Numerical modeling for studying tidal inlets stability

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The present study investigates the possibility of designing a stable tidal inlet with self flushing and stable channel using a numerical model. The numerical model is developed and verified to simulate the flow and sediment motion in tidal inlet under the effect of tides and fresh water discharge to the lagoon. The program has two main parts; hydrodynamics and sedimentation. With the help of the developed program and based on the stability criteria, the design of stable inlet is presented. The hydrodynamic part is used to estimate velocities, discharge, tidal prism, Kelugan coefficient and lagoon/bay water level as a function of inlet geometry, tide type and tidal range in the sea. The sedimentation part is used to compute the sediment transport into the channel based on the current field from the hydrodynamic part at each time step. The field data, collected for the two inlets of El-Bardawil lagoon were used to calibrate the model. The model was used to evaluate the present two inlets and also used to design a new stable inlet for this lagoon. The model has proven its capability in designing stable inlets with depths that can allow the trapping of sediment until it is flushed out.

تبين الدراسة الحالية مدى إمكانية تصميم مدخل مدى متزن يتميز بمجرى متزن قادر على تطهير نفسة ذاتيا وذلك باستخدام نموذج عددي. في هذه الدراسة تم إنشاء أحد البرامج العددية وتم معايرته باستخدام بيانات مقاسه في الطبيعة. هذا البرنامج يقوم بحساب السرعات والتصرفات في المجرى وأيضا حركة الرسوبيات وذلك تحت تأثير المد وكذلك المياه الإضافية التي تلقى في البحيرة من المصارف وغيرها. بالاستعانة بهذا البرنامج واعتمادا على أسس التصميم المعروفة في مجال مداخل المد تم عرض تصميم المدخل المتزن. يتكون البرنامج من جزأين رئيسيين هما: الجزء الهيدروديناميكى والجزء الأخر لحساب حركة الرسوبيات. الجزء الأول يستخدم لحساب السرعات, التصرفات, المنشور المدى, معامل (Kelugan), ومنسوب سطح الماء داخل البحيرة بدلالة قطاع المدخل ونوعية ومدى المد فى البحر. أما الجزء الأخر فيستخدم لحساب حركة الرسوبيات على أساس السرعات والتصرفات المحسوبة فى الجزء الأول من البرنامج وذلك عند كل خطوة زمنية. استخدمت البيانات المجمعة عند مدخلي بحيرة البردويل فى معايرة البرنامج.بعد ذلك استخدم البرنامج لدراسة مدى اتزان هذين المدخلين, كذلك استخدم لتصميم مداخل متزنة لهذه البحيرة. وقد أثبت هذا النموذج فاعليته في تصميم مداخل متزنة ذات أعماق كافية لاستيعاب الرواسب لحين أن تكسحها التيارات.

Keywords: Tide, Tidal inlets, Sediment transport, Numerical models, Stability

1. Introduction

The tidal inlet connects lagoon/bay to coastal oceans or seas. It provides many benefits, like navigational access to the lagoon/bay for commercial shipping, fishing, and recreational boating. Also the tidal prism flows through inlet during tidal cycle playing a dominant role in flushing the sediments from the inlet and maintaining the water quality and salinity level in the lagoon/bay.

The main parameters affecting the stability of tidal inlets are tied and fresh water discharge in the lagoon as a flushing parameters and the littoral drift as a filling parameter. The inlet morphology and surface area of the lagoon are also affecting the inlet stability.

To keep the inlet stable against closure without maintenance dredging, it is essential that the inlet should satisfy the requirements of the inlet stability curve of Escoffier [1], fig. 1. In this curve, the maximum velocity through an inlet increases with cross-sectional area. It reaches the peak value at the critical cross-sectional area, A_c* and then decreases for larger cross-sectional areas. This means that the inlet should fall on the stable side of the peak. The associated velocity should also be in accordance with Bruun's relationship [2], which is 0.8m/sec. $< V_{max.-mean} <$ 1.2 m/sec. Bruun also proposed a stability criteria which considers the relationship between the total rate of sediment transport feed the inlet channel (M_{tot}) and the spring tidal prism (P). He found that all stable inlets channels fulfill the following equation:

$$\frac{P}{M_{tot}} > 150 . \quad (1)$$

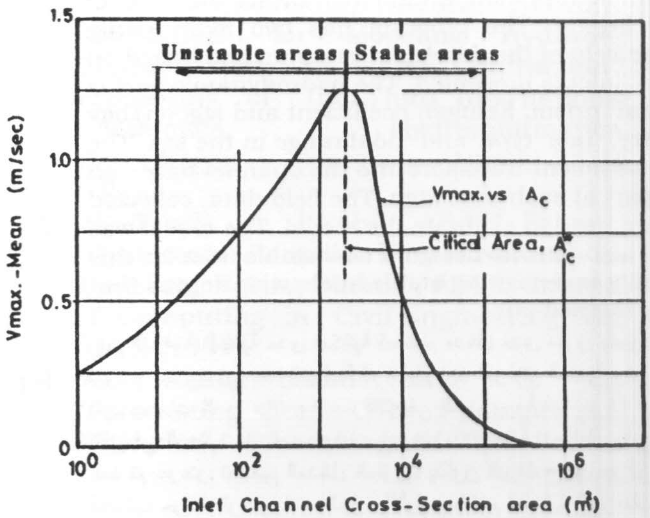

Fig. 1. Illustration of Escoffier's stability concept.

