Improving the carrying capacity of irrigation canals: Al-Tawfiyky diversion

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ABSTRACT
The morphological changes in the irrigation channel cross-section affect its hydraulic efficiency and carrying capacity with time. Periodic maintenance activities are applied to reach maximum carrying capacity. In many cases, removing the total amount of deposit inside canal cross-section above the design bed level is not the optimum maintenance solution hydraulically and economically. Additional discharge must be applied to canal intake to achieve the design water level. Al-Tawfiyky Diversion is one of the main irrigation canals in the Delta region. It extended with a length of 175 km to serve 716,540 feddan. The study encloses the first reach from intake to km 36,400 upstream Jamjara regulator. This research aims to detect the most inefficient reaches along the selected study canal reach based on the actual characteristics of the surveyed canal cross-sections, and identifying the most proper maintenance scenario hydraulically and economically. Three hundred and fifty-one cross-sections along the study reach were surveyed. The different hydraulic parameters of these cross-sections were calculated. The data was analyzed and criterion for detecting the most inefficient sub-reaches was introduced. An empirical equation connecting the applied maintenance activities with channel conveyance was deduced. A mathematical model for the study reach was built and calibrated using (SOBEK-1D) to evaluate the proposed four maintenance scenarios.

Introduction

Open channels are considered the main element in irrigation water delivery and distribution. The morphological changes in open channels cross-sections due to deposition or scour decrease the conveyance of open channel cross-sections and its carrying capacity. Periodic maintenance activities must be applied to enhance the efficiency of these channels. The most common applied maintenance activity is removing deposits from the entire channel length. Detecting the most inefficient reaches along the channel is very important to identify maintenance priorities. In addition, detecting the specified quantity of deposit that must be removed from the channel watercourse to achieve the optimum conveyance, and carrying capacity economize the maintenance cost.

Molden and Gates (1991) developed a number of performance measures that facilitate the analysis of irrigation water delivery in terms of adequacy, efficiency, dependability, and equity of water delivery. Bos (2011) summarized the performance indicators currently used in the Research Program on Irrigation Performance. These indicators cover water delivery, water use efficiency, maintenance, the sustainability of irrigation, environmental aspects, socio-economics, and management.

Vowinckel, Kempe, Frohlich, and Nikora (2012) investigated physical aspects of sediment transport in an open channel flow using direct numerical simulation. The sediment pattern found in the study can be subdivided into two regimes. Light particles move rather irregularly distributed within load bed sheets, whereas heavy particles form longitudinal ridges. Tulus and Situmorang (2016) derived a mathematical model of sedimentation processes in the irrigation channel. The results highlighted the contour of the volume fraction according to the water flow and the inlet and outlet position. Gandhi, Pal, and Singh (2016) investigated experimentally bed load transport and shear stress with uniform and non-uniform sediments in open channels. Empirical relations were proposed in terms of dimensionless shear stress and bed load transport parameters. Osman, Schultz, Osman, and Suryadi (2017) stated that, sediment accumulations create problems with adequate water supply and may lead to water shortage. A model for simulating cohesive sediment transport in irrigation canals was developed. The model is useful tool to predict cohesive sediment under different operations and maintenance scenarios. It was found that when the inflow is reduced by 51% during the period in 2011, the reduction in deposition was 48%.

Salah and Zayed (2016) studied experimentally the effect of different flow conditions and soil gradation on the efficiency of removing sand deposits by using a jet pump. The study reveals that soil gradation has...
a major effect on the efficiency of removing deposits by the jet pump.

Roca, Rushworth, and Dennes (2016) studied the potential of vegetation and sediment management on the conveyance capacity of a watercourse. The study presents a national-scale approach (United Kingdom) to identify the strategically important watercourses where conveyance related works produce the greatest benefit.

Akkuzu, Unal, Karatas, Avcı, and Asık (2008) assessed the state of maintenance according to the value of roughness coefficient (n) and active canal capacity. The fact that the values of (n) for the selected canals were higher than the limit value and that the related canal capacity is low, indicated that the maintenance is insufficient. It was suggested admitting more active role for the farmers who benefit from the system and supporting the responsible associations financially to apply maintenance activities. Thoreson, Slack, Satyal, and Neupane (1997) described the effect of maintenance events on irrigation system flows. The standered definitions for corrective and preventive maintenance were presented. Maintenance cost was compared with the income lost due to insufficient water supply for crop requirements. This comparison demonstrated that, maintenance decision levels should be set so that maximum evapotranspiration can be achieved. Barnes (2017) focused on the vital work of maintenance which keep irrigation canals in Egypt functioning and water flowing. The two forms of maintenance, that conducted by Egypt’s Ministry of Water Resources and Irrigation and that conducted by farmers were contrasted. It was revealed that this work maintains not only the materials but also social order.

