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A GEOSTATISTICAL APPROACH FOR THE SPATIAL DISTRIBUTION OF WATER TABLE DEPTH AND ASSESSMENT OF WATER LOGGED AREAS AT BUSTAN REGION, EGYPT

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ABSTRACT

The sustainable management and development of the newly reclaimed sandy soils at Bustan region is facing numerous problems. Amongst, poor soil physical and chemical characteristics, low soil fertility, water logging and soil salinity in some areas, and lack of sustainable crop rotation. Due to the expected water shortage in the next decades, water logging and the resultant salinity problems appeared to be the utmost.

The aim of this study was to determine the behavior of spatial distribution of water table depth (WTD), zones of water logging, and quality of groundwater for reuse in irrigation, to approach the best sustainable management of about 50,000 feddans (21,000 ha) in Bustan 1 and 2 (BUS1&2) areas.

A network of two grid systems monitored the WTD on monthly or bimonthly basis for 18 months, the first with 87 large-scale observation wells (LSOW) covering BUS1&2 areas, and the second with 92 small-scale observation wells (SSOW) distributed as 34, 31, and 27 in three villages suffering from water logging problems: Ali Ibn Abi Taleb (AIAT), Mohamed Refaat (MRFT), and Tawfeek El-Hakeem (THKM), respectively. Water samples from the observation wells were collected to assess the parameters of water quality.

Results showed that WTD were ranged from 0.23 to 7.52 m, which reflected the existence of continuous water logging problems in some areas especially at AIAT, MRFT, and THKM villages. The spatial distribution of WTD was characterized through the geostatistical approach, and the fitted variogram for temporal WTD was exponential. Field maps using the Kriging technique were produced to explore the spatial behavior of WTD, and to locate the areas with water logging problems. Results of the Kriging technique were evaluated to assure their accuracy and evidenced by low standard errors and highly significant correlation coefficients.

The water logging problem appeared in some areas of Bustan region was mainly due to seepage from irrigation canals, change from the installed modern (sprinkler and drip) irrigation systems to surface system, lack of information on crop water requirements and irrigation scheduling, and insufficient drainage system. This problem represents a major constraint for the sustainable agricultural production at the Bustan region.

INTRODUCTION

In Egypt, if properly managed, the newly reclaimed lands of a total area about 1.9 million feddans (0.8 million ha), will have a great share in crop production and food security. The newly reclaimed area at West Nubaria region including BUS1&2 represents about 40% of the total reclaimed areas. The risk of water logging and salinity in this area is quite high, and has to be defined early in the planning, designing and construction processes of new systems (Bourrfa and Zimmer, 1994). Schulze and de Ridder (1974) indicated that the introduction of irrigated agriculture and horticulture on the newly reclaimed land in the BUS1&2, within a relatively brief period, created series of problems and probably will generate more in the near future. Amongst the most severe problems is the steady rise in water table, accompanied by the formation of local groundwater mounds and reversals of groundwater flow directions, and the outflow of saline groundwater into the principal irrigation canals. El-Shal and Ismail (1979) studied the effects of the present irrigation and drainage systems on the hydrogeophysical properties of the soils of the Mechanized Farm at West Nubaria region. Their results indicated that the field drainage system present in this area is insufficient and led to rapid rise of the water table, and subsequently secondary salinization showed up in almost half of the farm area. They also indicated that the problem was intensified by the salinization of ground and irrigation waters. The Bustan Agricultural Development Project (BADP, 1995) reported that many constraints in the BUS1&2 areas (e.g., poor soil fertility and low organic matter content, poor soil physical characteristics, lack of appropriate cropping pattern and farming techniques, lack of proper skills, experience and extension advices, and marketing problems) are common to smallholders throughout the New Land areas. Problems of high water table and water logging are found in BUS1&2, where in some areas, WTD stands very close to soil surface causing adverse effects on the crop production and sustainable management.

Geostatistics is a great tool to characterize the spatial distribution of soil attributes. It has been applied by many researchers to describe the spatial variability using the semivariogram and predict the values of soil attributes at un-sampled locations by different kriging techniques (Trangmar *et al.*, 1985; Warrick *et al.*, 1986; El-Haris, 1987; Webster and Oliver, 1989; Webster, 1991; Bahnassy and Morsy, 1996; Goovaerts, 1998 and 1999; and Banerjee and Gelfand, 2002). The spatial relationship between the values of the attribute is governed by the regionalized variable theory, which states that observations close to each other are more correlated than observations taken at a further distance (Journel and Huijbregts, 1978). This means that points spatially close to the estimation points should be given higher weights than those further away (Cressie, 1993).

