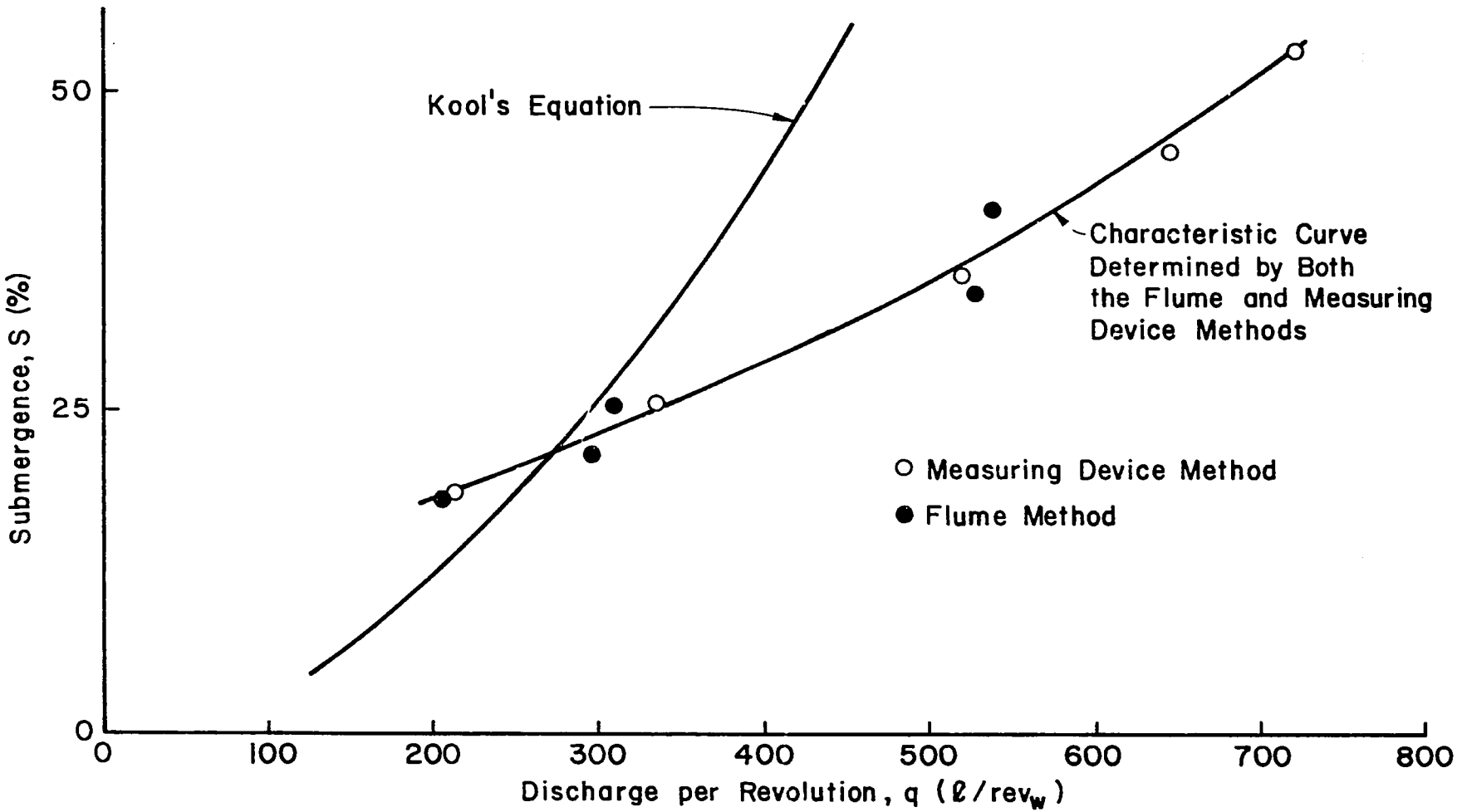

Figure 3. A characteristic curve drawn from flume and measuring-device data compared to characteristic curve predicted by Kool's method.

Figure 4. Slack using a measuring device to determine the submerged area at various submergence levels.

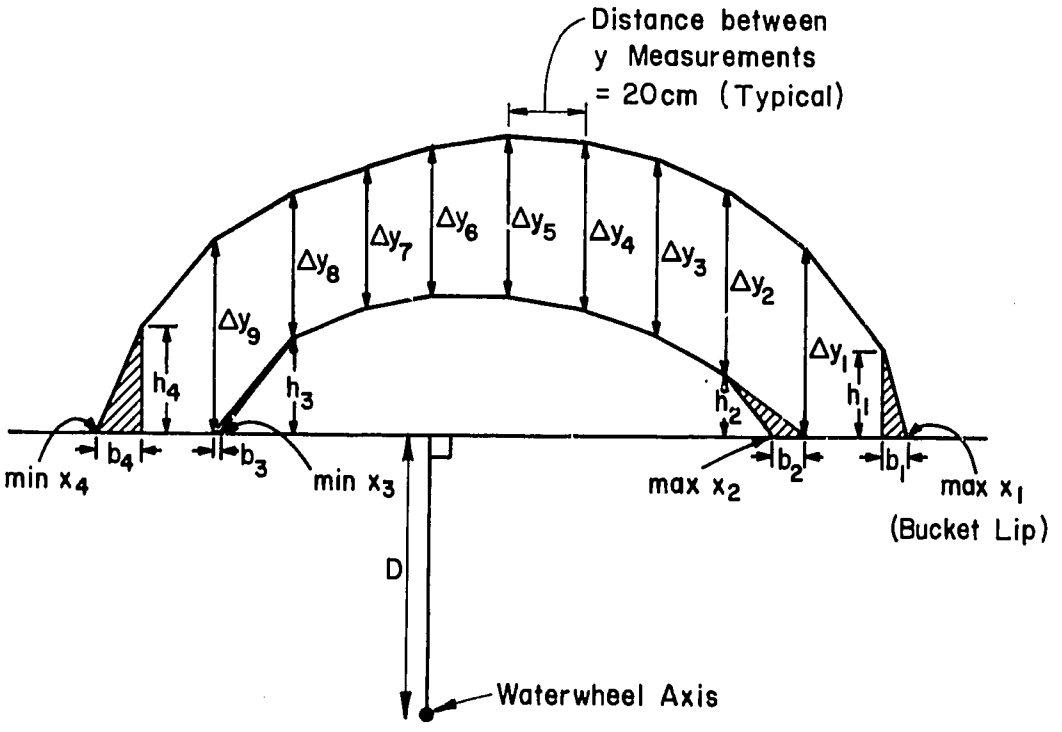

Figure 5. Submerged area of a single bucket based on the measured values.

