EFFECT OF GEOMETRY COMPUTATIONS AND NUMERICAL SCHEME ON THE RESISTANCE COEFFICIENT FOR UNSTEADY FLOW IN IRREGULAR CHANNELS

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Abstract

The problem of predicting flow resistance coefficient with sufficient accuracy is of great interest to hydraulic engineers. Realistic estimate of hydraulic resistance is important to the proper design and analysis of irrigation and drainage networks. Resistance (roughness) coefficient is a compound function of the geometric properties of the channel, the fluid properties, and the varied flow conditions prevalent in the open channel system. The purpose of this study is to demonstrate the response of the applied method of irregular geometric properties computation, the used numerical scheme, and the distance interval adopted in the numerical model on the calibrated value of resistance coefficient.

The rectangular grid scheme of the method of characteristics is applied with different methods of irregular geometric properties computation and different value of distance interval. While, the Leap-Frog finite difference scheme is used with only one method of geometric properties computation and one value of distance interval. Measured field data of Tanta Navigation canal are used to feed and calibrate the numerical models. Results of numerical experiments illustrate that inaccurate channel geometry representation in the numerical models leads to incorrect value for the calibrated value of roughness coefficient. Findings also demonstrate that the applied numerical scheme as well as the schematization to describe the channel geometry by a series of discrete representation along the reach being modeled has significant effect on the calibrated value of the roughness coefficient.

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Introduction

The main issue of the problem of flow in alluvial channels centers on the estimation of their hydraulic resistance. Knowledge of this factor is essential for accurate calculation of the sediment transport rate, stage-discharge relationships, channel stability, waterways design, and prediction of aggradation and degradation due to the presence of hydraulic structures. The resistance (roughness) coefficient is influenced by size, shape, and arrangement of granular material forming the wetted perimeter, geometry of the bed patterns (ripples, dunes, and antidunes) formed by the flow, rate of sediment transport, irregularity of channel cross sections, variation of shape and size of channel cross sections, channel alignment (meandering), vegetation characteristics and obstructions [14]. Each of these components contributes to the total resistance coefficient.

One of the characteristics of irregular channels is the geometric properties variation of cross sections, Area (A), top width (B), and wetted perimeter (P), along the channel reach. The non-uniform properties of channel cross sections (channel irregularity) affect the conveyance and storage characteristics of the channel reach. Channel irregularities control the variation of flow from section to section and, at particular section, the variation of flow with stage. Theses irregularities are directly responsible for modifications of flow characteristics along the channel reach. The measured cross sections of irregular channel must be chosen to ensure excellent feeding of the geometrical characteristics into the numerical model. They must be specified at locations along the channel reach where significant cross sections changes occur, i.e. the spacing of the measured cross sections, ΔX, depends on the degree of variation of cross section characteristics. Often this is a matter of economic balancing the value of additional accuracy versus the additional costs of data acquisitions.

The user of a computer program must decide the distance interval, ΔX, to be used in the computation and whether some of cross sections should be deleted (i.e., using larger distance interval) or additional ones introduced (say be interpolation). It is generally true that using smaller value of distance interval (step) in the numerical solution tends to give better accuracy, but requires more computation time [10 and 20]. There are different methods to simulate the measured geometric properties of cross sections in the numerical model. The numerical model user must consider how best to embody the physical characteristics and properties of the prototype system to the model.

The objective of this research is to study the effect of the used method for treatment of the measured geometric properties, the used distance interval, and the applied numerical scheme on the calibrated value of roughness coefficient. Numerical experiments are implemented using the rectangular grid scheme of the method of characteristics and the Leap-Frog scheme. Different methods of treatment of irregular geometric properties and different values of distance interval are applied. Measured field data of Tanta Navigation canal are used to carry out the numerical experiments.

Pervious Work

Most of the pervious researches used the calibration process to get the optimum value of the roughness coefficient, (n). Some of the pervious researches calibrated the roughness coefficient as a constant value [5, 9, 10, 16, 17, 18, 22, 24, and 26), or as a function of the longitudinal distance along the study reach (X) [3, 5, 12, 16, and 23]. While others calibrated the roughness coefficient as a function of the discharge (Q) [13, 17, and 20], as a function of the water depth (y) [19 and 26], or as a function of X and y [25]. It is found that the calibrated value of roughness coefficient is highly affected by the used boundary conditions [24] and including or omitting the non-prismatic term in the governing equations of unsteady flow [22].

Also, it is concluded that the measured field data errors and the local hydraulic conditions at the gauge site significantly influence the calibrated value of roughness coefficient [18]. Other researches calculated the value of roughness coefficient using measured field data of geometric properties, velocity (V) and water surface slope (S) at some selected cross sections along the study reach and applying Manning or Chezy equation [1, 6, 7, 8, 11 and 15]. While another research calculated the value of roughness coefficient in terms of the type of boundary material and bed forms at each measured cross section [10].

