A Simulation Model to Monitor the Soil Salinity in Irrigated Arable Land in Arid Areas Based upon Remote Sensing and GIS

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ABSTRACT

Field tests in the Baheira Province (Egypt) show that there is a strong relationship between the depth of the groundwater table and the electrical conductivity of the soil paste. By means of supervised image classification techniques it is possible to map the saline and waterlogged soils. Three images dating from 1977, 1989 and 1991, are studied. For these periods the waterlogged soils could be mapped. A clear evolution can be noticed; in some places the water logging has disappeared, while in other places recent water logging occurs. The three images are registered towards the Egyptian co-ordinate system. Also two separate maps were digitised from the topographical maps dating from 1947, one indicating the master irrigation- and drainage channels. Also a DEM was created based on the topographical maps. The proposed model starts from two principles, namely that salinization can be caused by irrigation water, as well as by drainage water. In the Nile delta farmers receive approximately 2 times during a 5 days period irrigation water per month. Those who are close to an irrigation channel pump more than needed, while farmers further away from an irrigation channel are not receiving enough. These farmers are often obliged to irrigate with drainage water, causing an increase of the soil salinity. Due to lack of sweet irrigation water the salts in the upper layers of the soil profile cannot be leached efficiently, resulting in a higher soil salinity. On the other hand water logging can also be caused by the master drainage channels themselves. In case of bad or non maintenance of the master drainage channels, development of reed vegetation can block the evacuation of drainage water. The salty drainage water is kept in the drain and can infiltrate the surrounding areas, resulting in a salt ground water table. If a master drainage channel is crossing a lower situated area the water can also penetrate the surrounding areas, resulting in an high local ground water table. A shallow ground water table is causing a low leaching fraction by which the risks on salinization are increasing.

The proposed model simulates the areas at a high risk of salinity, taking the distance from the irrigation channels as well as the topographical level into account. On the other hand the areas with a high risk of water logging and salinity caused by the fact that master drainage channels are crossing trough low level depressions are generated as well. The combination of the two simulations gives a ‘salinity risk map’. Field work shows that the areas characterised by salinity and water logging are indeed located in the potential dangerous areas. This is also confirmed by the two satellite image classifications. In the final stage a simulation is discussed when a new master drainage channel is dug or reactivated. The improvement can be simulated by the model as well.

Keywords: soil salinity, water logging, images classification, GIS, Remote Sensing

INTRODUCTION

This work is a part of the Desertification Project of the Belgian Ministry of Scientific Policy which is executed at the University of Gent in collaboration with the Egyptian Remote Sensing Centre in Cairo. The aim of the project is to evaluate the possibilities of remote sensing techniques
in combination with GIS to detect and to monitor the soil salinity status in parts of Egypt’s Nile Delta.

Salt-affected soils are found under a wide range of environmental conditions, however they are more pronounced in the arid and semi-arid regions. It has been estimated that about one-third of the cultivated land under irrigation in the world is considered to be already salt-affected (Framji, 1974). Many times the salt affected areas are occurring in the fertile alluvial plains in arid areas. El Gabaly (1959) estimated the area which suffers from primary or secondary salinity in Egypt at about 800,000 ha. This area represents approximately one-third of the entire area of arable land of the country. The extension of salt-affected soils is increasing as a result of practising perennial irrigation without an adequate drainage system. Also the need for irrigation water is increasing, following the start of the reclamation of desert soils for agricultural purposes. This is obvious in the Baheira Governorate. The ‘good quality’ irrigation water is partly diverted towards the New Reclaimed Areas, while the Old Land in the Delta Area with its fertile clayey soils is receiving less ‘good quality’ irrigation water. The local farmers therefore are sometimes obliged to irrigate with the salty drainage water in order not to lose their crops. In the future this can lead to an increase in the area of salt affected soils in the Nile delta. Although the New Reclaimed Areas are receiving only fresh irrigation water, also here a lot of saline soils are occurring (Abdel Salaam et. al; 1972,1973). Since Nasser’s times the reclamation of the desert fringes has been started. The wind blown sands were levelled and irrigation and drainage channels were constructed. In some parts of these New Reclaimed areas vast areas of saline and waterlogged soils are now developed.

While the project is dealing with soil salinity in the eastern as well as the western delta and old as well as newly reclaimed land, this paper is dealing with an area in the south edge of the Nile Delta in the western part.

1. ENVIRONMENTAL SETTINGS

The study area is situated approximately 60 km. south east of Alexandria.