Eq. (1) can be considered as a stability indicator in which the greater ratio of (P/M_{tot}) means the better entrance condition. The better entrance condition according to Bruun's criterion is the ability of the tidal flow to flush out the sediment that are carried by the waves and currents action to the inlet. These principles are very important and should be taken into consideration during the design of tidal inlets.

The aim of this paper is to present a numerical model to be used in designing stable inlets. This developed program is used to evaluate the stability of the present artificial inlets of El-Bardawil lagoon and also used to design stable inlets to this lagoon.

2. Numerical modeling

The numerical model has two main modules; hydrodynamic module and sedimentation module.

2.1. The hydrodynamic module

This model is based on one-dimensional momentum equation for the inlet and a continuity equation for the bay.

2.1.1. The momentum equation

The momentum equation in one dimensional form for the inlet channel can be expressed as the following:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -g\frac{\partial a}{\partial x} - g\frac{u|u|n^2}{Rc^{4/3}} . \quad (2)$$

Where; u is the average flow velocity in the x direction, a is the elevation of water level due to tide, n is Manning coefficient, and Rc is the hydraulic radius.

Considering the channel as a constant cross-section, the energy equation for the system is found by integrating of the momentum equation along the channel length (L_c).

$$a_s - a_b = \frac{L_c}{g} x \frac{\partial u}{\partial u} + (K_{en} + K_{ex} + \frac{2gL_c n^2}{R_c^{4/3}}) \frac{u|u|}{2g} . \quad (3)$$

Where; a_s is the water level elevation in the sea, a_b is the water level elevation in the bay, and K_{en} and K_{ex} are the head-loss coefficients at entrance and exit of the inlet channel, respectively.

Dean (1971, cited by Bruun [2]) recommended a value of K_{en}+K_{ex}= 1.3. As a value of K_{ex} = 1 is usually adopted by Bruun[2], then this sets K_{en}=0.3. These values were also adopted by Czerniak [3].

The variation of the total energy line along the inlet channel obtained by eq. (3) is shown in fig. 2.

2.1.2. The continuity equation

The rate of change of water level in the lagoon/bay is a function of inlet discharge plus discharges into the bay from other sources. This phenomenon can be described by a simple mass continuity equation as follows:

$$\frac{\partial a_b}{\partial t} = \frac{Q_t}{A_{bay}} + \frac{Q_f}{A_{bay}} . \quad (4)$$

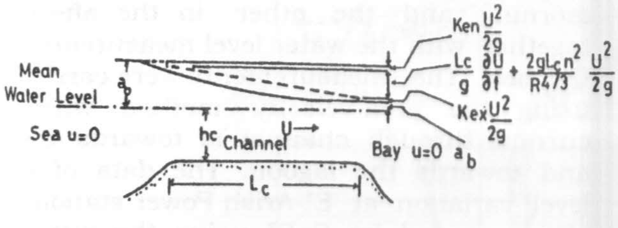

Fig. 2. Variation of total energy line along inlet channel.

Where;

A_{bay} is the surface area of the bay,
Q_i is the discharge of i^{th} inlet,
Q_f is the discharge into the bay from other sources such as (rivers, pumped inflows, etc.), and
Q_t is the total inlet discharge and is calculated using the following equation:

$$Q_t = \sum_{i=1}^{n} Q_i . \quad (5)$$

2.2. The sedimentation module

In this model, three equations of Engelund-Hansen [4] Engelund-Fredsoe [5] and Van-rijn [6, 7, 8] are used to compute the rate of sediment transport in the channel based on the average flow velocity from the hydrodynamic model at each time step. The average of these equations is obtained to get the volume of sediment transport in the channel.

The flow chart of this numerical modeling is given in fig. 3.

3. The boundary conditions

The boundary conditions of this system are the tidal water level variation in the sea, the lagoon representing a storage capacity and the inflow discharge to the lagoon/bay from other sources except the inlet.

