Design of irrigation canals with minimum overall cost using particle swarm optimization – case study: El-Sheikh Gaber canal, north Sinai Peninsula, Egypt

Hamdy A. El-Ghandour, Emad Elbeltagi and Mohamed E. Gabr

ABSTRACT

Nowadays, the scarcity of freshwater sources, climate change and the deterioration of freshwater quality have a great impact on the lives of human beings. As such, improving the design of irrigation canals will reduce water losses through evaporation and seepage. In this paper, particle swarm optimization (PSO) is used to determine the optimum design of irrigation canals' cross-sections with the objective to minimize the overall costs. The overall costs include the costs of earthwork, lining, and water loss by both seepage and evaporation. The velocity constraints for sedimentation and erosion have been taken into consideration in the proposed design method. The proposed PSO is compared with both the Probabilistic Global Search Lausanne (PGSL) and classical optimization methods to verify its usefulness in optimal design of canals' cross-sections. The proposed PSO is then used to design El-Sheikh Gaber canal, north Sinai Peninsula, Egypt and the obtained dimensions are compared with the existing canal dimensions. To facilitate the use of the developed model, optimal design graphs are presented. The results show that the reduction of overall cost ranged from 28 to 41% and consequently, the proposed PSO algorithm can be reliably used for the design of irrigation open canals without going through the conventional and cumbersome trial and error methods.

Key words | canal lining cost, canal section design, earthwork cost, overall costs, PSO, water losses

Hamdy A. El-Ghandour (corresponding author)
Irrigation and Hydraulics Department, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt
E-mail: *hamdy_elghandour@yahoo.com*

Emad Elbeltagi
Structural Engineering Department, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt

Mohamed E. Gabr
Civil Engineering Department, Higher Institute for Engineering and Technology, New Damietta, Egypt

HIGHLIGHTS

- Particle swarm optimization (PSO) algorithm is adopted for finding the optimal cross-section of irrigation canals with the objective of minimizing the overall costs.
- The performance of the PSO algorithm has been compared with the Probabilistic Global Search Lausanne (PGSL) and also with the nonlinear optimization method used by previous researchers.
- The model has been applied on El-Sheikh Gaber canal, north Sinai Peninsula, Egypt.
- Optimal design charts have been prepared and presented to facilitate the design of the minimum overall cost irrigation canal sections.
- Other charts have also been presented to calculate the costs of earthwork and lining and water losses due to evaporation and seepage corresponding to several values of design discharges.

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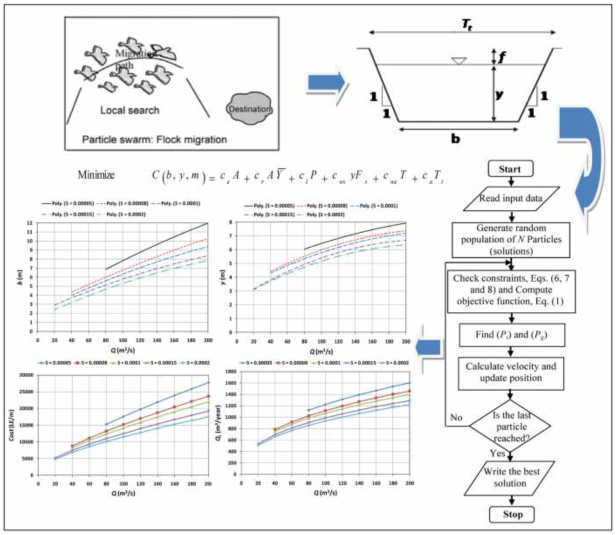
GRAPHICAL ABSTRACT



INTRODUCTION

Water canals are used to convey water from its source to its final destination for different purposes. One of the main objectives of these canals is to convey water for irrigation with minimal cost. As such, the design of water canals was investigated by many researchers. For example, Lindley (1919), Lacey (1930, 1946), and other researchers developed procedures for the design of stable water canals by the tractive force method originally developed by Lane (1937, 1955) and others. Recently, several optimization techniques have been applied to determine the optimal cross-section dimensions such as the non-linear method (Swamee *et al.* 2000a, 2000b, 2000c, 2001); particle swarm optimization (PSO) (Reddy & Adarsh 2010); differential evolution algorithm (Turan & Yurdusev 2011); Probabilistic Global Search Lausanne (PGSL) (Adarsh & Sahana 2013); genetic algorithm (GA) (Jain *et al.* 2004; Reddy & Adarsh 2010; Kentli & Mercan 2014); cat swarm optimization (Dong *et al.* 2016); and Lagrange multiplier optimization method (Ghazaw 2011; Han *et al.* 2019).

The optimization models used in the literature can be divided into three categories. The first category minimizes water losses due to both evaporation and seepage. Swamee & Chahar (2015) reported that about 50% of water supplied at the head of the canal may be lost in transit to the field. Seepage losses are mainly dependent on subsoil hydraulic conductivity, geometry of the canal, and water table location relative to the canal. Evaporation losses are directly proportional to the canal's surface area, particularly for long canals carrying small discharges in arid regions (Swamee & Chahar 2015). In the literature, much effort has been put into the optimal design of canal cross-sections. Swamee *et al.* (2000b), for example, applied non-linear optimization for the optimal design of three canal shapes with the objective of minimizing seepage losses. They found that trapezoidal sections have the least seepage losses and cross-sectional area. Ghazaw (2011) adopted Lagrange's method of undetermined multipliers to determine the optimal canal dimensions with the objective of minimizing both seepage and evaporation water losses. They presented a number of design charts to facilitate optimal canal design. Kentli & Mercan (2014) compared both GA and sequential quadratic programming methods for optimal canal sections design considering seepage and evaporation losses. They applied the two methods on several shapes of cross-sections. In a recent effort, Dong *et al.* (2016) presented an improved cat swarm optimization algorithm to design canals' cross-sections with low water losses in irrigation areas. They enhanced the efficiency of the conventional cat swarm optimization by adding exponential inertia weight coefficient and mutation. The application of the improved technique on a study area shows a 20% water loss reduction compared to the original design.

