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Regime equations development for the design of Egyptian sandy canals

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Abstract

The construction of the High Aswan Dam in Egypt led to reducing the solids suspension in water from more than 3,500 p.p.m. to less than 100 p.p.m. As the regime of Egyptian canals has been changed completely after the construction of the High Aswan Dam, the previous derived equations are not applicable any more, and using them leads to a shortage in the carrying capacity of the canals. In the current study, extensive field measurements have been carried out on 15 stable Egyptian canals, which cover various discharges of irrigation canals with sandy soils starting from 5 m^3/s to 50 m^3/s and d_{50} ranging from 0.196 to 0.538 mm. Then, applicable regime relationships for designing stable sandy channels were determined. The new equations are useful for designing new stable canals and redesigning unstable canals within the same range. The new regime equations were verified by using the HEC- RAS program. Finally, sensitivity analysis has been performed in order to investigate the effect of changing the deduced parameters on the discharge.

Key words: alluvial channels, canals design, Regime theory

Highlights

- The regime of Egyptian canals has been changed completely after the construction of the High Aswan Dam, the previous derived equations are not applicable any more, and using them leads to a shortage in the carrying capacity of the canals. In the current study, applicable regime relationships for designing stable sandy channels were determined. The new equations are useful for designing new stable canals and redesigning unstable canals.
- Regime equations are useful tools for designing the canals, so they do not suffer from hydraulic problems, and the equations accommodate their design discharge. So, the irrigation systems work efficiently and the farmers do not suffer from shortage of irrigation water.

NOMENCLATURE

A	cross-section area (m^2)
B	bed width (m)
d_{50}	median size of sediment particle (mm)
g	gravitational acceleration (m/s^2)
N	Manning's roughness coefficient
P	wetted perimeter of the water cross-section (m)
Q	discharge (m^3/s)

R	hydraulic radius, ($R = A/P$) (m)
S	channel slope (cm/km)
T_w	top width (width at the water surface) (m)
V	mean flow velocity (m/s)
Y	average flow depth (m)

ABBREVIATIONS

CMRI	Channel Maintenance Research Institute
GPS	global positioning system
HAD	High Aswan dam
NWRC	National Water Research Center
P.P.M	parts per million
SPSS	statistical package for social science

INTRODUCTION

Open channels are designed to transmit the required rate of flow, with minimum maintenance cost. Regime theory is one of the milestones of river engineering, as it is used for designing stable channels. Stable channels have a geometric configuration that optimizes the efficiency of flow transmission and sediment transport so that, in the long term, sediment storage in the channel is approximately constant and inputs to the system are balanced by outputs. When a channel has achieved this state, it is referred to as 'in regime'. At this state, the channel is self-regulating and maintains its average condition in space and time (Soar & Thorne 2001). The criterion for designing stable canals is that the water velocity should not be less than the minimum permissible velocity to prevent deposition along the channel bed, or more than the maximum permissible velocity to prevent erosion of the bed or bank materials (Blench & King (1941) and Leopold & Maddock (1953). Existing hydraulic geometry prediction methods are divided into three major categories: (1) stability method, (2) extremal method and (3) regime method. In regime methods, channel depth and width are given as a function of the channel discharge. Such relations were based on the canals being assumed to be in regime.

The regime theory began with Kennedy & Brooks (1965), and is a classic empirical equation that relates the velocity to the mean depth of flow as follows:

$$V = 0.55\ Y^{0.64} \tag{1}$$

where V is the mean velocity (m/s) and Y is the mean depth (m).

Many researchers derived equations to design Egyptian open channels, related to the regime before the construction of the High Aswan Dam (HAD). In 1922, Molesworth and Yenidunia introduced empirical formulae that depended on velocity, bed width, water depth, and water surface slope as follows (Molesworth & Yenidunia 1922);

$$V = 0.26\ Y^{1.5} \tag{2}$$

$$B = 0.32\ Y^{1.5} \tag{3}$$

$$Y = 0.1\ (S/2 + 4) \tag{4}$$

where S is the water surface slope (cm/km).

After the construction of the HAD, the regime condition of Egyptian canals was changed, therefore many new regime equations were deduced to design stable Egyptian canals.

Khattab *et al.* (1987) analyzed data of 23 stable earthen canals in Egypt, and developed the following equations:

$$A = 9.816\ Q^{0.65} \tag{5}$$

$$Y = 1.43\ Q^{0.24} \tag{6}$$

$$R = 1.078\ Q^{0.25} \tag{7}$$

$$V = 19.44\ (R^3S)^{0.58} \tag{8}$$

These equations, from (5) to (8), were valid for canals having sandy beds and banks with discharge from 90 to 200 m^3/s.

