



A Simplified Mathematical Equation to Study the Relationship between Water Driving Forces and Water Losses Amount in Irrigation Canals in the Field

Y. A. M. Abd-Allah ^{a*}

^a Soil, Water and Environment Research Inst. Agric. Res. Center, Giza, Egypt.

Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

This investigation aimed to study the effect of water driving forces in irrigation canals in the case of using one or two irrigation canals in the field and its impact on water losses amount by deriving a mathematical equation. The results across the two seasons showed that mean water driving forces (WDF) in the case of using one irrigation canal in field ($0.26\text{m}^3/16.63\text{minute}$) was greater than two irrigation canals ($0.24\text{m}^3/36.13\text{minute}$) and the water losses amount (WLA) resulted from using one irrigation canal (17.78 m^3) was less than the two irrigation canals (36.25 m^3) by saving 18.47m^3 of irrigation water. Consequently, there is an inverse relationship between water driving forces in irrigation canals in the field and water losses amount. Grain yield in the case of using one irrigation canal in the field was 1.414 mg ha^{-1} , while in the two irrigation canals recorded 1.365 mg ha^{-1} by increasing 49.17 kg ha^{-1} . Accordingly, a quantity of irrigation water can be saved during surface irrigation in order to achieve water abundance can be used to irrigate new lands. The quadratic model was the best statistical model to describe the relationship between Water Driving Force (WDF) and Water Movement Time (WMT) irrigation canal in field. Using the fitted quadratic model, it is clear that the Critical Water Movement Time (CWMT) which reflects the lowest WDF value was 25.55 min.

*Corresponding author: E-mail: yosriahmed560@gmail.com;

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1. INTRODUCTION

In arid and semi arid regions managing agriculture water for irrigation and yield productivity are essential ,in Egypt approximately 2.5 millionha¹irrigated by surface irrigation systems, its from approximately 1.04 millionha¹wheat, so used the optimum of irrigation canals in wheat planting may be achieve water abundance by reducing of water losses which can be used to cultivated new lands. Wheat has managed to increase its share of the winter cropped area ranged from 41 to 47%, and the cultivated area is limited to the narrow strip along the Nile Valley [1]. Therefore, attempts have been made to expand the cultivated area in Egypt by reclaiming new lands using irrigation. The amount of wheat production in Egypt is about of 9 million ton in 2021 with an increase of 1.12% from the previous years [2]. In a trial to increase wheat cultivation area to decrease dependency on wheat importing. Consequently, supply-oriented management strategies have been used to identify new potential water resources for agricultural purposes. However, climate change and continuous droughts in recent decades in arid regions have created challenges to the provision of a timely and sufficient water supply for agricultural water demand [3]. Meanwhile, the essential need for significant investments in agricultural water supply, conveyance and distribution infrastructure have limited the application of supply-oriented approaches. Therefore, in order to reduce water losses in the infrastructure and

increase water productivity, demand-oriented approaches have become priorities and have been widely employed on the on-farm scale through precision agriculture systems [4]. In recent years, water resources exposes to an increasing stress due to impacts of climate change, population increase and economic development. Water scarcity is recognized as a main threat particularly in the Mediterranean area. Thus, water utilities should become highly efficient throughout the entire water supply process, to guarantee sufficient quantities of good quality water. Since water is one of the most valuable natural resources, water losses in the Water Distribution System (WDS) represent an urgent problem that needs to be managed [5]. Water conveyance and distribution process may be less benefit during irrigation canals due to the effect on water losses, so it is necessary to evaluate the performance of water conveyance and estimation water losses in irrigation canals in the field [6]. Water conveyance efficiency is affected by several factors such as seepage, soil type, canal length, canal width and physical damages of the canals [7]. Also, the main factors that influence canal water losses are water level, soil hydraulic properties, groundwater table location and amount of sediment inside the canal [8]. Consequently, the reduction of seepage helps protect the limited water resources, minimize production of water treatment products and energy consumption [9]. The Egyptian country launched a program to lining water canals as part of a major project to reduce water losses in order to achieve water