The second category of optimization models considers the minimization of both earthwork and lining costs considering canal uniform flow condition. Earthwork costs depend on the flow area and vary with canal depth while the lining cost varies with the wetted perimeter length. Swamee *et al.* (2000c) applied a non-linear optimization technique for the minimum cost design of lining canals with different shapes. They concluded that the minimum area cross-section is the one that minimizes both costs of lining and earthworks. However, when costs of excavation with canal depth are taken into consideration, the optimal section is wider and shallower. This conclusion is also reached by Swamee *et al.* (2001) when applying non-linear optimization for minimizing the earthwork costs of several canal shapes.

Jain *et al.* (2004) applied GA to compute the dimensions of both trapezoidal and triangular canal sections with the objective of minimizing the costs of earthwork and lining per unit length of the canal. They presented design graphs to determine optimal canal dimensions of a composite trapezoidal cross-section. Reddy & Adarsh (2010) performed an optimal design of composite canals using GA and PSO to improve overall reliability and reduce cost. They minimized the total costs of earthwork and lining. Turan & Yurdusev (2011) adopted a differential evolution algorithm to calculate the optimum cross-sections of different canal geometries with the purpose of minimizing the costs of canal covering and excavation. Han *et al.* (2019) derived the general differential equation for canal sections having minimum construction cost (i.e. most economic section) using the Lagrange multiplier optimization method. They found that the proposed method is best when compared with classical optimization methods.

The third category of optimization models considers the minimization of the earthwork, lining, and water losses (seepage and evaporation) costs subject to uniform flow condition. The work of Swamee *et al.* (2000a) presented a methodology to minimize canal lining costs, earthwork costs, and water losses costs due to seepage and evaporation using non-linear optimization. They concluded that the optimal section is wider and shallower than the minimum area section due to the increased cost when the canal depth increases, while the wider canals increase the cost due to the evaporation water losses. Adarsh & Sahana (2013) used PGSL to determine the optimal dimensions of triangular, rectangular, and trapezoidal canal shapes by minimizing the costs of excavation, lining, water losses (due to seepage and evaporation) and land acquisition. They added two site-specific constraints to suit the design of real-field trapezoidal canals.

In the present study, the third category of optimization models is adopted in order to minimize the cost of excavation, lining, water losses due to seepage and evaporation. The proposed model uses the PSO optimization technique to determine the optimal design of canals' cross-sections. The proposed model is applied on triangular, rectangular, and trapezoidal canal shapes and the obtained results are compared with the corresponding literature for both the PGSL and other optimization techniques. The proposed PSO is applied on the design of three sections of El-Sheikh Gaber canal, located on the north Sinai Peninsula, Egypt, and the obtained dimensions are compared with the existing design (i.e. the actual cross-sections of the real canal). Finally, design charts are developed to facilitate the design process.

CANAL CROSS-SECTION OPTIMIZATION MODEL

In this section, an overall cost minimization model is presented that accounts for all costs associated with the irrigation canals including: excavation cost, lining cost, and costs of water losses as a result of seepage and evaporation. Estimating the different cost elements depends mainly on the geometrical shape of the canal cross-section, where rectangular and triangular cross-sections are considered as special cases of trapezoidal cross-sections. Figure 1 shows the geometry of the different canal cross-sections. The optimization model for minimizing canals' costs is formulated as follows (Swamee & Chahar 2015):

$$\text{Minimize}\, C(b, y, m) = c_e A + c_r A \bar{Y} + c_l P + c_{ws} y F_s + c_{we} T \qquad (1)$$

in which C is the total cost per unit canal length ($/m), c_e is the unit volume of earthwork cost at the ground level ($/m^3), c_r is the increase in the unit excavation cost per unit depth ($/m^4), A is the flow area (m^2) and $\bar{Y}$ is the

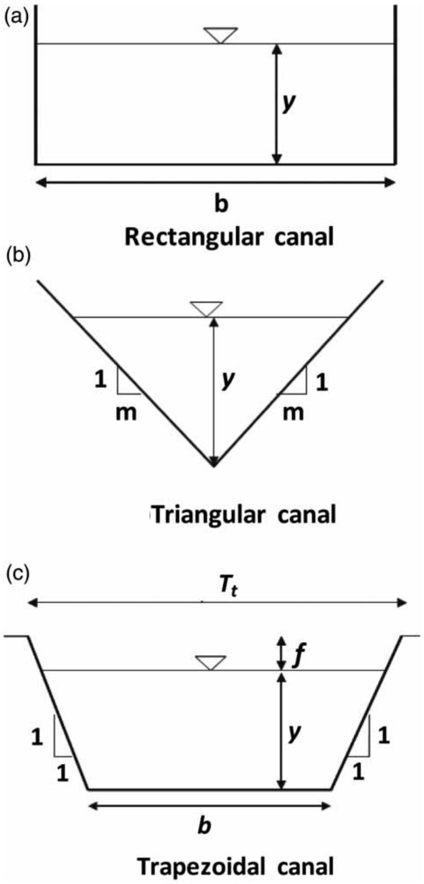


Figure 1 | Definition of different canal geometries.