El-Samman & Awad (1999) analyzed data of 22 stable earthen canals in Egypt, and developed the following equations for discharges of less than 5 m^3/s for canals having sandy beds and banks.

$$A = -0.244 + 1.846\ (nQ/S^{0.5})^{0.761} \tag{9}$$

$$Y = -3.909 + 4.384\ (nQ/S^{0.5})^{0.063} \tag{10}$$

$$B = -1.114 + 0.889\ (A/Y) \tag{11}$$

Abdelhaleem *et al.* (2016) analyzed data of 371 cross-sections for 26 canals in Egypt, and developed the following equations for the discharge range of 0.11–287.5 m^3/s:

$$A = 9.827\ Q^{0.645}\ d_{50}^{-0.008} \tag{12}$$

$$R = 0.73\ Q^{0.312}\ d_{50}^{-0.013} \tag{13}$$

$$Y = 0.717\ Q^{0.319}\ d_{50}^{-0.08} \tag{14}$$

$$S = 12.5\ Q^{-0.156}\ \ d_{50}^{0.42} \tag{15}$$

$$V = 1.96 \times 10^{-4}\ (RS)^{2.79}\ \ d_{50}^{-0.89} \tag{16}$$

where d_{50} is the median particle size (mm). It is worth noting that these equations were deduced from analyzing the field data of canals with stable cross-sections, and the same section had been measured for different discharges through the year. All these measurements were analyzed together, which led to inaccurate equations. Also, the equations were not categorized according to the different types of soil, or different discharge ranges.

Zidan *et al.* (2018) presented new regime equations for canals (case study Dakahliya governorate); these equations cover a wide discharge range from 0.40 to 234.70 m^3/s with d_{50} varying between 0.10 mm and 0.72 mm, and developed the following equations:

$$A = 2.77\ Q^{0.84} \tag{17}$$

$$R = 0.47\ Q^{0.44} \tag{18}$$

$$P = 5.88\ Q^{0.44} \tag{19}$$

$$B = 3.73\ Q^{0.43} \tag{20}$$

$$Y = 0.55\ Q^{0.44} \tag{21}$$

$$T_w = 5.56\ Q^{0.44} \tag{22}$$

The Appendix table in Supplementary Materials demonstrates a comparison of the deduced regime equations for Egypt after the construction of HAD. Mohamed (2013) used artificial neural network models (ANNs) to estimate the main design parameters such as hydraulic radius, wetted perimeter, and slope in the design of stable alluvial channels. Also, Bonakdari & Gholami (2016) used the ANN method for predicting the width of stable canals in gravel-bed rivers.

Shaghaghia *et al.* (2018) used Artificial Intelligence (AI), and non-linear regression (NLR) methods to develop new empirical equations to predict stable channel dimensions for Iranian rivers.

Most of the previous regime equations depend solely on the fact that discharge is the key element in the process of designing the open channels, while the median particle size (d_{50}) is ignored; in spite of that, the properties of the material that composes the bed and boundaries of the channel are very significant factors. So, previous derived equations are not applicable due to ignoring d_{50} or analyzing the data wrongly, which has led to a shortage in the carrying capacity of the canals and farmers suffering from irrigation water shortage.

The present study goal is to derive new applicable regime equations for designing stable sandy Egyptian canals that have discharges from 5 m^3/s to 50 m^3/s, taking into consideration the soil material sizes (d_{50}).

MATERIAL AND METHODS

Field measurements

Fifteen stable canals have been chosen to represent a wide range of operation conditions. Four of the canals are in the upper Nile valley, three are in the lower Nile valley, one is in Fayoum governorate and seven are in the Nile Delta, as shown in Table 1.

Table 1 | location of the selected canals

Location	Canal name
Upper Nile Valley	Asfoun, Kalabiya, East Naga Hammadi, and West Naga Hammadi.
Lower Nile valley	Aldiyrutia, Badrman, and Ibrahimiya
Fayoum governorate	Bahr El-Gharq
Delta canals	Alaintilaq, Almanayif, Almalak, Alseidia, El-Ismailia, El-Suez, and El-Tahadaa

Twenty-seven cross-sections were chosen after an accurate survey and examination of available data, as they proved to have been stable throughout the last ten years. Data for 27 cross-sections on 15 canals that are in the regime were collected. For each of the 27 cross-sections, the velocities were measured at maximum discharge, normal discharge and minimum discharge. The velocity measurement was accomplished utilizing a calibrated electromagnetic current meter. The required data was collected for each canal throughout its full capacity.