The land is relatively low, between -0.5 and 2 meters above sea level. The landscape is slightly undulating, but sometimes turtle backs are present. They reach 4 meters above the surrounding areas. The area is built by a braided river system. Hills (the turtle backs) and micro-depressions (the former back swamps) are the result and create a typical micro-topography in the area. As it will be shown later, it is this micro-topography which pays an important role in the development and creation of waterlogged and saline soils. The soils are entisols and consist of heavy alluvial clay. The land is artificially drained by a dense network of elementary and master drainage channels. The irrigation water comes from the Nile and is generally of good quality. The average EC is 1.4mS. The farmers are receiving principally fresh irrigation water twice a month during a five day period. The major crops are cotton, wheat and alfalfa.

2. MATERIALS AVAILABLE

Three satellite images, from three different sensors are available:

- a Landsat MSS scene of 29-01-1977
- a SPOT XS scene of 20-09-1989
- a Landsat TM scene of 19-02-1991

Besides these remote sensing date, topographical maps of the area were also available at a scale 1/25000 with a contour interval of 0.5 meter. These maps are dating from 1947. These maps are the most recent available for the area. In the mean time some new irrigation and drainage channels were constructed. This changes could be add using the remote sensing and field data.
3. FIELD WORK AND THE CAUSE OF THE SOIL SALINITY

In the first phase the salinity was studied by field investigations. During the field work almost 200 sample points were investigated. For each sample point the electrical conductivity of the soil paste (ECP) was measured. If terrain conditions allowed it, also the electrical conductivity of the irrigation water (ECIR), drainage water (ECD) and the ground water (ECS) were measured as well. Besides the different EC measurements also the depths of the oxido-reduction and reduction zone were measured, as well as the soil texture and the pH of the soil paste. The presence of calcium carbonate was checked by an HCl test. The different parameters were stored in a data base (reflect). Relations between the different parameters were calculated. Generally these relations showed to be weak or even not existing. A correlation between ECIR and ECD could be proved.

The most interesting relationship was between the EC of the soil paste (ECP) and the depth of the groundwater table. Two parameters were used, namely the depth of the oxido-reduction zone and the depth of the reduction zone. A parabolic relationship was found between ECP and the depth of the oxido-reduction zone. (See Fig 2)

The nick point of this graph is situated around 40 to 50 cm depth of the oxido-reduction phenomenon. The major conclusion is that the salinity of the soil is in a direct relation with the depth of the groundwater table. A high groundwater table results in a low leaching capacity by which the salts can be concentrated in the upper parts of the soil profile. The critical depth seems to be 50 cm. The graph shows also that a groundwater level higher than 50 cm results in a strong increase of the soil salinity. This is important since this depth is also the mean root depth of most of the crops, so these salts can affect the growth of the plants causing losses in yield.

Comparable results were also found by Kovda, V. (1975), Halverson, A.D. & Rhoades, J.D. (1974, and Rhoades, A.D. (1975). It has to be mentioned that the nick point that they found was situated around one meter. The differences between the foundings can be due to different parameters: differences in soil texture, the depth of the soil sample (40 cm versus 30 cm), differences in measuring methods.

In many places in the Baheira Governorate these places with a high groundwater table are used for rice cultivation. Rice is a crop which needs wet soils and which is quite tolerant to salinity (Loveday, J., 1984). Often rice is the only crop which still can be cultivated on these soils.

It can be concluded that, the problems of salinity are directly connected with the problems of soil drainage. The soil drainage conditions in the clayey deltaic soils seems to be the primary factor for salinity. It seems that the quality of the irrigation water is of minor importance in the Baheira Governorate. In fact all the irrigation water is derived from the Nile.

The waterlogging varies from poorly drained soils, with a groundwater table at a depth of approximately 50 cm depth till complete submerged soils. The salinity of these soils can reach 18 mS.

4. SALINITY BY IRRIGATION WATER

As mentioned above, the farmers are receiving principally fresh irrigation water twice a month during a five day period. This is the irrigation scheme that is applied by the irrigation authorities in the area. Twice a month the irrigation water is distributed by main irrigation channels from where primary channels are tapping the water. From here the farmers can tap the irrigation water and distribute it over the land. This is done by diesel pumps, or by the classical methods and as the 'sakia' and the 'shadouf'.