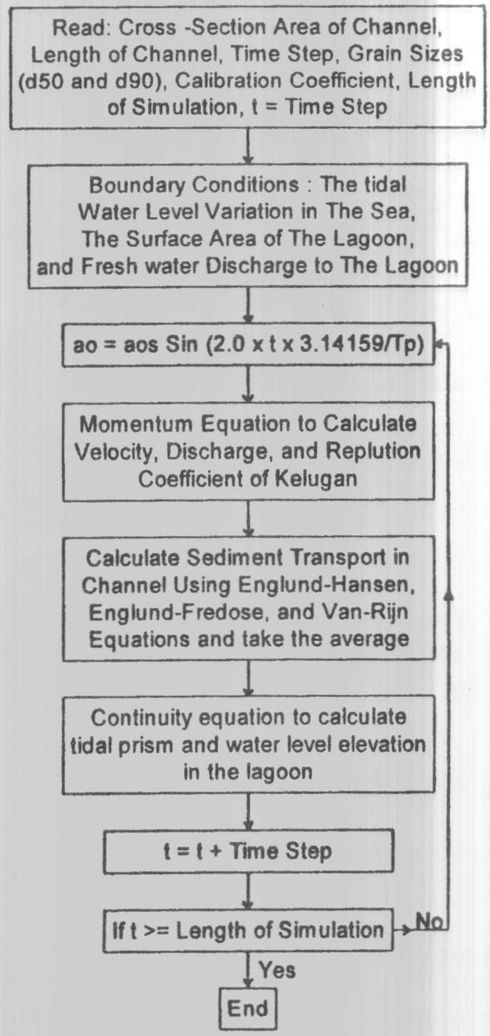

Fig. 3. Flow chart of the numerical modeling.

4. Numerical approach

The setup of the numerical system is based on eqs. (3) and (4) and to simplify the calculations the cross section area of the inlet is assumed to have a rectangular shape.

The equations are solved by the forward finite difference method, where the initial conditions are zero water level. The sinusoidal variation in the sea will initiate a flow in and out of the lagoon, and by calculation for several periods a steady varying flow is obtained.

Eqs. (3) and (4) are then discretized as the following:

$$1/2\left(a_s^{t+1}+a_s^t\right)-1/2\left(a_b^{t+1}+a_b^t\right)=\frac{L_c}{g}\times\frac{u^{t+1}-u^t}{\Delta t}$$

$$+\left(K_{en}+K_{ex}+\frac{2gL_cn^2}{R_c^{4/3}}\right)\frac{u^{t+1}\times u^t}{2g}\ , \qquad (6)$$

$$A_{bay}\frac{a_b^{t+1}-a_b^t}{\Delta t}=1/2\left(u^{t+1}+u^t\right)A_c^t+Q_f^t\ . \qquad (7)$$

Where;

$$A_c^t=B\times h_c^t\ , \qquad (8)$$

$$h_c^t=D+1/2\left(a_s^t+a_b^t\right) \qquad (9)$$

$$R_c^t=A_c^t/\left(B+2h_c^t\right)\ . \qquad (10)$$

The tidal elevation in the sea is given for all times by the sinusoidal variation as shown in eq. (11).

$$a_s=a_{os}\sin(\omega t)\ , \qquad (11)$$

$$\omega=2\times\pi/T_P\ . \qquad (12)$$

Where; B is the channel width, D is the water depth, T_p is the tidal period, a_{os} is the amplitude of tidal elevation in the sea.

The input data required for running the model are; tidal range, tidal period, length of channel, surface area of lagoon/bay, fresh water discharge and cross-sectional area of the channel.

5. Model verification

In order to verify the model, the field data of El-Bardawil Inlet velocities and the water level variation at El-Arish power station are used.

El-Bardawil lagoon is located at 40 km to the east of the Suez canal on the northern Sinai coast and at 25 km to the west of El-Arish city as shown in fig. 4. The only source of water feeding this lagoon is the tidal prism from the Mediterranean Sea through the two artificial inlets (No. 1 and 2) and the third which is natural at El-Zaraneek, figs. 5 and 6. The data of inlet velocities were measured by CoRI during July 1999 and the beginning of October 1999, (CoRI [9]). These velocities were measured two times per day one in the morning and the other in the afternoon, together with the water level measurements in the sea. The measurements were carried out using the area-velocity method, when the current through channel is towards the sea and towards the lagoon. The data of water level variation at El-Arish Power station were also recorded by CoRI using the automatic tide gauge during the period from April 1996 to June 1998, (CoRI [10]). Table 1 presents the input data for the model.

Table 1
The input data for the model

Input	Value
Spring tide range	0.42m (from tide gauge at El-Arish)
Neap tide range	0.15m (from tide gauge at El-Arish)
Area of inlets No. 1 and 2	1024 m² and 1390 m², respectively
Depth of inlets No. 1and 2	6.0 m and 6.6 m, respectively
Length of inlets No.1and 2	800 m and 600 m, respectively

The verification of the numerical model shows that Manning coefficient should be taken equal to .03 to give results in good agreement with the field data.

