Assessment of Garmsar Optimum Drainage Design Using a Successful Strategy for Salinity Control

Majid Ehteshami

Department of Civil Engineering, K.N. Toosi University of Technology, Tehran, Iran.

ABSTRACT

A methodology and computer model is developed to determine economically optimum closed subsurface drainage systems in irrigated areas to control salinity. The model maximizes net benefits by comparing profit driven by crop yield to drain system cost and selects an optimum drain layout. The optimization methodology used is the simplex method. The simplex method was linked to the subsurface drainage model DRAINMOD and to the surface hydraulic model KINE. The selected optimum drainage system maximizes the difference between total revenue and the total cost of installation, operation and management of a particular drainage system. A 42 meter drain spacing at depth of two meter in local loamy soil was almost the optimum drain design. The salt balance of the area was measured before and after installation of drainage system. Salinity was reduced by 44% for first three years of operation. The optimization sub-program provides a workable and simple procedure for optimizing sound environmentally water management simulation models.

KEYWORD

Drainage, DRAINMOD, KINE, Salinity Management, Optimization

INTRODUCTION

Historical records have revealed that many ancient civilizations that relied upon irrigated agriculture have failed. The Sumerian civilization of ancient Mesopotamia declined as agricultural productivity began to decrease due to water logging and soil salinization [1,2]. Skaggs [3] developed DRAINMOD as a tool for field evaluation of drainage systems. Agricultural drainage systems are mainly designed for moisture and salinity control in arid and semi-arid regions. Because drainage water contains agricultural nutrients and other chemicals leached from soils, drainage discharge has been blamed as a major contributor of agricultural non-point pollution [4,5]. Artificial drainage is widely practiced throughout the world for controlling soil salinity and shallow water tables. Of the 1200 Mha of rain fed cropland in the world, about 150–200 Mha have improved drainage [6]. Traditional drainage system management amounts to simply letting the system run continuously without any control, which is deemed necessary to prevent waterlogging and soil salinization. It is also the practice during leaching of salinized soil. However, management measures are needed to regulate flow and reduce the impact of saline drainage water on the environment [7]. Approximately 25–30% of the irrigated lands in the United States have crop yields that are negatively affected by high soil salinity levels [8,9, and 10]. Drainage water in arid irrigated regions may also contain salts, such as NaCl and CaSO4, and elements derived from the soil parent material, such as Se, B, and As. Selenium found in the drainage water originating from the soil on the west side of the San Joaquin Valley was responsible for the environmental problems identified at the Kesterson Reservoir [11]. All of these constituents may have serious negative environmental impacts on the receiving water bodies and downstream water users. Christen et al. [12] in a review of subsurface drainage across Australia, demonstrated that the majority of drainage systems were over-draining, as they were removing far more salt than was applied by irrigation water. Christen and Skean [13] describe the development and implementation of best management practices (BMP) that provide a basis for the design of drainage systems in irrigated areas. Ayars and McWhorter [14] demonstrated that the irrigation and ground water quality, the irrigation system efficiency, the crop salt tolerance, and the projected in situ use of shallow ground water by the crop could be schedule. Walker et al. [15] developed Kinematic-Wave Furrow Irrigation Model (KINE) to evaluate on farm furrow irrigation systems. Gonçalves et al. [16] used KINE model to evaluate furrow irrigation system design. However, studies by [17,18] demonstrated that deep and wide drain lateral placement increases the total salt load being discharged. Northey et al. [19] demonstrated an increase of salinity in the shallow ground water under furrow irrigated fields. Also, they

*Corresponding Author: Majid Ehteshami
E-mail: maehtesh@gmail.com
Telephone Number:
showed how the salinity of the ground water varies with depth across time and with irrigation and salinity increases with depth, as is common in irrigated areas. Jia et al. [20] showed, in arid and semi-arid regions, drainage have to cope with the conservative nature of salts leached from soils.

