Journal of Engineering and Computer Sciences, Qassim University
Vol. 3, No. 2, pp. 73-95 (July 2010/Rajab 1431H)

Design Charts of Optimal Canal Section for Minimum Water Loss

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(Received 17/12/2009; accepted for publication 1/5/2010)

Abstract. Seepage and evaporation are the most serious forms of water losses in an irrigation canal network. Seepage loss depends on the channel geometry, whereas evaporation loss is proportional to the area of the free surface. In this investigation, a methodology has been devised which describes the optimal canal dimensions to convey a particular discharge. The objective nonlinear water loss function, for the canal, which comprises seepage and evaporation losses, is developed. Two constrains, minimum permissible velocity as a limit for sedimentation and maximum permissible velocity as a limit for erosion of canal, have been taken into consideration in the canal design procedure. Using Lagrange's method of undetermined multipliers, the optimal canal dimensions are obtained which give the least water loss. Using a random search method, a simple computer program was developed to carry out design calculation and provide the optimal canal dimensions. A set of design charts has been prepared by plotting the results. The proposed charts facilitate easy design of the optimal canal dimensions guarantying minimum water loss and computation of water loss from the canal section without going through the conventional and cumbersome trial and error method. A design example with sensitivity analysis has been included to demonstrate the simplicity and practicability of the proposed method.

Keywords: canal design, optimal dimensions, seepage loss, and evaporation loss.

List of Symbols

A	flow area [m^2];
b	bed width of canal [m];
E	evaporation discharge per unit free surface area [m/s];
F_s	seepage function [dimensionless];
k	coefficient of permeability [m/s];
m	side slope [dimensionless];
n	Manning's roughness coefficient [dimensionless];
Q	discharge [m^3/s];
q_e	evaporation loss per unit length of canal [m^2/s];
q_s	seepage loss per unit length of canal [m^2/s];
q_w	total water loss per unit length of canal [m2/s];
R	hydraulic radius [m];
S_o	bed slope [dimensionless];
T	width of free surface [m];
V	average velocity [m/s];
V_L	limiting velocity [m/s];
y_n	normal depth [m];

1. Introduction

The trapezoidal section is the most common and practical canal cross section, which is used to convey water for irrigation, industrial and domestic uses around the world. An irrigation canal may be a rigid or mobile boundary canal. The loss of water due to seepage and evaporation from irrigation canals constitutes a substantial percentage of the usable water. According to the Bureau of Indian Standards, [1] the loss of water by the seepage from unlined canals in India generally varies from 0.3 to 7.0 m^3/s per 10^6 m^2 of wetted surface. The seepage loss from canals is governed by hydraulic conductivity of the subsoil, canal geometry, and location of water table relative to the canal.

Canals are lined to control the seepage. But canal lining deteriorates with time and hence, significant seepage losses continue to occur from a lined canal [2]. Therefore, seepage loss must be considered in the design of a canal section. Several investigators [3,4,5,6,7,8,9,10] presented canal design methods considering seepage loss.

A transmission canal conveys water from the source to a distribution canal. Many times the area to be irrigated lies very far from the source, and hence requires long transmission canals. For example, the Nobaria canal in Egypt has the transmission canal length of 190 km carrying a discharge about 160 m^3/s.

Water lost by seepage cannot be recovered without the use of costly pumping plant. In addition excessive seepage losses can cause low lying areas of land to become unworkable. As the water table rises, water logging and soil Stalinization can occur, necessitating the installation of elaborate and costly drainage systems. Furthermore the cultivable area is reduced, resulting in a loss of potential crop production.

By the time the water reaches the field, more than half of the water supplied at the head of the canal is lost in seepage and evaporation [11]. Seepage loss is the major and the most important part of the total water loss [8]. The other part i.e. evaporation loss is important particularly in water scarce areas. Considerable part of flow may be lost from a network of canals by the way of evaporation in high evaporating conditions. This needs special consideration for a long channel carrying small discharge in arid regions. Thus, care must be taken in the design of such canals to account for evaporative losses along with seepage loss.

Studies of canal design for minimum water loss have been carried out by several investigators [12-15]. These studies besides their difficulties to be applied by the practicing engineer, no attention has been made to consider the side slope constrain.

In the present study using explicit equations for seepage loss [8], the evaporation equation, and Manning's equation for open channel flow [16], minimum water loss sections have been obtained by applying Lagrange's method of undetermined multipliers [17] for triangular, rectangular, and trapezoidal canal sections and presented in easy use simple design charts.

2. Objective Function

The sum of seepage and evaporation losses is considered as an objective function. The aim is to minimize the objective function.

Water losses:

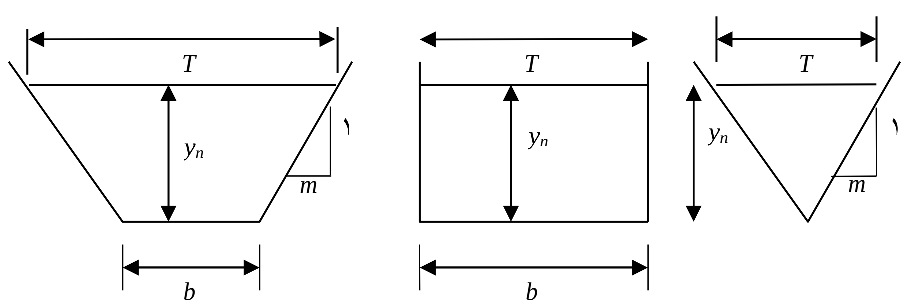
Water is lost from canals by seepage through the sides and bottom and by evaporation from the water surface. Seepage rates from unlined canals can be extremely large, and even lined channels never seem to eliminate water loss through sides and bottoms. Measured seepage rates from lined canals vary widely [18]. The best concrete-lined channels may lose about 8 mm/day of water through wetted boundary surfaces.

Evaporation Loss

The Evaporation loss from flowing canals, can be expressed as

$$q_e = E.T \tag{1}$$

where q_e = evaporation discharge per unit length of canal (m^2/s); E = evaporation discharge per unit free surface area (m/s); and T = width of free surface (m). See fig. (1).