depth of centroid of the flow area from the free surface (m), c_l is the cost per unit surface area of lining ($/m^2) which is independent of the thickness of lining, P is the canal wetted perimeter length (m), y is the depth of the flow water (m), T is the canal's free surface width (m), $C_{ws} = \left(3.156 \times 10^7 c_w k/r\right)$, k is the porous medium hydraulic conductivity (m/s), c_w is the cost per unit volume of water ($/m^3), r is the rate of interest ($/$/year), $C_{we} = (3.156 \times 10^6 c_w E/r)$, E is the unit surface area evaporation discharge (m/s), and F_s is the seepage function calculated from the following formulas for different geometries.

For triangular cross-section canals:

$$F_s = [(4\pi - \pi^2)^{1.3} + (2m)^{1.3}]^{0.77} \quad 0 \le m \le 1,000 \tag{2}$$

where m is the canal side slope.

For rectangular cross-section canals:

$$F_s = [(4\pi - \pi^2)^{0.77} + (b/y)^{0.77}]^{1.3} \quad 0 \le b/y \le 1,000 \tag{3}$$

where b is the canal bed width in meters.

For trapezoidal cross-section canals:

$$F_s = \left\{ [(4\pi - \pi^2)^{1.3} + (2m)^{1.3}]^{\frac{0.77+0.462m}{1.3+0.6m}} + \left(\frac{b}{y}\right)^{\frac{1+0.6m}{1.3+0.6m}} \right\}^{\frac{1.3+0.6m}{1+0.6m}} \tag{4}$$
$$0 \le m \le 1,000 \text{ and } 0 \le b/y \le 1,000$$

Subjected to the resistance equation given by Swamee & Chahar (2015):

$$Q = -2.457A\sqrt{gRs}\ln\left\{\frac{\varepsilon}{12R} + \frac{0.221\nu}{R\sqrt{gRs}}\right\} \tag{5}$$

in which Q is the flow rate of the canal in (m^3/s), g is the acceleration due to gravity (m/s^2); R is the hydraulic radius (m) defined ($=A/P$), s is the canal bed slope, ε is the average roughness height for the canal lining (m), and ν is the water kinematic viscosity (m^2/s).

The following constraints are considered:

$$\phi_1(b, y, m) = \xi - \left| Q + 2.457A\sqrt{gRs}\ln\left\{\frac{\varepsilon}{12R} + \frac{0.221\nu}{R\sqrt{gRs}}\right\}\right| \ge 0 \tag{6}$$

where ξ is a small positive number.

$$\phi_2(b, y, m) = V_{\max} - V \ge 0 \tag{7}$$

$$\phi_3(b, y, m) = V - V_{\min} \ge 0 \tag{8}$$

where V is the average flow velocity (m/s) and $V_{\max}$ and $V_{\min}$ are the maximum and minimum permissible velocities, respectively.

PARTICLE SWARM OPTIMIZATION

Particle swarm optimization was developed by Kennedy & Eberhart (1995), inspired by the social behavior of a flock of migrating birds. In PSO, each solution, referred to as a particle, is a 'bird' in the flock. Solutions (particles) are evolved socially while they search the solution space towards a destination (Shi & Eberhart 1998). In such social evolution, birds (particles) are communicating together to identify the best solution (best bird location). Then, they speed towards the best one from their current positions. After that, each bird searches its neighborhood based on its new position. The PSO search process, as such, involves a local search when birds look for good solutions in their neighborhood and a global search when birds look for the best bird position.

As a stochastic technique, it starts with a group of random solutions (particles). Each individual particle (solution) (i) is represented by its position on the S-dimensional solution space, where S represents the number of variables. During the evolution process, the position of each particle i, (X_i); the best position reached before for each particle i, (P_i); the moving velocity (V_i) of each particle i are identified as follows:

$$\text{Current particle}\, i \text{ position}\, X_i = (x_{i1}, x_{i2}, \ldots\ldots x_{iS})$$

$$\text{Best particle position}\, P_i = (p_{i1}, p_{i2}, \ldots\ldots p_{iS})$$

$$\text{Moving velocity}\, V_i = (v_{i1}, v_{i2}, \ldots\ldots v_{iS}) \tag{9}$$

Also, during each cycle of the evolution process, the position of the particle (g) having the best fitness (best objective function value) in the whole solution space (P_g) is determined. Accordingly, the velocity V_i of each particle is updated to reach the position of the best particle g, as follows (Shi & Eberhart 1998):

$$New\, V_i = \omega \times current\, V_i + c_1 \times RN_1 \times (P_i - X_i) + c_2 \times RN_2 \times (P_g - X_i) \tag{10}$$

Then, particles update their positions (new solutions generated) using their new velocities V_i, as follows:

$$New\, position\, X_i = current\, position\, X_i + New\, V_i \qquad V_{\max} \geq V_i \geq -V_{\max} \tag{11}$$

where c_1 and c_2 are positive constants (usually, $c_1 = c_2 = 2$) named learning factors; RN_1 and RN_2 are random numbers generated in the range [0, 1]; V_{max} is the maximum particle velocity change (Kennedy & Eberhart 1995); and ω is an operator proposed by Shi & Eberhart (1998) to limit the effect of the previous history of velocities on the current velocity and named the inertia weight. This operator is used to balance both the global search and the local search and proposed to decrease linearly with time (Shi & Eberhart 1998). As such, a global search starts with a large weight and then decreases with time to favor a local search over a global search (Eberhart & Shi 1998).