For each cross-section, a steel cable marked in meters, and stretched across the section under investigation, was located perpendicular to the direction of the flow. This steel cable was used to hold the boat at the required position and to fix its location relative to its initial position relative to the bank. The water top width was measured and recorded, then the water depth was measured using the Echo sounder instrument that was installed on the boat and attached to a global positioning system (GPS) unit. The top width was divided into the number of verticals (N); the distance between the verticals (G) is equal to '$G = T_w/(N+1)$', where T_w is the top width of the water surface, where the number of verticals was taken as $N = 15$ for $T_w < 15$ m, and was taken as $N = 10$ for $T_w > 15$ m (Gore & Banning 2017). The velocity was measured at 0.6 of water depth solely for water depths of less than 0.4 m, and this was considered the mean velocity for this vertical. For water depths greater than 0.4 m, the velocity was measured at 0.2 and 0.8 of water depth, and the average of the two measured velocities in this vertical was considered the mean velocity. After measuring the velocities, the velocity area method was applied to compute the flow discharge. The water slope was calculated along a sufficient length of straight reach by using staff gauges, which were fixed on steel angles. The levels of the staff gauges were correlated to the nearest known point level, from which the difference in elevation between the water surfaces at the two stations was computed, which gave the slope of the water surface. To collect the samples of soil materials, a Van-Veen grab sampler was used. Three samples of the soil were collected at the same location as each velocity cross-section (one sample from the bed and two samples from the left and right banks). Then, the samples were analyzed to deduce the grain size distribution of the soil materials.

Dimensional analysis

Dimensional analysis was used to relate the different dependent and independent variables. The main variables that affect the characteristics of the hydraulic cross-sections are fluid density (ρ), dynamic viscosity (μ), cross-section area (A), top width (T_w), hydraulic radius (R), wetted perimeter (P), median size of soil particle (d_{50}), bed width (B), mean depth (Y), water surface slope (S), side slope (Z), flow discharge (Q), flow mean velocity (V), and gravitational acceleration (g). The general functional relationship between the above variables can be written as the following:

$$f(\rho, \mu, A, T_w, R, P, Y, S, Q, V, g, B, Z, d_{50}) = 0 \tag{23}$$

Using the Buckingham theorem, the final functional relationship between the above variables can be represented as follows:

$$Q/(g^{0.5}.d_{50}^{2.5}) = f((A/d_{50}^2), (T_w/d_{50}), (R/d_{50}), (P/d_{50}), (B/d_{50}), (Y/d_{50}), S, Z, V/(g^{0.5}.d_{50}^{0.5})) \tag{24}$$

Data analysis

The measured data which was collected during the passing of the maximum discharge through each canal was analyzed, with the exclusion of abnormal measurements. The range of geometric and hydraulic data sets measured for the canals under study are shown in Table 2. By using the AutoCAD software package, the cross-sections have been plotted to determine the cross-sectional area, A, wetted perimeter, P, bed width, B, and top width, T_w. The average depth of each cross-section was obtained as $Y = (A/T_w)$ (Afzalimehr *et al.* 2010). The statistical software packages (SPSS, Excel, and GraphPad Prism) were used to derive evolutionarily multiple regression equations for 27 sets of field measurements. A nonlinear regression analysis was implemented to express area, velocity, depth, hydraulic radius, and wetted perimeter as a power function of both the discharge and the median grain size, d_{50}.

Table 2 | Range of the used data

Values	Q (m^3/s)	Y (m)	B (m)	A (m^2)	R (m)	P (m)	V (m/s)	S (cm/km)	d_{50} (mm)
Min. value	5.293	1.74	8.5	20.89	1.28	16.29	0.15	3	0.196
Max. value	49	4.31	26.5	124	3.14	39.51	0.5	10	0.538

RESULTS AND DISCUSSION

Development of regime equations

To get the best regime approach for canals which are under study, the analysis process has been divided into two categories as follows:

I. $113 \geq Q.\ g^{-0.5}.\ d_{50}^{-2.5} > 20$
II. $600 > Q.\ g^{-0.5}.\ \mathrm{d}_{50}^{-2.5} > 113$

For analyzing the measured data, the term $Q.g^{-0.5}.\ d_{50}^{-2.5}$ was plotted against the other parameters of cross-sectional area, bed width, wetted perimeter, hydraulic radius, average depth, and the mean velocity, as shown in Figure 1, for the first category $113 \geq Q.\ g^{-0.5}.\ d_{50}^{-2.5} > 20$.

The following equations were derived for the prediction of stable channel characteristics.