(a) (b) (c)

Fig. (1). Canal Sections: (a) Trapezoidal Section, (b) Rectangular section, (c) Triangular Section.

Seepage Loss

Providing perfect lining can prevent seepage loss from canals but cracks in lining develop due to several reasons and performance of canal lining deteriorates with time. An examination of canals [2] indicated that even with the greatest care the lining does not remain perfect. A well maintained canal with 99% perfect lining reduces seepage about 30-40% only [2]. Thus significant seepage losses occur from a canal even if it is lined. The seepage loss from canals is governed by hydraulic conductivity of the subsoil, canal geometry, and potential difference between the canal and the aquifer underneath which in turn depends on the initial and boundary conditions. Seepage losses are also influenced by clogging of the canal surfaces depending on the suspended sediment content of the water and on the grain size distribution of the suspended sediment particles. The clogging process can decrease the seepage discharge both through bottom and slopes. Thus the seepage loss can change within time and under certain conditions it can diminish. Therefore, the seepage loss can be higher at the beginning of the canal operation and can be lower after a few years of operation.

The seepage loss from a canal in an unconfined flow condition is finite and maximum when the potential difference is very large e.g. when the water table lies at very large depth. The steady seepage loss from an unlined or a cracked lined canal in a homogeneous and isotropic porous media, when water table is at very large depth, can be expressed as [8].

$$q_s = k.y_n.F_s \tag{2}$$

where q_s = seepage discharge per unit length of canal (m^2/s); k = coefficient of permeability (m); y_n = normal depth of flow in the canal (m); and F_s = seepage function (dimensionless), which is a function of channel geometry. Graphical representation of equation (1) is plotted in fig. (2).

The seepage function can be estimated for different sets of specific conditions for a known canal dimensions [3,19,20]. The analytical form of these solutions, which contain improper integrals and unknown implicit state variables, are not convenient in estimating seepage from the existing canals and in designing canals considering seepage loss. These methods have been simplified using numerical methods for easy computation of seepage function by Swamee *et al* [8].

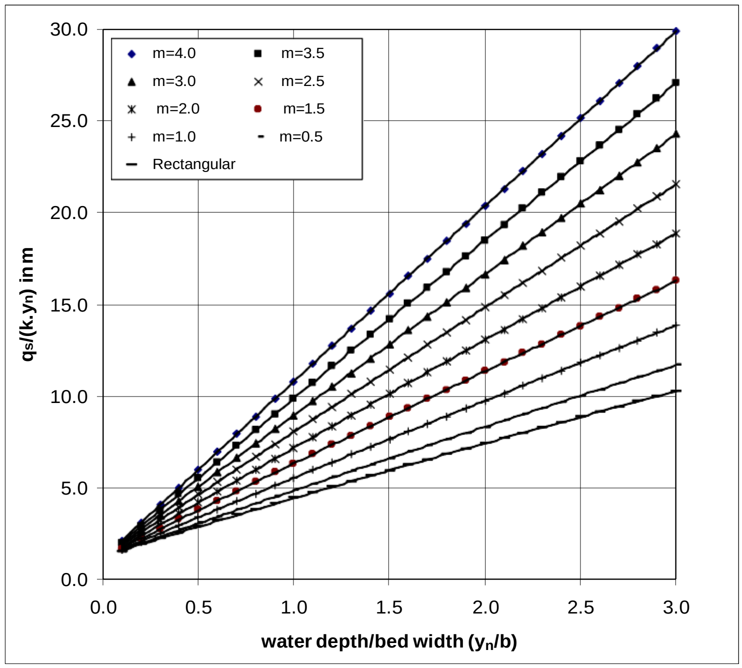


Fig. (2). Variation in seepage loss [$q_s/(k.y_n)$] with ratio of water depth / bed width for different side slope m.

Total Water Loss

Adding (1) and (2) the total water loss q_w (m^2/s) was expressed as:

$$q_w = k.y_n.F_s + E.T \tag{3}$$

Using Swamee *et al* [8] equations for F_s, Eq. (3) for trapezoidal section [See Fig. 1] was reduced to

$$q_w = k.y_n\left[\left(\left\{\pi\left(4-\pi\right)\right\}^{1.3} + \left\{2\sqrt{1+m^2}-m\right\}^{1.3}\right)^{\frac{0.77+0.462m}{1.3+0.6m}} + \left(\frac{b}{y_n}\right)^{\frac{1+0.6m}{1.3+0.6m}}\right]^{\frac{1.3+0.6m}{1+0.6m}} + E.\left[b+2m.y_n\right] \tag{4}$$

where m= side slope; b = bed width of the section.

Equation 4 is reduced to the following equation

$$q_w = k.y_n \left[c + \left(\frac{b}{y_n} \right)^{j_2} \right]^{j_1} + E.\left[b + 2m.y_n \right] \tag{5}$$

Where

$$c \left(4 \quad {}^{2} \; {}^{1.3} \quad 2m^{1.3} \right)^{\frac{0.77+0.462\,m}{1.3+0.6\,m}} ; \tag{6a}$$

$$j_1 = \frac{1.3 + 0.6m}{1 + 0.6m} \text{; and} \tag{6b}$$

$$j_2 = \frac{1.0 + 0.6m}{1.3 + 0.6m} \tag{6c}$$

3. Problem Constrain (Flow Function)

Constraints are the restrictions posed on the values of selected variables. For the present optimization problem, flow rate Q is required to be equal the value given by Manning's formula [16], that is

$$Q = \frac{\Psi}{n} R^{2/3}.S_o^{1/2}.A \tag{7}$$

where Q = canal discharge (m^3/s); A = flow area (m^2); R = hydraulic radius (m) defined as the ratio of the flow area to the flow perimeter P (m) (i.e., $R=A/P$) ; S_o = longitudinal channel bed slope; ψ = a constant (1.00 for SI units and 1.486 for U.S. Customary units) and n = Manning's roughness coefficient.

Bottom width of the cross section b and the side-slope ratio m need to equal or exceed zero (b = 0 yields a triangular cross section shape, and m = 0 produces a rectangular cross section shape). See fig. (1).