The objectives of this study were to: (i) characterize the spatial distribution of WTD through a geostatistical approach to construct the region WDT maps, (ii) assess the water logging zones, and (iii) define the quality of groundwater for reuse in irrigation to achieve the best sustainable management for the Bustan 1 and 2 areas.

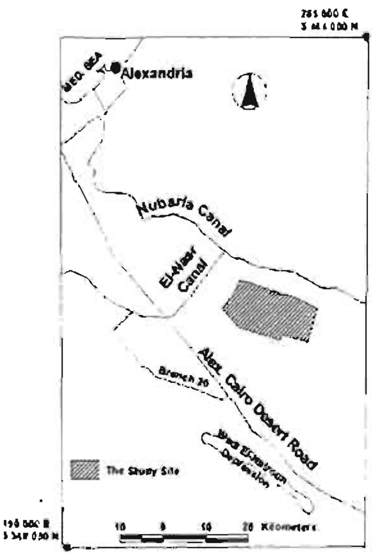
MATERIALS AND METHODS

The Study Site

The study site is located about 90 km south-east of Alexandria, east of Alex-Cairo desert road, covering BUS1&2. It is located between 30°42' - 30°47' N and 30°11' - 30°25' E. It is bounded to the west by the Bustan canal and to the east by the Nubaria canal (Map 1). The BUS1&2 areas are including eleven villages of area about 50,000 feddans (21,000 ha). Three villages namely: AIAT, MRFT, and THKM in these areas specifically suffered from shallow water table and water logging problems.

Land elevation -above sea level- of the study area was ranged between 5 m in the east and 35 m in the west, with an average east-west slope of 0.17%. The elevations -above sea level- of land surface of AIAT, MRFT and THKM were in the range of 14.7-19.0 m, 13.5-18.2 m, and 11.5-14.9 m, and decreased in the middle, northeast, and north directions of the villages, respectively. The depths -above sea level- of impermeable layer of AIAT, MRFT, THKM were in the range of 11.3-16.5 m, 10.0-12.0 m, 7.0-13.0 m, respectively.

The texture of soils is generally coarse and varies from loamy sand to sandy clay loam. Calcium carbonate content increased with depth in the range of 8.8-25.7 %, which is relatively high due to calcareous parent material since limestone is the bedrock in this area. However, this calcareous nature affects both physical and nutritional soil properties and causes undesired condition through the formation of soil crusts and hardpans. Soil pH was ranged between 7.6 and 8.3. Electrical conductivity (EC) of soil paste-extracts decreased with depth and varied from 0.8 to 2.1 dS m^{-1}, which lie in the moderate soil salinity range (0.7 to 3.0 dS m^{-1}).

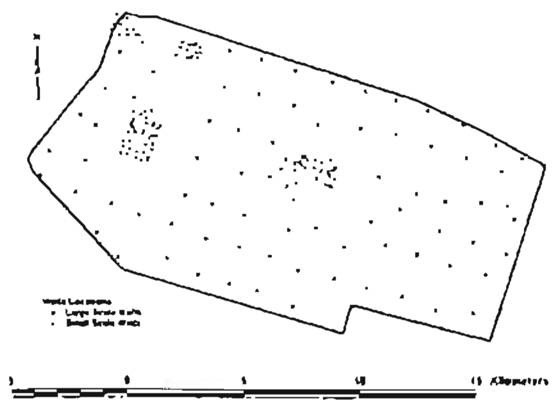


Map 1. Location of the study area.

Field measurements

The Grid system

Two grid systems of observation wells were used in monitoring WTD. The first was to cover the BUS1&2 (eleven villages) with a grid spacing of 1500×1500 m and resulted in 87 LSOW. The second was to cover the water-logged areas with spacing of about 300 m and resulted in 92 SSOW distributed as 34, 31 and 27 in AIAT, MRFT and THKM villages, respectively (Map 2). Additionally, the data of 35, 25, and 20 SSOW distributed in three other water-logged villages in vicinity of BUS1&2 namely: Abou Bakr (ABKR), El-Adl (EADL), and Taha Hussein (THSN), respectively, were analyzed for comparisons, and to assess the efficiency of the drainage system for the whole sector. The stem hydraulic auger was used to drill the observation wells through the BADP for the two grid systems. Sounders were used to measure WTD.



Map 2. Location of the large- and small-scale observation wells in Bustan 1 and 2 areas.

Soil hydraulic conductivity

Soil hydraulic conductivity (K_s) for the saturated conditions in the three water-logged villages was measured using the Auger-hole method (Amoozegar and Warrick, 1986).

