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Selection of Optimum Land Leveling Design Method for Surface Irrigation

Hassan Ibrahim Mohammed [1], Shaiban Mohamed Ahmed Mohamed [1], Omran Musa Abbas [1], Abdelkarim D. Elfadil [2,*]

[1] Department of Agricultural Engineering, Collage of Agricultural Studies, Sudan University of Science and Technology, Sudan
[2] Department of Agricultural Engineering, Faculty of Agricultural Sciences, University of Gezira, Sudan
*Corresponding authors email: karimfadild@gmail.com
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Abstract: Land leveling or land grading of surface irrigated fields improve irrigation water distribution and application efficiencies, conserve water and increases crop productivity. Land formation for irrigation face many constraints (ensuring proper slopes, prevention of flood, ensuring canal water command over the field, optimizing earthwork, minimizing truck travel distances, proper equipment utilization). Design engineers traditionally, perform site formation design manually by plane shape, least squire or linear programming methods. Such methods are with different characteristics. The main objective this study is to select and compare performance of these three design methods for proper land leveling design. Consequently, the basic theory of these alternative design methods are reviewed and their performance using data surveyed from five fields in Khartoum North-Sudan, each with different soil surface topographic configurations, is analyzed. The statistical analysis revealed that the linear programming method is the most appropriate design method. Employing the linear programming design method revealed that design slopes in row and cross row directions are within the acceptable range (0.1 to 0.5, the ratio of Cut/fill volumes is within the recommended range (1.1 to 1.3), uniformity of distribution of design elevations of grid points are acceptable and within the target limits (80%), while their deviation is at 80% of grid points around the mean before leveling.

Keywords: Land leveling design, Profile method, Plane shape, Linear programming

1. Introduction

According to SCS-USDA (2011) land leveling or land grading is referred to as shaping of the soil to specific slopes to control the movement of irrigation or drainage water and to prevent soil erosion [1]. Land smoothing involves shaping the land to remove irregular, uneven, mounded, broken, and jagged surfaces without adjusting the field slopes. Land leveling operation is typically performed by tractors pulling dirt buckets or carry-all scrapers that pick up soil in high points in a field and deposit it in low points in the field. Land smoothing is usually performed by a tractor pulling a land leveler or other type of smoothing implement.

Singh, (2003) and Rickman, (2002) stated that surface irrigation is widely used worldwide and in Sudan; but is described by its low irrigation application (66%) and distribution efficiencies (80 %) [2, 3]. To improve these efficiencies, and attain high crop productivity with minimum cost it is essential to ensure uniform depths and discharge over the field by land leveling.

The leveling operation, however, results on major topographical changes which are intensively most disruptive cultural practice applied to the field and several factors should be considered before implementing a land leveling project. Such factors are related to soil fertility in low cut areas, soil compaction or pulverization by traffic equipment of equipment, soil type and depth, slope, climate, crop types, and methods of irrigation [4]. For implementing precision land leveling in a new surface irrigated project or for rehabilitating an old project, one of two land leveling philosophies is to be selected; either to provide a slope which fits a water supply and drainage; or to level the field to its best condition with minimal earth movement [4]. This requires a land leveling simulation tool capable to compute the cut and fill volumes required to change from the actual elevations into the target elevations. The basic objectives of most of current land leveling design methods are to determine the design slope of plane which is best fit the original surface of the land and allow water level in the irrigation canal to command field level

[5]. The design slope is a function of the hydraulic requirement of the adopted type of the on-farm irrigation method (Basin, Borders, or Furrow). Basins are designed to be level in both field directions and borders are similar in having zero cross-slope, but may have advance slopes of up to two or three percent, depending on crop and soil conditions, while furrow systems work well with advance slopes up to one to three percent and cross-slopes of 0.5 to 1.5 percent. If the average natural slopes are greater than these ranges, terraces or benches should be planned as water harvesting systems.