Average canal velocities V = Q/A may also be of concern. If water travels too slowly, sediment carried by the flow can deposit and lead to higher water-surface elevations and reduced capacities. On the other hand, water moving at high speeds can erode beds and banks. For water carrying no silt load, minimum velocity has little significance except for its effect on plant growth. In general, minimum average barrel velocities of 0.6 to 0.9 m/s (2 to 3 feet/sec) are suitable when the percentages of silt-sized material present in channel flows are small, and average velocities greater than 0.8 m/s (2.5 feet/sec) will prevent growth of vegetation that might decrease flow-carrying capacities of channels [16,21]. Maximum allowable velocities that prevent erosion are usually based on the types of channel lining.

Limitations might also be imposed because of large super-elevation in bends and high degrees of wave action. Maximum permissible velocities for various canals are suggested by Etcheverry [22], Fortier and Scobey [23], Lane [24], and Swamee *et al* [9]. Side slopes may also be restricted by site conditions or construction-related factors.

4. Optimization Procedure

To get the minimum water loss design of canal cross section, the overall water loss per unit length, q_w, (equation 5) and the flow equation (the main constrain) should be minimized. The flow equation $\phi\,(y_n, b, m)$, can be written as:

$$\phi(y_n, b, m) = A^{\alpha}.P^{\beta} - \frac{Q.n}{\psi\sqrt{S_o}} = A^{5/3}.P^{-2/3} - \frac{Q.n}{\psi\sqrt{S_o}} = 0.0 \qquad (8)$$

Where $\frac{Q.n}{\psi\sqrt{S_o}}$ = section factor.

Applying Lagrange's method of undetermined multipliers with ζ as the undetermined multipliers, the following relations are obtained:

$$\frac{\partial q_w}{\partial y_n} + \zeta\frac{\partial\phi}{\partial y_n} = 0 \qquad (9)$$

$$\frac{\partial q_w}{\partial m} + \zeta\frac{\partial\phi}{\partial m} = 0 \qquad (10)$$

$$\frac{\partial q_w}{\partial b} + \zeta\frac{\partial\phi}{\partial b} = 0 \qquad (11)$$

Eliminating ζ between equations 9,10, and 11 one gets

$$\frac{\partial q_w}{\partial b}.\frac{\partial\phi}{\partial y_n} = \frac{\partial q_w}{\partial y_n}.\frac{\partial\phi}{\partial b} \qquad (12)$$

$$\frac{\partial q_w}{\partial b}.\frac{\partial\phi}{\partial m} = \frac{\partial q_w}{\partial m}.\frac{\partial\phi}{\partial b} \qquad (13)$$

Equation 8 is used to determine the partial derivatives $\frac{\partial\phi}{\partial y_n}$, $\frac{\partial\phi}{\partial m}$, and $\frac{\partial\phi}{\partial b}$. Using equations 12 and 13 the following two important equations, which are necessary for the minimization process, can be obtained:

$$\frac{\partial q_w}{\partial b}\cdot\left[\frac{\alpha}{A}\cdot\frac{\partial A}{\partial y_n}+\frac{\beta}{P}\cdot\frac{\partial P}{\partial y_n}\right]=\frac{\partial q_w}{\partial y_n}\cdot\left[\frac{\alpha}{A}\cdot\frac{\partial A}{\partial b}+\frac{\beta}{P}\cdot\frac{\partial P}{\partial b}\right] \qquad (14)$$

$$\frac{\partial q_w}{\partial b}\cdot\left[\frac{\alpha}{A}\cdot\frac{\partial A}{\partial m}+\frac{\beta}{P}\cdot\frac{\partial P}{\partial m}\right]=\frac{\partial q_w}{\partial m}\cdot\left[\frac{\alpha}{A}\cdot\frac{\partial A}{\partial b}+\frac{\beta}{P}\cdot\frac{\partial P}{\partial b}\right] \qquad (15)$$

The partial derivative of q_w is as follows

$$\frac{\partial q_w}{\partial y_n}=k.\left[c+\left(\frac{b}{y_n}\right)^{j_2}\right]^{j_1}-k.\left[c+\left(\frac{b}{y_n}\right)^{j_2}\right]^{j_1-1}.\left(\frac{b}{y_n}\right)^{j_2}+E.[2m] \qquad (16)$$

$$\frac{\partial q_w}{\partial b}=k\left[c+\left(\frac{b}{y_n}\right)^{j_2}\right]^{j_1-1}.\left(\frac{b}{y_n}\right)^{j_2-1}+E \qquad (17)$$

Case of constant side slope m

Practically, for a given canal bed material and according to the internal angle of repose, the canal side slope, m, is decided. In this case $\frac{\partial\phi}{\partial m}=\frac{\partial q_w}{\partial m}=0.0$, and only equation 14 is held true.

Substituting from equations 16 and 17 into equation 14 yields the following equation, which is necessary for minimization process.

$$\left[k\left[c+\left(\frac{b}{y_n}\right)^{j_2}\right]^{j_1-1}.\left(\frac{b}{y_n}\right)^{j_2-1}+E\right]\left[\frac{5}{A}\cdot\frac{\partial A}{\partial y_n}-\frac{2}{P}\cdot\frac{\partial P}{\partial y_n}\right]=$$
$$\left[k.\left[c+\left(\frac{b}{y_n}\right)^{j_2}\right]^{j_1}-k.\left[c+\left(\frac{b}{y_n}\right)^{j_2}\right]^{j_1-1}.\left(\frac{b}{y_n}\right)^{j_2}+E.[2m]\right]\left[\frac{5}{A}\cdot\frac{\partial A}{\partial b}-\frac{2}{P}\cdot\frac{\partial P}{\partial b}\right] \qquad (18)$$

In which

$$\frac{\partial A}{\partial y_n} = b + 2my_n;\quad \frac{\partial A}{\partial b} = y_n;\quad \frac{\partial P}{\partial y_n} = 2\sqrt{1+m^2};\ \text{and}\ \frac{\partial P}{\partial b} = 1 \qquad \text{(19a,b,c,d)}$$

Equation 18 may be simplified to be

$$\left[k\left(c+\left(\frac{b}{y_n}\right)^{j_2}\right)^{j_1-1}\cdot\left(\frac{b}{y_n}\right)^{j_2-1}\right] + E\left(5P\left(b+2my_n\right) - 2A\left(2\sqrt{1+m^2}\right)\right) =$$
$$\left[k\left(c+\left(\frac{b}{y_n}\right)^{j_2}\right)^{j_1} - k\left(c+\left(\frac{b}{y_n}\right)^{j_2}\right)^{j_1-1}\cdot\left(\frac{b}{y_n}\right)^{j_2}\right] + E\left[2m\right]\left(5Py_n - 2A\right) \qquad (20)$$

Using equations 20 and 8 the optimal canal cross section for minimum water loss for a specified value of ***m***, can obtained. Once, the value of b and y_n are calculated, the corresponding value of flow velocity, V, is determined, which must satisfy the allowable velocity.