6. Application of the model for El- Bardawil lagoon

The calibrated model was applied for the two artificial inlets of El-Bardawil lagoon. The numerical model results showed that the max.-mean velocity equals 1.2 m/sec. as shown in fig. 7-a. Also, the variation of sediment transport in inlet per time step has nearly the shape of sine curve, as shown in fig. 7-b. The sediment is transported when the velocity is greater than 0.3 m/sec and the rate of sediment increase with the increase of velocity. Moreover, the amount of sediment load coming during flood is nearly equals to the amount of sediment load going out during ebb period. The relationship between the cross

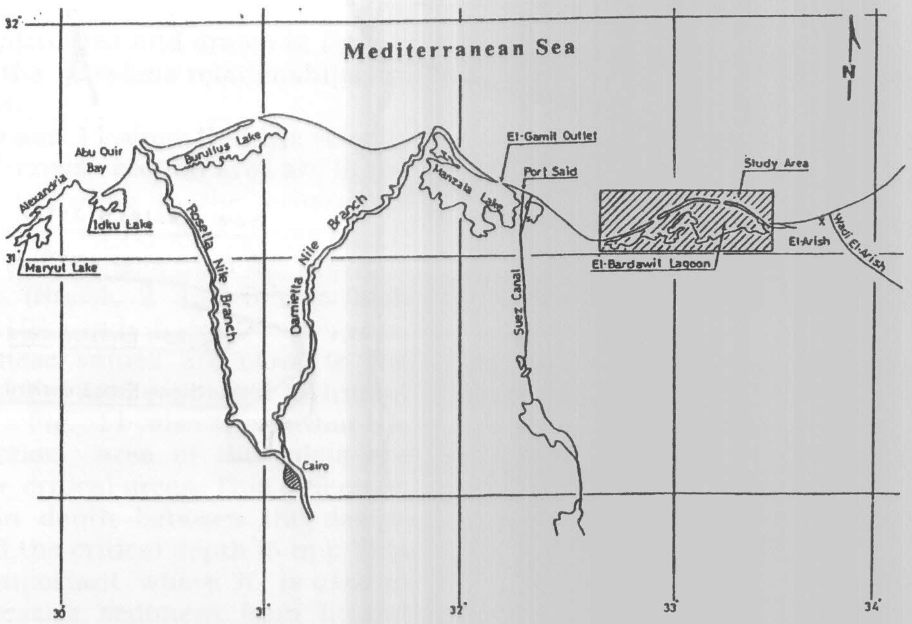

Fig. 4. General layout of the case study.

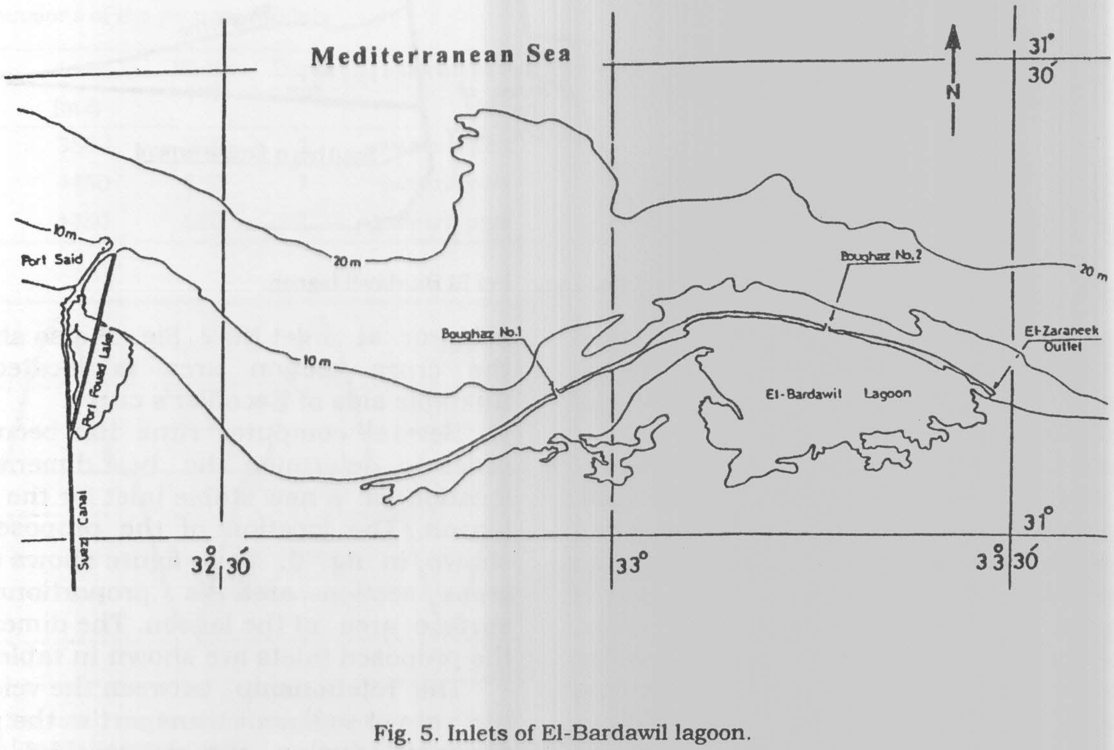

Fig. 5. Inlets of El-Bardawil lagoon.