Fig. 1. Experimental area

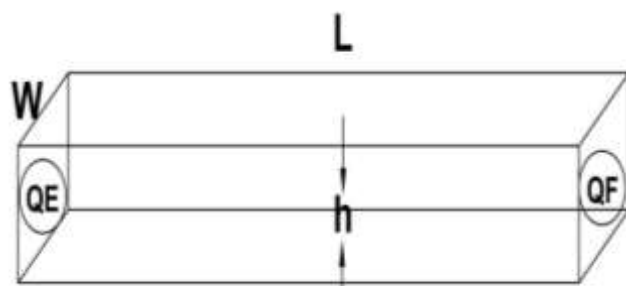
abundance within the national agricultural strategy 2030 to achieve this goal. Increasing water losses as a result to surface irrigation system reduces its efficiency. Therefore, the goal of the research is to reduce water losses by using irrigation canals with optimal planning of irrigation canals to increase the efficiency of water conveyance in irrigation canals in the field to achieve the least water losses amount. This research was carried out with the aim of studying the effect of water driving forces in irrigation canals in case of using one or two irrigation canal in the field and its impact on water losses amount by deriving a simple mathematical equation.'

2. MATERIALS AND METHODS

Tow field experiments were carried out at El-Gemmeiza Agricultural Research Station, El-Gharbia Governorate, Egypt, Middle of Nile Delta (30° 43' latitude and 31° 47' longitude) on clay soil during two winter seasons (2019/2020 and 2020/2021). Wheat cultivar, Gemmeiza 11 was planted on 16th and 18th November in two seasons, respectively and irrigated three times in addition to planting irrigation, where the experiment area was 2064m² (48m length × 43m width). The soil surface was leveled by laser. Wheat plants were harvested on 27th and 30th April for two seasons respectively. The objective of the research is studying the effect of water driving forces within irrigation canals in the field and its impact on water losses by deriving a simplified mathematical equation.

$$\text{Water driving forces (WDF), m}^3/\text{min} = \frac{L \times W \times H \times G}{T}$$

L: canal length, 48 m



w: canal width, one m
 H: water height in irrigation canal in field, 0.5m
 T: water move time, minute
 G: gravity 9.81m/second

Water losses amount (WLA), m³ = QE – QF

QE: Water amount entering in canal irrigation in field, m³

QF: Water amount flow out from canal irrigation in field, m³ at water stability

2.1 The Scientific Basis of the Equation

Water driving forces determine the direction and rate of water movement. As a result to water movement on soil surface and water physical properties (density and viscosity) change due to dissolved substances increasing in water as a result to water molecules rubbing with soil surface, according to Reilly and Goodman [10] and Reilly [11] they indicated that water density is important because it is a part of the driving forces for water, moreover water density and viscosity affect the hydraulic transmitting properties (permeability and hydraulic conductivity). Therefore, there is relationship between water driving forces and water losses amount.

2.2 The Equation Importance and its Applied Domains

- The optimum irrigation canal planning in agricultural lands in the case of surface irrigation system to achieve the least water losses.



Fig. 2. Description of the irrigation canal in the field

Table 1. Some soil characters of the experimental site

Soil depth, cm		0-10	10-30	Soil depth, cm		0-10	10-30	
Particle size distribution,%	Coarse sand	6.19	5.70	Settling, %		31.06	31.41	
	Fine sand	18.75	18.76		Pore size distribution,%	> 9 μ	21.88	22.42
	Silt	30.96	29.93			9 – 0.2 μ	11.89	12.19
	Clay	44.10	45.61			<0.2 μ	14.16	12.19
Texture class		Clay	Clay					
Bulk density (Db, g cm ⁻³)		1.34	1.36	Hydraulic conductivity (Kh, cm hr ⁻¹)		0.48	0.44	
Total porosity (E, %)		49.43	48.68	Soil pH, 1:2.5 (suspension)		7.75	7.79	
Void ratio (e)		0.98	0.95	Soil EC, dSm ⁻¹ (soil paste extract)		2.37	2.54	

- By calculating water driving forces by using mathematical equation can be achieving water abundance by the reducing of water losses which can be used to irrigate new lands.
- Achieving one of the objectives of agricultural strategy 2030(water abundance) in Egypt.