Velocity-constrains

The minimum permissible velocity, V_{min} or the non-silting velocity is the lowest velocity that will not initiate sedimentation and will not induce the growth of vegetation. Sedimentation and growth of vegetation decrease the carrying capacity and increase the maintenance cost of the canal. In general, an average velocity of 0.6 to 0.9 m/s will prevent sedimentation when the silt load of the flow is low and a velocity of 0.75 m/s is usually sufficient to prevent the growth of vegetation [16]. Hence, the minimum permissible velocity can be assumed in the range from 0.75 to 0.9 m/s.

The higher velocities are desired in rigid boundary canals to reduce costs. However, high velocities may cause scour and erosion of the boundaries. In rigid boundary canals the maximum permissible velocity or the limiting velocity, V_{max} (m/s) that will not cause erosion depends on the channel surface material. Table 1 lists the limiting velocities for different type of channel surface materials [11,25].

Table (1). Limiting Velocities

Lining Material	Limiting Velocity (m/s)
Boulder	1.0-1.5
Brunt Clay Tile	1.5- 2.0
Concrete Tile	2.0-2.5
Concrete	2.5-3.0

The flow velocity, V, must be checked with the maximum, and the minimum velocity limits.

If such flow velocity, V, is greater than V_{max}, or less than V_{min}, the optimal values of b* and y* will not equal those given by solving Equation 8 and 20. The proper dimensions of the channel may be obtained by solving Manning's equation along with one of the following two equations.

Case 1: $V<V_{min}$

$$A(y,b) = Q/V_{min} \tag{21}$$

Case 2: $V>V_{max}$

$$A(y,b) = Q/V_{max} \tag{22}$$

5. Computer Program and Design Charts

Solving Equations 8 and 20 for optimum bed width and optimum water depth, y*, requires iteration. A FORTRAN computer program, using random search method is developed to solve the above mentioned equations.

Reasonable upper and lower limit value of both, bed width, *b*, and water depth, y_n, are essential to quick the calculation. The following equations give the maximum expected values of water depth y_{max}, and bed width b_{max}.

$$y_{max} = 2^{0.25}.\frac{\left(1+m^2\right)^{1/8}}{m^{5/8}}\left[\frac{Q.n}{\psi\sqrt{S_o}}\right]^{0.375} \tag{23}$$

$$b_{max} = 2^{1.25}.\frac{\left(1+m^2\right)^{1/8}}{m^{5/8}}\left[\frac{Q.n}{\psi\sqrt{S_o}}\right]^{0.375} \tag{24}$$

The results are plotted on design chart forms (figures 3,4,5,6) to assist the designer to get out the optimal dimension of the canal for known values of *Q, n, m,* S_o*, and E/K.*

The graphical correlation method [25,26] with the aid of computer facilities, is used to construct alternative and compact design charts, figures 8a, 8b, 8c , that would be used to find the optimal dimension of the canal for known values of *Q, n, m,* S_o*, and E/K.*

6. Procedure to Use the Design Charts

To find optimal bed width ***b*** of the desired canal, fig. (8a), the bottom axis is entered with the desired ***K/E***, then vertically up to the desired ***m***, then horizontally to the desired section factor SF, then vertically up to optimal bed width ***b***.

To find optimal water depth y_n of the desired canal, fig. (8b), the bottom axis is entered with the desired ***K/E***, then vertically up to the desired ***m***, then horizontally to the desired section factor SF, then vertically up to optimal water depth y_n.

To find minimum water loss q_w/E of the desired canal, fig. (8c), the bottom axis is entered with the desired ***K/E***, then vertically up to the desired ***m***, then horizontally to the desired section factor SF, then vertically up to water loss q_w/E.

7. Discussions

In figures (3a, 4a, 5a, 6a) variation of optimal bed width b with section factor [Q.n/ψ.So^.5] and side slope ***m*** for ***K/E***=0.50, 1.00, 2.00, and 5.00 were plotted.

In figures (3b, 4b, 5b, 6b) variation of optimal water depth y_n with section factor [Q.n/ψ.So^.5] and side slope ***m*** for ***K/E***=0.50, 1.00, 2.00, and 5.00 were plotted.

In figures (3c, 4c, 5c, 6c) variation of water loss q_w/E with section factor [Q.n/ψ.So^.5] and side slope ***m*** for ***K/E***=0.50, 1.00, 2.00, and 5.00 were plotted.

Figures (3a, 4a, 5a, 6a) show that bed width of the optimal section decrease with increase in side slope ***m*** for all values of ***K/E***. For $m \geq 1.0$ the optimum shifts to $b = 0$ (triangular section).

A perusal of Figures (3c, 4c, 5c, 6c) for water loss reveals that water loss q_w increase with increase in side slope ***m*** for all values of ***m***≥0.5.

The optimal trapezoidal section permits less water loss than the optimal rectangular section for ***K/E*** ≥ 1.0.

Design examples

Example 1

Design a minimum water loss concrete lined rectangular canal section for carrying a discharge of 6.25m^3/s on a longitudinal slope of 0.0004, Manning's coefficient n= 0.016., evaporation rate, E = 3.0m/year, conductivity of underlain soil, K= 1.5m/year. It is required also to calculate total water loss from the canal if total length of the canal is 12 km.

