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Challenges of Sustainable Land Management in Siwa Oasis: The Waterlogging Problem in the Newly Reclaimed Desert Land

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Abd EL-Kawy, O. R.*

Department of Soil and Water Sciences, Faculty of Agriculture, Alexandria University, Egypt.

ABSTRACT

Accurate and frequent information about waterlogging problems is very necessary for the sustainable land management. The objectives of this research are to detect and mapping the vegetated and waterlogged areas in a newly reclaimed desert land in Siwa oasis, using remote sensing data and techniques; and suggest a future plan to solve the waterlogging problem. The Normalized Difference Vegetation Index (NDVI) and the Modified Normalized Difference Water Index (MNDWI) algorithms were applied on four Landsat images (2009, 2012, 2015 and 2018) to detect and map the vegetation and waterlogging states, respectively. The results of NDVI revealed that the cultivated land was increased by 2.3 times in nine years (2009-2018) due to private land reclamation process. The results of MNDWI indicated that the waterlogged area was increased remarkably by 21 times during nine years, where it increased remarkably from 19 ha in 2009 to 393 ha in 2018. The development of the waterlogged areas was most likely due to the increase in the surface water level of Lake Aghormy North of the study area, as well as the trapping of the agricultural drainage water and well-water overflow between the sand dune formations. This study recommended a strategy to solve the waterlogging problem, which include the establishment of a surface drainage network covering the study area. This network should be connected with a main drain at the Northern border of the study area. This strategy will enhance the drainage conditions and solve the waterlogging problem in the area.

Keywords: NDVI; MNDWI, waterlogging, Siwa oasis, Egypt.

INTRODUCTION

Siwa oasis is a unique fragile ecosystem represented by a closed depression in the northwest part of the western desert of Egypt. It is the largest oasis among the Egyptian oases, which is located about 530 kilometers west of the Nile valley and 250 kilometers south of the Mediterranean Sea. It represents a promising area for land reclamation and agriculture expansion in the western desert of Egypt due to the availability of water resources (Elnaggar *et al* 2017). At the same time, environmental problems, such as waterlogging and soil salinization, are major challenges that undermine sustainable land management and consequently agriculture sustainability in Siwa oasis, where agriculture represents the basis of Siwa economy (IUCN 2000; Al-Kadi 2003). Historically, due to the uncontrolled water discharge from natural springs and wells in addition to the unique characteristics of Siwa, as it is a closed depression, water table level rises by 4.5 cm year^{-1}. This led to waterlogging and soil salinization problems and increase in the surface area of the saltwater lakes (IUCN 2000; Samy 2010).

Several authors have documented these environmental problems and their negative impact on the agricultural land of the oasis (AbdelRahman *et al* 2019; Aly 2019; Elnaggar *et al* 2017; Rashed 2016; Abdul Ghafar 2014; Masoud and Koike 2006). Generally, waterlogging problems can be classified as natural, quasi-natural and anthropogenic based on their origin and they may be permanent or seasonal based on time scale (Sahu 2018). Natural waterlogging forms due to geological or morphological factors of an area site (Sahu 2018; Holden *et al*., 2009; Merot *et al*., 1995).

Anthropogenic waterlogging is created due to human activities such as road or canal constructions, buildings, built-up areas, etc (Mehmood *et al.* 2017; Li 2012).