Settling percentage of the soil aggregates was determined in soil aggregates of 2 – 5 mm size, as the method described by Williams and Cooke [12] and Hartge [13].

Pore size distribution was calculated according to De Leen her and De Boodt [14].

Amount of water applied: the discharge through an orifice was determined from the following equation as described by Israelson and Hansen [15].

$$Q = CA(2Gy)^{1/2}$$

Where: Q = Discharge rate, m³sce⁻¹, C = discharge coefficient ranges from 0.6 to 0.8, A= area of orifice opening (m²), G= accelerating of gravity (9.8 msec⁻¹), Y= the head causing free flow where Y is the upstream head measured from the center of orifice opening.

Soil bulk density (Db, gcm⁻³) was determined using the core methods [16]. Total porosity (E,%) and void ratio (e) were calculated using the following equations:-

$$E, \% = \left(1 - \frac{Db}{Dr}\right) \times 100$$

$$\text{and } e = \frac{Dr}{Db} - 1$$

Where:

Db = the bulk density, gcm⁻³

Dr = the real density, 2.65 gcm⁻³

Hydraulic conductivity (cmhr⁻¹) was determined using undisturbed soil cores using a constant water head according to Richards [17]. Soil pH in soil water suspension (1: 2.5) and soil electrical conductivity (EC, dSm⁻¹) in soil paste extract were measured.

Climatic Condition The meteorological data including: maximum temperatures (T- max)^oC, minimum temperatures (T- min)^oC, relative humidity(RH): %, wind speed (WS)m/s and rainfall (RF)m. mduring the two years of study were recorded and their monthly mean values are presented in Table 2.

2.3 Response Curve Analysis

Description of the relationship between Water Driving Force (WDF) and Water Movement Time (WMT) involved fitting three types of models over the data collected under the four irrigations during the two wheat growing seasons, according to Neter et al., [18]. Considering the canal length is constant, the tested models were linear, quadratic and logarithmic model.

(1): The linear model is defined by the equation;

$$WDF = a + b (WMT)$$

(2): The quadratic model is defined by equation;

$$WDF = a + b (WMT) + c (WMT)^2$$

(3): The logarithmic model is defined by equation;

$$WDF = a + b \ln (WMT)$$

Where, (a) represents as intercept, b and c are coefficients of the regression equation. Coefficient of determination (R²), standard error of estimate (SE) and significance of the model were used as the basis for comparing the above-mentioned response models. The model that had the highest (R²) value and the lowest estimate (SE) was the best model for describing the

Table 2. Meteorological data in 2019/2020 and 2020/2021 growing season

Month	T-max		T-min		T-mean		RH		WS		RF		
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	
November	21.02	24.64	8.25	10.78	14.64	17.71	65.32		63.38	7.49	8.16	0.11	0.36
December	18.85	22.57	6.17	6.93	12.51	14.75	61.55		60.63	6.48	6.38	0.08	0.02
January	17.63	21.52	5.32	2.03	11.48	11.78	69.18		59.04	5.61	5.62	0.55	0.07
February	20.11	21.78	6.11	5.14	13.11	13.46	66.43		61.52	5.93	5.68	0.67	0.72
March	24.42	23.27	6.83	6.90	15.63	15.09	59.88		62.38	6.36	6.32	2.39	3.36
April	26.88	29.43	8.63	6.68	17.76	18.06	57.24		50.20	7.13	6.29	2.86	0.13
May	32.57	36.84	10.55	7.84	21.56	22.34	50.77		36.64	8.17	6.89	0.0067	0.00

* Source: *Water Requirement and Field irrigation Res.*, Dept

- Abbreviations: T-max: Maximum temperatures, T-min: Minimum temperatures, RH: Relative humidity, WS: Wind Speed, RF: Rainfall

relationship between Water Driving Force (WDF) and Water Movement Time (WMT). By taking the first derivative of the optimum quadratic equation with respect to WMT and equating that to zero, it gets the Critical Water Movement Time (CWMT) which reflect the lowest WDF. In other words, Water Driving Force (WDF) should not significantly after this critical time period.