Design steps

$$\text{Section factor.} = \frac{Q.n}{\psi\sqrt{S_o}} = \frac{6.25(0.016)}{\sqrt{0.0004}} = 5$$

From chart (3 a) b*= 2.45 m
From chart (3 b) y*= 2.35 m
From chart (3 c) q_w/E= 7.74 m^2/year
Then minimum water loss is 7.74*3*12000 =278640 m^3/year

Example 2

Design a trapezoidal canal section for the same data above, and side slope m =0.5

Design steps

Section factor. = $\dfrac{Q.n}{\psi\sqrt{S_o}} = \dfrac{6.25(0.016)}{\sqrt{0.0004}} = 5$

From chart (3 a) b*= 1.5m
From chart (3 b) y*= 2.15m
From chart (3 c) q_w/E= 8.4 m^2/year
Then minimum water loss is 8.4*3*12000 =302400 m^3/year

Sensitivity of optimal dimension

For ***b*** ranging from 0.5 m to 7 m and ***m*** ranging from 0 to 2.0, the normal water depths were obtained using Manning's equation. Furthermore, water losses were calculated by (3). Figure. (7) shows the variation of q_w with ***b*** and ***m*** for section factor [Q.n/ψ.So^.5] = 5.0 and ***K/E***= 0.50. It can be seen that the water loss from a rectangular section with bed width of 2.45 m is the global minimum. Furthermore, the optimum is less sensitive to the increase in bed width and more sensitive to increase in side slope. This trend of sensitivity continues for $0 < m < 1.0$. For $m \geq 1.0$ the optimum shifts to $b = 0$ (triangular section). However, as seen in Fig. (7) the optimum for a rectangular section ($m = 0$) is highly sensitive to a decrease in bed width.

Error in optimal bed width ***b*** calculation in the range ± 10% will result only in an increase in water loss by a value less than 0.80 %, this means that the design charts can be used easily and safely to get the optimal value of ***b***. The value of ***b*** can then rounded off.

8. Conclusions

Using Lagrange's method of undetermined multipliers, the optimal dimensions of canal cross section for minimum water loss have been obtained. Design charts, based on the obtained results, in terms of canal geometry have been given to facilitate design of the minimum water loss canals. Charts based on the optimal dimension, are developed to calculate the minimum water loss from the designed canal. The results show that, Water loss from a triangular canal is minimum for $m \geq 1.5$ for all cases of ***K/E*** and section factor [Q.n/ψ.So^.5]. Also the results show that as K/E increase, the bed width is increase. The design examples have demonstrated the simplicity of the method. The sensitivity analysis for the rectangular and trapezoidal canal section design has revealed that the optimum is less sensitive to the increase in bed width and more sensitive otherwise.

The proposed method can be applied to other complicated canal cross sections that can not be solved by traditional method of variation.

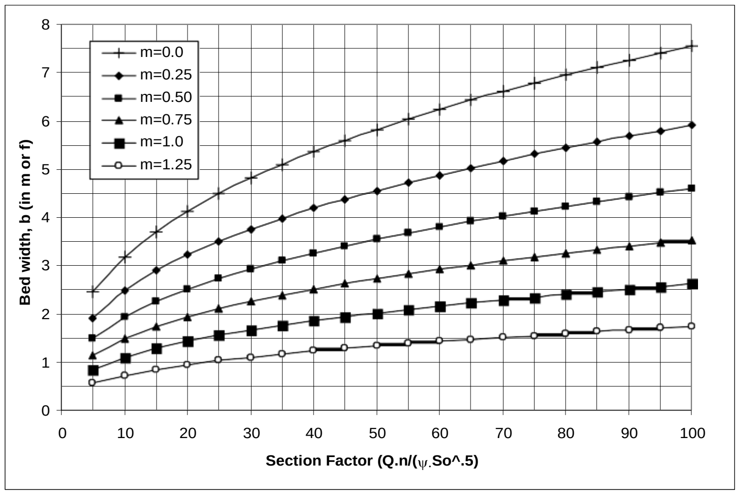


Fig. (3a). Variation of Bed width B with section factor [Q.n/ψ.So^.5] and Side slope *m* for *K/E*=0.50.

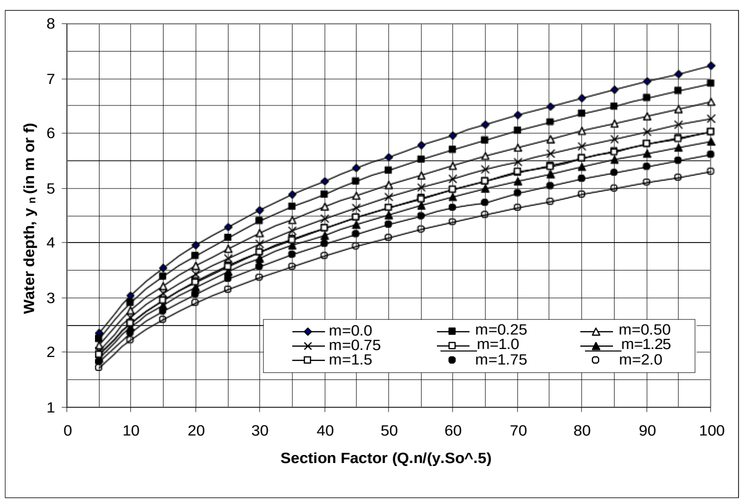


Fig. (3b). Variation of water depth y_n with section factor [Q.n/ψ.So^.5] and Side slope *m* for *K/E*=0.50.

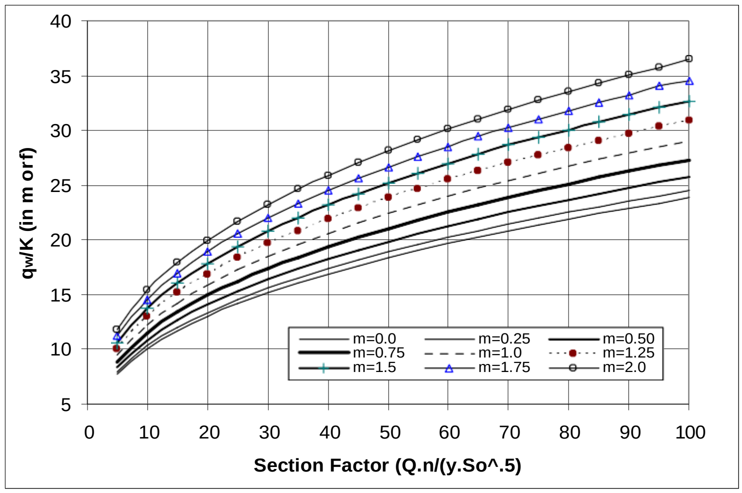


Fig. (3c). Variation of water loss q_w with section factor [Q.n/ψ.So^.5] and Side slope *m* for *K/E*=0.50.