Water samples

Three groundwater samples were collected from three randomly selected test wells in each of the three villages (total of 9) of BUS1&2 for the determination of EC, soluble bicarbonates (HCO_3), nitrate-nitrogen (NO_3-N) and soluble cations for SAR calculation. Total soluble salts, soluble bicarbonate using the acid titration method, and NO_3-N were determined according to Bower and Wilcox (1982), Allison and Moodie (1982), and Bremner (1982), respectively.

Collected Data

This study analyzed the data of WTD which monitored on monthly or bimonthly basis in LSOW throughout the period from April 1999 to August 2000, and in SSOW for the same period, in addition to the December of 2003.

Descriptive Statistical Analysis

The data of WTD were analyzed for descriptive statistics which include mean, variance, standard deviation, minimum, maximum, skewness, and kurtosis (SPSS, 2003).

Variogram

The variogram (or as named semivariogram) is defined as half of the average squared difference between two attribute values separated by vector *h*, for one variable (Burrough and McDonnell, 1998):

$$\gamma(\mathrm{h}) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \{Z(x_i) - Z(x_i + h)\}^2$$

where $N(h)$ is the number of pairs at lag *h*, $Z(x_i)$ is the value of the attribute at location (x_i) and $Z(x_i + h)$ is the value of the attribute at location $(x_i + h)$ separated by distance *h*. The separation vector *h* is specified with some direction and distance (lag) tolerance. This variogram is used to characterize the spatial dependence of WTD and then fitting them to one of the known models, i.e. Linear, Spherical, Exponential, and Gaussian (McBratney and Webster, 1986). Unbiased estimator is called experimental or sample variogram.

Kriging

The Kriging technique is optimal technique that provides linear estimator $Z'(x_o)$ in a sense that the weights of local averaging are chosen to give unbiased estimates while keeping the estimation variance at minimum (Journal and Huijbregts, 1978; Webster, 1985; El-Haris, 1987; Isaaks and Srivastava. 1989; and Banerjee and Gelfand, 2002):

$$Z'(x_o) = \sum_{i=1}^{n} w_i \, Z(x_i)$$

where w_i are the weight factors that related to spatial dependence and point geometry whereby near points generally carry more weights than distant points, *n* is the number of points. The lack of bias conditions yields:

$$\sum_{i=1}^{n} w_i = 1$$

The parameters from experimental variogram (nugget, sill, and range) were needed in Kriging to perform interpolation.

Cross Validation

Cross validation is a technique that is used to compare estimated and true values using the information available in the data set. In cross validation, the estimation method is tested at the locations of existing samples. The sample value at a particular location is temporarily discarded from the sample data set; the value at the same location is then estimated using the remaining samples. Once the estimate is calculated, it is compared to the true sample value that was initially removed from the sample data set. This procedure is repeated for all samples. The error (e) expressed as (Issaks and Srivastava, 1989):

$$e = Z'(x_i) - Z(x_i)$$

where $Z'(x_i)$ is the estimated value and $Z(x_i)$ the true value. Mean square error (MSE) is calculated from the formula:

$$MSE = \frac{1}{n}\sum_{i=1}^{n} e^2$$

The Linkage between Geostatistics and Geographic Information Systems (GIS)

The estimates from kriging technique, and the associated error (Gamma Design, 2001) were exported to Arc View GIS software (ESRI, 1997) for better visualization, mapping, and printout.

RESULTS AND DISCUSSION

Soil hydraulic conductivity

The field K_s values were 4.59×10^{-5}, 4.78×10^{-5}, and 4.48×10^{-5} m s^{-1} for AIAT, MRFT and THKM villages, respectively, with an average value of 4.62×10^{-5} m s^{-1} which indicated the fast movement of water in the soil profile, and the sandy nature of the soil in the region.

Groundwater Analysis

The analyses of the groundwater samples collected from the test wells are presented in Table (1). According to the guidelines of water quality for agriculture (Ayers and Westcot, 1985), the salinities ranged from moderate (1.5 dS m^{-1}) to high (5.3 dS m^{-1}) saline water. Moreover, generally, the low values of SAR showed that no expected sodicity or permeability problems may take place. Nitrate-nitrogen concentrations are of moderate range. Bicarbonate concentrations are of moderate to high risks with the sprinkler irrigation system.

Table (1): Average groundwater analysis for three villages at of Bustan 1 and 2 areas.