holes in the waterwheel or to flow lost through the outlet flange seal. Taking these losses into account, the discharge per revolution can be estimated using:

$$q = AN\,w - v \tag{1}$$

where,

q = discharge per revolution of the waterwheel (L^3/rev_w)

A = average submerged area of all the buckets of a waterwheel at a given submergence (L^2/bucket)

w = width of the waterwheel (L)

N = number of spiral buckets (buckets)

v = volume of backflow per revolution of the wheel (L^3/rev_w)

A calibrated cutthroat flume was used to verify the accuracy of the measuring device technique. The flow rate from the installation was converted to a discharge per revolution using data on the period of rotation of the wheel. A single characteristic curve is drawn within the accuracy of both methods as shown in Figure 3. The low amount of scatter in the measuring-device data suggests that it may be more accurate than the flume method. However, additional data are needed to determine more precisely the relative accuracies of these methods.

Measuring device data were collected on thirty-five installations in the Kafr El-Sheikh and Mansuriya areas in Egypt. A 20 cm interval was used between y measurements. These data provided insufficient resolution to accurately characterize the eight installations with 2 m diameter wheels, and they were not included in further analysis. Data on the remaining installations were analyzed to develop a general method of determining the discharge per revolution.

A review of the available literature suggested that the Archimedes curve equation might be useful in understanding the curves of the waterwheel,

$$r = C\Psi \tag{2}$$

where,

r = radial distance of the sprial measured from the center (L)

C = Archimedes curve constant (L/rad)

Ψ = angle measured from a datum (rad)

The curves of most of the waterwheels followed an Archimedes curve, except near the inlet to the bucket where they were "scooped out" to increase the volume of water collected at low submergency (bucket #5, Figure 2). The geometric similarity of the bucket curves was explored by introducing the concept of a characteristic angle, Ψ_c(rad), which is defined as,

$$\Psi_c = \frac{R}{C} \tag{3}$$

where,

R = radius of the waterwheel

Regardless of scale, curves are geometrically similar if they have the same characteristic angle. This formed a basis of comparison between waterwheels. Wheels could be divided into geometrically similar curve classes on the basis of characteristic curves.

Another means of determining the geometrically similar class of a wheel is to use the characteristic submergence, S_c. This is defined as,

$$S_c = \left(\frac{R-D_c}{R} \right) 100 \tag{4}$$

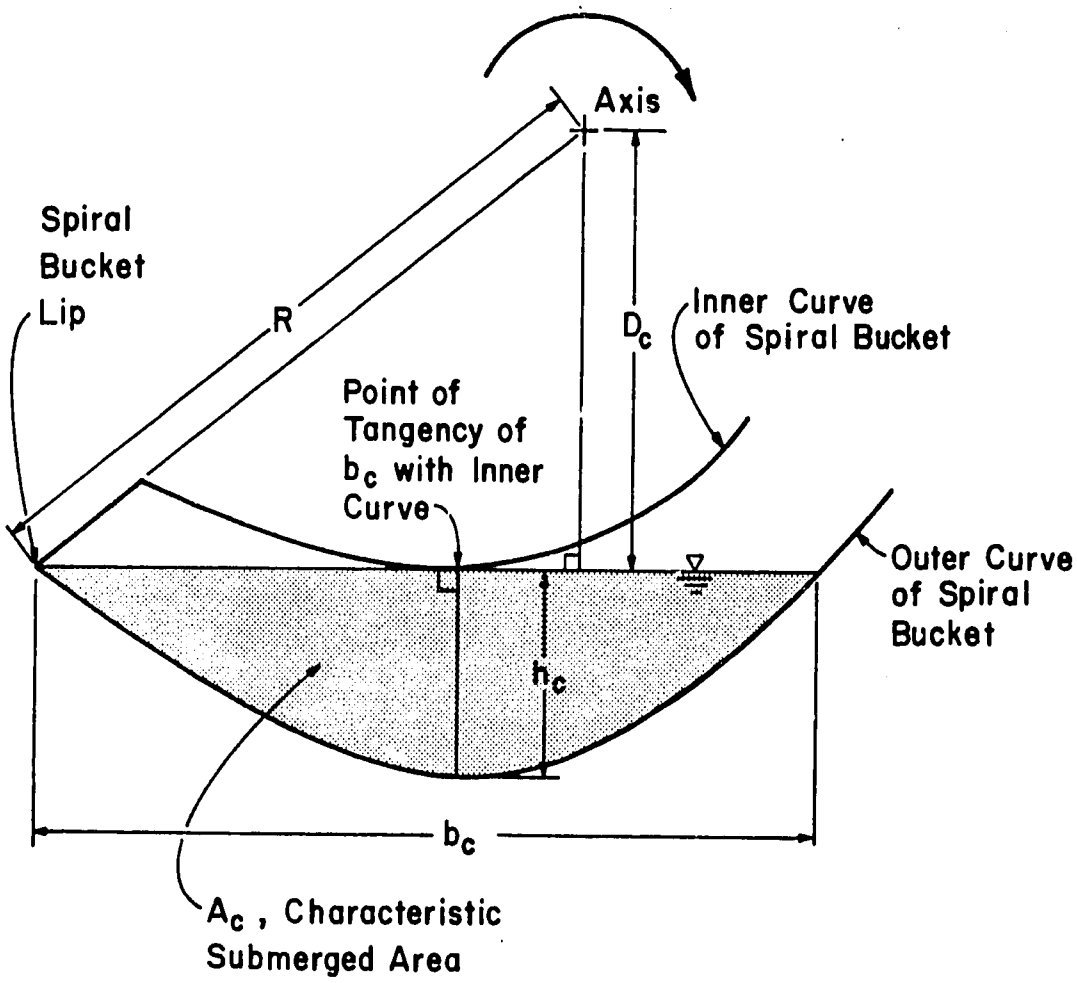

Figure 6. The characteristic submerged area of a bucket, A_c, showing the important parameters to measure.