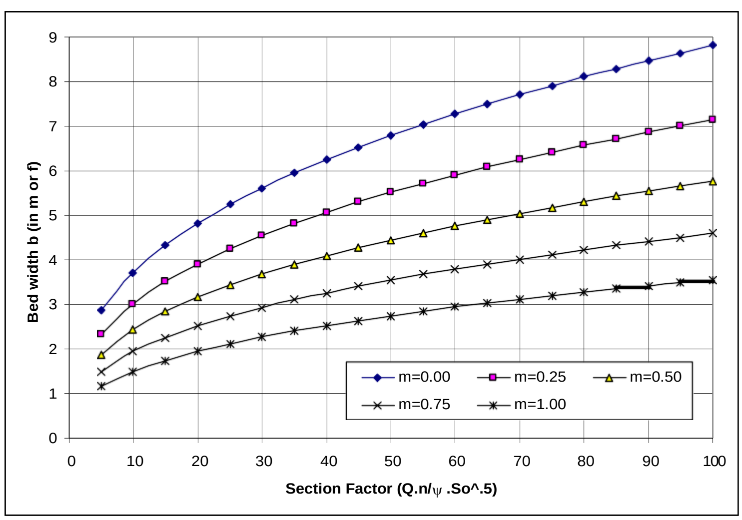


Fig. (4a). Variation of Bed width B with section factor [Q.n/ψ.So^.5] and Side slope *m* for *K/E*=1.00.

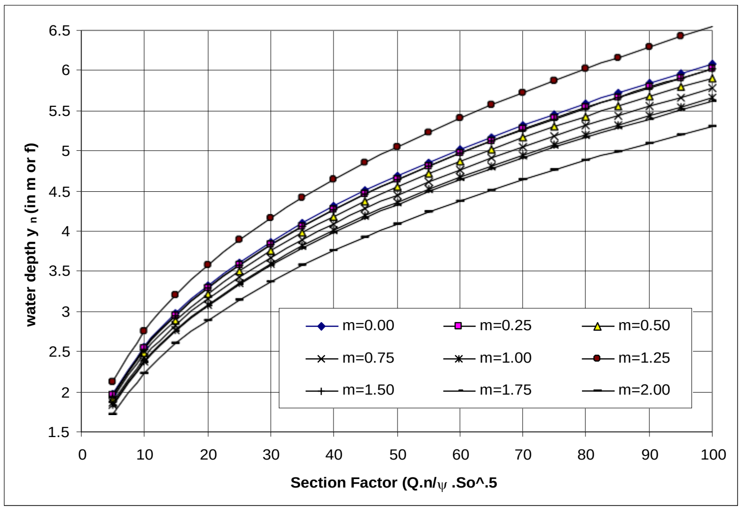


Fig. (4b). Variation of water depth y_n with section factor [Q.n/ψ.So^.5] and Side slope *m* for *K/E*=1.00.

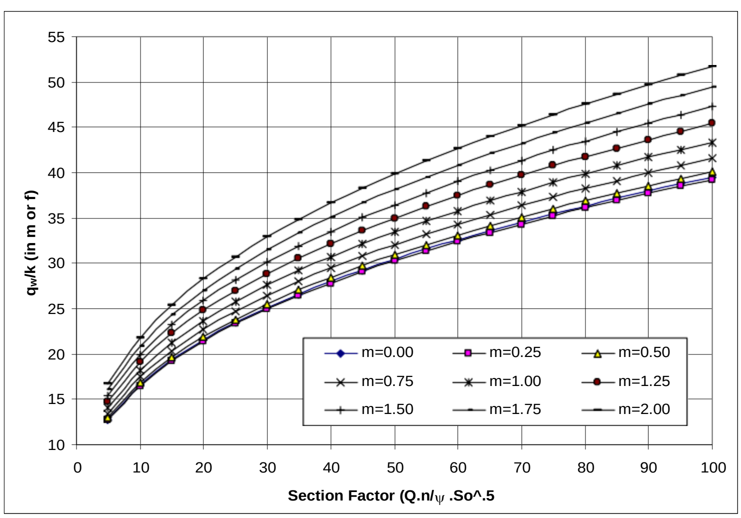


Fig. (4c). Variation of water loss q_w with section factor [Q.n/ψ.So^.5] and Side slope *m* for *K/E*=1.00.

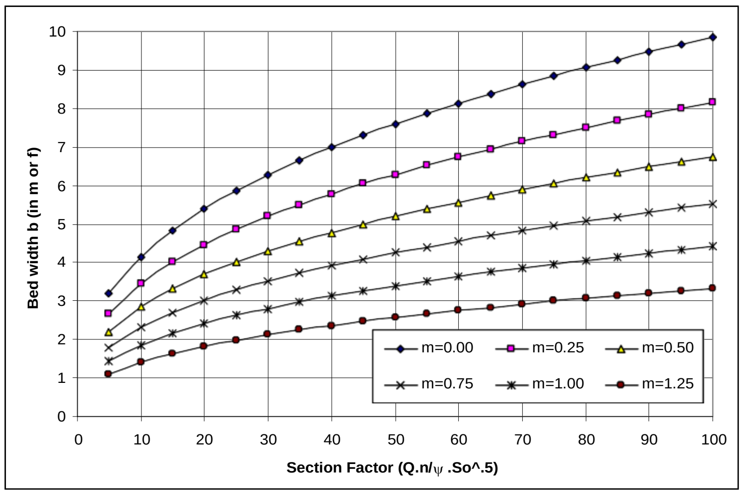


Fig. (5a). Variation of Bed width b with section factor [Q.n/ψ.So^.5] and Side slope *m* for *K/E*=2.00.