Village	EC (dSm^{-1})	SAR	HCO_3 (meq/l)	NO_3 (mg/l)
Ali Ibn Abi Talab (AIAT)	1.5	3.2	7.4	12.9
Mohamed Refaat (MRFT)	2.3	5.3	10.8	25.3
Tawfeek El-Hakeem (THKM)	5.3	12.5	24.5	29.3

Descriptive Statistics

The classical statistics are given in Table (2) covering the BUS1&2 with LSOW, and the six villages, three from inside and three from outside BUS1&2, with SSOW. The values of mean, minimum, and maximum of the six villages AIAT, MRFT, THKM, ABKR, EADL, and THSN indicated the water logging problems. The situation was even worse outside BUS1&2. The high values of standard deviation indicated larger heterogeneities of WTD in the Bustan region. The % CV values reflected medium variation of WTD according to Warrick and Nielsen (1980). Skewness and kurtosis for a normal frequency distribution are zero, and their significant values indicate non-normal distribution (Snedecor and Cochran, 1980). Results of LSOW indicated that WTD was close to non-normal distribution. The distribution of WTD based on SSOW measurements at ABKR and THSN were non-normal

Table (2). Descriptive statistics for water table depth (m) for Bustan 1 and 2 areas, and for six villages based on large- and small-scale observation wells during the period from April 1999 to August 2000.

Parameter	SSOW inside BUS1&2 at village[1]			SSOW outside BUS1&2 at village[1]			LSOW (All BUS1&2)
	AIAT	MRFT	THKM	ABKR	EADL	THSN	
Mean	2.22	2.66	2.14	1.89	1.68	1.52	3.61
Standard Deviation	1.01	1.06	0.74	0.79	0.74	0.57	1.42
CV (coefficient of variation, %)	45.58	39.82	34.79	41.72	44.14	37.80	39.26
Variance	1.02	1.12	0.55	0.62	0.55	0.33	2.01
Minimum	0.23	0.57	0.76	0.30	0.28	0.21	0.57
Maximum	4.22	4.59	3.77	4.22	3.38	3.25	7.52
Skewness	0.16	-0.14	0.27**	0.39**	0.26*	0.26*	1.09
Kurtosis	1.96	2.18	2.06	2.90**	2.05	2.57**	6.93**
n (Number of readings)	578	527	459	595	425	340	1479

[1]SSOW=small-scale and LSOW=large-scale observation well, BUS1&2=Bustan 1 and 2, AIAT=Ali Ibn Abi Taleb, MRFT=Mohamed Refaat, THAM=Tawfeek El-Hakeem, ABKR=Abu Bakr, EADL=El-Adl, and THSN=Taha Hussein village.

*,** Significant at 0.05 and 0.01 level of probability, respectively.

The Best-Fitted Variogram Models for Temporal Data

The spatial dependence between neighboring points i.e. the average rate of change over distance, and interpolation based Kriging, are all depend on the variogram. The estimation of a valid variogram is critical for geostatistics. Kriging depends on an accurate variogram for estimating weights for interpolation. Using incorrect variograms can leads to unfavorable precision of the kriged estimates.

The variogram analysis reveals that the spatial dependence of the WTD throughout the study period is exponential which formulated as follows:

$$\gamma(h) = C_o + C_i(1 - \exp(-\frac{h}{a}))$$

All the parameters of the exponential variogram for WTDs that measured in LSOW at selected months are given in Table (3), and the variograms are shown in Figure (1).

Mapping Water Table

The parameter of the exponential model fitted to the variogram of the predicted WTD were used as input to the kriging process to interpolate estimates at all points of large-scale grid. The maps represent the temporal spatial distribution for BUS1&2 areas (Figures 2 and 3). Zones of water logging were clearly observed, and greatly verified with the measurements of SSOW. The obtained maps are of great importance for assessing the behavior of WTD, and water-logged zones. This would help delineate management zones, based on the spatial variability of water table fluctuations in the study area.

Table 3. Variogram models for water table depth in Bustan 1 and 2 areas based on the measurements of large-scale observation wells during the period from April 1999 to August 2000.

Month	Model	Nugget (C_0)	Sill (C_1)	Range (a)	R^2	Lag
Apr. 1999	Exponential	0.151	2.034	1430	0.875**	1500
Jul. 1999	Exponential	0.001	2.027	1640	0.901**	1500
Oct. 1999	Exponential	0.320	1.933	1810	0.862**	1500
Jan. 2000	Exponential	0.305	1.919	1800	0.873**	1500
Apr. 2000	Exponential	0.225	1.971	1500	0.868**	1500
Jul. 2000	Exponential	0.089	1.849	1410	0.852**	1500