Once a particle's new position is determined (i.e. new solution is formed) using Equation (11), the particle then moves towards it (Shi & Eberhart 1998). The main parameters of the PSO optimization are the population size (number of particles), number of evolution cycles, the maximum change of a particle velocity $V_{\max}$ and ω. Figure 2 shows the flow chart of the PSO algorithm.

MODEL VERIFICATION

The PSO model is verified through applying it on trapezoidal, rectangular, and triangular canal cross-section shapes and the obtained results are compared with the corresponding results of the PGSL and classical optimization methods given by Adarsh & Sahana (2013). The used data are (Adarsh & Sahana 2013): Q (design canal discharge) $= 250$ m^3/s, s (longitudinal bed slop) $= 0.0001$, ε (average roughness height for canal lining) $= 1$ mm. The lining of the canal is assumed to be cracked with k equals 1×10^{-6} m/s. The maximum evaporation loss, E, equals 2.5×10^{-6} m/s. The temperature of the water is assumed to be 20 °C and ν (kinematic viscosity) $=$ 1.1×10^{-6} m^2/s. The permissible velocity is to be within the range of 1.5–2 m/s. The ratios of unit cost elements are: $c_e/c_r = 7$ m, $c_l/c_e = 12$ m, $c_{ws}/c_e = 10$ m and $c_{we}/c_e = 2$ m.

A sensitivity analysis is carried out to determine the suitable parameters of the PSO as follows: number of particles $= 500$, number of cycles $= 500$, and $V_{\max} = 2$. The factor ω is linearly decreasing with the increase of the number of generations from a value of 1.4 to 0.4. The value of c_e is assumed equal to unity (Adarsh & Sahana 2013). Table 1 shows a comparison between the obtained results

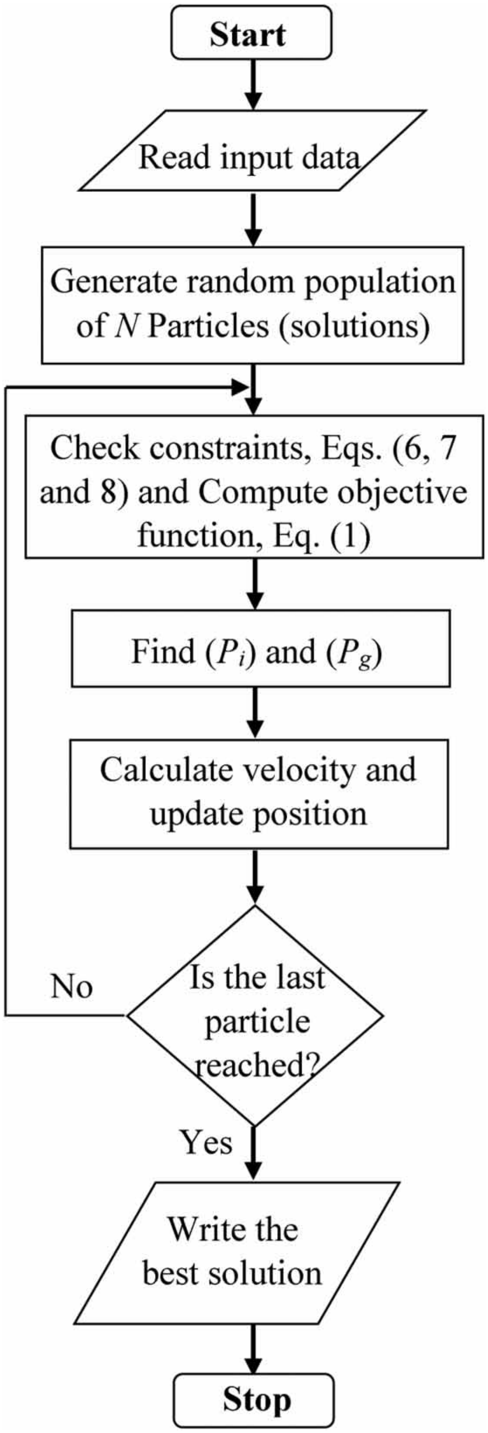


Figure 2 | Flow chart of the PSO algorithm.

(i.e. geometric elements for each cross-section shape, flow velocity, flow discharge, and the total cost of canal unit length) and the corresponding ones given by Adarsh & Sahana (2013). From this table it can be seen that the obtained results are close to the solution obtained using the PGSL method with a saving of 0.76, 0.88 and 0.84 $/m for the total cost of the trapezoidal, rectangular, and triangular canal sections' shapes, respectively. Although the obtained solution is inferior with respect to the classical optimization method used, it is noted that a violation of nearly 5 m^3/s occurred in the flow constraint, thus meaning that the obtained solution using the classical optimization method is infeasible. The proposed method was able to determine the optimal solution, which satisfied the required discharge for the different shapes of the canal cross-sections. As such, the cost obtained by the current method is larger as the discharge is higher than the classical optimization. Consequently, the proposed PSO algorithm is applicable for the optimal design of real-life canal sections.