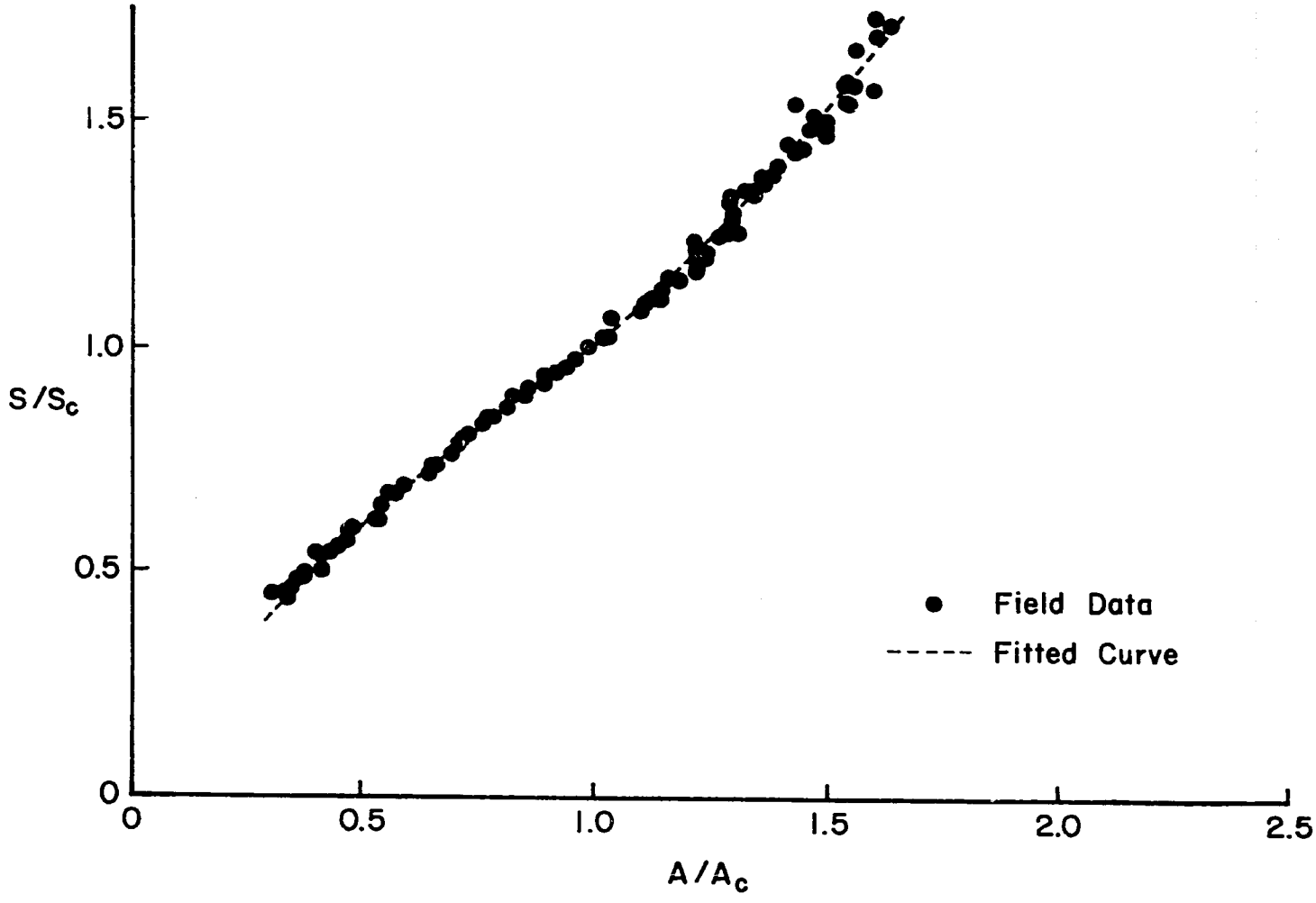

Figure 7. The graph of S/S_c vs. A/A_c for 22, 6-bucket waterwheels.