Bouisse, Baume, and Gassama (2011) illustrates the advantages of using the transient regime for the design of a networked feeder system with substantial storage capacity. Watson and Biedenharn (2002) described how incised channel evolution models might be coupled with a dimensionless stability diagram to facilitate the evaluation of rehabilitation alternatives. Nawazbhutta, Alishahid, and Van der Velde (1996) used a computer-based model, RAJBH, to assist and support canal systems manager in planning and targeting maintenance activities on secondary canals. The discharge and water levels of the study canals were measured pre-maintenance and post-maintenance periods. The study confirmed that suitably calibrated hydraulic simulation models can be effectively used in decision support planning capacity to target and prioritize maintenance inputs.

Delft Hydraulic Institute produced the SOBEK software which has been widely used for a range of similar studies internationally and within Egypt.

The open channel maintenance budget is increasing annually due to increasing the encroachments of beneficiaries and pollution. This brings out the need of adopting a new maintenance approach based on maintenance priority and economy.

The main objective of this research is to determine the most economic maintenance practice either by identifying the most inefficient reaches and maintenance priorities or by identifying the minimum quantity of sediment that should be removed from the channel watercourse.

**Site investigation**

The study encloses the first reach from intake to km 36.400 upstream Jamjara regulator on El-Tawfiyki Diversion. The study reach serves 324,450 feddan distributed on eleven branch canals (Ageeb, Aboul Atta, Ezizah, & Abdelmoaty 2019). There are 15 bridges, 4 drinking water stations, and 1 power station along the study reach. The study reach represents a good example of the effect of waterway morphological changes on its conveyance. Most of the study reach cross-sections were suffering from widening due to improper periodic maintenance activities. The average resultant cross-section area after removing all deposits from the study reach watercourse is greater than the corresponding design one by 12%. Rehabilitating the entire length of the study reach by reshaping to fit the design hydraulic characteristics costs a lot. The traditional maintenance approach is removing the deposits inside the channel waterway, which is not the most economic and hydraulically efficient approach. Figure 1 shows a sketch drawing for the study reach.

**Methodology**

An intensive field measurement and data analysis program was designed and implemented to achieve the objectives of the study. All the available data of the design hydraulic parameters of the study reach, the eleven branch canals, the served areas, the different hydraulic structures, and the discharge of the four drinking water stations were collected (Qalubia General Irrigation Directorate). Hydrographic and land survey for 351 existing cross-sections along the study reach using DGPS and survey Echo-Sound was implemented, the flow velocities were measured for 10 cross-sections along the study reach and just downstream the intake of the eleven branch canals situated along the reach using electromagnetic current meter, and the existing water level was surveyed (Channel Maintenance Research Institute). SOBEK1D mathematical model which has been successfully applied to river systems all over the world (Prinsen & Becker 2011) was built and calibrated to simulate the selected canal reach to identify the best maintenance scenario from the point of view of irrigation needs. The surveyed cross-sections were plotted and compared with the corresponding design ones; the hydraulic characteristics of the existing cross-sections
were deduced including scour and deposit areas. The linear stepwise regression analysis was used to deduce an equation relating the open channel cross section conveyance to applied maintenance activities (desilting-back filling).

**Results and discussion**

The channel carrying capacity is mainly depend on the hydraulic characteristics of the channel cross sections. The expression $AR^{2/3}$ (where $A$ is cross-section area and $R$ is the hydraulic radius) is called the section factor is important in the computation of uniform flow discharge. It depends mainly on the geometry of the water area. It is a reliable indicator of the conveyance of the channel cross-section (Chow, 1959).

$$K = \frac{Q}{\sqrt{S}} = \frac{1}{n} AR^{2/3} = \frac{SF}{n} \quad (1)$$

Where: $K$ is the conveyance of the channel section, $Q$ is the discharge, $S$ is the water surface slope, $n$ is the Manning’s roughness coefficient, and $SF$ is the section factor. **Figure 2** shows the variance of the conveyance values for the surveyed cross-sections along the study reach which is generally lesser than the corresponding design ones that range between 31,700 and 40,000.

Through this section, a criterion for indicating the most inefficient reaches is introduced, and a relation between the applied maintenance activities and cross section factor is deduced. The deduced equation is used to detect the proper maintenance scenario, which is evaluated using mathematical model.