MODEL APPLICATION ON A REAL-LIFE CASE STUDY

The proposed PSO algorithm is applied to design three cross-sections of trapezoidal shape for the El-Sheikh Gaber canal, located in the north of Sinai Peninsula, which is considered one of the main canals in the El-Salam canal project, Egypt. The El-Salam canal project was designed for reclamation and cultivation of 620,000 feddans in the eastern part of Egypt. The project consists of two stages: in the first stage, El-Salam canal receives the water from the Damietta branch of the River Nile to the western side of the Suez Canal for serving an area of 220,000 feddans. Infrastructure works in this stage were completed and nearly 180,000 feddans are currently being cultivated. El-Salam canal crosses the Suez Canal eastward through a syphon structure at 27.7 km south of Port Said city to convey the water to El-Sheikh Gaber Canal (Figure 3). In the second stage of the project, it was planned to extend El-Sheikh Gaber canal for 155 km length eastward in the Sinai Peninsula for serving an area of 400,000 feddans in the north Sinai development project (NSDP) (Gabr 2018). The current implemented length of the canal is about 86.5 km with a discharge varying from 96 to 160 m^3/s and the canal width varies from 20 to 40 m with an average depth of 4 m. The first 24.5 km of the canal is located in a clay soil and lined with gabions while the remaining length, located in a sandy dunes soil, is lined with plain concrete over polyvinyl

Table 1 | Comparison between the obtained results and the corresponding ones given by Adarsh & Sahana (2013)

		Geometric elements					
Shape	**Method**	***b* (m)**	***y* (m)**	***m***	***V* (m/s)**	***Q* (Equation (5)) (m^3/s)**	***C* (Equation (1)) ($/m)**
Trapezoidal	PSO[a]	12.177	8.257	0.596	1.771	249.997	1098.69
	PGSL[b]	12.354	8.253	0.576	1.769	250.038	1099.45
	Classical[b]	12.380	8.290	0.532	1.796	245.297	1087.7
Rectangular	PSO[a]	18.677	7.812	0.000	1.714	250	1165.509
	PGSL[b]	18.678	7.817	0.000	1.712	249.986	1166.39
	Classical[b]	18.620	7.739	0.000	1.735	245.716	1156.5
Triangle	PSO[a]	0.000	11.329	1.137	1.713	250	1168.56
	PGSL[b]	0.000	11.411	1.121	1.713	250.002	1169.40
	Classical[b]	0.000	11.363	1.116	1.735	245.889	1160.3

[a]Present study.
[b]Adarsh & Sahana (2013).

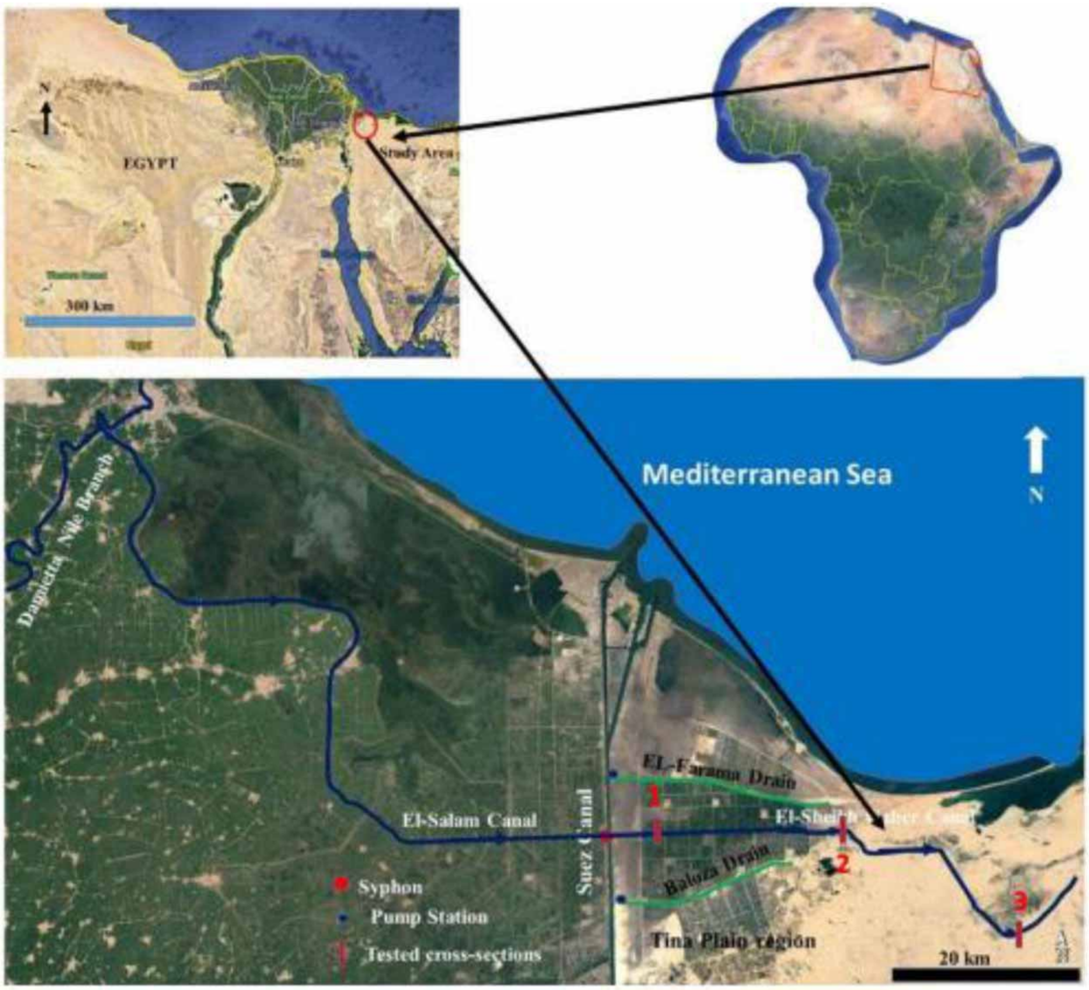


Figure 3 | Layout of El-Sheikh Gaber canal, north Sinai Peninsula, Egypt.