Various methods have been applied to represent the cross-sectional properties of irregular channels in the numerical models. Three board groups may be distinguished as follows:

1- using exact method, which calculates the geometric properties (A, P, and B) at each measured cross section for any value of water depth [10];

2- replacement of the actual irregular channel by only one cross section defined by regular shape of rectangular or trapezoidal cross section [26 and 27], or by cross-sectional properties defined by table of y versus A, P, and B or developed relationships of y versus A, P, and B [3, 10, 17, and 19];

3- replacement of the measured cross sections by cross sections defined by regular shape [12, 18, and 26], by tables of y versus A, P, and B at each sections [2, 9, and 10], or by developed relationships of y versus A, P, and B at each section [3, 4 and 10].

Governing Equations

The unsteady one-dimensional open channel flow equations can be derived from the principles of conservation of mass and momentum. The resulting equations are hyperbolic, non-linear, first order partial differential equations known as the de Saint Venant equations [21]. They can be expressed in terms of velocity and water depth as follows [21]:

$$A\frac{\partial V}{\partial X}+VB\frac{\partial y}{\partial X}+B\frac{\partial y}{\partial t}+V\left(\frac{\partial A}{\partial X}\right)_y=0 \qquad (1)$$

$$\frac{\partial y}{\partial X}+\frac{V}{g}\frac{\partial V}{\partial X}+\frac{1}{g}\frac{\partial V}{\partial t}=S_o-S_f \qquad (2)$$

in which; A is the cross-sectional area; V is the velocity; B is the canal top width at the water level; X is the longitudinal distance along the study reach; y is the water depth; t is the time; S_O is the bed slope; and S_f is the friction slope which calculated by Manning or Chezy equation, and $\left(\frac{\partial A}{\partial X}\right)_y$ is the nonprismatic term = rate of variation of A with respect to X when y is kept constant.

If the discharge and the cross-sectional area are used as dependent variables , the governing equations are expressed as follows[21]:

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial X}=0 \qquad (3)$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial X}\left(\frac{Q^2}{A}+gAY_{c.g}\right)=gA(S_o-S_f) \qquad (4)$$

in which; Q is the discharge and $Y_{c.g}$ is the depth of centroid of water section below water surface.

Models Used in Numerical Experiments

In this study, two numerical methods are used to solve the governing equations of unsteady flow in open channels. The first one is the rectangular grid scheme of the method of characteristics, MOC. While, the second one is explicit finite difference method (Leap-Frog Scheme).

Method of Characteristics (MOC)

Equations (1 and 2) can be written in the characteristic form as follows [10]:

$$\frac{dX}{dt}=V\pm C \qquad (5)$$

$$\frac{1}{g}\frac{dV}{dt} \pm \frac{1}{C}\frac{dy}{dt} = S_o - S_f \mp \frac{VC}{gA}\left(\frac{\partial A}{\partial X}\right)_y \tag{6}$$

in which; C is the wave celerity = $(gA/B)^{0.5}$

Using the first order approximation, i.e., explicit solution, and the rectangular grid scheme of the method of characteristics, the characteristic equations can be written as:

$$X_P - X_R = (V + C)_R (t_P - t_R) \tag{7}$$

$$X_P - X_S = (V - C)_S (t_P - t_S) \tag{8}$$

$$V_P - V_R + \frac{g}{C_R}(y_P - y_R) - g(S_o - S_{fR})(t_P - t_R) + g\left(\frac{Vc}{gA}\right)_R \left(\frac{\partial A}{\partial X}\right)_y (t_P - t_R) = 0 \tag{9}$$

$$V_P - V_S - \frac{g}{C_S}(y_P - y_S) - g(S_o - S_{fS})(t_P - t_S) - g\left(\frac{Vc}{gA}\right)_S \left(\frac{\partial A}{\partial X}\right)_y (t_P - t_S) = 0 \tag{10}$$

in which the subscripts indicate the point in Fig. (1) at which quantity is referred. The variables *V, R* (hydraulic radius), *C* (wave celerity), and *y* at the points R and S, Fig. (1), are calculated by interpolation between the adjacent nodes. By solving the above equations, the values of V_p and y_p can be obtained.

Leap-Frog Scheme

This scheme is explicit finite difference scheme, which is of second order accuracy. Equations (3 and 4) are expressed in finite difference [21] as follows, Fig. (1):

$$\frac{A_i^{j+1} - A_i^{j-1}}{2\Delta t} + \frac{Q_{i+1}^j - Q_{i-1}^j}{2\Delta X} = 0 \tag{11}$$

$$\frac{Q_i^{j+1} - Q_i^{j-1}}{2\Delta t} + \frac{F_{i+1}^j - F_{i-1}^j}{2\Delta X} = E_i^j \tag{12}$$

in which; $F = (Q^2/A + gAY_{c.g})$; and $E = gA\,(S_o - S_f)$

Equations (11 and 12) yield expressions for A and Q at the (j+1)th time level in terms of the dependent variables at the (j)th and (j-1)th time levels. Equations (11 and 12) are linear equations, which can be solved easily.