Ayars et al. [21] used Hydrus-2D to model the effect of water table and lateral depth as a criteria on required drain spacing assuming. Kellnersra et al. [22] modeled long term drainage water salinity of pipe drains. Wahba et al. [23] used DRAINMOD-S to demonstrate the effect of doubling the drain spacing by blocking every other drain and modifying the drain depth by installing control structures. Bahc et al. [24] used SaltMod and tested the model with data collected from a pilot area. Houk et al. [25] showed a sophisticated approach for estimating the impact of both water logging and soil salinity on drainage system revenue. Durnford et al. [26] presented a procedure which can be used to identify economically optimum subsurface drainage system designs in an irrigated area. Also a water balance approach for subsurface drainage design has been proposed [27]. Qureshi et al. [28] reveal that the installed drainage systems were initially successful in lowering groundwater table and reducing salinity. Ritzea et al. [29] reported, a hydro salinity model, SALTMOD [30], was used to make long-term predictions of the soil salinity and the depth to water table [31]. The likely performance of an artificial drainage system can be assessed through modelling [32]. Drainage environmental impact study says drainage is bound to result in undesirable environmental effects if left unmanaged [33]. The need to make an economic evaluation of agricultural drainage systems is well recognized among numerous researchers. The method used by Wiser et al. [34], gives an estimation of the effect of water table changes on crop response. The criterion for final system choice is maximization of net benefits [35]. The change in water table height was calculated using an equation developed by Van Schilfgaarde [36], which estimates the water table height at any time due to an assumed pulse input which is uniform over the period. The water table height is a function of the drain spacing, depth and input to the water table.

In order to design an effective environmentally drainage system, the determination of the functional requirements is an essential step. In the Garmsar Irrigation District, with nearly 50,000 Ha cultivated land, the irrigated areas increased rapidly at the beginning of this century. By the 1960’s waterlogging and salinity problems began to appear and by the end of 1970’s, hectares temporarily went out of production. In 1970, construction was begun on the planned system of closed drainage systems [37].

SITE LOCATION

The Garmsar irrigation district is located approximately 120 km southeast of Tehran, at the southern fringe of the Alburz mountain range, where the HablehRud River emerges and where the Dasht-e-Kavir desert begins. The elevation of the area ranges between 800 to 900 m above sea level with 35°05'12" to 35°16'47" north latitude and 52°17'10" to 52°36'50" east longitude geographic coordination (Figure 1). The water of the HablehRud at BoneKuh has a salinity of about 1 g/l or an electric conductivity (EC) of 1.7 dS/m. This signifies a medium quality for irrigation. In the major part of the alluvial fan, the natural drainage to the underground is high. Hence, enough leaching can take place to avoid soil salinity problems. The major part (90%) of the salts consists of chlorides and sulfates. Sodium salts (60%) are slightly in excess of calcium and magnesium (40%). The residual sodium carbonate content is low, hence the water is not giving serious alkalinity problems [38]. Irrigation is performed by tapping water from the numerous branches of the HablehRud River fanning out over the area. The water is led from here into earthen irrigation canals. Shallow pumped wells are used to supplement the surface water, especially in summer and in periods of drought. Towards the fringes of the alluvial fan at least 30 Ghanats (artificial underground galleries) were dug to abstract water from the aquifer by gravity. In the mid-eighties, a new irrigation system was constructed and in 1990 it was put into operation. The main purpose of the system was to reduce the deep percolation losses from the many natural watercourses (Figure 2). Drainage system can be found in the lower parts of the fan to combat problems of shallow water-tables and water-logging in the wet periods when the HablehRud brings relatively large quantities of water consecutively during a number of years. The recharge of the Garmsar aquifer in the irrigated area rises the water-tables height. The drainage systems to control the water logging and salinity are in the lower parts of the plane consist of open ditch-drains and closed drain pipes.

![Fig. 1. The Location map of Garmsar, (Google Earth 7.1.2.2041)](image)

PROCEDURE

The following procedure was adapted for maximization of the net benefit. The objective function (Obj), for optimizing the net benefit can be formulated as follows:

\[
\text{Obj} = \text{maximize net benefit}
\]

(1)

To practically compute the objective function, acceptable limits such as the following must be set out:

\[
\text{min.\,Spacing} < \text{drain\,Spacing} < \text{max.\,Spacing}
\]

\[
\text{min.\,Depth} < \text{drain\,Depth} < \text{max.\,Depth}
\]
\[
\text{min. Diameter} < \text{drain Diameter} < \text{max. Diameter}
\]

\[
\text{min. Q } < \text{furrow inflow Q } < \text{max. Q}
\]

\[
\text{min. LF } < \text{furrow length} < \text{max. LF}
\]