The mathematical methods widely used for land leveling design are the least squares [6], the plane-inspection, the contour adjustment, and the linear programming method [7]. In contrast, both plane-inspection methods, and the contour adjustment method do not treat minimization of earth volumes mathematically [2, 4]. The profile method is limited for it ignores canal water command level as a control point, and it rather balances the field according to its centroid to arrive to equal volume of cut and fill, which is not the real world case. The least squire is a simplified method that use trial and error to specify a linear plane of best fit without selecting the slope that minimize earth volumes but work on principle of least squired deviation of field level from design one. Such design overlooked optimization of the cases of inclined and curvilinear field surfaces commonly found in many surface irrigated paddy fields [8]. To minimize labour effort Osari (2003) advised to avoid reverse inclination by using the effective design technique (where the height on the irrigation canal side is lower than that on the drainage canal side) [8]. However, the plane method proposed by ASAE (1998) requires graphical determination of distances and is considered to be too complicated [5]. For the linear programming method Chaudhuri, et al (2005) developed an optimal land grading design model that uses an objective function which minimize the total volume of cut to obtain both plane and curved surfaces and specify the designed surface statistical properties with an unbiased estimate and minimum variance [9]. The developed linear programming design methods are criticized by their ignorance of canal water command level as a control point in formulating design constraints.

The main benefits of precision land leveling include the improvement of the water control in surface irrigation systems due to the reduction of the advance time and the volume of water needed to complete the advance, thus providing a uniform distribution and water savings, a higher adoption of deficit irrigation and a better control of the leaching fraction [10]. Aiad and Azza (2020) investigated the impact of three land leveling levels and three irrigation treatments on some water relationships, cotton yield and also some its components, they found that land leveling and cut-off irrigation treatments have highly significant effect on increasing the cotton yield, its components and fiber technological properties [11].

Leveling quality depends on design method used and efficiency and the skill and efficiency of the equipment operator performance in performing the leveling operation. A good design field levels are to provide variation of field levels within plus or minus 10 cm; and a recommended variations of Cut/fill ratios (C/F) values according to soil texture in the ranges of (1.15-1.25), (1.25-1.40); (1.40-1.60), and (1.50-1.80) for Sandy, Loamy ,Loamy-clay and Clay soil respectively. According to Ayranci, and Temizel (2011) indicators to judge the quality of leveling design may include: slopes limits and direction of inclination, minimization of cut volumes, limits of cut: fill ratio, percentage deviation of field elevations around the mean (80% variation criterion), and uniformity of design elevation along the inclination of both row and cross-row directions [12]. The main objective of this study is to select and compare performance of three land leveling design methods (profile "least squire", linear programming, and the plane shape adjustment methods) for proper land leveling design of five fields with different soil surface topographic configurations (convex, sloppy, concave, curved and flat) on basis of five land leveling quality criteria (design slopes, minimum movement of earth volumes, range of Cut/fill ratio, and percentage deviation of the design elevations from the field mean).

2. Materials and Methods

2.1 Materials

This study was conducted at the farm of college agricultural Studies in Khartoum North (Latitude 15º N, Longitude 32º S) during the summer period of April-May, 2016. The soil is clay cracking soil in an arid dry climate (evaporation of 9-12 mm/day) with short period of rain during summer time (July to September), and low amount of less than 200 mm per annum on average. Topographic data was collected using ordinary surveying equipments following the procedure described by Walker (1989) and SCS-USDA (2011) from five fields (each 60×85 m, and different soil surface topographic configurations of convex, sloppy, concave, and curved and flat) with grid dimension of (15×17m). The adopted framework for the general design method is shown by the flowchart of Figure (1) [1, 4].

Three land leveling design methods were employed: profile "least squire", linear programming, and the plane shape adjustment methods.

A. **Profile (least squire) method:**

Following SCS-USDA (2011), the employed calculation procedure is depicted in the general framework shown in figure (1), using the following five steps:

1- Determine the centroid of the field and the average elevation
2- Determine the slope of the field for (x) direction and (y) direction by the equation:

Slope (x,y) = [sum (d , e)-(sum d) (sum e)/ n] / [sum (d) ^{2}-(sum d) ^{2}/n]………. (1)

Where: d: distance. e: elevation of the point. n: number of the points.

3-Determine the elevation of any point in the field by equation:

E=A+ (Sx×S) + (Sy×Y) ………… (2)

Where: E: the elevation of any point in the field. A: elevation in the center of the field. Sx: slope in X direction. X: distance in X direction. Sy: slope in Y direction. Y: distance in Y direction.
4- Determine the volume of cut and volume of fill:

$Vc = (G^2/4) \times ((Hc^2)/ (Hc + Hf))$ ………… (3)
$Vf = (G^2/4) \times ((Hf^2)/ (Hc + Hf))$ ………… (4)

Where: Vc = volume of cut in individual grid; Vf = volume of fill in individual grid; Hc= Sum of depths of cuts at the corners of the grid; Hf= Sum of depths of fill at the corners of the grid; G = grid spacing or distance between adjacent stations.