** significant at 0.01 level of probability.

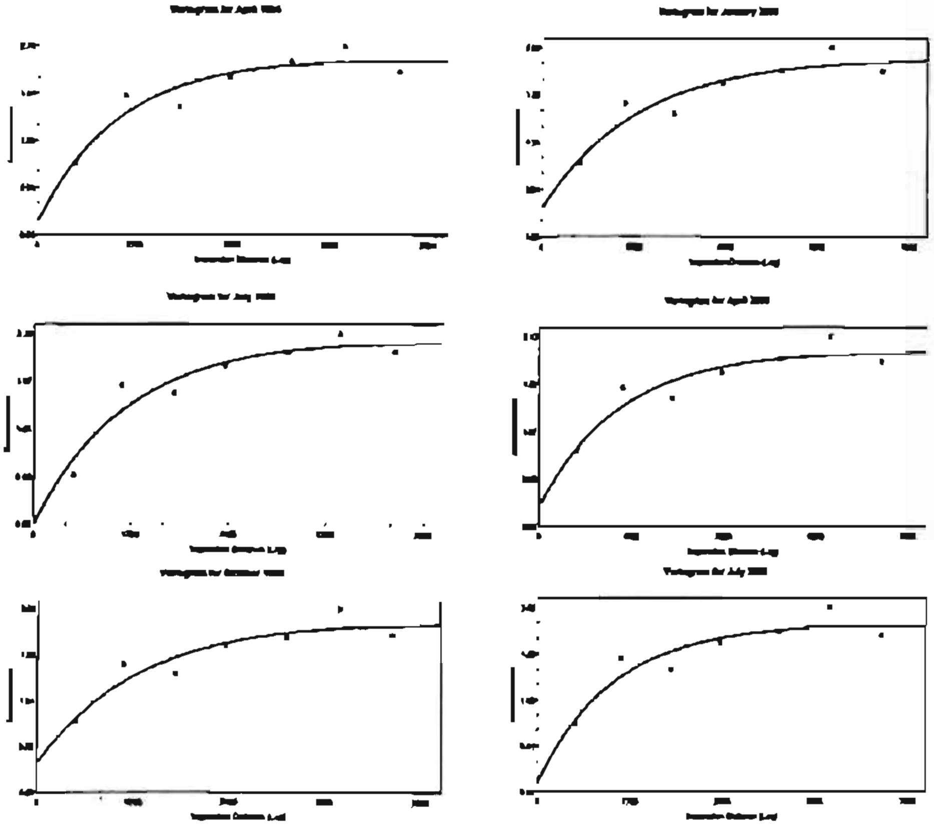


Figure (1): The fitted exponential variograms for water table depth in Bustan 1 and 2 areas throughout the study period.

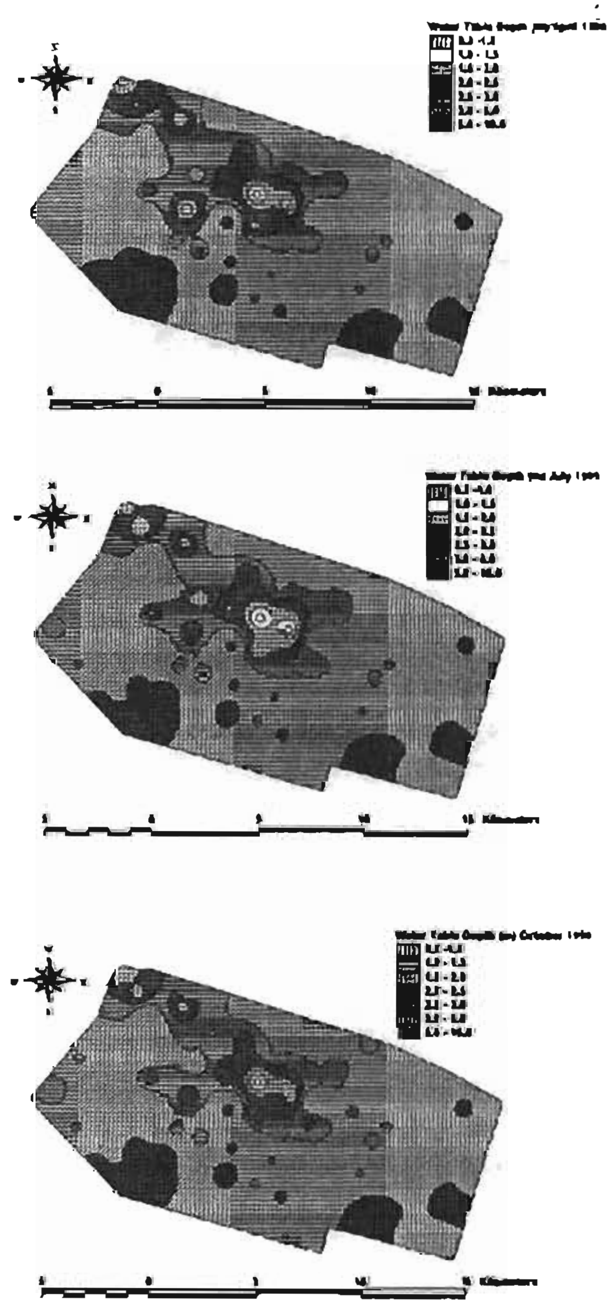


Figure (2): Kriged maps of water table depths in Bustan 1 and 2 areas for the year of 1999.