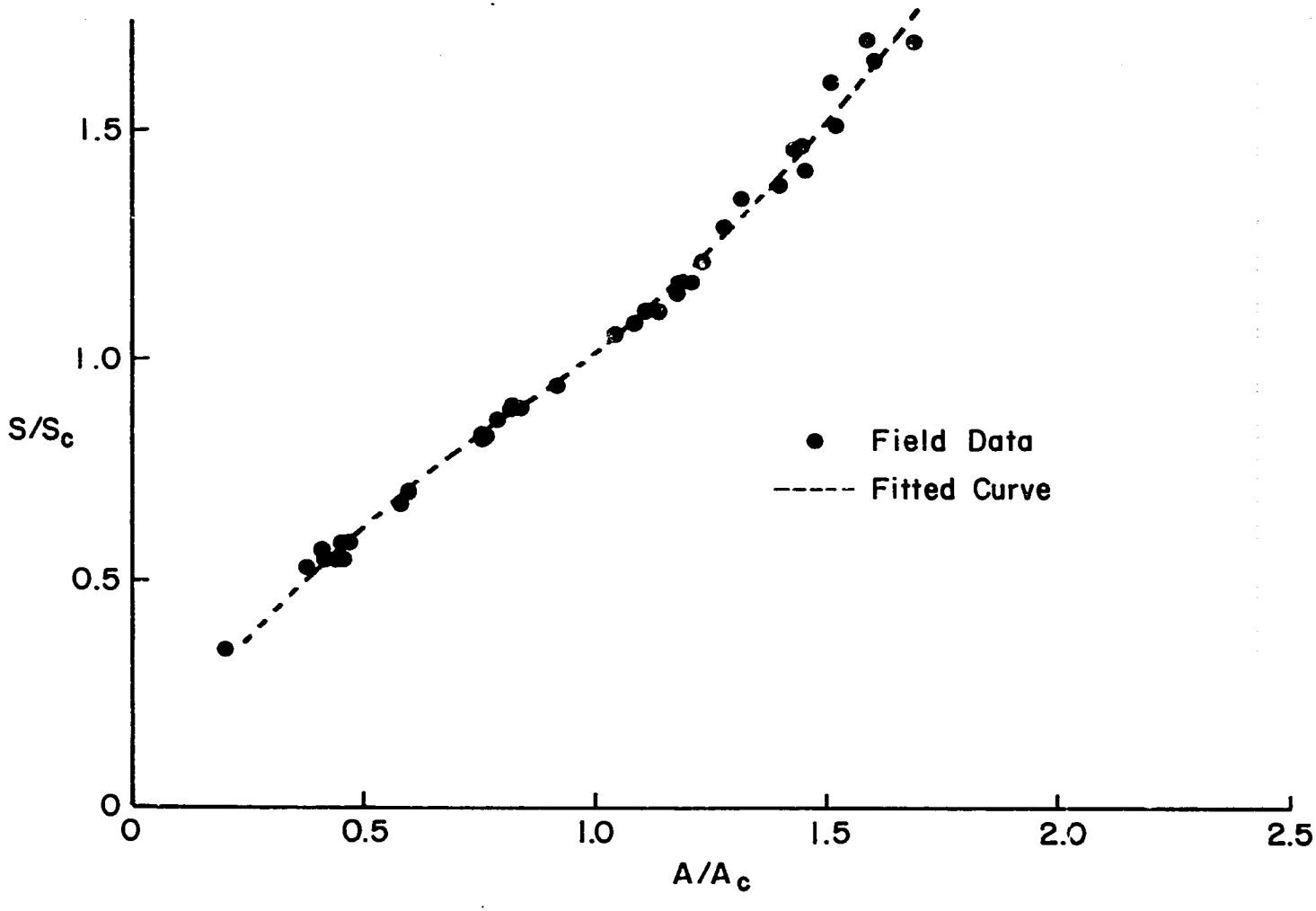

Figure 8. The graph of S/S_c vs. A/A_c for 7, 4-bucket waterwheels.