5-The plan position is iteratively changed until the cut to fill ratio becomes > 1.0 and < 1.2.

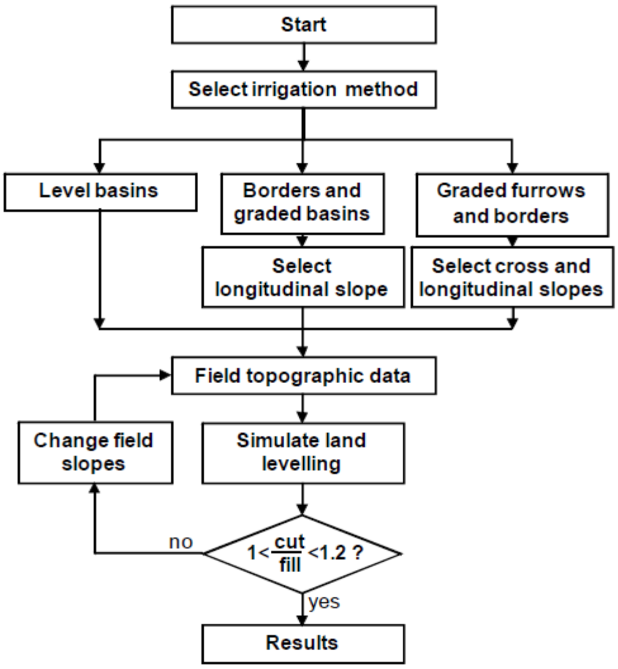

Figure 1 Flowchart showing the adopted model general framework (Adapted from Ref 4).

B. Linear programming method: To determine the final height of each node, by cutting and filling and the technical design aspects given in the general framework depicted in figure (2) are considered

1. Object function: The total volume of cuts and fills must be minimized.

Minimize = (0.6*X11+1.0*X12+1.0*X13+1.0*X14+1.0*X15+1.0*X16+1.0*X21+1.0*X22+1.0*X23+1.0*X24+1.0*X25+1.0*X26+1.0*X31+1.0*X32+1.0*X33+1.0*X34+1.0*X35+1.0*X36+1.0*X41+1.0*X142+1.0*X43+1.0*X44+1.0*X45+1.0*X46+1.0*X51+1.0*X52+1.0*X53+1.0*X54+1.0*X55+1.0*X56+1.0*X61+1.0*X62+1.0*X63+1.0*X64+1.0*X65+1.0*X66) ……..….(5)

2. Land slope constraints in X-direction: Sx (min.) = 0.001 and Sx (max.) =0.005……..…. (6)

3. Land slope constraints in Y-direction: Sy (min.) = 0.001 and Sy (max.) = 0.005……..…. (7)

4. Cut to fill ratio constraint. In many projects the ratio of total volume of cuts to total volume of fill (C/F) to fit within a specified range of (1.1 to 1.2) ; such that: Min. value ≤(C/F) ≤ max. value

5- Canal Command constraint: It is based on the assumption that the level of highest point in field to be less than the water level in the irrigation delivery canal (Command = Canal level – Field level) by minimum of 20 cm and over it by a maximum of 50 cm (min "20 cm" ≤ (Command) ≤ max."50 cm)

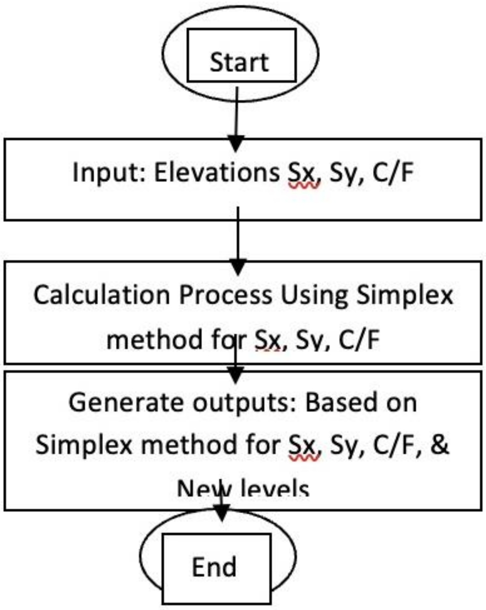

Figure 2 Flowchart showing a General Framework for Linear programming method.