Field Data

The purpose of field measurements is to feed and calibrate the numerical model. In this research, a reach of 15-km length of Tanta Navigation canal, from km 0.0

to km 15.0, is chosen to measure the field data required for the numerical model. This reach of the canal is located in Al-Menufiya Governrate. This canal is stable alluvial canal, which takes water from Bahr Shebin at km. 53.50, Fig. (2). The geometric properties of cross sections for the study reach are measured at equal distance of 1km. For each cross section, the level of canal bed and its sides are measured every 2m along the canal sections, Figs (3 and 4) are examples of the measured cross sections.

The flow is assumed to be steady nonuniform at the initial line, at time (t) = 0, to get the initial water depth at all cross sections along the study reach. This is carried out by employing Manning's equation with the same roughness coefficient and the same method of geometric properties simulation used in the numerical model. Daily water level hydrograph at downstream boundary of the study reach is measured through a period of 21 days. Daily water level and discharge hydrographs at the upstream boundary of the study reach are obtained from the Ministry of Water Resources and Irrigation. Daily discharge hydrograph at a section of 6 km away from the upstream boundary is measured through a period of 21 days, Fig. (7).

The mean velocities of canal cross section are measured using a marked wire and the currentmeter. The cross section is divided into a number of subsections of width 5m. The mean velocity of each subsection is measured with the currentmeter. For shallow depths, the mean velocity is considered to be equal to the measured velocity at 0.6 water depth measured from the water surface. While for other depths, the mean velocity is considered to be equal to the average of the measured velocities at 0.2 and 0.8 water depth below the water surface. Least square method is used to get the longitudinal bed slope, which is 6.4 cm / km.

Numerical Experiments

In this study, the rectangular grid scheme of the method of characteristics is applied using distance interval of 2 km and different methods to simulate the measured geometric properties of the study reach. These methods are as follows:
1- using exact method, which calculates the geometric properties (A, P, and B) at each measured cross section for any value of water depth, y;

2- replacement of each measured irregular cross section by cross-sectional properties defined by table of y versus A, P, and B;

3- replacement of each measured irregular cross section by developed relationships of y versus A, P, and B;

4- replacement of the measured irregular cross sections by only one cross section defined by developed relationships of y versus A, P, and B; and

5- by using a ***newly developed method***, which replace each measured irregular cross section by developed relationships of y versus A, P, and B as follows:

- Divide each measured cross section into two parts; the first part is below the minimum expected water level, while the second part is above the minimum expected water level, Fig. (5);
- Using the exact method (method No.1 mentioned above), calculate the area (A_o), the wetted perimeter (P_o), and the top width (B_o) for the first part of the measured cross section corresponding to the expected minimum water level ;
- Develop relationships (functions) , of y_U versus A, P, and B_U, for the second part of the measured cross section, Fig. (5):

$$A = f_1 (y_U) \quad , \quad P = f_2 (y_U) \quad , \quad B_U = f_3 (y_U)$$

Where; y_U is any value of water depth above the expected minimum water level and B_U is the increase in top width corresponding to y_U.

These functions are obtained by assuming different values of y_U above the minimum expected water levels and calculating the corresponding values of A, P, and B_U by using the exact method (method No.1 mentioned above).

- For each measured cross section, the values of A, P, and B (for the first and the second part of the section, i.e., for the whole section) at any value of y are calculated as:

$$A = A_o + f_1 (y_U) \quad , P = P_o + f_2 (y_U) \quad , B = B_o + f_3 (y_U)$$

It is worth to mention that the above mentioned methods (method No.2 to method No.5) apply method No.1 to form the tables or to develop the relationships of y versus A, P, and B. The above mentioned methods are labeled herein as method1, method2, method3, method4, and method5; respectively.

Also, different values of distance interval are applied using the rectangular grid scheme with the two cases of measured geometric properties computation; case1 and method4. The used values of distance interval are 1km, 2km, and 3km, i.e., it is assumed that the information of the measured cross section is only available at distances of 1km, 2km, and 3km; respectively. The Leap-Frog scheme is applied using method1 of measured geometric properties computation with distance step of 2km.