**Indicating the most inefficient sub-reach along the canal’s main reach**

The term $(SF - 1)$ could be used as a good indicator of the efficiency of the canal cross-section and its conveyance. Where $SF$ is the relative section factor, which equals (the section factor of the actual cross-section/the section factor of the corresponding design one). For any cross-section, the zero value is the optimum value for the term $(SF - 1)$. It means that the cross-section geometry is very close to the corresponding design one and it needs no rehabilitation. The negative value indicates that the cross-section conveyance and the ability of canal reach to

**Figure 1.** Sketch drawing for the study reach.

**Figure 2.** The different values of the conveyance of the channel sections.
carry more discharge is lower than the designed one while the positive value indicates a higher carrying capacity. Figure 3 shows the different values of this term for all surveyed cross-sections along the study reach. It could be used to indicate the most inefficient reaches along the study canal. This is very important in detecting maintenance priorities according to the available maintenance budget.

**Relation between the applied maintenance activities and section factor**

The cross-section conveyance is affected by the different cross-section parameters, $A_d$ area of deposit, $A_s$ area of scouring, $T$ Top width, and $P$ witted perimeter.

Linear stepwise regression analysis was used to detect the relationship between the section factor and the most effective cross-section parameters. The detected equation was in the form:

$$SF_r = 0.988 A_{sr} - 1.354 A_{dr} + 0.97$$  \(2\)

Where:

$A_{sr}$: relative scour area = area of scour/design cross section area.

$A_{dr}$: relative deposit area = area of deposit/design cross section area.

The linear stepwise regression analysis showed that the most effective parameters on the section factor and so as to conveyance were the deposition and scour areas. The less effective parameters were excluded from the equation. To determine whether there is any statistically significant difference between the independent data groups, the analysis of variance test (ANOVA) is applied. The result of ANOVA test is shown in Table 1. The high value of ($F$) and zero significance ensure that there is significant difference between data groups. The coefficient and significance of the different variables in the equation are listed in Table 2. It was clear that the correlation between dependent variable ($SF_r$) and independent ones ($A_{sr}$ and $A_{dr}$) is high which reached 77.5% and 82.7%, respectively, with significance value = 0.00 which mean strong relationship between variables.

The resulted values of $SF_r$ from the equation were compared by the calculated from the measured actual

### Table 1. Results of the ANOVA test.

| Model | Sum of Squares | df | Mean Square | $F$ | Sig. |
|-------|----------------|----|-------------|-----|------|
| 1 Regression | 7.820 | 2 | 3.910 | 898.083 | 0.000 |
| Residual | 1.437 | 330 | 0.004 | | |
| Total | 9.257 | 332 | | | |

### Table 2. Coefficient and significance of different variables in Equation (2).

| Model | Unstandardized Coefficients | Standardized Coefficients | Correlations |
|-------|-----------------------------|---------------------------|--------------|
|       | $B$            | Std. Error | Beta | $t$   | Sig. | Partial | Part   |
| T (Constant) | 0.970 | 0.011 | | 90.755 | 0.00 | | |
| $R_{acc}$ | 0.988 | 0.044 | 0.512 | 22.295 | 0.00 | 0.775 | 0.484 |
| $R_{dep}$ | −1.354 | 0.051 | −0.613 | −26.698 | 0.00 | −0.827 | −0.579 |
hydraulic parameters and design ones as shown in Figure 4. The resultant trend line equation was:

\[ SF_r(\text{Predicted}) = 0.914SF_r(\text{Measured}) + 0.0786 \quad (3) \]

With an inclination angle, 42.45°, which is very close to the ideal case (inclination angle 45°) which means that the predicted values from the equation, is accurate enough to represent that obtained from measured data.

**Detecting the optimum maintenance scenario**

Four maintenance scenarios were applied to detect the optimum maintenance scenario. For the first maintenance scenario which is the traditional one, all deposit above the level of the design bed is removed. For the other three scenarios, a new bed level is defined according to the amount of removed deposit (75%, 60%, and 50%) of the total amount of deposit inside the watercourse of the canal study reach.

Figure 5 shows an illustrative sketch for the removed deposit for the different maintenance scenarios. Equation (1) is used to estimate the relative section factor (SF_r) for the different cross-sections of the four scenarios. Figures 6–9 show (SF_r − 1) for the different cross-sections of the four maintenance scenarios.

For the first maintenance scenario, most of the values of the term (SF_r − 1) are greater than zero with average mean value of (+0.82), which means high conveyance and carrying capacity of the canal reach. In the second maintenance scenario, some cross-section shows the negative value. The average mean value for (SF_r − 1) was (+0.036), which means lower carrying capacity of the canal reach than the first maintenance scenario. The last two scenarios are so close to the ideal case. The average mean value for (SF_r − 1) was (+0.0094, and −0.0075) respectively. Zero value is the ideal value for the term (SF_r − 1), which means that the canal cross-section dimensions are similar to the design one. Therefore, the third and fourth maintenance scenarios are the most proper ones. However, to determine optimum maintenance scenario, mathematical model should be used to simulate the different maintenance scenario in terms of irrigation needs (discharge-water level).