C. The plane shape adjustment method: This method is based on the horizontal plane; and uses the "range" and an imposed uniform design slopes in each water flow direction to estimate new field elevations from the existing field levels without the need for using trial and error procedures. It is assumed that before and after grading, the soil volumes measured from a reference elevation are equal. The method general flow chart (figure 3) and calculation steps are delineated bellow:

1. Determine the assumed average highest point (S=H/D), and the assumed average lowest point of field elevations (H=S×D). Where: S is the recommended slope between the highest and lowest points of the field. H is the vertical height between the highest and lowest points. D is distance between the highest and lowest points.
2. Determine the point at the half distance of the end of the field (base) by the average between mid-point and lowest point of the field.
3. Determine slope (X and Y) by: SX is (midpoint of field-point at half base)/distance between them, and SY= (half base point-lowest point)/ distance between them.
4. Determine the fixed height between points if the distance between them is equal by following equations:

Fixed height of X = (SX)(distance between points on X direction). ……..…. (8)

, and Fixed height of Y = (SY)(distance between points on Y direction). ……..…. (9)

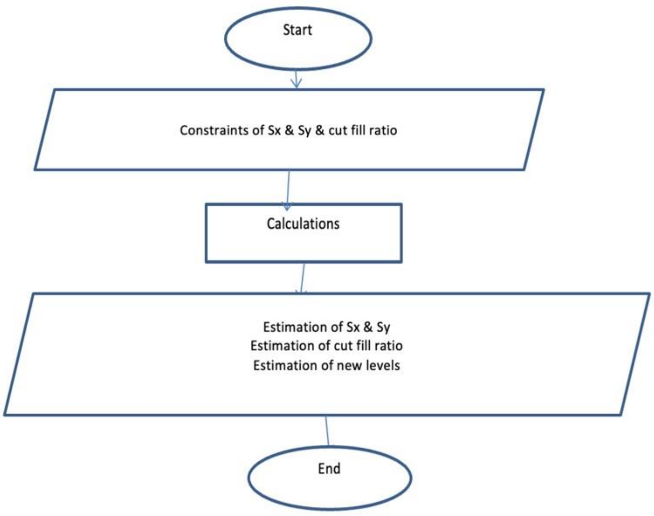

Figure 3 Flowchart showing a General Framework for plane shape adjustment method.

Data analysis

Data from the three design methods is coded and analyzed using Excel Spreadsheets and Solver were used. Descriptive statistics and completely randomized design were used for comparison between the three design methods [13].

Results and Discussions

In accordance with [4, 6, 9, 14, 15] indicators used as quality criteria for comparisons between the three design methods are:

1- Generated design slopes in X and Y directions in reference to recommended ranges.
2- Minimization of Calculated Cut and fill volumes (calculated by the four-point method)
3- Cut/fill ratio to be within the range: 1.1 to 1.3.
4- Deviation of the design elevation of the 80% of grid points around the Mean before leveling
5- Uniformity of distribution of design elevations of grid points in row and cross row direction.

The profile method is taken as standard method of comparison (due to its wide applicability). The field configurations are convex, sloppy, concave, curved, and flat and referred to in the following figures as 1, 2, 3.4, and 5 respectively.

1. **Generated design slopes in X and Y directions:** The generated design slope in X direction for the different field configurations and the three design methods is shown in figure 4. On average, the results of the two design methods differ from the profile method (12%). The differences for LP method are more pronounced in concave and less pronounced in curved fields and shows acceptable differences with other field shapes. While the difference for plane adjustment methods is more significant in flat and concave fields. As given in figure 4 for the calculated slope in X-direction by linear programming and the profile standard method showed almost typical values.