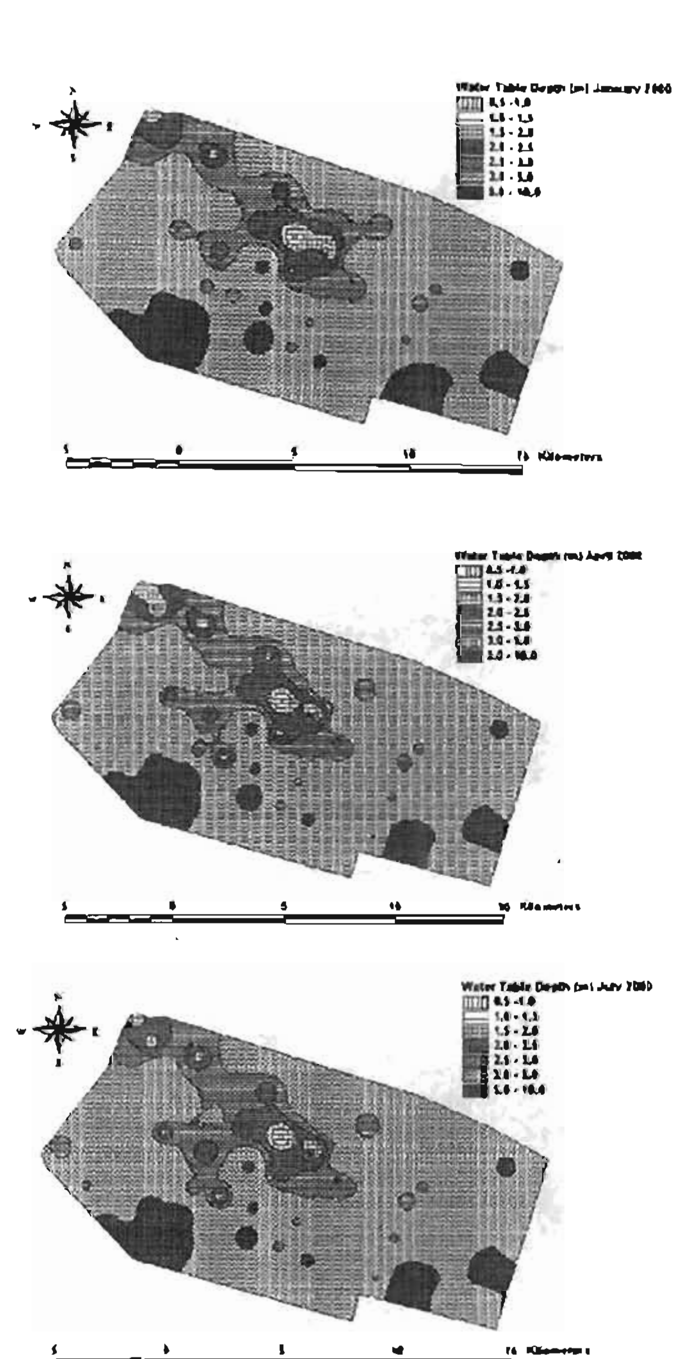


Figure (3): Kriged maps of water table depths in Bustan 1 and 2 areas for the year of 2000.

Based on the kriged maps, the percentage of the areas in BUS1&2 were 0.02-0.12 %, 0.26-1.35 %, 0.84-6.60 %, 3.54-8.40 %, 9.61-14.26 %, 63.38-75.79 %, and 8.27-10.13 % for the WTDs 0.5-1.0 m, 1.0-1.5 m, 1.5-2.0 m, 2.0-2.5 m, 2.5-3.0 m, 3.0-5.0 m, and 5.0-10.0 m, respectively, throughout the period from April 1999 to August 2000.