2.4 Experiments Design

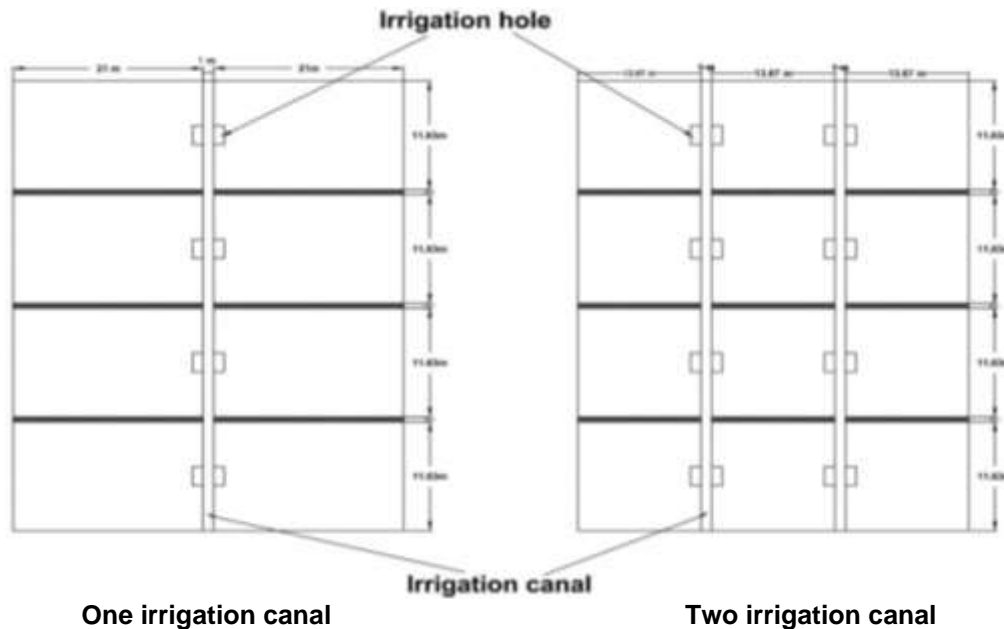


Fig. 3. Irrigation canal

3. RESULTS AND DISCUSSION

The results in Tables 3 and 4 showed that water losses amount were 17.26 and 18.29 m³ in the two seasons, respectively at the rate of water driving forces 0.25m³ in 16.50 minute in the first season and 0.27 m³ in 16.75minute in the second season by using one irrigation canal. These results may be attributed to the effect of several factors of water driving forces such as canal length, canal width and change in water density and viscosity by the controlling in the conveyance of water by increasing water driving forces can be reducing of water losses in the irrigation canals in the field. These results are in agreement with those obtained by Yao et al. [8] and Sen et al. [7].

The results in Tables 5 and 6 obtained that water movement in irrigation canal were affected by water driving forces 0.24m³/34.75 minute in the first season and 0.23m³/37.50 minute in the second season led to water losses amount 35.11 and 37.39m³ in the two seasons, respectively by using two irrigation canal in the field. These results may be attributed to the effect of water driving forces on water movement in irrigation

canal, consequently water losses amount were affected by the relationship between water driving forces and water movement time by increasing water driving forces, water movement time decreased in the irrigation canals. These results are in parallel line with those reported by Ashton and Hope [9] and Sen et al. [7].

Across the two seasons, the results in Table 7 referred that mean water driving forces (WDF) in the case of using one irrigation canal in field (0.26m³/16.63minute) was greater than its corresponding value under two irrigation canals (0.24m³/36.13minute) while water losses amount (WLA) from one irrigation canal (17.78 m³) was less than its value under the two irrigation canals (36.25 m³) by saving 18.47m³ of water. Consequently, there is an inverse relationship between water driving forces in irrigation canals in the field and water losses amount. On the other hand, grain yield in the case of using one irrigation canal in field was 1.414mg ha⁻¹, while the productivity in the two irrigation canals was 1.365 mg ha⁻¹ by increasing 49.17 kg ha⁻¹, which may be increase the total production of wheat cultivated area in Egypt by surface irrigation.