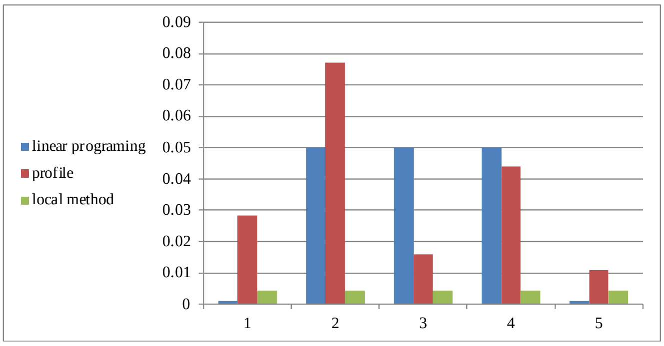

Figure 4 Slopes in X direction for the different field configurations and the three design methods.

Slope Y: Obtained results for cross row slope (slope Y) using the three design methods and for the different field shapes is depicted in figure 5. The slopes estimated by both plane adjustment profile methods do not differ due difference in field shape. However, in plane adjustment the imposed slope is constant. In contrast, slopes of Linear programming method are estimated and are not decided by the user. In the Linear programming method there is no differences in the values of cross-slope for concave and curved shapes. As given in figure (5) for the calculated slope in Y-direction by linear programming and the profile standard method differ significantly from those obtained using the profile method.

2. **Minimization of Calculated Cut and fill volumes:** **Volume of Cut:** Table (1) shows the values of cut volume for each method and each type of fields. As shown in table (1) volume of cut showed no significant difference between the methods. Although the linear programming method main

objective is minimizing of the volume of cut the profile method resulted in minimum earth to cut ratio. The increase of volume of cut calculated by linear programming over that obtained by profile method may be due to fulfillments of the design constraints considered by the linear programming method and ignored by other two methods. With respect to field configuration in general the minimum earth work is calculated with linear programming and the sloping field resulted in most reduced volume of cut.

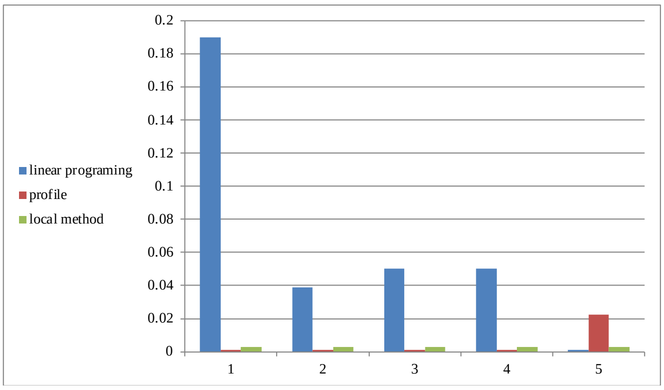

Figure 5 Slopes in Y direction for the different field configurations and the three design methods.

Volume of fill: Table (2) shows the values of fill volume for each method and each type of fields. Volume of fill showed high significant difference between the methods. The obtained results are typical to those calculated for earth volumes of cut.

As given in figure (6) the plane adjustment resulted in excessive and high volume of fill for almost all field shapes. In contrast, linear programming method resulted in the minimum volume of fill.

3. **Cut/fill ratio (C/F):** Recall that the recommend (C/F) is 1.1 to 1.3 and the only method fulfilled that is the linear programming method for all field shapes (Table 3). . Other design methods resulted in lower cut values and do not grantee to obtain the recommend design specification and require borrowing soil from out of the field (fig. 5). This is expected for soil in fill areas shrink due to decrease in porosity by time. This result is in agreement with the previously reported values [4, 16].

Table 1. Cut volumes (m³) for the different field configurations and the three design methods

Field surface configuration	Leveling method				
	Profile	Plane adjustment	Plane Adj. /Profile (%)	Linear programming. (LP)	LP/Profile (%)
Convex	5396	3053	1889	1889	4
Sloppy	843	3106	1984	843	6
Concave	3233	3106	1955	1955	31
Curved	3111	3114	2124	2124	11
Flat	3482	3191	2011	2011	9
Min	843	3053	1889	843	4
Average	3213	3114	1993	1764	12.2

Table 2. Fill volumes (m³) for the different field configurations and the three design methods

Field surface shape	Leveling method			
	Profile	Plane	Linear prog.	Min
Convex	2398	4413	1801	1801
Sloppy	1101	4466	1454	1101
Concave	4222	4466	1755	1755
Curved	3111	4474	1561	1561
Flat	3482	4551	1729	1729
Min	1101	4413	1454	1101
Average	2863	4474	1660	1589