Since the reclamation of new land in the desert to the south of the study area, more and more irrigation water is needed over there. The traditional agricultural areas, mainly situated on the alluvial clay deposits, are receiving less fresh irrigation water, since more and more water is diverted towards the Newly Reclaimed Areas in the south. Farmers in the Delta who have their land close to a main irrigation channel are pumping the quantities of water they need, or even more. Farmers who have their land further away from an irrigation channel are often not receiving the necessary amounts of water. Those people or obliged to irrigate with the salty drainage water, not to loose their crops. This procedure can lead to reductions of the yield, but this is preferred instead of loosing the crop. This procedure may
lead to an increase of the soil salinity. The water will evapotranspire but the salts can remain in the soil especially in case of a bad leaching. It can be concluded that the greater the distance is from a main irrigation channel, the greater the risk is for the increase of the soil salinity. A map showing this risk was made by the digitalisation of the main irrigation channels and than calculating the distances from these channels. This "distance map" can be considered as a risk map for soil salinity caused by the lack of fresh irrigation water: the bigger the distance from a main irrigation channel, the bigger the risk for the soil salinity. Since the higher parts of the landscape are seldom cultivated, and therefore not irrigated, these areas are marked in the map. This has been done using the DEM and a cut-off point at 0.5 meter above sea level was chosen. The resulting areas with a high digital distance value and at a level below 0.5 meter can thus be considered as areas with a risk for soil salinity. This result is presented in the Fig.3. (the colours ranging from bleu to yellow are representing the distances).

Fig. 3 - Risk for salinity due to the lack of fresh irrigation water = red colour. (Black = topographical higher area).

5. SALINITY BY DRAINAGE WATER

A high groundwater table is resulting also in high soil salinity since these soil are characterised by a low leaching capacity. Waterlogging often occurs when a master drainage channel is crossing a depression. The salty drainage water can penetrate in the soil of the surrounding areas, resulting in a high groundwater table and waterlogging. A map showing the risk of soil salinity caused waterlogging was generated. The master drainage channels were digitised from the topographical map and a distance map from the drains was calculated. As a critical distance, as estimated from soil drillings during the field work, a value of 500 meter away from the master drainage channels is chosen. The location of the areas within a distance of 250 meters were compared with the DEM. Relatively high situated areas in the neighbourhood of a master drain can be considered as not sensitive for soil salinity since the groundwater table can not rise close to the surface. Using the DEM, a map is created showing the areas at a distance of 500 meter away from the master drainage channels and situated below 0.5 meter level. This map can be considered as a risk map for soil salinity caused by the penetration of salty drainage water into the soil. This result is shown in the Fig. 4. (the colours ranging from bleu to red are representing the distances from the drains).

Fig. 4 - Risk for salinity and waterlogging due to the penetration of salty drainage water from the master drains.

6. THE COMBINATION OF THE TWO MAPS

Both maps are combined and superimposed with the DEM (Fig. 5: the colours ranging from bleu to red are representing the DEM). This model is checked during field work. It can be stated that the areas of waterlogging and salinity as they are occurring in the field are localised in the zones where the model predicts a risk.

Fig. 5 - Combined risks for salinity white: from the master drains - magenta: by lack of fresh irrigation water - yellow: intersection between the two risks.
7. IMAGE CLASSIFICATION

The three satellite images are classified using supervised techniques based on the field data. The fact that the images are derived from three different sensors creates some problems during the classification due to differences in spatial and especially spectral resolution. The best classification results could be obtained using the Landsat TM imagery.

Since no field data from the period of 1977 was available, the image classification was performed using similarities in spectral characteristics as they were used with the image classification of the Landsat TM and SPOT images.

For the test area in the neighbourhood of the village of Hosh Eisa different classes could be distinguished. The 3 classes of waterlogging could be distinguished based on field work, like soil drillings and profile descriptions. The other classes are based on field observation and visual image analysis.

The following classes could be retrained:

1) submerged soils with the groundwater table above the topographical surface: waterlogged1
2) wet soils with a shallow groundwater table: waterlogged2
3) wet soils with a relatively deeper groundwater table where the top soil can be dried out and salt crystals are deposited at the surface: waterlogged3.

This is illustrated in the scheme below.

![Fig. 6 - Scheme illustrating the three classes of soil waterlogging.]

4) The class 'village' was split up into two sub-classes, because it was noticed that the bigger centre of Hosh Eisa (class village2) has a rather stronger reflection in almost all the band, and especially in Landsat TM band 6, compared with the rural villages.

5) irrigation: this class contains the barren fields which are on the moment of the image recording, under flood irrigation.

6) vegetation: this class contains the fields with crops, mainly clover, wheat and maize.

The means and standard deviations of the different classes are mentioned in table 1.

It was tried to distinguish these classes on the three different satellite data. This was not always possible. For instance during the classification of the SPOT image only two classes of waterlogging could be obtained, namely wetland (shallow groundwater table) and salt crust. It has here to be mentioned that the SPOT image was recorded in the summer, so a lot of water is on that moment already evaporated.

The best results, compared with the field data, was obtained using the Landsat TM imagery. The divergence matrix (Singh, A., 1984) between the different classes is shown in the table below.