Cross Validation for Kriging Prediction

The process of cross validation between the estimated and the true values permits the evaluation of accuracy. The close relationships between measured and predicted values are evidenced by the low standard error (SE) values and the significance of the correlation coefficient (r) at 0.01 level of probability. The regression equations resulted from the kriging cross validation are as follows:

April 1999	kriged WTD (predicted) = 1.28 + 0.66 WTD (measured)	
	$r = 0.39^{**}$	SE prediction = 0.17
July 1999	kriged WTD (predicted) = 1.41 + 0.62 WTD (measured)	
	$r = 0.40^{**}$	SE prediction = 0.15
October 1999	kriged WTD (predicted) = 1.26 + 0.68 WTD (measured)	
	$r = 0.38^{**}$	SE prediction = 0.18
January 2000	kriged WTD (predicted) = 1.40 + 0.63 WTD (measured)	
	$r = 0.36^{**}$	SE prediction = 0.18
April 2000	kriged WTD (predicted) = 1.42 + 0.62 WTD (measured)	
	$r = 0.36^{**}$	SE prediction = 0.18
July 2000	kriged WTD (predicted) = 1.50 + 0.60 WTD (measured)	
	$r = 0.35^{**}$	SE prediction = 0.18
Average	kriged WTD (predicted) = 1.38 + 0.63 WTD (measured)	
	$r = 0.37^{**}$	SE prediction = 0.17

Fluctuation of Water Table with Time

The average fluctuation of water table with time for the AIAT, MRFT, and THKM, along with ABKR, EADL, and THSN villages based on SSOW measurements are shown in Figure (4). Relative to the average fluctuation of the region, the temporal changes of water table for the water-logged villages were different, which indicated the severity of water logging problem. This revealed that the installation of a complete network of ditch-, sub-main, and main drains in BUS1&2 areas is essential to avoid water logging problems in the future.

Effect of the Construction of Main Drains on Water Logging Problems

The Drainage Authority (Ministry of Irrigation and Public Works) constructed the main drains to intercept the percolated water and partially solved the preached water table problems. Figure (5) showed the effect of installing main drain (Husha drain) on the average of WTD at AIAT, MRFT, THKM, ABKR, EADL, and THSN villages. The water table levels decreased in most of the observation wells at these villages. However, AIAT, MRFT, and THKM villages of BUS1&2, in addition to the other villages outside BUS1&2: ABKR, EADL, and THSN still need an efficient drainage system.

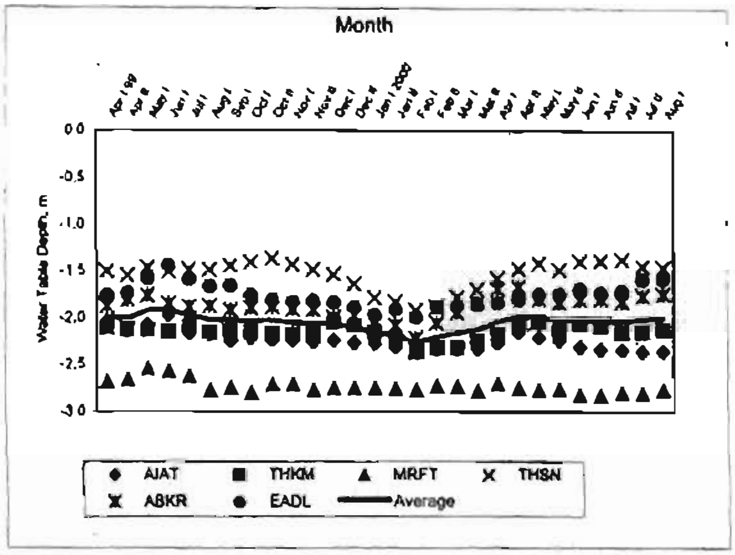


Figure (4): Average temporal fluctuation of water table for three villages of Bustan 1 and 2 areas (Ali Ibn Abi Taleb=AIAT, Mohamed Refaat=MRFT, and Tawfeek El-Hakeem=THKM), and three other villages (Abou Bakr=ABKR, El-Adl=EADL, and Taha Hussein=THSN) in the vicinity for the period from April 1999 to August 2000.

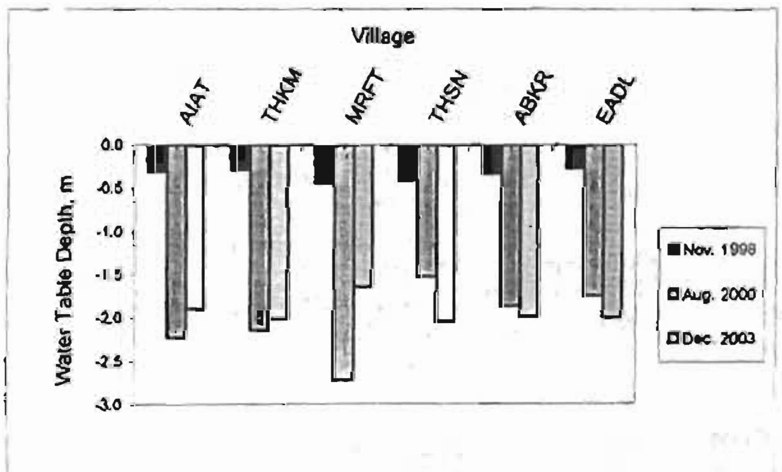


Figure (5): Average water table depths as before (November 1998) and after the installation of the main drain. (Ali Ibn Abi Taleb=AIAT, Mohamed Refaat=MRFT, and Tawfeek El-Hakeem=THKM), and three other villages (Abou Bakr=ABKR, El-Adl=EADL, and Taha Hussein=THSN) In the vicinity of Bustan 1 and 2.