I. $113 \geq Q.\ g^{-0.5}.\ d_{50}^{-2} > 20$

$$A = 46.239\ Q^{0.414} d_{50}^{0.965} \tag{25}$$

$$B = 9.534\ Q^{0.2594} d_{50}^{0.3515} \tag{26}$$

$$Y = 3.126\ Q^{0.1722} d_{50}^{0.5695} \tag{27}$$

$$R = 2.11\ Q^{0.1882} d_{50}^{0.5295} \tag{28}$$

$$P = 22.964\ Q^{0.217} d_{50}^{0.4575} \tag{29}$$

$$V = 0.0225\ Q^{0.5788}\ d_{50}^{-0.947} \tag{30}$$

II. $600 > Q.\ g^{-0.5}.\ d_{50}^{-2.5} > 113$

$$A = 6.375\ Q^{0.7512} d_{50}^{0.122} \tag{31}$$

$$B = 1.061\ Q^{0.624}\ d_{50}^{-0.56} \tag{32}$$

$$Y = 2.402\ Q^{0.2233} d_{50}^{0.4418} \tag{33}$$

$$R = 1.205\ Q^{0.2879} d_{50}^{0.2803} \tag{34}$$

$$P = 5.3345\ Q^{0.4621} d_{50}^{0.4575} \tag{35}$$

$$V = 0.1534\ Q^{0.2523} d_{50}^{-0.1308} \tag{36}$$

where A is the cross-section area (m^2), Q is the discharge (m^3/s), d_{50} is the median particle size (mm), Y is the mean water depth (m), R is the hydraulic radius (m), B is the bed width (m), V is the mean velocity (m/s), g is the gravitational acceleration (m/s^2), and P is the wetted perimeter (m). The regression coefficient R^2 for the derived equations is relatively high as it ranges between 0.95 and 0.99, which indicates that the derived relations are satisfactory and the designer could rely on them for designing stable Egyptian sandy canals. The comparisons between the measured and the predicted data which was derived from the previous equations are plotted in Figure 2. The calculated values of each hydraulic property were plotted against the measured ones to display the variance around the line of perfect agreement. The figures revealed that the calculated data from the derived equations are accurate, as their accuracy is about ±5% for most of the data.