Table 3. Water losses amount of one irrigation canal in the first season

Planting irrigation		First irrigation		Second irrigation		Third irrigation	
QE = 34.16m ³	Water	QE = 29.37m ³	Water	QE = 26.83m ³	Water	QE = 24.29m ³	Water
QF = 26.27m ³	movement time(23 minute)	QF = 24.19m ³	movement time (17 minute)	QF = 23.82m ³	movement time (14 minute)	QF = 23.11m ³	movement time (12 minute)

$$\begin{aligned}
 & \text{Total QE} = 114.65\text{m}^3 \\
 & \text{Total QF} = 97.39\text{m}^3 \\
 & \text{Water losses amount, Total(QE - QF)} = 17.26\text{m}^3 \\
 & \text{Water driving forces} = \frac{L \times W \times h \times g}{T} \\
 & \text{WDF}_{T23} = \frac{48 \times 1 \times 0.5 \times 9.81}{23 \times 60} = 0.17\text{m}^3/\text{min} \\
 & \text{WDF}_{T17} = \frac{48 \times 1 \times 0.5 \times 9.81}{17 \times 60} = 0.23\text{m}^3/\text{min} \\
 & \text{WDF}_{T14} = \frac{48 \times 1 \times 0.5 \times 9.81}{14 \times 60} = 0.28\text{m}^3/\text{min} \\
 & \text{WDF}_{T12} = \frac{48 \times 1 \times 0.5 \times 9.81}{12 \times 60} = 0.33\text{m}^3/\text{min} \\
 & \text{Mean WDF}_{16.50} = 0.25\text{m}^3/\text{min}
 \end{aligned}$$

Table 4. Water losses amount of one irrigation canal in the second season

Planting irrigation		First irrigation		Second irrigation		Third irrigation	
QE = 34.72m ³	Water	QE = 29.84m ³	Water	QE = 27.18m ³	Water	QE = 24.68m ³	Water
QF = 27.37m ³	movement time (25 minute)	QF = 24.47m ³	movement time (19 minute)	QF = 23.56m ³	movement time (13 minute)	QF = 22.73m ³	movement time (10 minute)

$$\begin{aligned}
 & \text{Total QE} = 116.42\text{m}^3 \\
 & \text{Total QF} = 98.13\text{m}^3 \\
 & \text{Water losses amount, Total (QE - QF)} = 18.29\text{m}^3 \\
 & \text{Water driving forces} = \frac{L \times W \times h \times g}{T} \\
 & \text{WDF}_{T25} = \frac{48 \times 1 \times 0.5 \times 9.81}{25 \times 60} = 0.16\text{m}^3/\text{min} \\
 & \text{WDF}_{T19} = \frac{48 \times 1 \times 0.5 \times 9.81}{19 \times 60} = 0.21\text{m}^3/\text{min} \\
 & \text{WDF}_{T13} = \frac{48 \times 1 \times 0.5 \times 9.81}{13 \times 60} = 0.30\text{m}^3/\text{min} \\
 & \text{WDF}_{T10} = \frac{48 \times 1 \times 0.5 \times 9.81}{10 \times 60} = 0.39\text{m}^3/\text{min} \\
 & \text{Mean WDF}_{16.75} = 0.27\text{m}^3/\text{min}
 \end{aligned}$$

Table 5. Water losses amount of two irrigation canal in the first season

Planting irrigation		First irrigation		Second irrigation		Third irrigation	
QE = 70.13m ³	Water	QE = 59.64m ³	Water	QE = 55.38m ³	Water	QE = 51.86m ³	Water movement
QF = 54.72m ³	movement time (49 minute)	QF = 51.19m ³	movement time (36 minute)	QF = 48.43m ³	movement time (29 minute)	QF = 47.56m ³	time (25 minute)