CONCLUSION

Field maps using Kriging technique were produced for detecting the spatial behavior of water table depth, and to locate areas with water logging problems. The main reasons of the shallow water table and water logging problems, generally at the Bustan region and specially at Bustan 1 and 2 in Ali Ibn Abi Taleb, Mohamed Refaat and Tawfeek El-Hakeem villages, were identified due to the presence of impermeable layer close to the soil surface, seepage from irrigation canals, the excessive water applied in irrigation through the use of the surface instead of the installed modern irrigation system, and inadequate drainage system in the region. The constructed main drains were insufficient to meet the drainage requirements of the area. The installation of a complete network of ditch-, sub-main, and main-drains is essential to avoid any future problems of water logging.

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نهج جيوإحصائى للتوزيع المكانى لعمق مستوى الماء الأرضى وتحديد المناطق الغدقة بمنطقة البستان – مصر

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تواجه الإدارة والتنمية المستدامة للتربة الرملية المستصلحة حديثا فى مناطق البستان مشاكل عدة منها سوء خواص التربة الطبيعية والكيميائية ، إنخفاض خصوبة التربة ، وجود بعض المناطق التى تعانى من الغدق وتملح التربة ، وعدم وجود دورات زراعية مستدامة. ونظرا لنقص المياه المتوقع فى الأعوام القادمة تعد مشكلة الغدق والتملح هى الأهم.

تهدف هذه الدراسة إلى تقدير سلوك التوزيع المكانى لمستوى الماء الأرضى ، وتحديد مناطق الغدق ، وكذلك جودة المياه الجوفية لإعادة إستخدامها فى الرى من أجل الوصول للإدارة المستدامة لحوالى ٥٠ ألف فدان (٢١ ألف هكتار) فى مناطق البستان ١ ، ٢ .

اشتملت هذه الدراسة على شبكتين لأبار الملاحظة لقياس مستوى الماء الأرضى مرة أو مرتين شهريا لمدة ١٨ شهر. تكون النظام الشبكى الأول من ٨٧ بئر ملاحظة على مقياس كبير لينطى مناطق البستان ١ ، ٢ – وتكون النظام الشبكى الثانى من ٩٢ بئر ملاحظة على مقياس صغير موزعة كالآتى ٣٤ ، ٣١ ، ٢٧ وذلك بثلاثة قرى تعانى من الغدق وهى على بن أبى طالب ، ومحمد رفعت ، وتوفيق الحكيم ، على الترتيب. وأخذت عينات مياه من أبار الملاحظة لتقدير معايير جودتها.

أوضحت النتائج أن عمق الماء الأرضى تراوح من ٠,٢٣ – ٧,٥٢ م مما يعكس استمرارية وجود مشاكل غدق فى بعض الأجزاء وبخاصة فى قرى على بن أبى طالب ، ومحمد رفعت ، وتوفيق الحكيم. تم تحديد التوزيع المكانى لمستوى الماء الأرضى من خلال النهج الجيوإحصائى وكان أفضل شكل لتوزيع الاختلافات Variogram للقراءات الدورية تابعا للنموذج الأسى Exponential . وقد تم إعداد خرائط مستوى الماء الأرضى لتحديد التوزيع المكانى وذلك بتقنية الكريكنج Kriging . واستخدمت الخرائط فى تحديد المناطق التى تعرضت لمشاكل الغدق. تم تقييم النتائج المتحصل عليها بتقنية الكريكنج Kriging لضمان دقتها وأكدتها القيم المنخفضة من الخطأ القياسى ومعاملات الإرتباط ذات المعنوية العالية.

مشكلة الغدق التى ظهرت ببعض مناطق البستان كانت أساسا نتيجة للرشح من قنوات الرى، وتغيير نظم الرى الحديثة التى تم تركيبها (الرش والتنقيط) إلى نظام الرى السطحى (الغمر) ، ونقص فى المعلومات عن الإحتياجات المائية للمحاصيل وجدولة الرى ، وعدم وجود نظام صرف كافى ، مما يشكل أحد المعوقات الهامة نحو إستدامة الإنتاج الزراعى بهذه المناطق.