Method of Accuracy Assessment

In this study, the results of numerical experiments are compared with the measured discharge hydrograph at km 6. The accuracy refers to how closely the computed values agree with the measured field values. This means that the difference between the simulated results of a certain numerical solution and the measured values is a measure of accuracy of that solution. This difference (error) is expressed in mean of the percentage relative errors, where;

Percentage relative error = 100 * |measured value − calculated value| / (measured value)

The statistical methods used in this study are percentage relative accuracy and standard deviation of the percentage relative errors (S.D.), where;
Percentage relative accuracy = 100 – mean of percentage relative errors;
While the mean of percentage relative errors is defined as the summation of the percentage errors divided by the number of observations.

Analysis of the Numerical Results

The results of the numerical experiments applying the rectangular grid scheme of the method of characteristics with different methods of geometric properties computation and distance interval of 2km are shown in Table (1).

Table (1) Effect of using different methods of geometric properties computation on the calibrated value of roughness coefficient.

Method1	Value of n	0.027	0.0275	0.028	0.0285	0.029
	% relative accuracy	95.8913	96.1837	96.3853	96.2067	96.0171
	S.D.	0.8492	0.8238	0.8035	0.8217	0.8483
Method2	Value of n	0.0275	0.028	0.0285	0.029	0.0295
	% relative accuracy	95.4053	95.6019	95.7925	95.5973	95.3868
	S.D.	0.8901	0.8703	0.8518	0.8723	0.8917
	Comutation time = 49.26 % of that of method1					
Method3	Value of n	0.028	0.0285	0.029	0.0295	0.030
	% relative accuracy	94.9088	95.1339	95.3830	95.1467	94.9173
	S.D.	0.9175	0.8946	0.8706	0.8937	0.0.9165
	Comutation time = 34.38 % of that of method1					
Method4	Value of n	0.030	0.0305	0.031	0.315	0.032
	% relative accuracy	93.6047	93.9225	94.3065	93.9616	93.6143
	S.D.	1.0216	0.9895	0.9526	0.9886	1.0209
	Comutation time = 31.57 % of that of method1					
Method5	Value of n	0.0275	0.028	0.0285	0.029	0.0295
	% relative accuracy	95.3326	95.5478	95.7166	95.5256	95.3282
	S.D.	0.8980	0.8776	0.8576	0.8781	0.8988
	Comutation time = 34.76 % of that of method1					

Referring to Table (1), the following conclusions are found:

1- The value of Manning's roughness coefficient, n, of 0.025, which is usually applied in design of Egyptian earthen canal, could be improper value and requires more studies.

2- The value of the calibrated roughness coefficient in irregular channel is highly dependent on the applied method for geometric properties representation.

3- The accuracy of the *newly developed* method of geometric properties computation (method5) is 99.31 % of the accuracy of method1, while requires computation time equal to 34.76 of that of method1.

4- The accuracy of the newly developed method (method5) is 99.92 % of the accuracy of method2, while requires computation time equal to 70.56 of that of method2.

5- The calibrated value of roughness coefficient for the newly developed method (method) equals that for the method2 and slightly differs from that for the method1.

The results of applying the rectangular grid scheme of the method of characteristics using different values of distance interval with method1 and method4 of geometric properties computation are shown in Table (2) and Fig. (6).

Table (2) influence of using different values of distance interval with method1 and method4

Method1	ΔX = 1km	Value of n	0.0265	0.027	0.0275	0.028	0.0285
		% relative accuracy	96.608	96.712	96.803	96.702	96.591
		S.D.	0.8071	0.7998	0.7842	0.7971	0.8033
	ΔX =3 km	Value of n	0.0275	0.028	0.0285	0.029	0.0295
		% relative accuracy	95.168	95.522	95.903	95.539	95.174
		S.D.	0.9084	0.8805	0.8416	0.8792	0.9076
Method4	ΔX = 1km	Value of n	0.029	0.0295	0.030	0.0305	0.031
		% relative accuracy	94.671	94.870	95.079	94.864	94.664
		S.D.	0.9312	0.9138	0.8991	0.9151	0.9338
	ΔX =3 km	Value of n	0.031	0.0315	0.032	0.325	0.033
		% relative accuracy	92.144	92.801	93.429	92.793	92.131
		S.D.	1.2854	1.2289	1.1762	1.2305	1.2881

Referring to Table (2) and Fig. (6), it is concluded that:

1- The calibrated value of roughness coefficient is significantly on the used distance interval.

2- The decrease of the distance interval value using method4 from 2km to 1km increases the accuracy of the results by a value of is 0.75%, while the corresponding value using method1 is 0.43%. This means that the increase in the accuracy of the results by decreasing the value of distance step using method4 is higher than that of method1.

3- For the case of $\Delta X = 1km$, a value of 0.005 change in the value of n from its optimum value results in 0.10% and 0.20% decrease of the accuracy for method1 and method4; respectively. While, the corresponding values are 0.37% and 0.62%; respectively for the case of $\Delta X = 3km$. This means that the improvement of the accuracy of the results by using optimum value of roughness coefficient depends on the method of geometric properties computation, especially for higher values of ΔX.