Accurate and frequent information on the spatial extent of waterlogging is required for monitoring and conservation of land resources. Satellite remote sensing provides the necessary data needed for that purpose. Several studies have demonstrated that Landsat sensors provide temporal data which are useful in mapping and detection of vegetation and waterlogged areas (Acharya *et al.* 2018; Sahu 2018; Mehmood *et al.* 2017; Taufik *et al.* 2016; Meera Gandhi *et al.* 2015). Many vegetation and waterlogging extraction techniques have been applied for remotely sensed data. Among them, the band ratio approach has been developed, which utilize two multispectral bands. One band represents the visible wavelength and the second from the near-infrared (NIR) or the micro-wavelengths. The Normalized Difference Vegetation Index (NDVI) and the Modified Normalized Difference Water Index (MNDWI) are band ratio algorithms, which have significant application to identify vegetated and waterlogged areas, respectively (Albarakat and Lakshmi 2019; Chu *et al.* 2019; Li *et al.* 2019; Acharya *et al.* 2018; Baniya *et al.* 2018; Sahu 2018; Mehmood *et al.* 2017; Singh *et al.* 2015). NDVI was developed based on the red and near-infrared wavelengths (Rouse *et al* 1974), while MNDWI was developed based on the green and short-wave-infrared wavelengths (Xu 2006).

* **Corresponding author.**
E-mail address: usama.abdelkawi@alexu.edu.eg
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The prime objectives of this paper are to: 1) extract and detect the vegetated and waterlogged areas in the newly reclaimed desert land, located East of Siwa oasis, through the application of NDVI and MNDWI algorithms on temporal Landsat images; 2) recommend a future plan for management of the waterlogging problem in the study area.

MATERIALS AND METHODS

Study area

Geographically, the study area is situated in the Southeastern part of Siwa depression right on the southern borders of Lake Aghormy and Lake Zeitun (Fig. 1). It occupies an area of 16,875 ha and locates at longitudes 25° 31' 28" and 25° 46' 22" E and latitudes 29° 2' 41" and 29° 11' 50" N. The topographic map of Siwa oasis indicates that the study area includes several sand dunes scattered in the southern and southwestern parts. The study area is geologically composed of both Tertiary and Quaternary sediments. The Tertiary limestone outcrops belong to the middle Miocene and cover lower sandstone rocks. These Tertiary deposits are represented by the scattered mountains in the study area. The Quaternary deposits composed of unconsolidated gravel and sand, which are mainly represented by sand sheets, sand dunes and desert pavements (El Gindy and El Askary 1969). The study area is characterized by extreme arid climate conditions, with very low rainfall (average 8 mm year^{-1}), high evaporation rate (17 mm day^{-1} in July to 5.2 mm day^{-1} in December) and high summer temperature (maximum 48 °C in July) (Al Dumairy and Dahlfelt 2012; Misak *et al.* 1997). Since the beginning of the current millennium, the study area has witnessed private land reclamation projects and agriculture expansion by using ground water for irrigation. According to the sustainable development strategy of Egypt's vision 2030 (SDS-2030, 2017), a new area of 12600 hectares will be reclaimed and cultivated in the eastern part of Siwa, where the study area is mostly located (Fig. 1).

Field observations, satellite data, and image pre-processing

However the study area is a newly reclaimed desert land, several waterlogged areas have continuously grown. To monitor the land reclamation process and the waterlogging problem in the area, four Landsat images with zero cloud cover were used, which acquired during the summer of 2009, 2012, 2015, and 2018 (Table 1). For 2012, the Enhanced Thematic Mapper (ETM+) sensor of Landsat7 failed to produce full image covering the study area because the scan-line corrector (SLC) of Landsat7 (ETM+) failed to scan (SLC-off) about 20% of the image pixels (USGS 2003). Although the SLC-off is a major limitation of using Landsat7 data in land use/cover mapping, the unscanned data can be recovered by assembling composite data from a previous or subsequent image acquired for the same area (Abd El-Kawy *et al.* 2011; USGS 2003). In this study, the SLC-off was corrected for the 2012 ETM+ image (acquired in July 19) by using another ETM+ image acquired in August 4 (Table 1). A full 2012 image was produce through the image mosaicking process in ERDAS imagine (ERDAS 2007).