$$\begin{aligned}
 & \text{Total QE} = 237.01\text{m}^3 \\
 & \text{Total QF} = 201.90\text{m}^3 \\
 & \text{Water losses amount, Total (QE - QF)} = 35.11\text{m}^3 \\
 & \text{Water driving forces} = \frac{L \times W \times h \times g}{T} \\
 & WDF_{T49} = \frac{(48 \times 1 \times 0.5 \times 9.81) \times 2}{49 \times 60} = 0.16\text{m}^3/\text{min} \\
 & WDF_{T36} = \frac{(48 \times 1 \times 0.5 \times 9.81) \times 2}{36 \times 60} = 0.22\text{m}^3/\text{min} \\
 & WDF_{T29} = \frac{(48 \times 1 \times 0.5 \times 9.81) \times 2}{29 \times 60} = 0.27\text{m}^3/\text{min} \\
 & WDF_{T25} = \frac{(48 \times 1 \times 0.5 \times 9.81) \times 2}{25 \times 60} = 0.31\text{m}^3/\text{min} \\
 & \text{Mean } WDF_{34.75} = 0.24\text{m}^3/\text{min}
 \end{aligned}$$

Table 6. Water losses amount of two irrigation canal in the second season

Planting irrigation		First irrigation		Second irrigation		Third irrigation	
QE = 71.92m ³	Water	QE = 61.86m ³	Water	QE = 56.18m ³	Water	QE = 49.74m ³	Water
QF = 56.46m ³	movement time (54 minute)	QF = 50.37m ³	movement time (40 minute)	QF = 48.92m ³	movement time (29 minute)	QF = 46.56m ³	movement time (27 minute)

$$\begin{aligned}
 & \text{Total QE} = 239.70\text{m}^3 \\
 & \text{Total QF} = 202.31\text{m}^3 \\
 & \text{Water losses amount, Total (QE - QF)} = 37.39\text{m}^3 \\
 & \text{Water driving forces} = \frac{L \times W \times h \times g}{T} \\
 & WDF_{T54} = \frac{(48 \times 1 \times 0.5 \times 9.81) \times 2}{54 \times 60} = 0.15\text{m}^3/\text{min} \\
 & WDF_{T40} = \frac{(48 \times 1 \times 0.5 \times 9.81) \times 2}{40 \times 60} = 0.20\text{m}^3/\text{min} \\
 & WDF_{T29} = \frac{(48 \times 1 \times 0.5 \times 9.81) \times 2}{29 \times 60} = 0.27\text{m}^3/\text{min} \\
 & WDF_{T27} = \frac{(48 \times 1 \times 0.5 \times 9.81) \times 2}{27 \times 60} = 0.29\text{m}^3/\text{min} \\
 & \text{Mean } WDF_{37.50} = 0.23\text{m}^3/\text{min}
 \end{aligned}$$

Table 7. Mean water driving forces, water losses amount, water saving and grain yield across the two seasons

Season	In the case of one irrigation canal		In the case of two irrigation canal		Grain yield		Saving water
	Water driving forces	Water losses amount	Water driving forces	Water losses amount	one irrigation canal	two irrigation canal	
First	0.25 m ³ /16.50 min	17.26 m ³	0.24 m ³ /34.75 min	35.11 m ³	1.363 mg ha ⁻¹	1.310 mg ha ⁻¹	18.47 m ³
Second	0.27 m ³ /16.75 min	18.29 m ³	0.23 m ³ /37.50 min	37.39 m ³	1.465 mg ha ⁻¹	1.420 mg ha ⁻¹	
Mean	0.26 m ³ /16.63 min	17.78 m ³	0.24 m ³ /36.13 min	36.25 m ³	1.414 mg ha ⁻¹	1.365 mg ha ⁻¹	

Table 8. Linear, quadratic and logarithmic models describing the relationship between Water Driving Force (WDF) and Water Movement Time (WMT) under the four irrigations during the two wheat growing seasons

Regression models	Regression equation	R ² %	SE	Sig.
Linear	WDF = -0.0145 + 0.4995 WMT	93.5	0.022	000
Quadratic	WDF = 0.7596 - 0.0467 WMT + 0.0009 WMT ²	99.6	0.006	000
Logarithmic	WDF = 0.94 - 0.247 ln (WMT)	98.2	0.012	000