The results of applying the Leap-Frog scheme using $\Delta X = 2km$ and method1 of geometric properties computation are shown in Table (3) and Fig. (7).

Table (3) The results of applying the Leap-Frog scheme with method1 using $\Delta X = 2km$

Value of n	0.026	0.0265	0.027	0.0275	0.028
% relative accuracy	96.1091	96.2917	96.4732	96.3064	96.1112
S.D.	0.8458	0.8211	0.8014	0.8203	0.8449

Referring to Tables (1 and 3) and Fig. (7), it is found that:

1- The calibrated value of roughness coefficient for the Leap-Frog scheme is not equal to that of the rectangular grid scheme of the methof of characteristics.

2- The accuracy of the Leap-Frog scheme and the rectangular grid scheme of the method of characteristics are approximately equal.

3- The change of the value of n from its optimum value produce decrease in the accuracy of the leap-Frog scheme is approximately to that of the rectangular grid scheme.

Conclusions

The conclusions of this research can be summarized as follows:

1- The value of Manning's roughness coefficient is could be different from the value of 0.025, which is commonly used in the design of Egyptian earthen canal. Considerable attention should be paid in evaluating the value of roughness coefficient.

2- If an irregular channel is simulated as an equivalent regular channel or as a sequence of equivalent regular channel segments, the calibrated value of roughness coefficient will be larger than its true value.

3- The value of roughness coefficient is highly influenced by the used value of distance interval. Different value of distance interval yields to different value of roughness coefficient.

4- The sensitivity of the rectangular grid scheme of the method of characteristics to the used distance interval is significantly dependent on the used method of geometric properties computation.

5- The sensitivity of the rectangular grid scheme of the method of characteristics to the value of roughness coefficient is highly dependent on the used method of geometric properties computation and the used value of distance interval.
6- The calibrated value of roughness coefficient is significantly affected by the applied numerical scheme.
7- The sensitivity of the rectangular grid scheme of the method of characteristics to the value of roughness coefficient is equal to that of the Leap-Frog scheme.

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Nomenclature

A	cross-sectional area;
B	top width at the water level;
B_U	increase in top width corresponding to y_U;
C	wave celerity = $(gA/B)^{0.5}$;
E	$gA\,(S_o - S_f)$;
F	$Q^2/A + gAY_{c.g}$;

g	acceleration due to gravity;
n	Manning's roughness coefficient;
P	wetted perimeter;
Q	discharge;
S_o	bed slope;
S_f	friction slope;
t	time;
X	longitudinal distance along the study reach;
y	water depth;
y_U	water depth above the expected water level;
$Y_{c.g}$	depth of centroid of water section below water surface;
Δt	time interval;
ΔX	distance interval; and
$(\partial A/\partial X)_y$	rate of variation of A with respect to X when y is held constant.