Fig. 2. Sketch of the alluvial fan of Garmsar, [38]

\[
\text{min. Zn } < \text{depth applied at end of furrow} < \text{max. Zn}
\]

\[
\text{min. F } < \text{irrigation frequency F} < \text{max. F}
\]

and,

\[
\text{Net Benefit} = \text{Total Benefit} - \text{Total Costs}
\]

Where, Total Benefit in this case is the income to the farmer from any additional crop yield, and Total Costs included drainage system costs plus irrigation system costs plus production costs.

**Drainage Costs**

The total cost of drainage system is a function of several variables as follows:

\[
\text{Totcd} = \text{CMN} + \text{CMA} + \text{CTU} + \text{CIN} + \text{COU} + \text{CFI}
\]

\[
\text{Totcd} = \left(\frac{C5}{L} + \left(i \times C6 \times D\text{depth}^{C7}/L\right) + i \times C8 \times d\text{diam}^{C9}/L\right) + \left(i \times C10/\text{MANL} \times L\right) + \left(i \times C11/L \times \text{OUTL}\right) + \left(i \times C21/L\right)
\]

And,

\[
C21 = C14 \times 0.00164 \times d\text{diam}^{-0.30}(5)
\]

Where \(\text{Totcd}\) is total drainage cost per unit area, \(\text{CMN}\) is cost of drain maintenance per unit area, \(\text{CMA}\) is cost of drain installation per unit area, \(\text{CTU}\) is cost of tubing per unit area, \(\text{CIN}\) is cost of man holes per unit area, \(\text{COU}\) is cost of outlets per unit area, \(\text{CFI}\) is cost of envelope per unit area, \(L\) is drain spacing (m), \(D\) depth is drain depth (m), \(i\) is the annualized economic factor, \(\text{MANL}\) is distance between each manhole (m), \(\text{OUTL}\) is distance between each outlet (m), \(C5, C6, C7, C8, C9, C10\) and \(C11\) are cost coefficients. \(C21\) is cost per linear meter of envelop material, \(C21\) could be approximated by a simple power function (Equation 5), where \(d\text{diam}\) is drain diameter (mm), and \(C14\) is a cost coefficient.

**Irrigation Costs**

Total cost of irrigation system is:

\[
\text{Totci} = N\text{ise} (C\text{otlb} + C\text{otwt}) + C\text{othd}
\]

Or,

\[
\text{Totci} = N\text{ise} ((1/60 \times C2 \times C4 \times T\text{i}rr) \times (C1 \times Nf \times Tco/Effc)) + C3 \times Wf
\]

And,

\[
N\text{oset} = Nf/Nfs
\]

\[
Nfs = Qmax/Qin
\]

\[
T\text{i}rr = Tco \times N\text{oset}
\]

\[
Nf = 10,000/Lf \times Fs
\]

\[
Wf = Nf \times Fs
\]

Where, \(\text{Totci}\) is total cost of the irrigation system, \(\text{Nise}\) is number of irrigations per season, \(\text{Cotlb}\) is cost of labor per unit area, \(\text{Cotwt}\) is water cost, \(\text{Cothd}\) is cost of head ditch construction per unit area, \(T\text{i}rr\) is time of irrigation, \(N\text{oset}\) is number of irrigation sets, \(Nf\) is number of furrows per set, \(Q\text{max}\) is maximum volume of available water, \(Q\text{in}\) is volume of inflow to one furrow, \(Tco\) is time of inflow cutoff to furrow, \(Lf\) is furrow length, \(Fs\) is furrow spacing, \(Wf\) is head ditch length, \(Effc\) is conveyance efficiency, \(C1, C2, C3\) are cost coefficients, and \(C4\) is fraction of time. The surface irrigation hydraulic performance was simulated using the KINE model [15].

**Production Cost**

\(Cp\) is the agronomic production cost per ha, excluding the cost of drainage and irrigation system construction and operation. A production cost of 500$/ha is assumed.