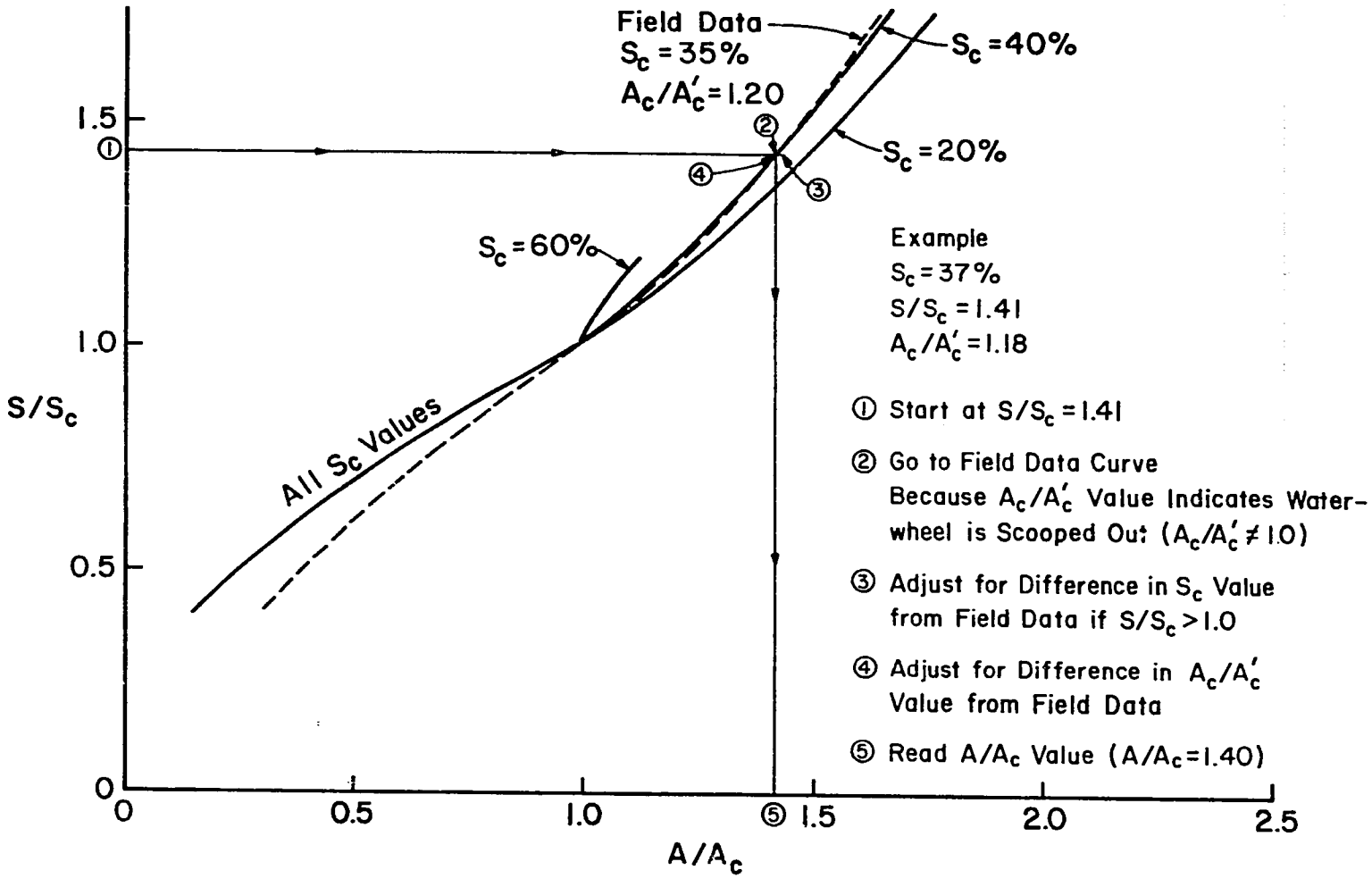

Figure 9. The general characteristic curves for 6-bucket waterwheels (ideal data at S_c = 20%, 40%, 60% and the field data for the Kafr el-Sheikh area).

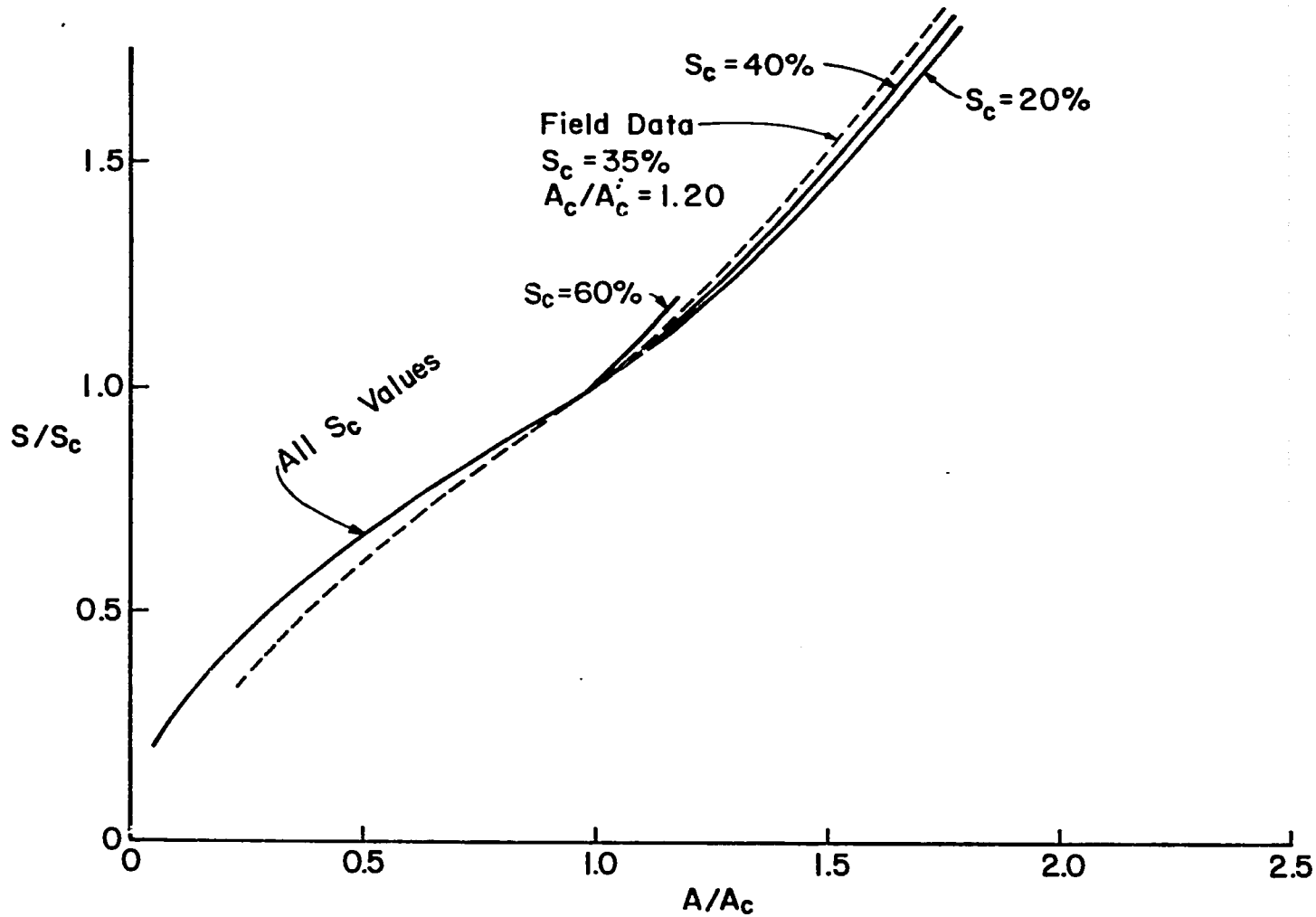

Figure 10. The general characteristic curves for 4-bucket waterwheels (ideal data at S_c = 20%, 40%, 60% and the field data for the Kafr el Shiekh area).

where,

D_c = characteristic depth to water, measured when the water level is tangent to the inner curve of the bucket as the lip of the bucket is leaving the water (Figure 6) (L).

For a given value of Ψ_c, there corresponds a unique value of S_c. If the curve is altered, then both S_c and Ψ_c change. The value of S_c is more directly related to the amount of water collected, more sensitive to variations in the submerged portion of the bucket, and is therefore of greater utility than Ψ_c.

A characteristic area, A_c, is defined as the submerged area of a bucket at a submergence level of S_c (Figure 6). Using S_c, A_c and the width of the wheel, w, the axes of the characteristic curve graph are normalized to become S/S_c vs. A/A_c.

It was found expedient to collect data for an arbitrary maximum submergence level and use a programmable calculator to manipulate the data. Submerged areas were determined for the maximum submergence as well as desired submergences smaller than the maximum. Data on the twenty-two, six-bucket waterwheels are shown in Figure 7. The plot for the seven four-bucket waterwheels is shown in Figure 8.