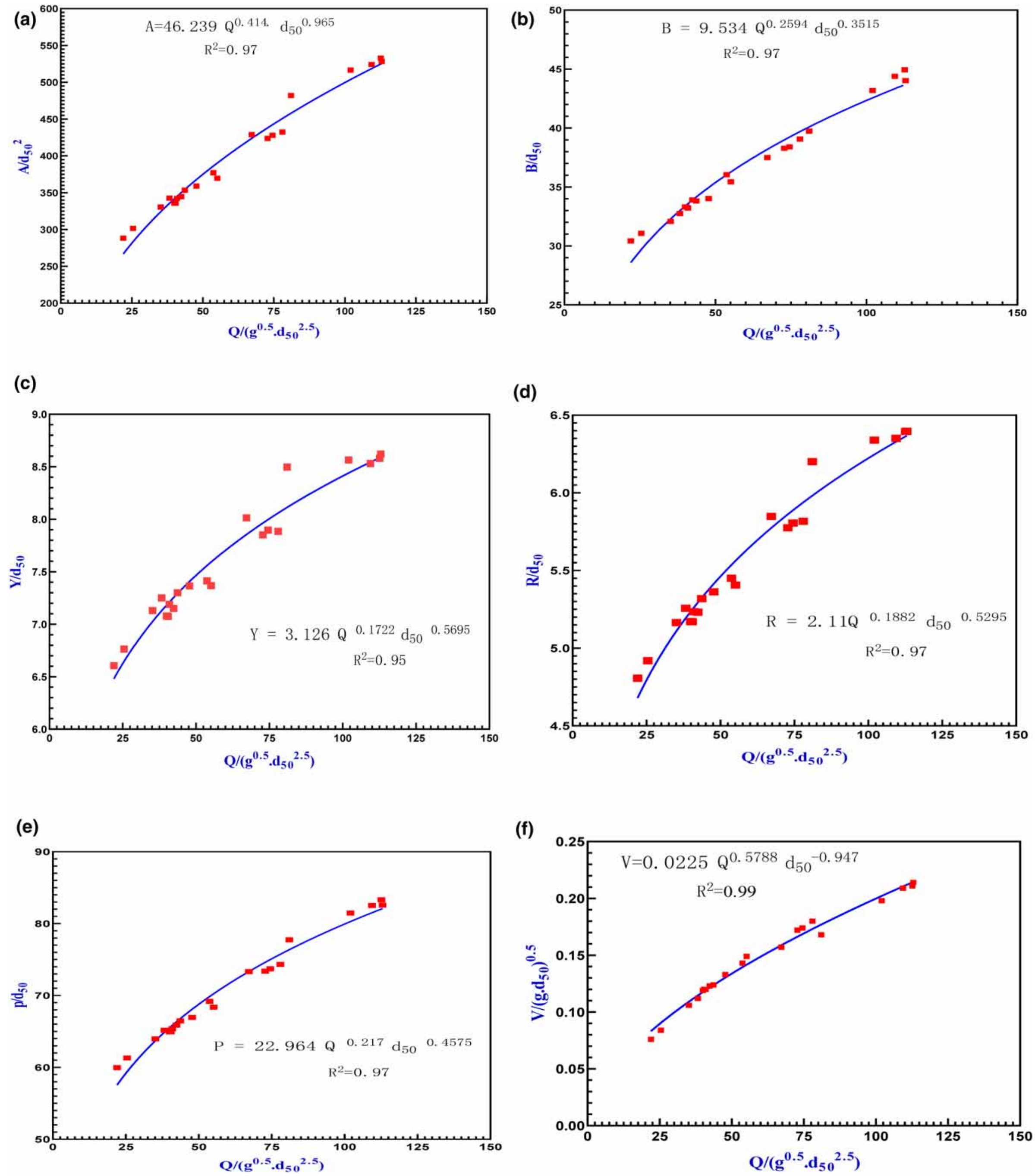

Figure 1 | Relation between $Q/(g^{0.5}.d_{50}^{2.5})$ and (a) (A/d_{50}^{2}), (b) (B/d_{50}), (c) (Y/d_{50}), (d) (R/d_{50}), (e) (P/d_{50}), (f) $V/(g.d_{50})^{0.5}$.

Verification of the developed equations

To verify the derived equations, Bahr El-Nazla canal at El-Fayoum governorate in Egypt was chosen as a stable canal, to compare its measured parameters (*A*, *B*, *Y*, *R*, *P*, and *V*) with those deduced from this study. Bahr El-Nazla canal was chosen because it has a discharge and median particle size d_{50} within the range of this study. It carries a discharge of 8.64 m^3/s, its median particle size d_{50} is 0.230 mm and the measured longitudinal water surface slope is 3.36 cm/km. Table 3 represents the parameters' values, which were deduced from the current study, and the relative error (RE%) for each parameter. Also, the equations of other previous studies were applied to deduce the canal parameters, to compare the accuracy of the current equations with the previous ones. As shown in