chloride (PVC) sheets to prevent seepage losses. There are three large pump stations located along El-Sheikh Gaber canal: pump station No. 4 is located at 3.100 km with maximum discharge of 160 m^3/sec and static head of 2 m. Pump Station No. 5 is located at 24.750 km with maximum discharge of 112 m^3/sec and static head of 12.13 m, and pump station No. 6 is located at 46.500 km with maximum discharge of 96 m^3/sec and static head of 9.43 m (Gabr 2018).

The selected three cross-sections to be designed at El-Sheikh Gaber canal are at the 3, 25, and 47 km downstream El-Salam syphon respectively (i.e. nearly at the location of the three pump stations). The available data corresponding to each selected cross-section is summarized in Table 2. The permissible velocity is to be within the range of 1.0–1.5 m/s. The values of c_e, c_r, and c_l, are taken as equal to 70.0 LE/m^3, 10.0 LE/m^4, and 300.0 LE/m^2, respectively. The value of c_w is assumed equal to 1.0 LE/m^3 (LE is the Egyptian Pound ≈ 0.064 US$). The parameters of PSO are the same as those presented in the model verification section.

Table 3 presents the results obtained from applying the PSO algorithm (i.e. geometric elements, flow velocity, flow discharge, and the total cost of the canal unit length) for the selected three cross-sections and the corresponding existing design values. From this table, it is reported that all flow velocities corresponding to the three sections either obtained from the PSO technique or the existing design ones are nearly in the allowable range and consequently, there is no violation in flow velocity constraint. Also, it is noted that a violation occurred in the flow constraints of nearly 73.5, 12.4, and 18.7 m^3/sec, respectively for the actual values of the canal three cross-sections (Gabr 2018), while in the present study there is no violation with the actual design discharges. The large violation in the discharges obtained from the existing design may be due to adopting the trial and error method in the design of the cross-sections. Consequently, savings in the total costs per unit length of the canal of 41.25, 25.0 and 27.67% are obtained for the three designed cross-sections, respectively.

Table 2 | Data of the adopted three cross-sections of El-Sheikh Gaber canal

Property	Sec. (1)	Sec. (2)	Sec. (3)
Q (m^3/sec)	160.0	112.0	96.0
s (cm/Km)	6.0	8.0	8.0
ε (mm)	5.0	1.0	1.0
k (m/sec)	8.6×10^{-3}	1.0×10^{-6}	1.0×10^{-6}
E (m/sec)	5.8×10^{-8}	5.8×10^{-8}	5.8×10^{-8}
ν (m^2/sec)	1.1×10^{-6}	1.1×10^{-6}	1.1×10^{-6}

OPTIMAL DESIGN CHARTS

The PSO algorithm is utilized in this section to prepare and present optimal design charts that achieve minimum total cost (Figures 4–7). The land acquisition cost is considered as one of the cost elements that should be incorporated to achieve minimum total costs (Adarsh & Sahana 2013). Consequently, the objective function, Equation (1), is modified as follows:

$$\text{Minimize } C(b, y, m) = c_eA + c_rA\bar{Y} + c_lP + c_{ws}yF_s + c_{we}T + c_aT_t \quad (12)$$

Table 3 | Comparison between the obtained results and the existing ones of the three cross-sections of El-Sheikh Gaber canal

		Geometric elements						
Cross-section	**Method**	***b*** **(m)**	***y*** **(m)**	***m***	***V*** **(m/s)**	***Q*** **(Equation (5)) (m^3/s)**	***C*** **(Equation (1)) (LE/m)**	**Saving in *C* (Equation (1))**
1	PSO[a]	10.104	7.787	1.003	1.147	160.0	8.4×10^7	41.25%
	Existing design[b]	40.0	4.4	3	0.998	233.526	14.3×10^7	
2	PSO[a]	7.301	6.203	1.004	1.334	112.0	2.4×10^4	25.0%
	Existing design[b]	22.0	3.6	2	1.183	124.353	3.2×10^4	
3	PSO[a]	6.544	5.637	1.217	1.271	96.0	2.2×10^4	27.67%
	Existing design[b]	20.0	3.6	2	1.171	114.659	3×10^4	

[a]Present study.
[b]Gabr (2018).