In addition, a calculator program was used to determine the characteristic curve for idealized waterwheels which have curves conforming strictly to the Archimedes curve equation. The characteristic curves shown in Figure 9 and 10 are essentially the same for all values of S_c at S/S_c values of less than one. For S/S_c values greater than one, the characteristic curves for various values of S_c are discrete.

The variation between the idealized curve data and the field data is entirely attributable to the "scooping out" of the bucket curves which is commonly found in the field. The ratio of the characteristic area of the field wheel A_c to that of the corresponding ideal wheel A_c', that is, A_c/A_c', is useful in accounting for variations in the degree to which a bucket is "scooped out". A procedure was developed to estimate the values of A_c' and A_c so that the general characteristic curves could be used to determine the specific characteristic curve of a field installation. To accomplish this, two relationships were developed. First, calculator generated data on the idealized wheels indicated that the idealized characteristic area could be determined from

$$A_c' = R^2 (k_1 S_c + k_2) \tag{5}$$

where for a four-bucket waterwheel the constants are:

$k_1 = 0.608$

$k_2 = 0.0216$

and for a six-bucket wheel:

$k_1 = 0.479$

$k_2 = 0.0128$

In both cases, the coefficient of determination (R^2) was 0.9997.

To quickly estimate A_c in the field, two characteristic measurements, b_c and h_c are introduced (Figure 6). The characteristic base, b_c, is the length of the line segment from the lip of the bucket, tangent to the inner curve of the bucket, to the point of intersection with the outer curve. The characteristic height, h_c, is the distance between the

inner and outer curves of the bucket measured perpendicular to b_c from the point of tangency. It was found that,

$$A_c = k\ b_c h_c \tag{6}$$

where, for four-bucket wheels:

$k = 0.70$ (with a standard deviation of 0.01)

and for six-bucket wheels:

$K = 0.68$ (with a standard deviation of 0.03)

Easily measured field parameters supply the necessary data to determine the discharge per revolution to within ± 15% of the total discharge. The value of A is determined using Equations 5 and 6 in conjunction with the general characteristic curves of the appropriate Figure 9 or 10. The discharge per revolution can then be calculated using Equation 1. This method indicates that a typical installation with a 3 m diameter six-bucket wheel, would discharge about 400 liter/rev_w at a lift of 1 m and 600 liter/rev_w at a lift of 75 cm (these estimates are based on S_c = 35%, A_c/A_c' = 1.20, 2 = 17 cm).

Discharge per Revolution -- Data Collection and Analysis

Only a few easily measured parameters are required: N, R, w, D, D_c, h_c, b_c and v. The value of w is measured to the nearest millimeter while R, D, D_c, h_c and b_c values are measured to the nearest 5 mm. In addition, the volume, v, of backflow must be estimated. This estimate requires the judgement of the person collecting the data since it is often difficult to measure this parameter in the field. Collected data are analyzed to determine the discharge per revolution by the following procedure:

1. Calculate submergence at which the discharge per revolution is desired using:

   $$S = \left(\frac{R - D}{R}\right) 100 .$$

2. Calculate the characteristic submergence of the wheel using:

   $$S_c = \left(\frac{R - D_c}{R}\right) 100 .$$

3. Calculate S/S_c.
4. Calculate A_c using: $A_c = k\, b_c h_c$ where k = 0.7 for either four or six- bucket waterwheels.
5. Calculate $A' = R^2(k_1 S_c + k_c)$

   where,

   k_1 = 0.608 and k_2 = -0.0216 for four-bucket waterwheels and

   k_1 = 0.479 and k_2 = -0.0128 for six-bucket waterwheels.
6. Calculate A_c/A'_c .
7. Choose the graph corresponding to the number of buckets (Figure 9 or 10).
8. Enter the graph on the vertical axis at the calculated value of S/S_c (1 in Figure 9).

9. If the waterwheel is "scooped out" ($A_c/A_c' > 1.1$), read over to the field data curve. If the waterwheel is not significantly "scooped out" use the theoretical curve, which is nearest the S_c value. (2 in Figure 9).
10. If $S/S_c > 1.0$ use graphical interpolation to adjust horizontally to the exact S_c value. The relative positions of the theoretical curves can be used as a guid (3 in Figure 9).
11. Use graphical interpoltion to adjust horizontally to the exact A_c/A_c' value. (4 in Figure 9).
12. Read down to the horizontal axis to determine the A/A_c value (5 in Figure 9).
13. Calculate $A = (A/A_c)\ A_c$.
14. Calculate $q = ANw - v$, converting from cm^3/rev_w to $liter/rev_w$.
15. The volume discharged in a time period can be determined by multiplying the discharge per revolution by the number of revolutions during the period. Measurements must be taken often, since the q value will fluctuate as the level of water in the reservoir changes.

Mechanical Efficiency -- Theoretical Development

Mechanical efficiency is defined as:

$$eff = \left(\frac{P_o}{P_i}\right) 100 \qquad (7)$$

where,

P_o = useful power output by the waterwheel installation (FL/T)

P_i = power input by the animal to the installation (FL/T)

No discussion of the measurement or typical values of mechanical efficiency was found in the available literature on the Egyptian waterwheels.

Expressing the efficiency in terms of easily measurable field parameters gives

$$eff = \frac{\gamma\, q\, L}{F\, G\, \frac{2\pi R_a}{rev_a}}\, 100 \qquad (8)$$

where:

γ = specific weight of water (F/L^3)

L = lift, the difference in the water level between the supply canal and the field head ditch (L)

F = force applied by the animal to turn the waterwheel (F)

G = gear ratio, ratio of the number of rotations of the animal to the number of rotations fo the waterwheel (rev_a/rev_w)

R_a = pulling radius of the animal (L)

To facilitate measurement, the lift can be broken down into a series of measurements (Figure 1),

$$L = D - H_i - D_e - H_o \qquad (9)$$

where,

D = depth to water measured from the axis of the waterwheel during operation (L)

H_i= head loss through the inlet pipe (L)

D_e= depth to water in the exit channel measured from the waterwheel axis (L)

H_o= head loss through the outlet pipe (L)

In many installations H_o may be assumed to be zero and D and H_i can be combined into one measurement of the depth to water from the axis when the wheel is not operating. Head loss in the inlet may be significant if the inlet pipe is undersized or has been allowed to fill with sediment.