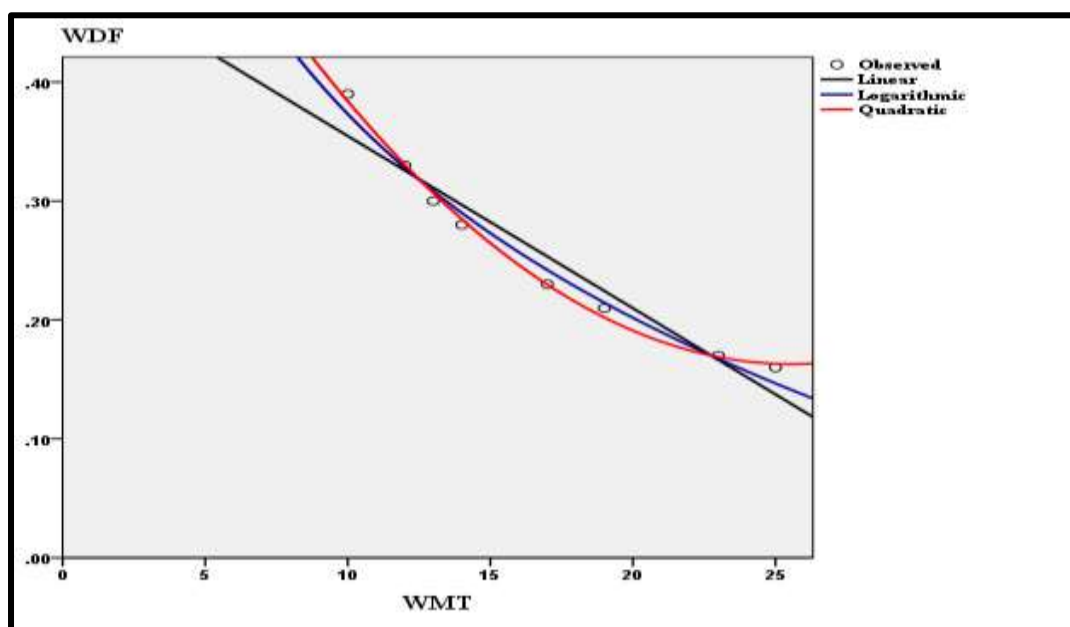


Fig. 4. Graphical Presentation of Linear, quadratic and logarithmic models for describing the relationship between Water Driving Force (WDF) and Water Movement Time (WMT)

Linear, quadratic and Logarithmic models were fitted to describe the relationship between Water Driving Force (WDF) and Water Movement Time (WMT) under the four irrigations during the two wheat growing seasons. Three statistical bases were considered to compare the three models i.e. coefficient of determination (R^2), standard error of estimate (SE) and the significance of the model. The significant model which had the highest R^2 and lowest SE was the best model fitted to the yield data.

The results in Table 8 and Fig. 4 indicated clearly that the highest value of the coefficient of determination (R^2) was in favor of the significant quadratic model in addition to its lower SE confirmed that the quadratic model is the best model compared to others. Accordingly, the Critical Water Movement Time (CWMT) which reflects the lowest WDF value was calculated as follows:

$$\begin{aligned} \text{Critical Water Movement Time (CWMT)} &= \frac{-b}{2c} \\ &= \frac{-(-0.04672)}{2(0.000914)} = 25.55 \text{ min.} \end{aligned}$$

This means that Water Driving Force (WDF) did not decrease significantly after 25.55 minutes. On the other hand, the Water Driving Force (WDF) at the moment it enters the irrigation canal (WMT = zero) would equal 0.7596 m^3/min .

The results in Fig. 4 obtained that, the relationship between water driving forces and water movement time is by increasing water driving forces, water movement time reduced, consequently water losses amount reduced in the irrigation canals in the field.

4. CONCLUSION

The present research showed that there is an inverse relationship between water driving forces in irrigation canals in the field and water losses amount. When water driving forces increased, water losses amount reduced. The potential areas for future research are the optimum irrigation canals planning in agriculture lands in the case of surface irrigation system to achieve the least water losses and by calculating water driving forces by using mathematical equation can be achieving water abundance by the reducing of water losses in irrigation canals in the field which can be used to irrigate new lands.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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