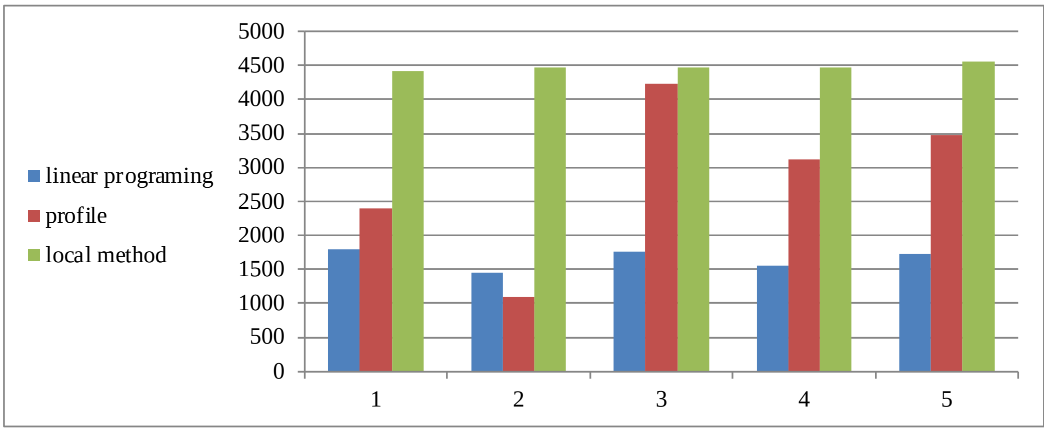

Figure 6 Volumes of fill obtained for the different field configurations and the three design methods

Table 3 Cut to fill volumes (m^3) for the different field configurations and the three design methods.

Field surface shape	Leveling method			
	Profile method	Plane method	Linear programming	Mean
Convex	2.2	0.69	1.04	1.31
Sloppy	2.2	0.69	1.3	0.9
Concave	2.2	0.69	1.1	0.83
Curvy	2.2	0.69	1.3	1
Flat	2.2	0.7	1.1	0.93
Mean	2.2	0.69	1.17	0.99

Table 4 Range of deviation of the design elevation from field mean for the three design methods

Land shape	Local method	Profile method	Linear programming
Convex	89%	96%	97%
Sloppy	91%	86%	94%
Concave	88%	94%	96%
Curvy	88%	92%	94%
Flat	92%	94%	99%

Table 5 Uniformity of distribution of design elevations by three design methods in different fields

Land shape	Profile method	Plane method	Linear programming	Mean
Convex	92%	89%	82%	88%
Sloppy	78%	84%	85%	82%
Concave	95%	91%	82%	89%
Curvy	87%	89%	80%	85%
Flat	91%	90%	99%	93%
Mean	89%	89%	86%	88%