Mechanical Efficiency -- Field Data Collection

The discharge per revolution can be determined using the previously discussed method. To determine the mechanical efficiency, the parameters F, R_a, G, L must also be measured.

A simple method for determing F is to place a 500 or 1000 N spring scale on the rope between the animal and the pulling arm. This force must be averaged since it fluctuates as the configuration in the waterwheel changes. This can be measured to within 20 N in most installations.

The pulling radius of the animal is the horizontal distance from the vertical axis of the waterwheel to the point of attachment of the rope to the pulling arm. This measurement is recorded to the nearest centimeter. The gear ratio can be determined exactly by counting the teeth of the vertical axis gear and dividing by the number of teeth of the horizontal gear.

Equation 9 can be used to determine L. The value of $D+H_i$ is the depth to water in the reservoir from the waterwheel axis when the installation is not operating. This measurement can be read easily to the nearest 5 mm in most cases.

Two parameters, D_e and H_o, are more difficult to measure. Since the exit channel and the outlet passage often slope, the selection of the location to measure D_e is critical. Also, there is no easy method to measure H_o. As soon as the waterwheel stops, the flow on the inlet side of the passage adjusts to the level of water in the outlet side. The measurement is difficult because the field head ditch is usually sloped so that water continues to flow and the level of water at the head of this ditch drops rapidly. One accurate method of collecting

data is to use surveying instruments to measure both D_e and H_o together. During operation, the level of the water at the head of the field ditch is determined relative to the horizontal axis.

Fortunately, H_o can often be neglected because the outlet passage is large enough to carry the flow without causing significant head loss. Thus, it is sufficient to measure or estimate D_e. Due to variations in the geometry, there is not a specific point where the water level is measured. If H_o is being neglected, the water level should be measured at a point that, in the judgment of the measurer, best approximates the water level in the field head ditch.

Data on the efficiency of eleven installations are presented in Figure 11. There was insufficient data to draw an eff vs. S curve for any installation. However, the data indicates that a good value for the operating efficiency might be 45%, while low efficiencies of about 25% were also found. Larger efficiencies tend to occur at higher submergence levels.

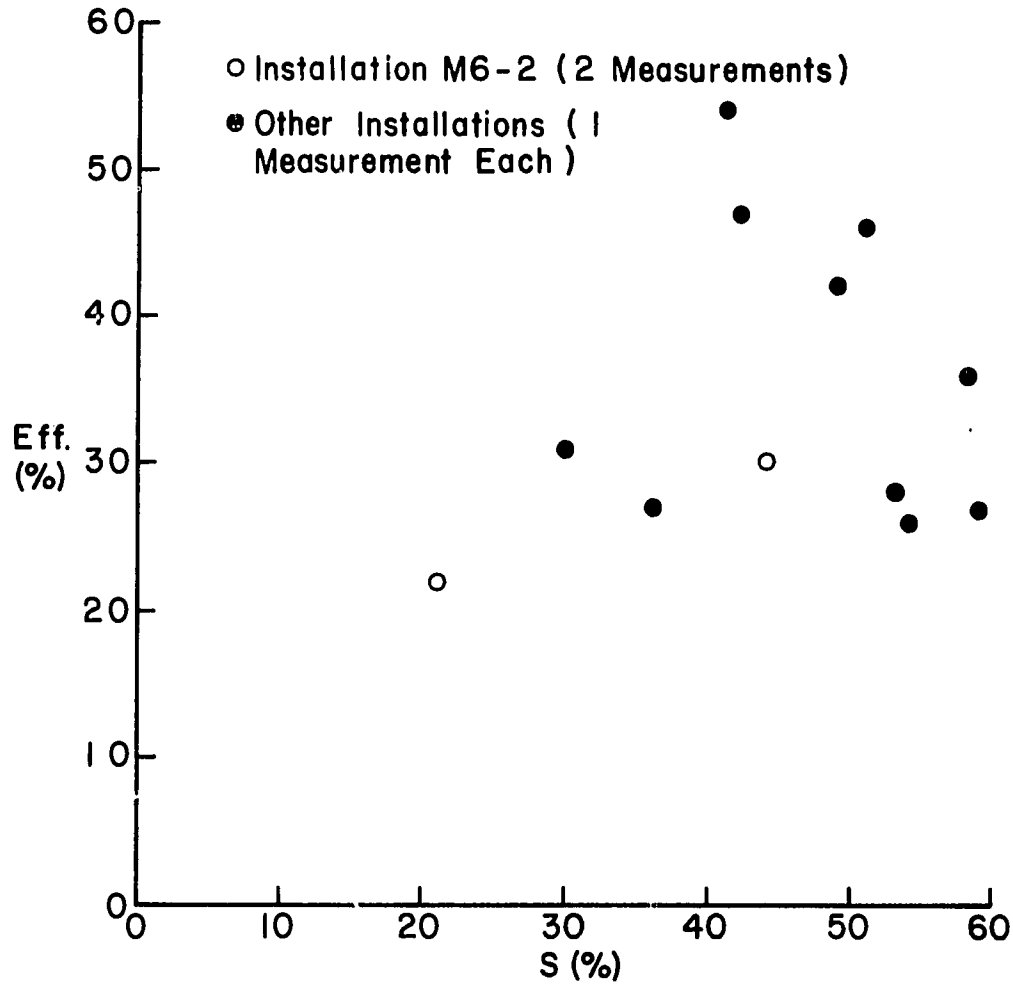

Figure 11. The mechanical efficiency vs. submergence for eleven installations.