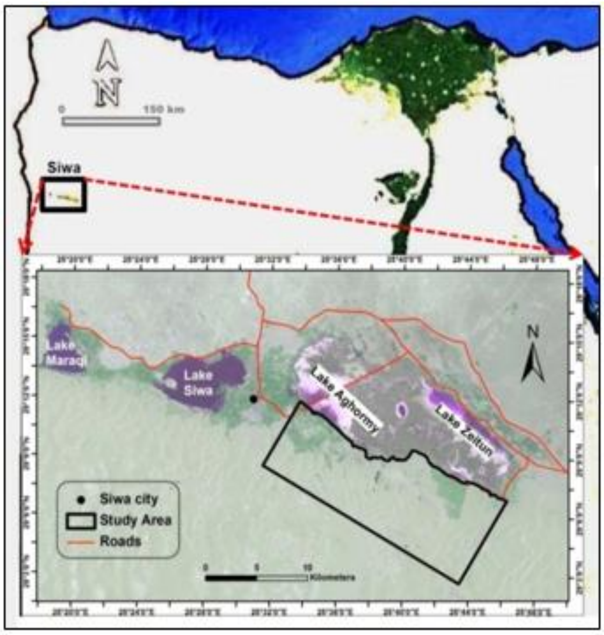

Fig.1. Location of the study area within Egypt.

Image geometric correction was performed for all Landsat images based on a geo-referenced topographic map covering the study area and twenty ground control points collected during field survey in 2018. All images were calibrated and subset to the study area (Fig. 2).

Table 1. The selected Landsat images and their characteristics.

Landsat sensor	Accusation date	Accusation time	Used bands	Pixel size
Landsat5 (TM)	19/07/2009	08:37:53	2,3,4,5	30 m
Landsat7 (ETM+)	19/07/2012	08:43:48	2,3,4,5	30 m
Landsat7 (ETM+)	04/08/2012	08:43:58	2,3,4,5	30 m
Landsat8 (OLI)	04/07/2015	08:48:24	3,4,5,6	30 m
Landsat8 (OLI)	12/07/2018	08:48:07	3,4,5,6	30 m

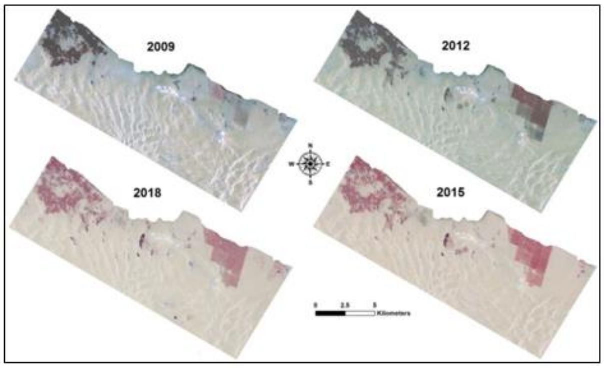

Fig.2. The selected Landsat images used for the study.

A Digital Elevation Model (DEM 30 m grid) for the Shuttle Radar Topographic Mission (SRTM) was used to display the elevations and generate the slopes and water streams in the study area. All Landsat and SRTM data were freely downloaded from the US Geological Survey website (https://earthexplorer.usgs.gov) (USGS 2019).

Calculation of Remote Sensing Indices

NDVI, as a vegetation index, was calculated from the selected Landsat images (from 2009 to 2018) to monitor the land reclamation process and agriculture expansion. At the same time, MNDWI was calculated to detect the waterlogging problem in the study area for the same period. Based on the equations listed in Table 2, NDVI and MNDWI were calculated.

Table 2. The equations used for NDVI and MNDWI calculations

Landsat sensor	Index equation	Reference
TM & ETM+	NDVI= (NIR-R)/(NIR+R) = (band4-band3) /(band4+band3) MNDWI= (G-SWIR)/(G+SWIR) = (band2-band5)/(band2+band5)	(Rouse et al 1974) (Xu 2006)
OLI	NDVI= (NIR-R)/(NIR+R) = (band5-band4)/(band5+band4) MNDWI= (G-SWIR)/(G+SWIR) = (band3-band6)/(band3+band6)	(Rouse et al 1974) (Xu 2006)

Where, NIR is the near infrared reflectance, R is the visible red reflectance, G is the green reflectance, and SWIR is the short-wave infrared reflectance.