**Benefit or Unit Income**

Total Benefit can be described as:

\[
B\text{eft} = R\text{y} \times P\text{y} \times C1
\]

Where \(B\text{eft}\) is the total benefit ($ per unit area or $/ha), \(R\text{y}\) is relative yield (%). The relative yield has computed using DRAINMOD [39]. \(P\text{y}\) is potential yield (kg/ha) and \(C1\) is price of the corn crop ($/kg).

**Solution to the Optimization Problem**

Maximization of the net benefit is more comprehensive than minimization of cost in that it incorporates a decision about the desired level of system performance. In this study, benefit will be measured in terms of crop yield value, and the net benefit is defined as that income derived by the farmer from any additional crop yield attributed to installation of a drain system minus the cost of that system. Maximization of net benefits further implies that differing levels of system performance are compared. Assuming that the level of performance as a function of maximizing net benefit can be quantified satisfactorily, then for each performance level there is a consequent minimum system and operation cost at which that performance level is achieved. The relationship between benefits, cost and system performance level can be visualized as shown in Figure 3.

In figure 3 benefits and costs are plotted. The net benefit is the distance between the two curves. In general, it is expected that as the performance level of the system
increases, the benefit or yield increases at least to a point. The cost must also increase to obtain the additional performance. In the example shown, it is assumed that some benefit is derived from the land with no artificial drainage. In addition, benefits are shown as leveling off as the crop yields approach some minimum level. Finally, the derived net benefits level off as the crop yield approach some maximum attainable level and may even decline beyond this point, i.e., extra contribution of the cost which is due to additional crop protection. In the economic consideration of the particular drainage system, the level of protection should not be increased if the total cost exceeds the total benefit. Therefore, theoretically, the point where marginal cost equal marginal benefit or, in another word, where the slope of the cost function and the benefit function are equal represents an optimum point.

![Fig. 3. Example curve showing cost relationships between cost, benefit and net benefit, for one system performance level](image)

The problem then is, to define the best system and develop a feasible procedure for finding this system. As above, in this study, it is assumed that the best system is the one which maximizes net benefits on the farm level. The general procedure commonly used to find a solution for the best system can be classified as two types: 1. Simulation and 2. Optimization. Using the best approach, the simulation method, possible drain spacing and depth and surface irrigation parameters and their effects on crop yield and salinity can be determined realistically. The second approach, optimization requires more detailed analysis than the simulation model, but it is capable of including most of the interdependencies inherent in irrigation and drainage systems. A simplified optimization routine which provides most of the advantage of the optimization method, can be employed.

Spendley et al. [40] introduced a clever idea for tracking optimum function conditions by evaluating, from the output form a set of points forming a simplex in the space and called it “SIMPLEX”. The procedure was modified by Nelder and Mead [41]. The name simplex is derived from its shape in space. The Spendley method employs a regular sequential pattern search of points in the design space while maintaining efficiency compared to the simple direct method. The idea is to pick a base point and, rather than attempting to cover the entire range of the variables, to evaluate the design parameters in some pattern about the base point. For example, in two dimensions, a triangular pattern which the best of them (the node with the lowest value of the objective function) would be selected as the next base point around, which to locate the next pattern of points. If none of the corner points is better than the base point, the scale of the grid is reduced and the search continues.

In this method the search to optimize the objective function, trail X vectors Figure 4, can be selected as a point in space, at the vertices of the simplex. The objective function can be evaluated at each of the vertices of the simplex, and a projection made from the point yielding the highest value of the objective function (point \( x_1 \) in Figure 4) through the centroid of the simplex. Point \( x_1 \) is deleted and a new simplex is formed by reflection, expansion or contraction. The simplex is then composed of remaining old points and the one new point, and then the procedure continues until a prescribed error tolerance is met and optimization reaches final convergence.

![Fig. 4. An outlook of the Simplex Method with sequence of Simplexes obtained in maximization of the objective function](image)

Some definitions are as follows from Nelder and Mead [41]. Reflection: the reflection of \( P_h \) is denoted by \( P^* \), and its coordinates are defined by the relation:

\[
P^* = (1 + \alpha)P_h - \alpha P_l
\]

where \( \alpha \) is a positive constant, the reflection coefficient, \( \bar{P} \) is centered of simplex, and \( P_h \) is value of vertex with function in highest value (the suffix of \( h, l \) are define high and low respectively).