Conclusions and Recommendations

A technique was developed to determine the discharge per revolution using a set of general characteristic curves and data on a few easily measured parameters of the waterwheel installation. The technique offers results accurate to approximately ± 15% of the total discharge. The precision (lack of scatter) in the sakia measuring device data suggests it may provide more accurate data than a flume, however more research is needed to verify this. Also, the effects of regional variations on the discharge per revolution should be studied.

In addition, a technique for determining the mechanical efficiency of waterwheel installations was presented. The power input was measured using a spring scale to determine the force applied by the animal as it moved around its circular path. The power output was based on the quantity of water and the height lifted. Data collected showed that a good efficiency might by 45%, but efficiencies as low as 25% were determined. More data are needed to conclusively characterize the range of typical efficiencies to be found in the field. Current research is focusing on impoved designs of the sakia outlet to minimize water losses back to the sakia reservoir. In addition, other research is being carried out on improved year designs. The mechanical efficiency will provide useful information for (1) studies directed at improving the current waterwheel installation designs, and (2) studies comparing different methods of lifting water.

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Appendix I

Nomenclature

Symbol	Definition
A	Average of the submerged areas of all the buckets of a waterwheel at a given submergence (L^2/bucket)
A_c	Characteristic area, the submerged area of the corresponding ideal (Archimedes curve) bucket at the characteristic submergence (L^2/bucket)
b_c	Characteristic base (L)
C	Archimedes curve constant (L/rad)
D	Depth to water measured from the waterwheel axis during operation (L)
D_c	Characteristic depth to water (L)
D_e	Depth to water in the exit channel measured from the waterwheel axis (L)
F	Force applied by the animal to turn the waterwheel (F)
G	Gear ratio, ratio of the number of rotations of the animal to the numberof rotations of the waterwheel (rev_a/rev_w)
h_c	Characteristic height (L)
H_i	Head loss through the inlet pipe (L)
H_o	Head loss through the outlet pipe (L)
k	Constant used to estimate A_c (dimensionless)
k_1	First constant used to estimate A_c' (dimensionless)
k_2	Second constant used to estimate A_c' (dimensionless)
L	Lift, the difference in water level between the supply canal and the field head ditch (L)
N	Number of buckets of a waterwheel (buckets)
P_i	Power input by the animal to the installation (FL/T)

P_o	Useful power output by the installation (FL/T)
q	Discharge per revolution of the waterwheel (L^3/rev_w)
r	Radial distance of the spiral measured from the center (L)
rev_a	Revolution of the animal (rev_a)
rev_w	Revolution of the waterwheel (rev_w)
R	Waterwheel radius, measured from the waterwheel axis to the lip of a bucket (L)
R_a	Pulling radius of the animal (L)
S	Submergence of the waterwheel measured as a percent of the radius (%)
S_c	Characteristic submergence, submergence of the waterwheel at the characteristic depth to water (%)
	Volume of backflow from the waterwheel per revolution (L^3/rev_w)
w	Width of the waterwheel corresponding to the submerged area (L)
γ	Specific weight of water (F/L^3)
π	3.1415...
ψ	Angle of a point on the Archimedes spiral curve measured from a datum (rad)
ψ_c	Characterisitic angle of the waterwheel (rad)

AMERICAN EQUIVALENTS OF EGYPTIAN ARABIC TERMS AND MEASURES COMMONLY USED IN IRRIGATION WORK

Land Area	In Sq. Meters	In Acres	In Feddans	In Hectares
1 acre	4,046.856	1	0.96335	0.40469
1 feddan	4,200.8335	1.03805	1	0.42008
1 hectare (ha)	10,000.00	2.47105	2.38048	1
1 sq. kilometer	100×10^4	247.105	238.048	100.00
1 sq. mile	259×10^6	640.00	616.4	259.00

Water Measures

1 billion m^3 = 810,710 acre-feet

1000 m^3 = 0.81071 acre-foot = 9.72852 acre-inch

1000 m^3/feddan = 0.781 acre-foot/acre = 9.372 acre-inch/acre

(= 238 mm of rainfall)

Other Conversions

1 ardab = 198 liters = 5.62 bushels (U.S.)

1 ardab/feddan = 5.41 bushels/acre

1 kg/feddan = 2.12 lb/acre

1 donkey load = 100 kg

1 camel load = 250 kg

1 donkey load of manure = 0.1 m^3

1 camel load of manure = 0.25 m^3

Egyptian Unit for Field Crops

Crop	Eg. Unit	In Kg.	In Lbs.	In Bushels
Lentils	ardab	160.0	352.42	5.87
Clover	ardab	157.0	345.81	5.76
Broad Beans	ardab	155.0	341.41	6.10
Wheat	ardab	150.0	330.40	5.51
Maize, Sorghum	ardab	140.0	308.37	5.51
Barley	ardab	120.0	264.32	5.51
Cottonseed	ardab	120.0	264.32	8.26
Sesame	ardab	120.0	264.32	
Groundnut	ardab	75.0	165.20	7.51
Rice	dariba	945.0	2081.50	46.26
Chick-peas	ardab	150.0	330.40	
Lupine	ardab	150.0	330.40	
Linseed	ardab	122.0	268.72	
Fenugreek	ardab	155.0	341.41	
Cotton (unginned)	metric qintar	157.5	346.92	
Cotton (lint or ginned)	metric qintar	50.0	110.13	

Egyptian Farming and Irrigation Terms

fara = branch
marwa = small distributer, irrigation ditch
masraf = field drain
mesqa = small canal feeding from 10 to 40 farms
qirat = cf. English "Karat," a land measure of 1/24 feddan, 175.03 m^2
qarfa = village
sahm = 1/24th of qirat, 7.29 m^2
saqia = animal powered water wheel
sarf = drain (vb.), or drainage. See also masraf, (n.)