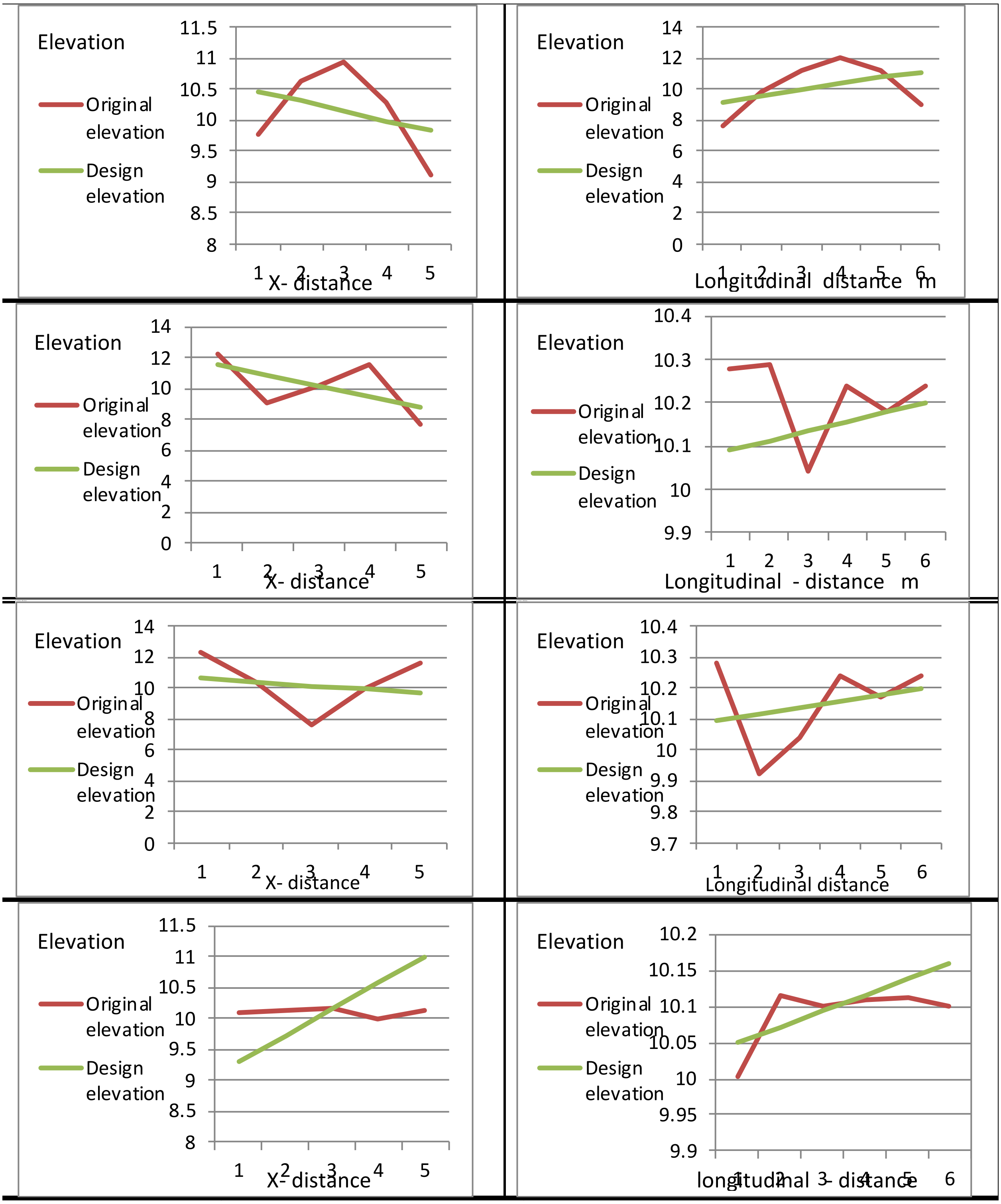

Figure 7 The elevations before and after design.

4. **Deviation of the design elevation from field mean:** The range of deviation of the design elevation from field mean in different fields according to the three design methods is shown in table 4. The table indicates that: the linear programming method has the highest range of deviation.
5. **Uniformity of distribution of design elevations:** Uniformity of distribution of grid points over the field need to be more than 80% to facilitate water movement over the soil surface. As given by table (5) almost all methods and for all fields the field elevations are within the recommended percentage.
6. **Comparison of design methods:** The performance of application the three methods over different field shapes reveals that (figure7): the disadvantages of LP optimization are that it cannot guarantee generation of even local optimal solutions, particularly for large-scale systems, and it requires extensive fine-tuning of algorithmic parameters, which are highly dependent on the individual problem, and its computations consume much time. The disadvantages of Profile method it does not determine the command level, and depends on the balance between cut volumes and fill volumes. For Plane adjustment method the disadvantages are that it gives small cut fill ratio, and the generated design slopes are inappropriate.

4. Conclusion

From the obtained results it is evident that: The reliability of the modified LP model was validated in the consequent case study. Generated design slopes in X and Y directions in reference to recommended ranges indicate that it is better to employ methods that fit actual field conditions rather than to impose different values. Minimization of Calculated Cut and fill volumes reveals that the lower values are achieved by LP method and Cut/fill ratio is within the range: 1.1 to 1.3. Determination of both deviation of the design elevations of the 80% of grid points around the Mean before leveling and Uniformity of distribution of design elevations of grid points in row and cross row direction reflects the superiority of LP method over other design methods. The sensitivity of the tested methods with respect to variation of input data needs to be tested in future.

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Conflict of interest
The Authors has no conflicts of interest to declare that they are relevant to the content of this article.

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