If \( y^* \) is less than \( y_l \), i.e., if reflection produced a new minimum, then we expand \( P^* \) to \( P^{**} \) by the relation:

\[
P^{**} = \gamma P^* + (1 - \gamma)\bar{P}
\]

where \( \gamma \) is expansion coefficient, which is greater than unity and finally if on reflecting \( P \) to \( P^* \) it is found that \( y^* \) is bigger than \( y_l \) for all \( \# h \), i.e., that replacing \( P \) by \( P^* \) leaves \( y^* \) the maximum, \( y \) is function value at \( P_l \) then we define a new \( P_h \) to be either the old \( P_h \) or \( P^* \), whichever has the lower function value and form:

\[
P^{**} = \beta P_h + (1 - \beta)\bar{P}
\]

where \( \beta \) is contraction coefficient which lies between 0 to 1. The final point of concern is halting the procedure which is concerned with the variation in the \( y \) values over the simplex. The form chosen is to compare the standard error of \( y \)’s in the form of:

\[
Err = \sqrt{\frac{(\bar{y} - \bar{y})^2}{n}}
\]
Where \( y \) is mean value of \( y \), \( n \) is number of vertices that are compared to a present value (Err) or to so-called error tolerances and to stop when the value falls below this value.

**RESULTS**

The Simplex method is a useful technique for optimizing simulation models. The method was used to optimize interaction between irrigation and drainage requirement of the crop. The drainage system optimization model could be used for comparing a wide range of design parameter values and to produce a series of graphs that will allow practicing drainage engineers and farmers to select a subsurface drainage system optimized for a given set of conditions.

The estimated costs of drain installation and materials are shown in Table 1. The drain design computed by the drainage optimization model is the least cost system for the highest level of yield that would be achieved based on the input cost data, soil conditions, crop production, and one particular irrigation layout (table 2). The computational procedure, as described, is an iterative process. For example, for a field situation where a single corn crop is planted each year, and the costs for a closed drain system are shown in Table 3. By using these values and an initial trial drain spacing of, for example, 60 meters (Table 3), a relative yield of 82% would be determined using the drainage system design results with the yield model. The net benefit from this particular system was determined to be 170$/ha/year. The optimization model then evaluates a second alternative spacing of 69 meters and determines a corresponding relative yield of 68% and net benefit of 35$/ha/year. Therefore, the net benefit gradient is negative and the net benefit will decrease if the spacing is increased. Since a higher net benefit is required, the optimization sub-model decrease the spacing to 58 meters and re-evaluates the corresponding costs and benefits, and the gradient for the new results is determined. Table 3 shows the sequence of

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cost Assumed</th>
<th>Units</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>0.01</td>
<td>$/m³</td>
<td>Water cost</td>
</tr>
<tr>
<td>C2</td>
<td>4</td>
<td>$/hr</td>
<td>Labor cost</td>
</tr>
<tr>
<td>C3</td>
<td>3.1</td>
<td>$/m</td>
<td>Annual cost of ditch construction</td>
</tr>
<tr>
<td>C4</td>
<td>1</td>
<td>-</td>
<td>Fraction of time</td>
</tr>
<tr>
<td>C5</td>
<td>0.0311</td>
<td>$/m/year</td>
<td>maintain cost</td>
</tr>
<tr>
<td>C6</td>
<td>0.277</td>
<td>$/m</td>
<td>inst. cost</td>
</tr>
<tr>
<td>C7</td>
<td>2.18</td>
<td>$/m</td>
<td>inst. cost</td>
</tr>
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<td>$/m</td>
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<td>C14</td>
<td>8.76</td>
<td>$/m³</td>
<td>Envelope cost</td>
</tr>
<tr>
<td>Price/kg</td>
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<td>$/kg</td>
<td>Price of crop</td>
</tr>
<tr>
<td>Rate</td>
<td>0.132</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