**Mathematical model and numerical simulation**

SOBEK1D model was used to simulate the selected canal reach to identify the best maintenance scenario from the point of view of irrigation needs. Delft Hydraulic Institute produced the SOBEK software. It has been widely used for a range of similar studies internationally and within Egypt.

**Mathematical model calibration**

The built model was calibrated for steady flow condition at a specific discharge value (the existing flow discharge = 190.86 m³/s, water level at km 37.000 (12.28)). The simulated water surface profile levels were compared with the actual ones. Figure 10 shows the result of the calibration process. The simulated water surface profiles coincide with the actual water surface profile with standard error of 0.001, which means that the built model is representing the study reach with high accuracy.

**Evaluating the existing carrying capacity of the study reach**

Several runs were operated on the calibrated model for the study reach. First, the design flow discharge was
Figure 5. The four maintenance scenarios.

Figure 6. SF, for the different cross sections when 100% of deposit are removed (Scenario 1).
Figure 7. \( S_f \), for the different cross sections when 75\% deposit are removed (Scenario 2).

Figure 8. \( S_f \), for the different cross sections when 60\% deposit are removed (Scenario 3).

passed through the model intake. The resultant water surface level at intake is higher than the design one by 0.65 m as shown in Figure 11. This means that the existing study reach is not capable of carrying the design discharge. In the following runs, we decrease the passing flow discharge from the intake and detect the resultant water surface profile at the intake until we reach the design water level. The passing flow discharge that corresponds to the designed water level is the maximum carrying capacity of the existing study reach as shown in Figure 12. It reached 75.5\% of the design discharge, which means that the study reach needs to be maintained.

**Evaluating the different maintenance scenarios**

Four mathematical models were built for the study reach representing the four maintenance scenarios. In the first model, all the deposits were removed to the designed bed level. In the other three models, the whole reach was considered as one unit. The total amount of deposit that left after maintenance is calculated and then the constant depth of deposit remaining in the study reach bed is identified. For each scenario there is a new bed level parallel to the design one and above the design level by constant height \( y \). The values of \( y \) were; 21 cm, 34 cm, 42 cm for the three scenarios in our case of study, respectively. This ensures the regularity of the study reach bed and practical in implementing maintenance. So, for the second and third and fourth maintenance scenarios the amount of deposit is removed from the total length of the study reach not from individual cross-sections.

For the model of the first maintenance scenario (removing all amount of deposit), when passing the design discharge the resultant water level is lower than
the design one by 34.0 cm at the canal intake as shown in Figure 13. The water depth at the intake reaches 93% of the design depth. To achieve the design water levels to fulfill the branch canals intake water levels, the discharge of the intake must be increased to reach 116% of the design discharge.

For the other three maintenance scenarios, the quantity of removed deposit was decreased by increasing the bed level of the study reach by a distance (y) related to the unremoved quantity of deposit. Figure 14 shows the resultant water surface profile when passing the design discharge through the mathematical model of study reach for maintenance scenarios (2, 3, and 4). The resultant water surface profiles were lower than the design water level at the intake by (22.4 cm and 10.0 cm) for the second and third maintenance scenarios. For the fourth maintenance scenario, the resultant water level is almost equal to the design one. This means that in our case of study, we can achieve both of design discharge and water levels by removing 50% of all deposits in the study reach. In addition to this, the ability of canal reach to receive deposit will be decreased due to higher
**Figure 11.** The result of the run of passing design discharge in the existing study reach.

**Figure 12.** Maximum carrying capacity of the existing study reach.

**Figure 13.** The resultant water levels for the first maintenance scenario.
flow velocities resulted from applying this scenario and the stability of channel side slopes is preserved.

**Conclusions**

An intensive field measurements and data analysis were implemented through the study. The summary of its finding could be concluded:

SOBEK1D mathematical model was calibrated to simulate the selected canal reach to identify the best maintenance scenario. The hydraulic characteristics of the existing cross-sections were deduced including scour and deposit areas. The linear stepwise regression analysis was used to deduce an equation relating the open channel cross section conveyance to applied maintenance activities (desilting-back filling). The most inefficient reaches along the study channels were detected to identify maintenance priorities. Removing all amounts of accumulated deposits entire open channel watercourse mostly is not the optimum maintenance choice hydraulically and economically. In our case of study, the optimum maintenance scenario could be achieved when only 50% of the total accumulated amount of deposits is removed from the study reach. Conducting intensive analytical studies before applying maintenance activities ensure achieving the best hydraulic performance with most economic costs as the quantity of removed deposits is decreased adding to this that the flow discharge required to reach the design water level is lesser by 16%. Finally, periodic maintenance of open channels is essential for achieving proper hydraulic efficiency, conveyance, and carrying capacity.

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