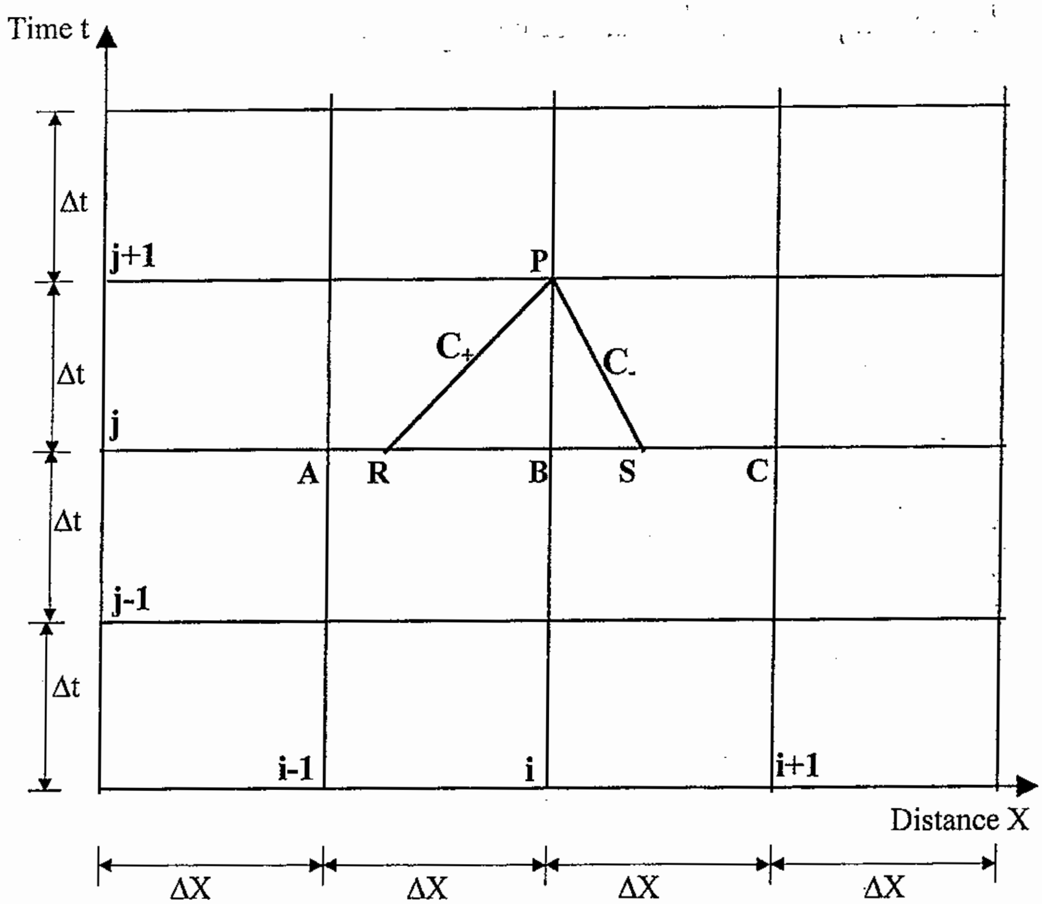

Fig. (1) Definition Sketch of Rectangular grid scheme of the method of characteristics and Leap-Frog scheme

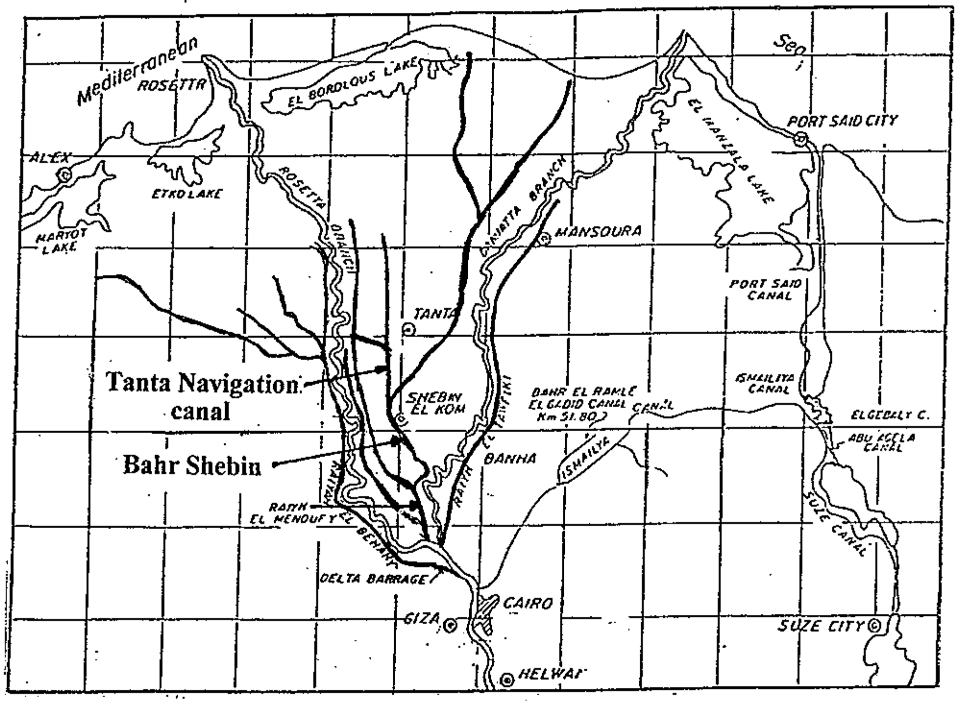

Fig.(2) General layout

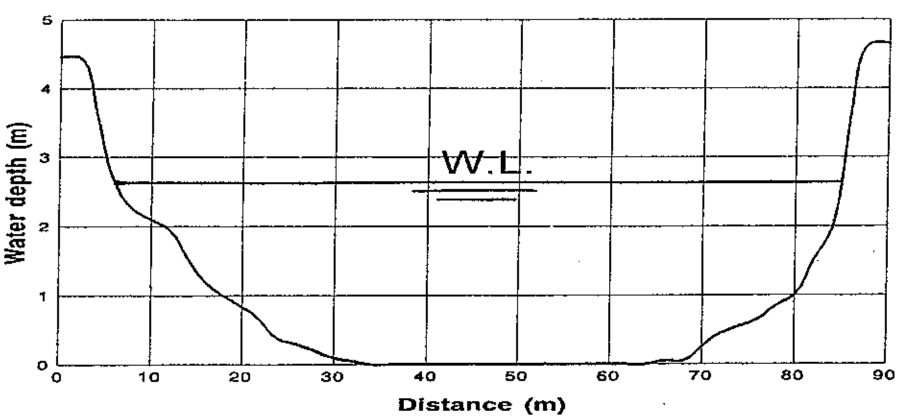

Fig.(3) Cross section at Km. (3.00)