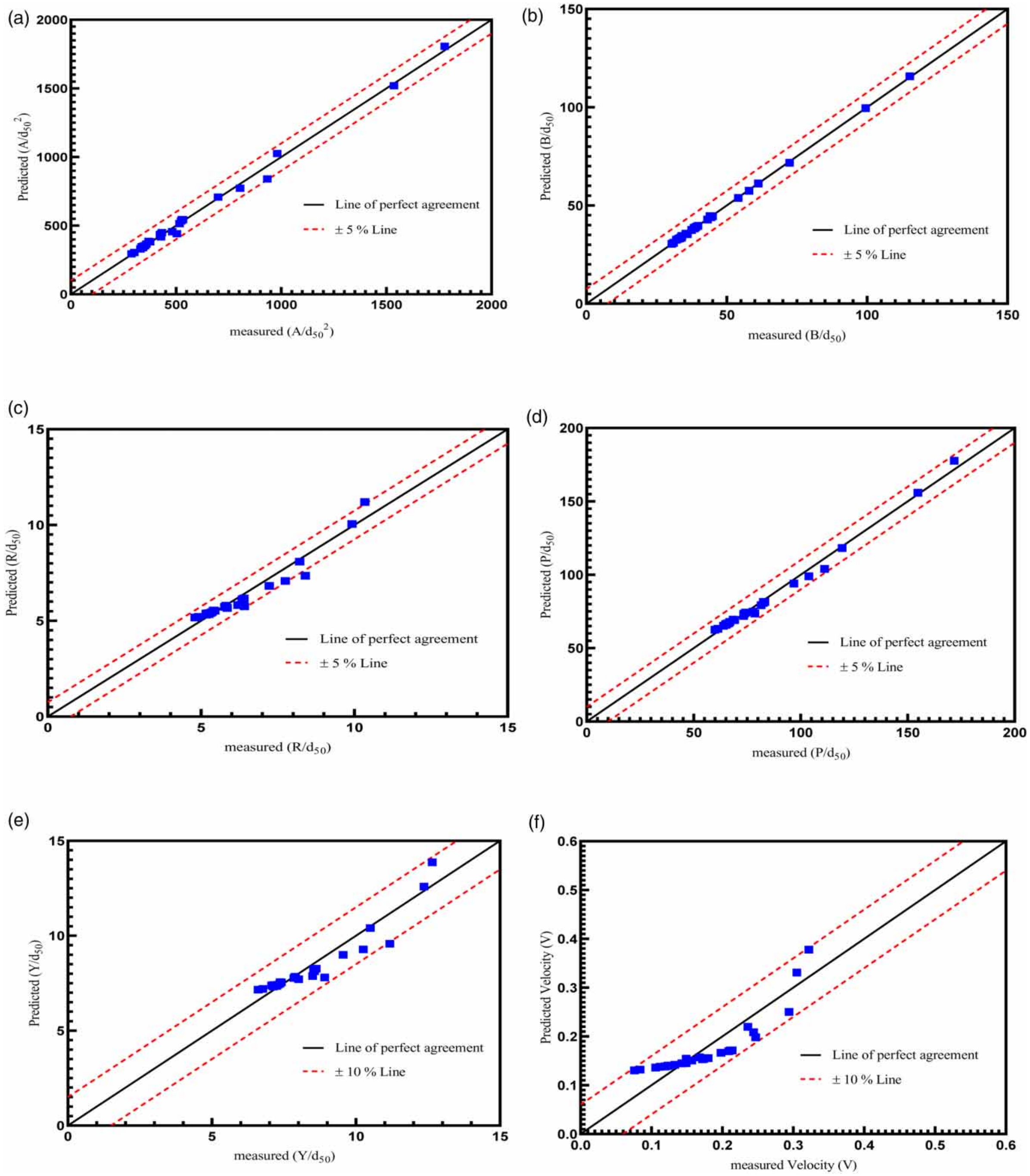

Figure 2 | Measured and predicted data (a) area (b) bed width (c) hydraulic radius (d) wetted perimeter (e) depth (f) velocity.

Table 3 | Application of different design equations for Bahr El-Nazla

	Cross-section Area		**Bed width**		**Mean flow depth**		**Hydraulic radius**		**Wetted perimeter**		**Mean velocity**	
Method	**A (m^2)**	**RE (%)**	**B (m)**	**RE (%)**	**Y (m)**	**RE (%)**	**R (m)**	**RE (%)**	**P (m)**	**RE (%)**	**V (m/s)**	**RE (%)**
Measured parameters	27.50	—	10	—	2	—	1.45	—	18.75	—	0.32	—
The new design formulas	27.34	−0.58	9.95	−0.5	1.96	−2	1.45	0	18.72	−0.16	0.32	0
Zidan and Saqr [9]	16.95	−38.37	9.43	−5.7	1.42	−28.98	1.21	−16.3	15.19	−19.0	—	—
Abdelhaleem and Amin[8]	39.96	45.29	—	—	1.60	−19.78	1.46	−0.56	—	—	0.18	−47.8

Table 3, the relative errors when using the currently developed formulas for area, bed width, mean depth, hydraulic radius, wetted perimeter, and the mean velocity are very small compared to those of the previous equations.

Verification by using a mathematical model

Abu Jabal canal, which is located within the general administration of Assiut Irrigation in Egypt and has a side slope of 2:1, was chosen for the model simulation. This canal suffers from hydraulic problems, as the canal could not accommodate its design discharge, which is 7.5 m^3/s. The maximum discharge that could be passed through Abu Jabal canal, in its current situation, is 5 m^3/s. The mathematical model (HEC-RAS), which was developed by the US Army Corps of Engineers Hydrologic Engineering Center, was used to represent the reach of the canal under study. The length of the chosen reach is 2,300 km, and it was represented on the HEC-RAS program by 24 cross-sections, with an occasional cross-section every 100 meters. First, the model was calibrated by feeding the model with the reach geometry, Manning's roughness coefficient, and the discharge value, which is 5 m^3/s as an initial condition. The controlling factor that is affecting the performance of the model is the Manning's roughness coefficient. So, the value of this coefficient was adjusted till the water surface profile that was determined from the model coincided with that determined from the field measurements, as shown in Figure 3. Then, the new regime equations were used to redesign the canal to carry the required design discharge $Q = 7.5\ m^3/s$. The median particle size d_{50} was produced from laboratory tests, and its value is 0.259 mm. The first category of regime equations was used ($113 \geq Q.\ g^{-0.5}.\ {d_{50}}^{-2.5} > 20$). The new cross-section characteristics should be $B = 10$ m, $Y = 2.05$ m, $A = 28.91\ m^2$, $R = 1.51$ m, $P = 19.17$ m, $V = 0.26$ m/s, and $S = 8$ cm/km. Figure 4 shows the comparison between the actual, old, and the new cross-section designs, which were produced by the new regime equations. Moreover, the proposed new cross-section, which resulted from the deduced equations and corresponds to $Q = 7.5\ m^3/s$, was integrated in the program with $Q = 7.5\ m^3/s$ as an initial condition. Figure 5 represents the comparison of the water surface profile estimated from the program with that produced from the regime equation. It is obvious that the water surface profile produced from the regime equations coincides with that determined from the program.