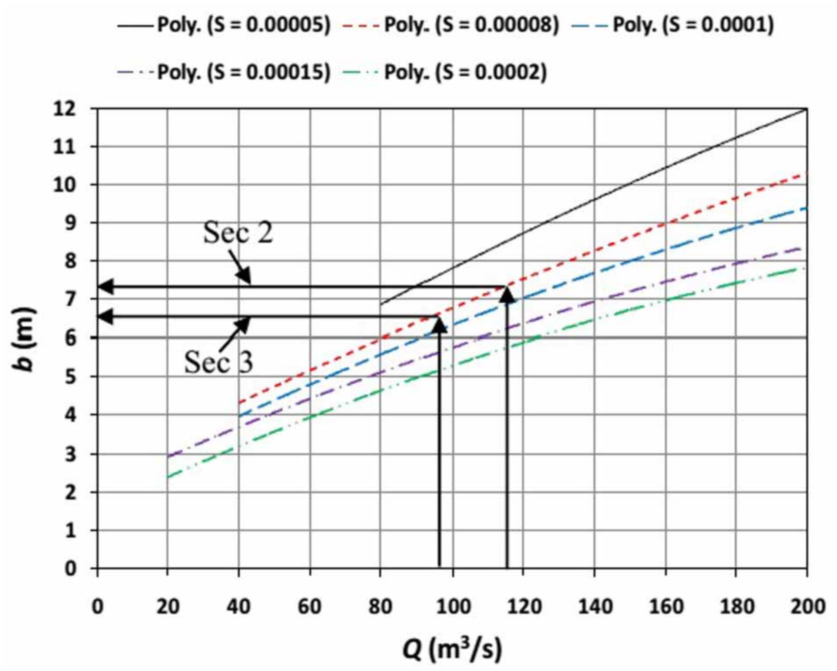


Figure 4 | *Q* versus *b* for optimal trapezoidal cross-sections.

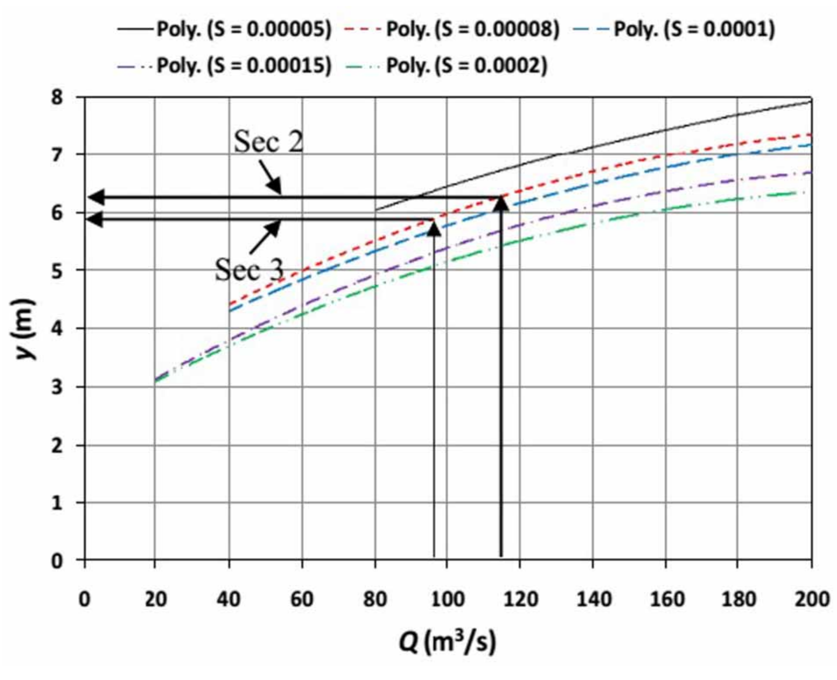


Figure 5 | *Q* versus *y* for optimal trapezoidal cross-sections.

in which $T_t = b + 2\,m\,(y + f)$ is the top width of the trapezoidal cross-section, Figure 1(c), f is the freeboard and c_a is land acquisition cost (LE/m^2). The ratio c_e/c_a is assumed equal to 2 and f equals 0.5 m (Adarsh & Sahana 2013).

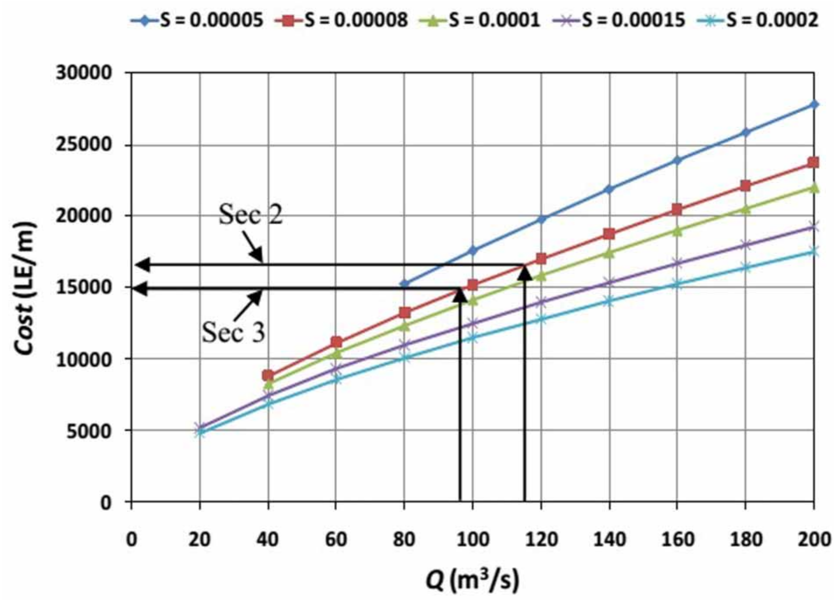


Figure 6 | *Q* versus *cost* for optimal trapezoidal cross-sections.