| Tab. 2. Summary of the input data used in drainage and optimization model |
|-----------------------------|-------------------|------------|----------------|
| Input Parameters            | Value             | Input Parameters | Value         |
| Years of simulation         | 2011-2014         | Length of furrow (m) | 200,300       |
| Rainfall station (#)        | 12345678          | Furrow spacing (m) | 1             |
| Temperature station (#)     | 23456789          | Roughness coefficient | 0.04          |
| Crop type                   | Corn              | Field slop (m/m) | 0.014         |
| Planting date (Julian day)  | 105               | Hydraulic section parameters | 0.66, 2.87 |
| Growing season (days)       | 130,142           | Furrow geometry parameter | 0.96, 0.604 |
| Drain depth (cm)            | 180,200,220       | Kostiakov-Lewis infiltration parameters | 0.0088, 0.212, 0.00017 |
| Drain spacing (cm)          | 40,005,000        | Flow rate (1/s) | 0.5-0.07     |
| Profile depth (cm)          | 230               | Water applied at end of furrow (m) | 0.05-0.07   |
| Drain tubing (mm)           | 104               | Maximum flow available (m³/sec) | 10           |
| Soil layers                 | 2                 | Potential yield (kg/ha) | 10,000       |
| Saturated hydraulic conductivity (cm/hr) | 2.3, 4, 5 | Distance between each manhole (m) | 500          |
| Infiltration parameters A and B | 3.3, 1          | Distance between each outlet (m) | 500          |
|                             | 6.1               | Irrigation frequencies | 10-20        |

The estimated costs of drain installation and materials are shown in Table 1. The drain design computed by the drainage optimization model is the least cost system for the highest level of yield that would be achieved based on the input cost data, soil conditions, crop production, and one particular irrigation layout (table 2). The computational procedure, as described, is an iterative process. For example, for a field situation where a single corn crop is planted each year, and the costs for a closed drain system are shown in Table 3. By using these values and an initial trial drain spacing of, for example, 60 meters (Table 3), a relative yield of 82% would be determined using the drainage system design results with the yield model. The net benefit from this particular system was determined to be 170$/ha/year. The optimization model then evaluates a second alternative spacing of 69 meters and determines a corresponding relative yield of 68% and net benefit of 35$/ha/year. Therefore, the net benefit gradient is negative and the net benefit will decrease if the spacing is increased. Since a higher net benefit is required, the optimization sub-model decrease the spacing to 58 meters and re-evaluates the corresponding costs and benefits, and the gradient for the new results is determined. Table 3 shows the sequence of
Tab. 3. Sequence for optimization trail in one particular case

<table>
<thead>
<tr>
<th>#</th>
<th>Spacing (m)</th>
<th>Relative Yield (%)</th>
<th>Net Benefit ($/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>82</td>
<td>170</td>
</tr>
<tr>
<td>2</td>
<td>69</td>
<td>68</td>
<td>130</td>
</tr>
<tr>
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<td>86</td>
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</tr>
<tr>
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<td>53</td>
<td>92</td>
<td>270</td>
</tr>
<tr>
<td>5</td>
<td>47</td>
<td>97</td>
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<td>34</td>
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<tr>
<td>11</td>
<td>41</td>
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</tbody>
</table>

The sensitivity analyses of model as a function of drain spacing was evaluated by varying the surface irrigation design parameters such as length and furrow inflow. Figure 6 shows the effect of various furrow length on annual net benefit due to the subsurface drainage system. Figure 7 indicates that the furrow inflow is a major parameter influence on the net benefit. It is obvious from figures 6 and 7 that changes in the cost of the system components which could affect system design, would change the net benefit, and it could significantly affecting the drain spacing. A 42 meter drain spacing at depth of two meter in local loamy soil was almost the optimum drain design.

Model 32-50 Conductivity Salinity meter is used to measure salinity of the drain effluent water. The three years of monthly data collected is shown in Figure 8. Figure 8 shows effect of installed drainage system before and after three years of operation in the Garmsar province. It shows the value of salinity has reduced dramatically by 44% as it is supported by [42,43,44, and 45].

CONCLUSIONS

The procedure concluded in this study introduces the use of state-of-the-art computer simulation techniques to optimize environmentally water management models. The Simplex algorithm was linked together with the surface irrigation and subsurface drainage model to optimize environmentally water management decisions in irrigated agriculture. The optimization routine is proven to be an effective methodology.
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