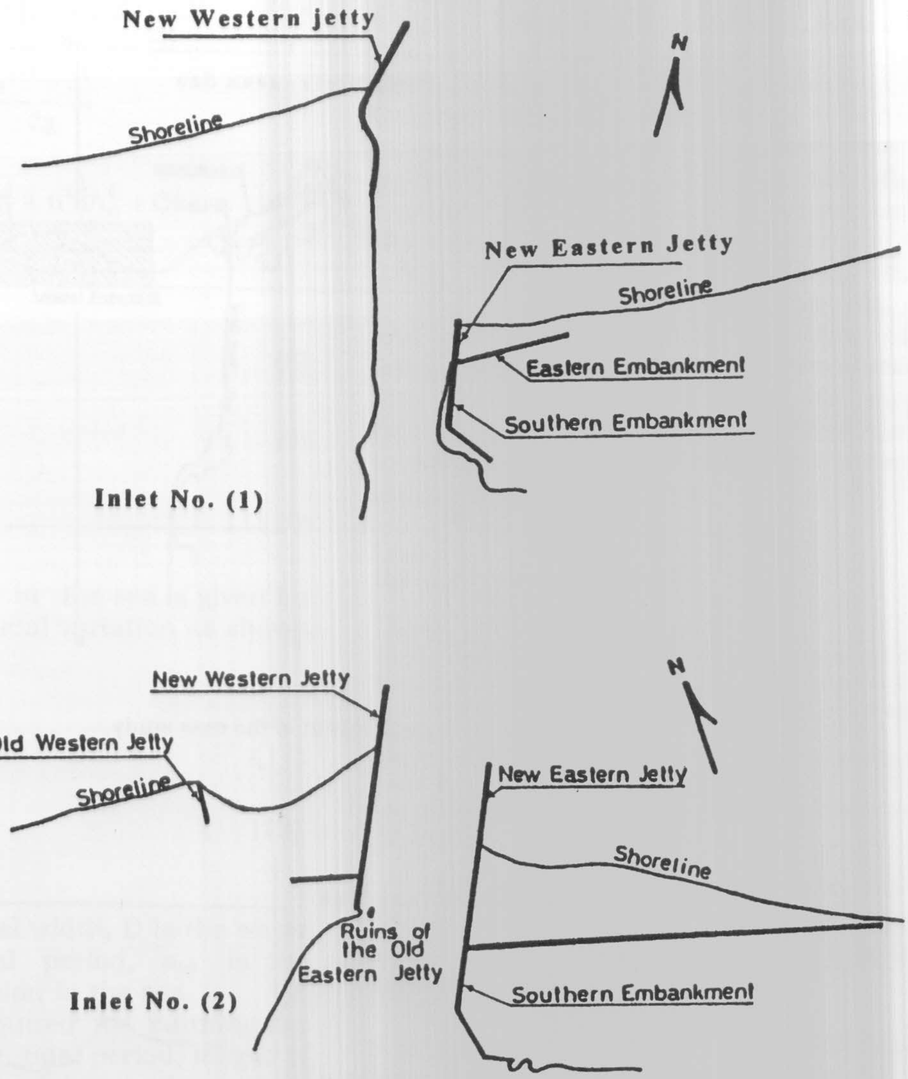

Fig. 6. Inlets No. 1 and 2 of El Bardawil lagoon.

-section area and max.-mean velocity, tidal prism, discharge, and the rate of sediment transport in channel are calculated and represented in fig. 8.

From fig. 8, the max. -mean velocity is 1.2 m/sec and the tidal prism is about $47x10^6$ m^3, ($20x10^6$ m^3 and $27x10^6$ m^3 for inlet No 1 and 2, respectively). Based on eq. (1) and using the previous tidal prisms, the inlets (No.1 and 2) can flush $130x10^3$ and $180x10^3$ m^3/year, respectively. These values are much smaller than the actual sediment transport in the field according to Inman and Harris [11]. They estimated the eastward sand transport to be $400x10^3$ m^3/year at inlet No.1 and $450x10^3$ m^3/year at inlet No.2. Fig. 8 also shows that the cross section area is located on the unstable side of Escoffier's curve.