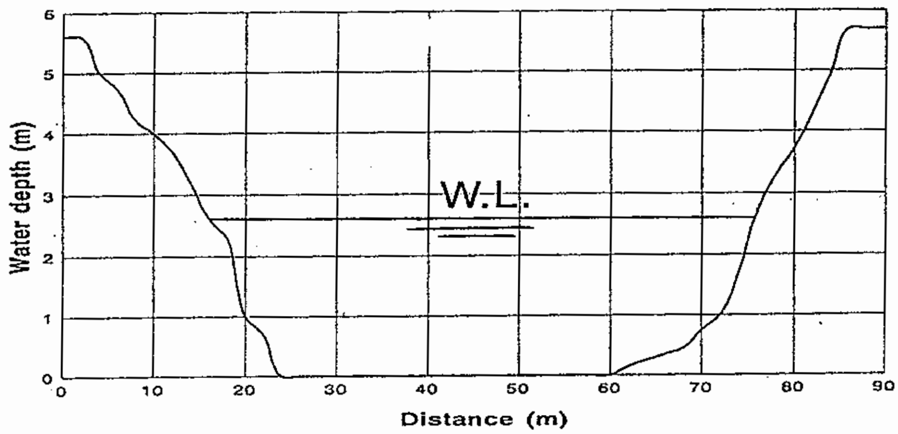

Fig.(4) Cross section at Km. (9.00)

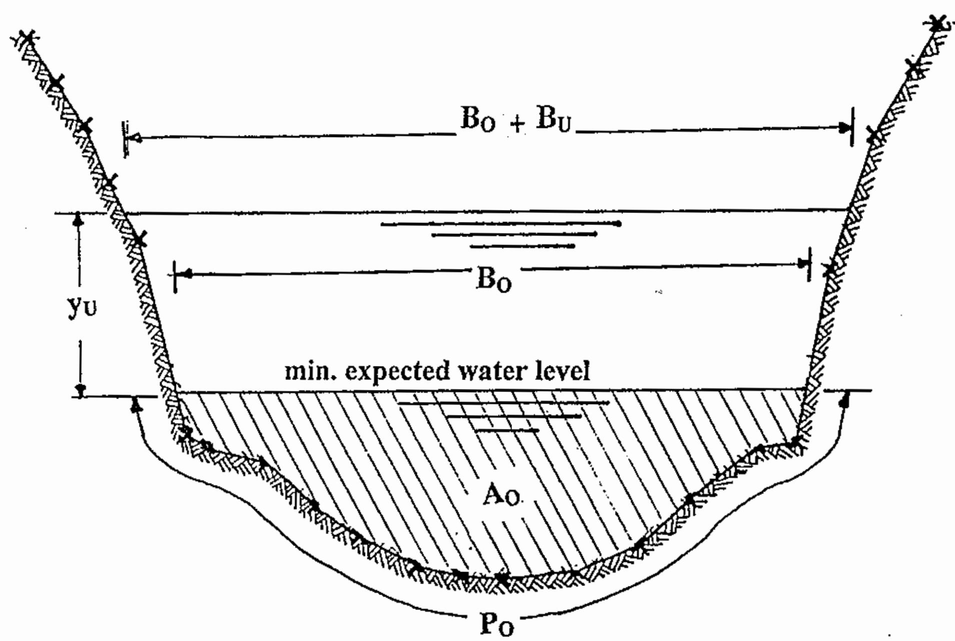

Fig. (5) Generalized sketch of a channel cross section illustrating method5 of geometric properties computation