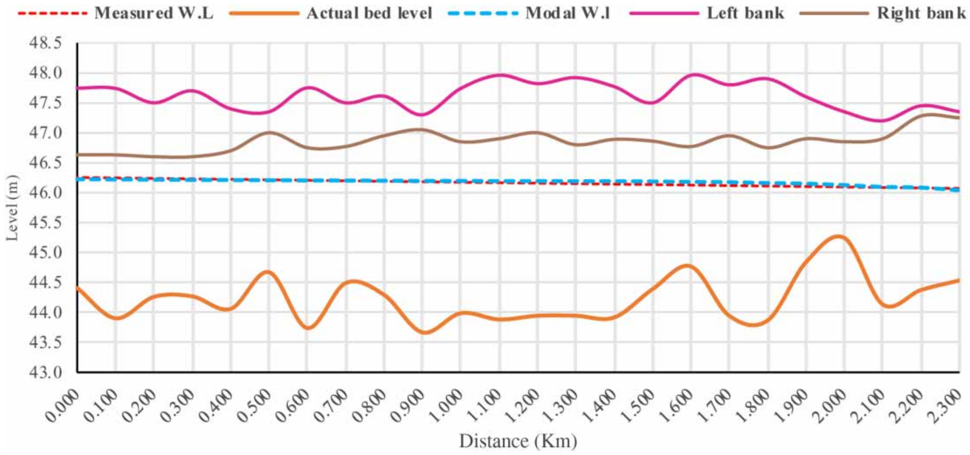

Figure 3 | The calibration of the model.

Sensitivity analysis

Sensitivity analysis has been performed in order to investigate the effect of changing the deduced parameters on the discharge. It is obvious that the variable which has the biggest effect on the total

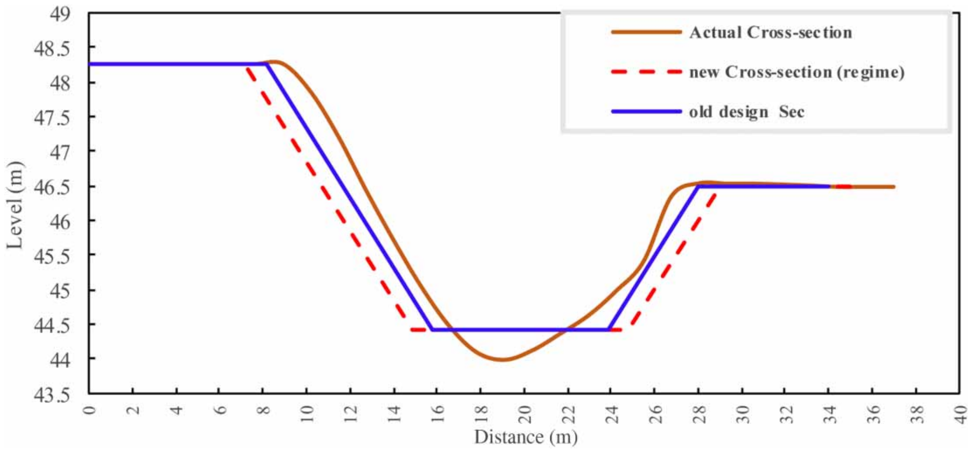

Figure 4 | Comparison between actual, old design and new design regime.

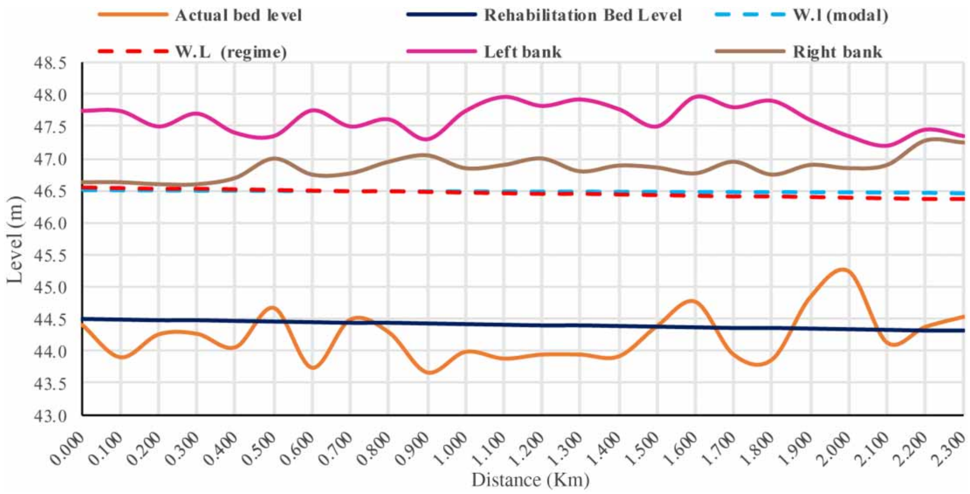

Figure 5 | Comparison between actual and redesigned cross-section by regime.