Several computer runs has been made in order to determine the best dimensions and location of a new stable inlet for the Bardawil lagoon. The location of the proposed inlet is shown in fig. 9. This figure shows that inlet cross section area is proportional to the surface area of the lagoon. The dimensions of the proposed inlets are shown in table 2.

The relationship between the velocity and the rate of sediment transport in the proposed channels during the spring tidal cycle are shown in fig. 10-a, and 10-b. Also the relationship between the cross-section area and max.-mean velocity, tidal prism, discharge, and rate of sediment transport in channel were calculated and drawn in fig. 11. The results of the previous relationships are shown in table 3.

Figs. 10-a,b and 11 show that the velocity and position of cross section area are in the stability region according to the criterion of Bruun [2] and Escoffier [1]. Also, using eq. (1) and the data of tidal prisms from the previous table, the inlets (No. 1, 2 and 3) can flush $396x10^3$, $515x10^3$ and $515x10^3$ m^3/year, respectively. These values are close to the actual values in the field estimated by Inman and Harris [11]. Fig. 11 also shows that the stable cross-section area of the inlets are greater than the critical areas. This difference is about 2 m in depth between the design depth (7 m.) and the critical depth (5 m.). This depth is very important where it is used to collect the excessive sediment from littoral drift during storms. The trapped sediment will be eroded later when flushing capacity of the inlet is larger than the total drift,(M_{tot}), coming from the adjacent shores.

Table 2
The dimensions of the proposed inlets

Inlet	Area (m2)	Width (m)	Depth (m)	Location
1	3500	500	7	western part
2	4450	650	7	eastern part
3	4450	650	7	eastern part

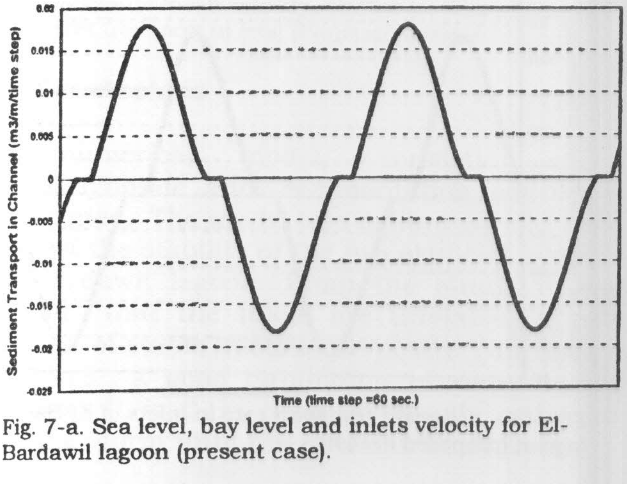

Fig. 7-a. Sea level, bay level and inlets velocity for El-Bardawil lagoon (present case).

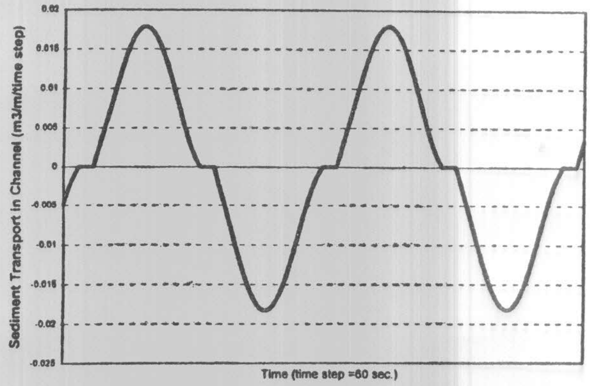

Fig. 7-b. Sediment transport rate in inlets of El-Bardawil lagoon (present case).