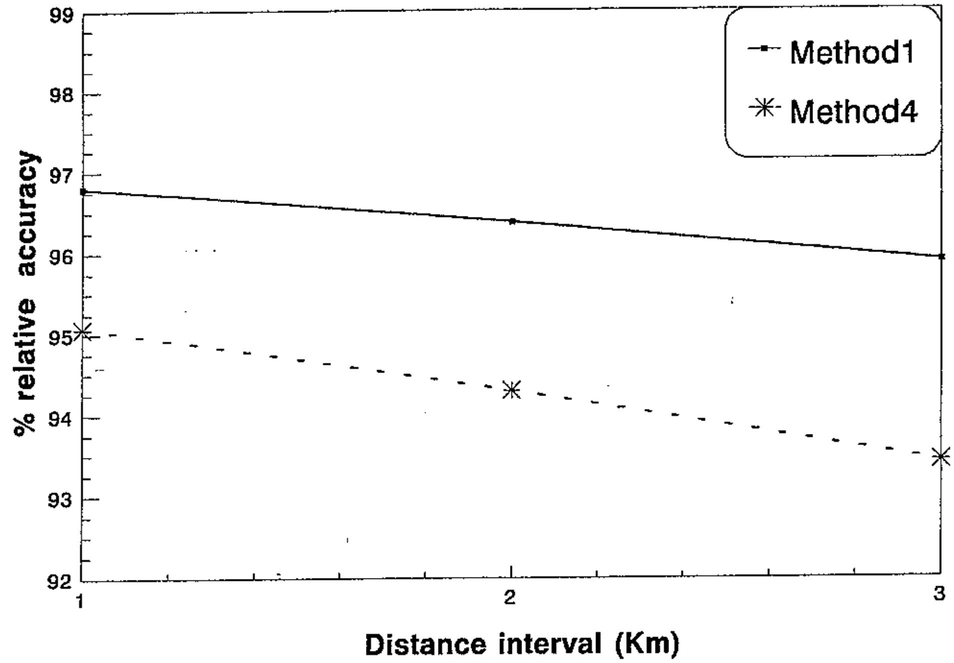

Fig.(6) Accuracy of Mehod1 and Method4

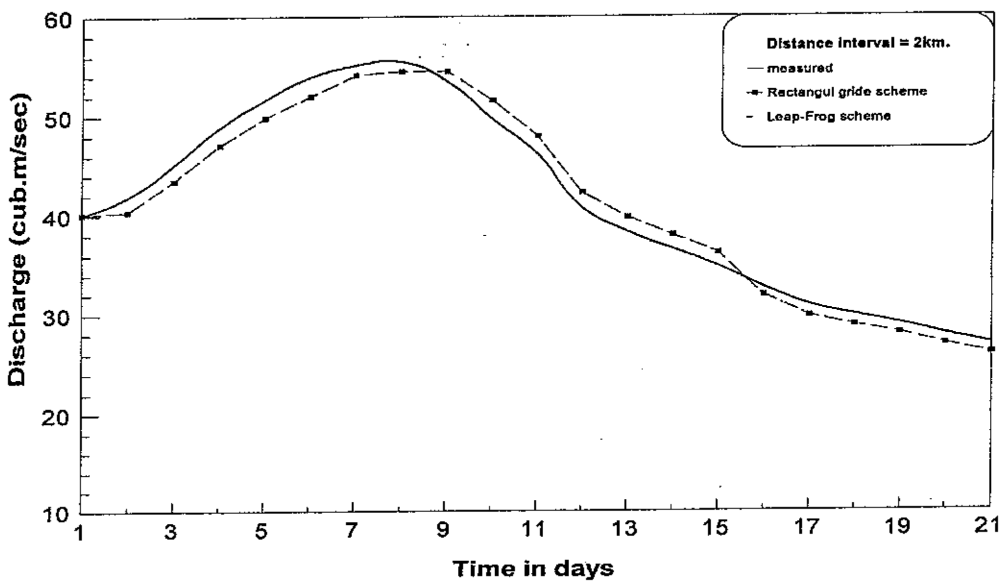

Fig.(7) Comparison between the measured and simulated discharge hydrographs.

تأثير حساب الخواص الهندسية والنموذج الرياضي على معامل الإحتكاك للسريان الغير مستقر فى القنوات الغير منتظمة

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معـــامل الإحتكاك (المقاومة) يعتمد على الخواص الهندسية لقطاعات المجرى المائى و خواص السريان وخواص السائل ويعتبر تحديد قيمة معامل الإحتكاك بدقة من أهم العناصر فى تصميم قطاعـــات الـــترع و المصارف وغالبا يتم إيجاد قيمة معامل الإحتكاك بالمعايرة. يوجد طرق مـــتعددة لحساب الخواص الهندسية للقطاعات فى الترع الغير منتظمة. الغرض من هذا البحث هـــو دراسة تأثير طريقة حساب الخواص الهندسية للقطاعات و طريقة حل النموذج الرياضي على قيمة معامل الإحتكاك المعاير فى الترع الغير منتظمة القطاعات.

وتمـــت الدراســـة مـــن خـــلال نموذج رياضي لترعة غير منتظمة وتم حل النموذج الرياضي باســـتخدام نموذج الشبكة المستطيلة للطريقة المميزة وكذلك باستخدام نموذج (Leap-Frog) لطـــريقة الفـــروق المحددة. وتم قياس بيانات حقلية لقناة طنطا الملاحية و تمت مقارنة نتائج الـــنموذج الرياضـــي مـــع القياســـات الحقلية. ووجد أن طريقة حساب الخواص الهندسية للقطاعـــات لها تأثير كبير على قيمة معامل الإحتكاك المعاير. وكذلك وجد أن طريقة حل الـــنموذج لهـــا تأثـــير على قيمة معامل الإحتكاك المعاير. ووجد أيضا أن المسافة المستخدمة (ΔX) فى النموذج الرياضي تؤثر على قيمة معامل الإحتكاك المعاير.