The classification of the Landsat TM scene gave the best result (Fig. 7). Band one was not used, all the other six bands were used.

The Landsat MSS and SPOT XS images were classified as well. In general these classification results were comparable, only between the classes waterlogging and irrigation some confusion was occurring. The classified images were geometrically corrected and warped towards the DEM.

![Fig. 7 - Classification of the Landsat TM image. - blue=waterlogged1, cyan=waterlogged2, red=waterlogged3, green=vegetation, yellow=irrigation, magenta=villeage1, white=villeage2, black=not classified.]

<table>
<thead>
<tr>
<th>Class</th>
<th>2 m</th>
<th>3 m</th>
<th>4 m</th>
<th>5 m</th>
<th>6 m</th>
<th>7 m</th>
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<td>waterlogged1</td>
<td>34.1</td>
<td>2.0</td>
<td>37.0</td>
<td>2.4</td>
<td>34.0</td>
<td>6.2</td>
</tr>
<tr>
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<td>29.1</td>
<td>2.6</td>
<td>32.2</td>
<td>3.2</td>
<td>36.3</td>
<td>7.2</td>
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<tr>
<td>waterlogged3</td>
<td>48.3</td>
<td>4.4</td>
<td>59.7</td>
<td>6.2</td>
<td>61.1</td>
<td>6.3</td>
</tr>
<tr>
<td>vegetation</td>
<td>25.7</td>
<td>0.9</td>
<td>21.4</td>
<td>1.0</td>
<td>92.7</td>
<td>5.9</td>
</tr>
<tr>
<td>irrigation</td>
<td>26.1</td>
<td>0.7</td>
<td>26.9</td>
<td>1.2</td>
<td>35.9</td>
<td>5.6</td>
</tr>
<tr>
<td>village1</td>
<td>35.8</td>
<td>1.5</td>
<td>40.3</td>
<td>4.8</td>
<td>47.0</td>
<td>5.8</td>
</tr>
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<td>village2</td>
<td>38.1</td>
<td>2.5</td>
<td>45.8</td>
<td>3.6</td>
<td>47.6</td>
<td>4.1</td>
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Table 2: Divergence matrix for the different classes of the Landsat TM-data.

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<th>3</th>
<th>4</th>
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<td>100</td>
<td>99</td>
<td>100</td>
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<td>100</td>
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<tr>
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<td>100</td>
<td>84</td>
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<td>100</td>
<td>100</td>
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<td></td>
<td></td>
<td></td>
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<td>100</td>
<td>100</td>
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<tr>
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RESULTS AND DISCUSSION

The classified images were checked in the field during a field work campaign in February 1992. It can be stated that the areas which are classified in the image as waterlogged are so indeed. It is also to notify that all areas characterised by waterlogging are situated in the risk areas as it was predicted by the simulation model. This means that special attention has to be paid to the areas situated in the risk zones. In case of a non or bad maintenance of the master drainage channels waterlogging and salinity can occur here as well in a very short time span. So the model allows to predict the creation of waterlogged soils and salinity, but also the opposite is possible. The improvement of the soil waterlogging and salinity can be simulated as well. This can be illustrated with the waterlogged area situated in the eastern part of the test area. This extended area was present as it is shown on the image and the image classification of the Landsat MSS data from 1977. They started in 1989 with the reactivation of the master drain which is crossing the area. The master drain was thoroughly deepened and in the same time, parallel to the master drain a main irrigation channel was dug. The effect was that in a two year time span the groundwater table dropped 1.5 meter and that the salts could be washed out with the fresh water. This can be seen on the satellite images and the derived classifications. From 1991 on, it was possible to start with agriculture. Wheat and vegetables are cultivated now. By adding the new irrigation channel to the model and run it again, it is noticed that the risk for soil salinity caused by the lack of fresh irrigation water is disappeared (Fig. 8: the colours ranging from bleu to red are representing the distances from the irrigation channels). Anyhow the risk for waterlogging in the area remains due to the fact that the master drain is crossing a relatively low situated closed depression. In case of the non or bad maintenance the groundwater table will be 'restored' in a very short time span.

The model allows as well to check if the risks for salinity and waterlogging are increasing or decreasing in case of a new master drain (Fig 9: showing the potential risks for soil salinity and waterlogging(magenta colour), superimposed on the DEM, ranging from bleu to red colour). The planned channel must be digitised in the GIS and the model must be run again.

Fig. 8 - Risk for salinity due to lack of irrigation water after the construction of a new irrigation channel. No high risks are occurring.

Fig. 9 - Risk for soil salinity and waterlogging after the construction of a new master drain (magenta colour).
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