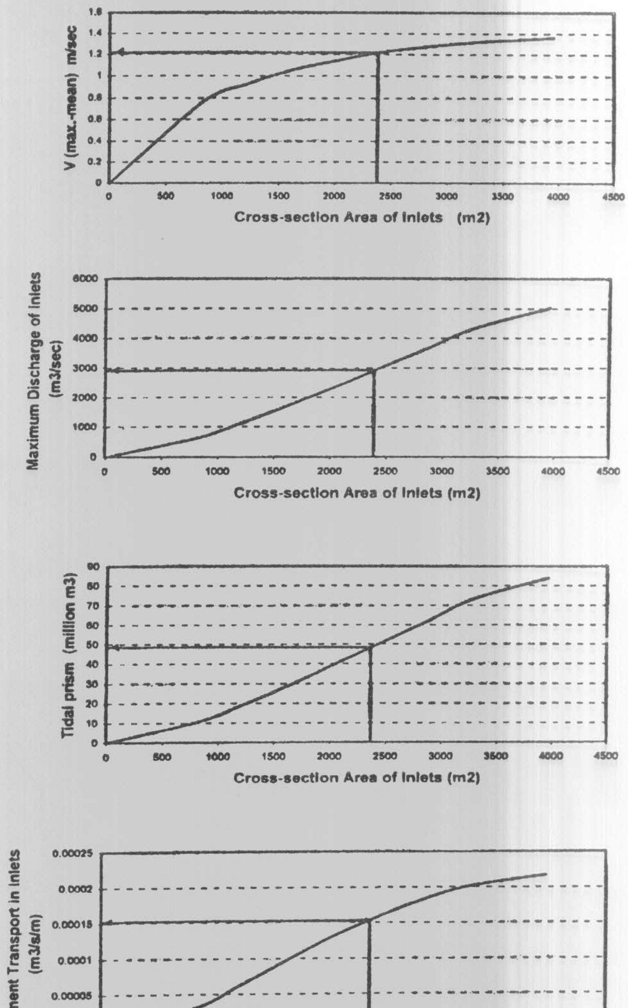

Fig. 8. Relationship between cross-section area of inlets and maximum mean velocity, discharge tidal prism, and sediment transport in inlets. (Present case).

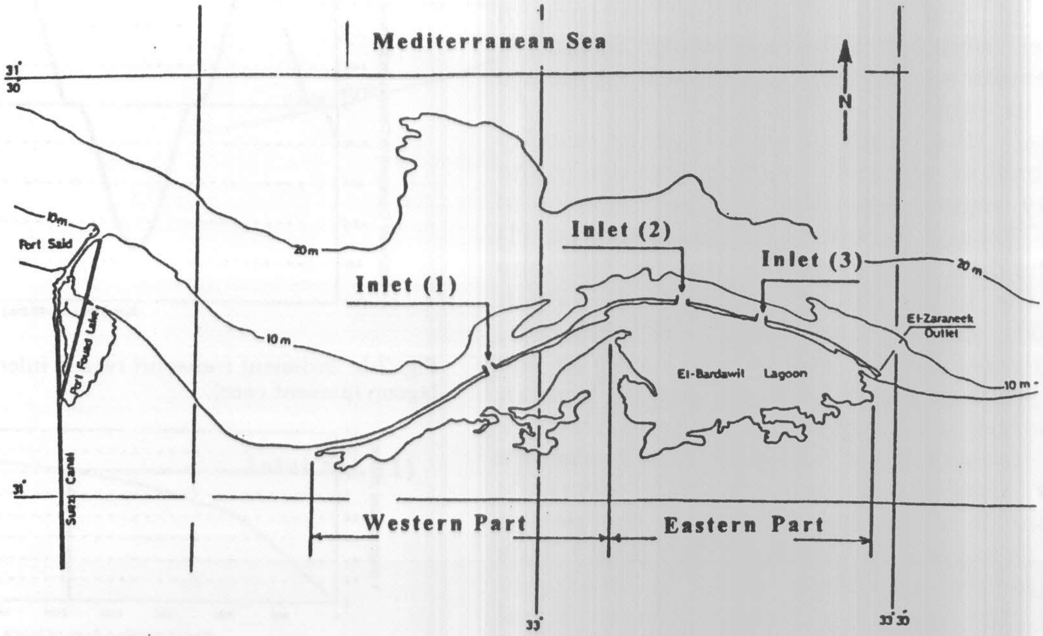

Fig. 9. A proposed design for El-Bardawil inlets.

Table 3
Results for different inlets

	Inlet 1	Inlet 2	Inlet 3
The max.-mean velocity (at spring tide) for all inlets (m)	1.0	1.0	1.0
The tidal prism (m^3)	59.4	77.3	77.3
Max. discharge (m^3/sec.)	3570.0	4641.0	4641.0
Flushing capacity (m^3/year/m)	850.0	850.0	850.0

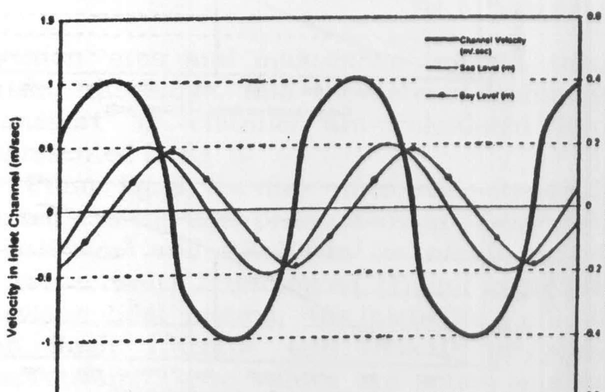

Fig 10-a. Sea level, bay level and inlets velocity for El-Bardawil lagoon (proposed design).