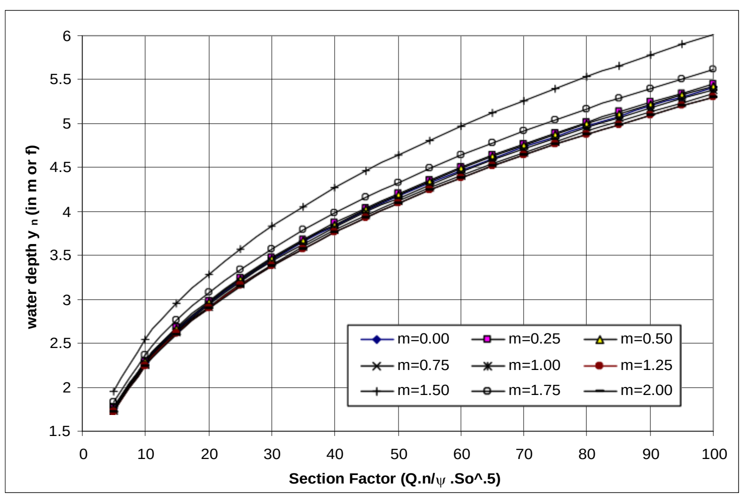


Fig. (5b). Variation of water depth y_n with section factor [Q.n/ψ.So^.5] and Side slope *m* for *K/E*=2.0.

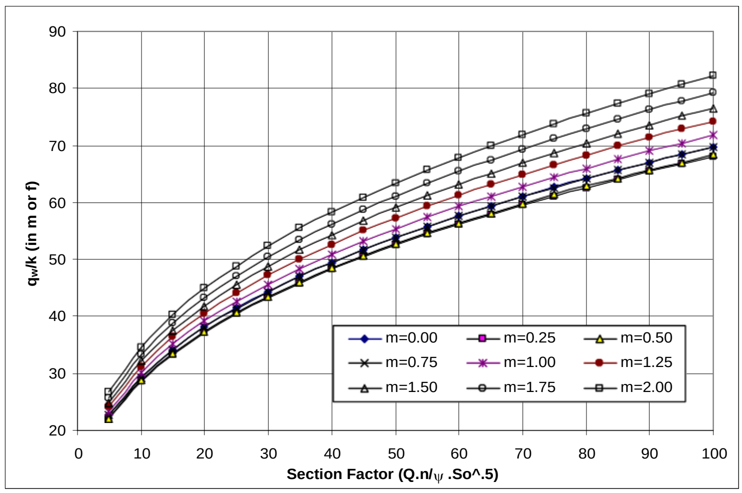


Fig. (5c). Variation of water loss q_w with section factor [Q.n/ψ.So^.5] and Side slope *m* for *K/E*=2.0.

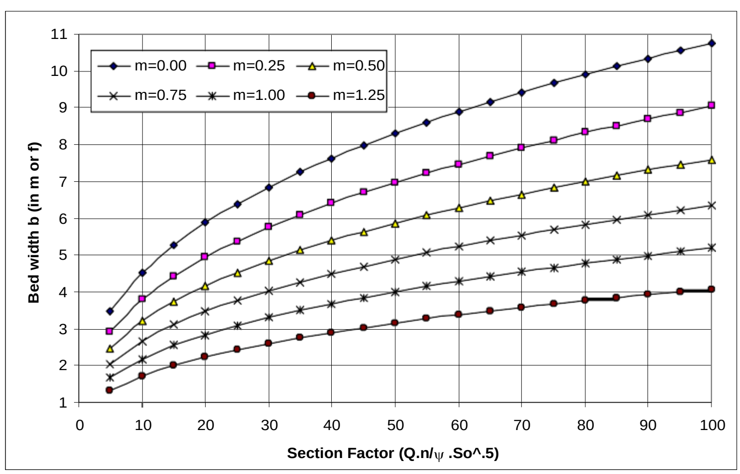


Fig. (6a). Variation of Bed width B with section factor [Q.n/ψ.So^.5] and Side slope *m* for *K/E*=5.0.

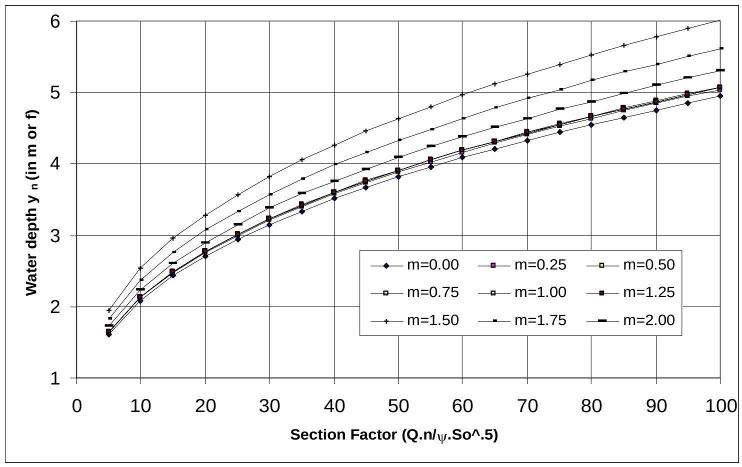


Fig. (6b). Variation of water depth y_n with section factor [Q.n/ψ.So^.5] and Side slope *m* for *K/E*=5.0.

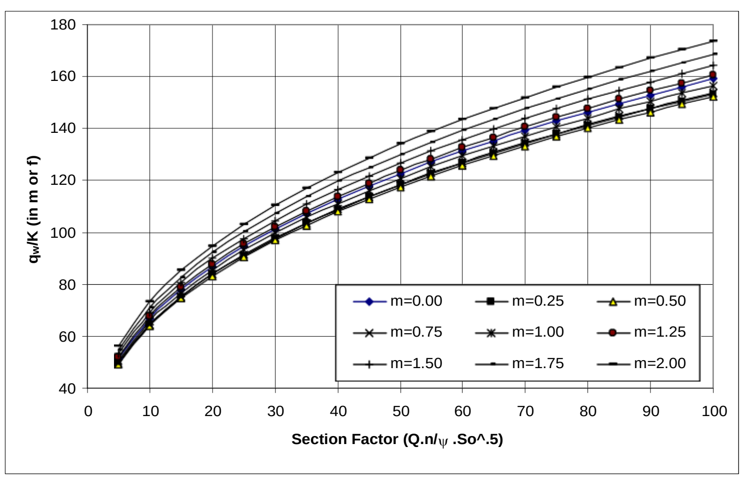


Fig. (6c). Variation of water loss q_w with section factor [Q.n/ψ.So^.5] and Side slope *m* for *K/E*=5.0.