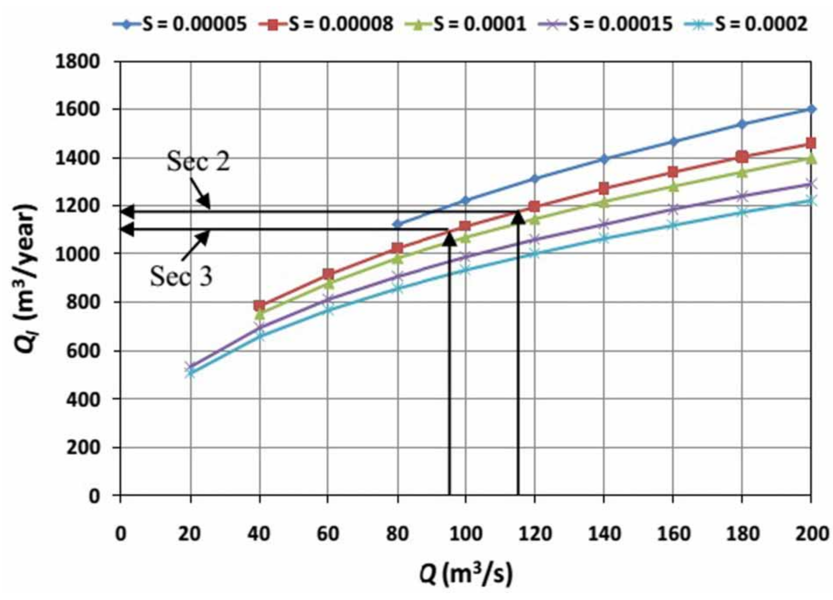


Figure 7 | *Q* versus Q_l for optimal trapezoidal cross-sections.

The optimal design charts for the design of a trapezoidal concrete lining canal cross-section have a design Q in the range between 20 and 200 m^3/s, s varies from 0.00005 to 0.0002, and m is assumed equal to 1.0 in all cases. The lining of the canal has ϵ equal to 1 mm. The canal lining is assumed to be cracked and having k equal to 1×10^{-6} m/s. The maximum value of E is taken as 5.8×10^{-8} m/s. The temperature of the water is 20 °C and ν equals 1.1×10^{-6} m^2/s. The permissible velocity is maintained between 1.0 and 2.0 m/s. The values of c_e, c_r, and c_l, are taken as equal to 70.0 LE/m^3, 10.0 LE/m^4 and 300.0 LE/m^2, respectively. The value of c_w is assumed to be 1.0 LE/m^3.

The design of the optimal canal cross-section requires the identification of five decision variables (i.e. b, y, s, $cost$, and Q_l) for a given discharge, lining materials, freeboard, and side slope. The cost includes the costs of both earthwork and lining only while Q_l is the rate of water lost per year due to both seepage and evaporation. The design charts are generated for different bed slope values; $s = 0.00005$, 0.00008, 0.0001, 0.00015, and 0.0002. For each s value, the optimum values of the bottom width (b), the flow depth (y), *cost*, and Q_l are determined at different Q values (20–200 m^3/s). Once the optimal values of b, y, *cost* and Q_l are determined for different designs of Q, four separate design charts are prepared. The first design chart, Figure 4, can be used to determine the optimal value of b; the second design chart, Figure 5, can be used to determine the optimal value of y; the third design chart, Figure 6, can be used to determine the earthwork and lining costs; while the fourth design chart, Figure 7, can be used to determine the seepage and evaporation water losses for a given design discharge and bed slope of the trapezoidal cross-section.

It is noticed from the developed design charts that, for a given discharge, b, y, *cost* and Q_l decrease as the value of the bed slope (s) increases. Also, both the values of bottom width and flow depth increase as the design discharge increases but the rate of increase of the bottom width is larger than the flow depth. It can be seen that for a given small design discharge the costs of both earthwork and lining decrease as the value of the bed slope (s) increases with a small rate compared with a large relative rate in larger design discharges.

The procedure of using these charts is given as follows: (1) identify the canal design discharge and bed slope; (2) for the given discharge, draw a vertical line on each of the design charts to intersect with the curve representing the selected s value; and (3) at the point of intersection draw a horizontal line to determine the value of b, y, *cost* and Q_l.

To verify the design charts with the results obtained before (Table 3), both Q and s for sections 2 and 3 in El-Sheikh Gaber canal are adopted. The results obtained from Figures 4–7 for b, y, Q, and Q_l are 7.3 m, 6.2 m, 16,000 LE/m, and 1190 m^3/year, respectively, for section 2 and 6.6 m, 5.9 m, 15,000 LE/m and 1,100 m^3/year, respectively for section 3. It is noticed that the results of section 2 are the same as those listed in Table 3 while the results of section 3 are close to those listed in Table 3 because m is considered equal to 1 and the corresponding value in Table 3 is 1.217.

CONCLUSIONS

In this paper, the PSO algorithm is adopted to determine the optimal geometric design of rectangular, triangular, and trapezoidal canals' cross-sections for minimum overall cost. The proposed PSO is compared with both the PGSL and classical optimization methods, given in the literature, to verify its usefulness in canals' cross-sections optimization. The proposed PSO is then applied to the design of a real-life case, El-Sheikh Gaber canal, north Sinai Peninsula, Egypt and the obtained dimensions were compared with the existing design. Optimal design charts, based on the obtained results, in terms of canal geometry were prepared and presented to facilitate the design of the minimum overall cost irrigation canal sections. Other charts are presented to calculate the costs of earthwork and lining and water losses due to evaporation and seepage corresponding to several values of design discharges. The results show that the reduction of overall cost ranged from 28 to 41% and consequently, the proposed PSO algorithm can be used for the reliable design of irrigation open canals without the need for the conventional trial and error methods.

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