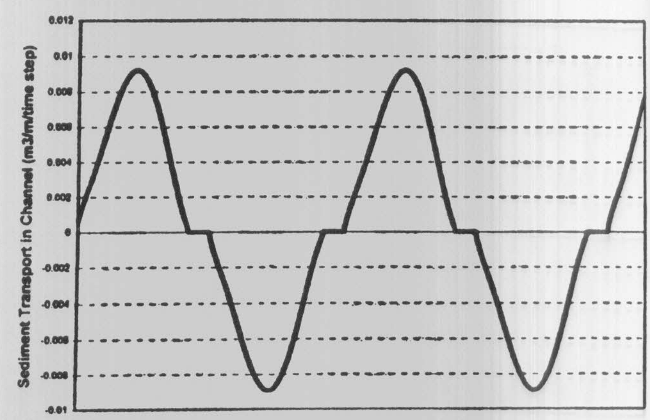

Fig 10-b. Sediment transport rate in inlets of El-Bardawil lagoon (proposed design).

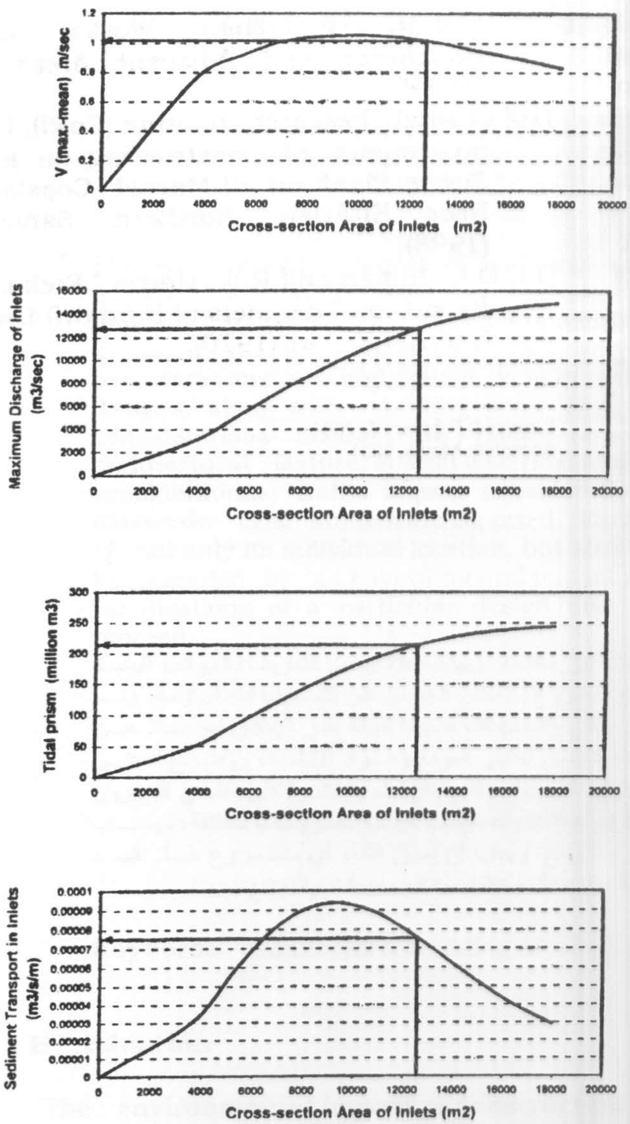

Fig. 11. Relationship between cross section area of inlets and maximum mean velocity, discharge, tidal prism, and sediment transport in lets. (Proposed design).

7. Conclusions

A numerical model, consisting of a hydrodynamic and sedimentation modules is presented. The model was calibrated and used to test the stability of the two artificial inlets of El-Bardawil lagoon. From the study, it was found that the inlets are unstable. A new design of stable inlets is proposed. This design ensures a good circulation of water inside lagoon. It is 2 m deep to trap the sediment during storm until the inlet can flush it out.

Nomenclature

a	Elevation of water level due to tide.
a_s	Water level elevation in the sea.
a_b	Water level elevation in the bay.
A_{bay}	Surface area of the bay.
A_c	Cross-sectional area of the inlet.
A_c^*	Critical cross-sectional area of the inlet.
B	Width of channel.
D	Water depth.
h_c	Local depth in channel.
K_{en}	Entrance head-loss. coefficient.
K_{ex}	Exit head-loss coefficient.
L_c	Length of channel.
M_{tot}	Total sediment transport from. adjacent shores into the inlet.
n	Manning coefficient.
P	Spring tidal prism.
Q_t	Total inlet discharge.
Q_i	Discharge of each inlet (case of multiple inlets).
Q_f	Discharge into the bay from sources other than the inlet(s) such as (rivers, pumped inflows, etc.).
R_c	Hydraulic radius.
t	Time.
T_p	Tidal period.
U	Average flow velocity in the x direction.

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