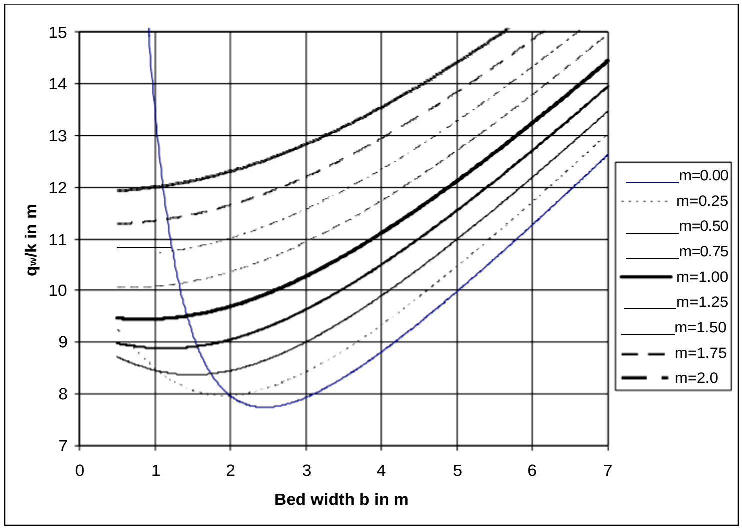


Fig. (7). Variation of water loss q_w/k with bed width *b* and Side slope *m* for *K/E*=0.50 and section Factor [Q.n/ψ.So^.5]=5.0.

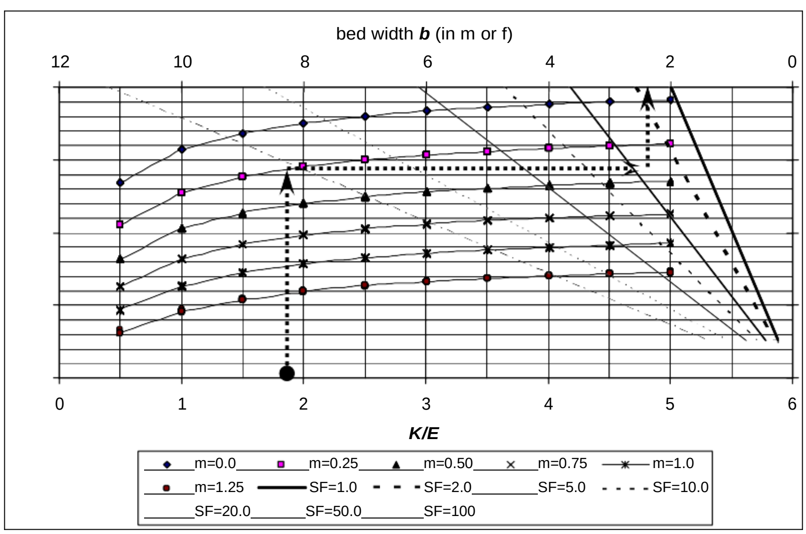


Fig. (8.a). Optimal bed width *b* as a function of *K/E*, side slope *m*, and Section Factor SF, [Q.n/ψ.So^.5].

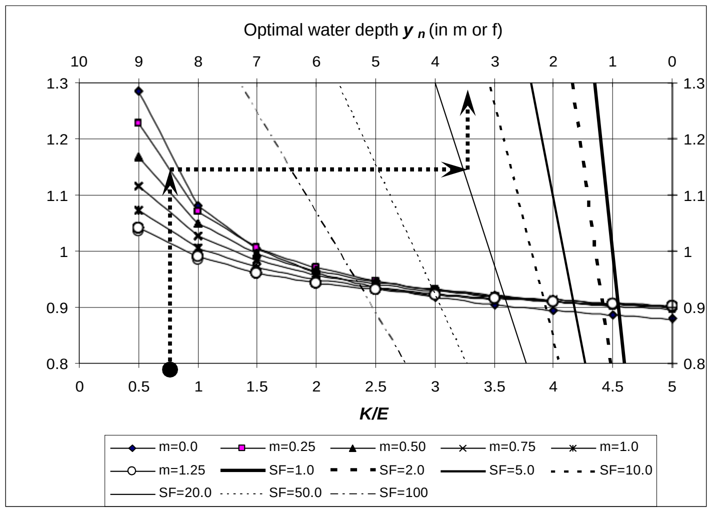


Fig. (8.b). Optimal water depth y_n as a function of *K/E*, side slope *m*, and Section Factor SF, [Q.n/ψ.So^.5].

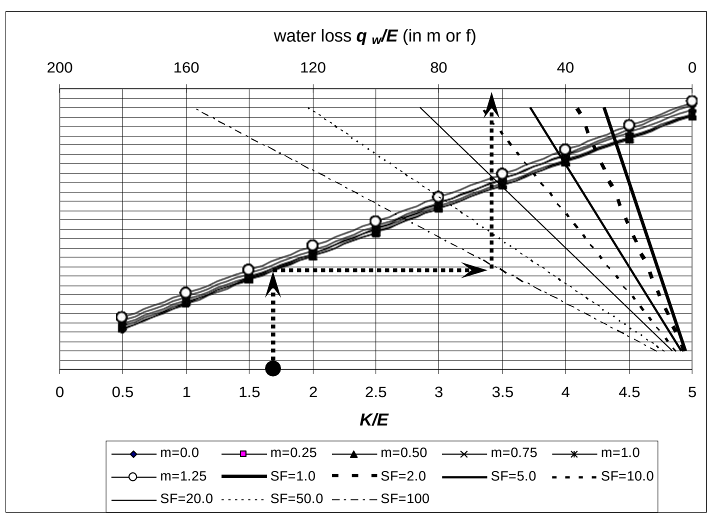


Fig. (8.c). Water loss q_w/E as a function of *K/E*, side slope *m*, and Section Factor SF, [Q.n/ψ.So^.5].

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