discharge is the water depth, as shown in Figure 6. Also, it is noticed that the change in the bed width has the smallest effect on the discharge relative to the other parameters (*Y*, *R*, and *P*).

CONCLUSION

In the present study, extensive field measurements have been implemented to deduce practical regime equations that could be used efficiently for designing and rehabilitating Egyptian sandy canals. The following conclusions are drawn:

The regime equations presented in this study are practical design procedures for designing new and unstable Egyptian canals with sandy soil, which have a discharge range 5–50 m^3/s and median grain size d_{50} range from 0.196 mm to 0.538 mm.

Median grain size d_{50} is an effective parameter, and it should not be ignored in determining the regime equations.

The applicability of the deduced regime equations has been verified, and there is a perfect agreement between the canal's parameters deduced from the regime equations and the real ones produced from the field measurements.

The mean depth is the most affective parameter in the new regime equations.

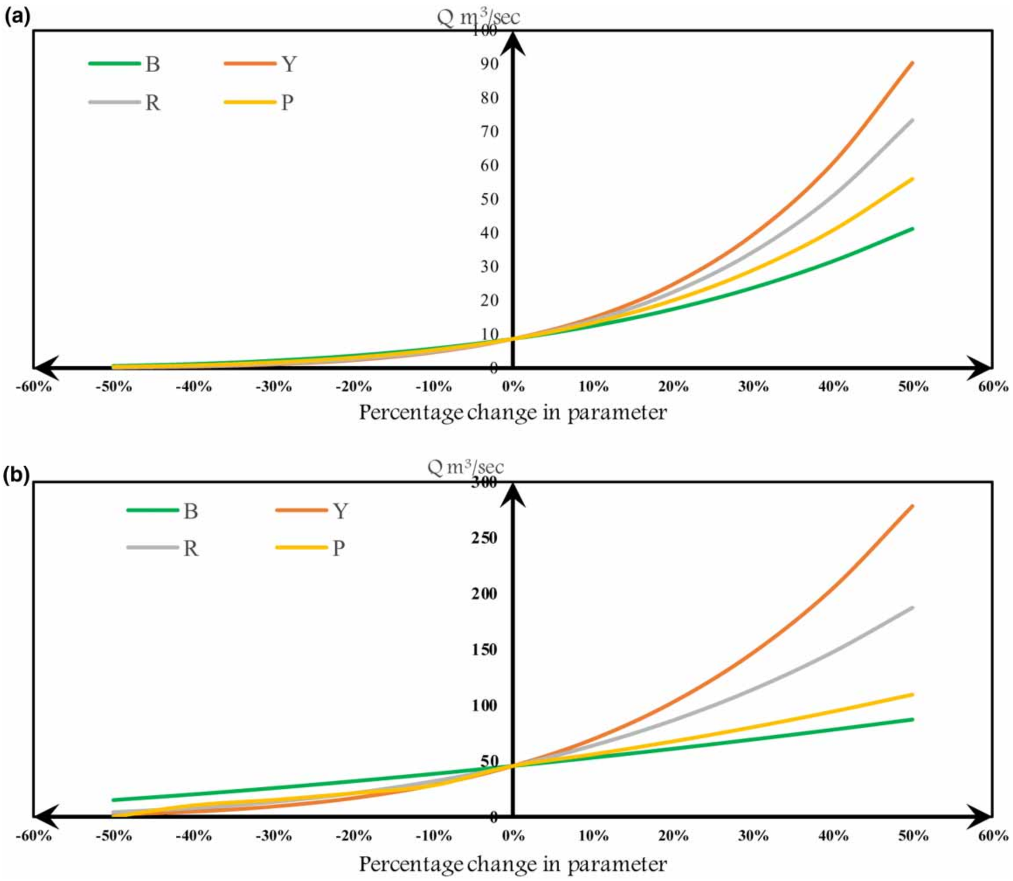

Figure 6 | Sensitivity analysis for (a) first category of new regime equations (b) second category of new regime equations.

More studies should be implemented on other soil types and different discharge ranges to cover all the Egyptian irrigation network.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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