The resulting NDVI and MNDWI values range between -1 and +1 (Tucker *et al* 1985; Xu 2006). The positive NDVI values indicate vegetated areas, while zero and negative values correspond to non-vegetated areas (Albarakat and Lakshmi 2019). The positive MNDWI values associated with waterlogged or oversaturated areas, while negative values indicate the non-waterlogged areas, which usually represent vegetation or bare soil (Mehmood *et al*. 2017; Xu 2006). Thus, the positive values of the calculated NDVI and MNDWI were used to extract the extent of vegetation and waterlogging, respectively, in the study area for each year (i.e., 2009, 2012, 2015, and 2018). To study the validity of NDVI and MNDWI thresholding, 43 truth points were collected and used.

RESULTS AND DISCUSSION

Based on DEM analysis in a GIS environment, the elevations, slopes and water streams in the study area were addressed and generated (Fig. 3). The elevations ranged from 36 m below sea level to 84 m above sea level. The highlands mostly distributed in the southern and southwestern parts of the area, while the lowlands located in the northern and northeastern parts, where Lake Aghormy and Lake Zeitun are generally situated (Figs 1 and 3). It was observed that most of the study area is characterized by macro topography, particularly, in the southern and southwestern parts, where several elongated sand dunes are scattered and extended from the northwestern to the southern and southeastern directions. The majority of the study area (83%) is characterized by slope percent less than 5%, while most of the existing sand dunes have slope percent from 5 to 10%. In Figure 3, it is clear that water streams generally directed transversely in the study area from South (the sand dune region) to North (Lake Aghormy and Lake Zeitun), since it is the dominant slop direction.

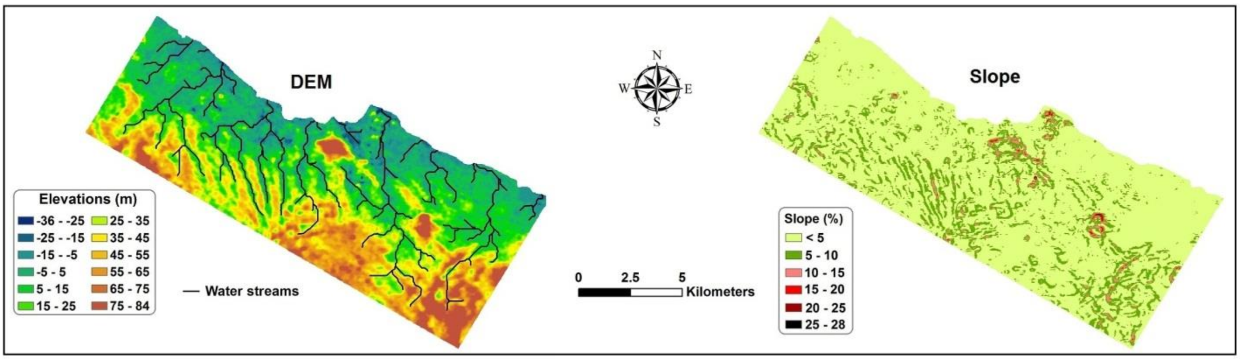

Fig.3. The elevations, surface water streams, and slope of the study area.

Before using the results of NDVI and MNDWI for the analyses, they were assessed against real data and resulting a strong accuracy. The obtained overall accuracies for NDVI were 92%, 95%, 92%, and 97% in 2009, 2012, 2015, and 2018, respectively. The overall accuracies of MNDWI were 87%, 90%, 85%, and 92% in 2009, 2012, 2015, and 2018, respectively.

The results of NDVI revealed that desert land reclamation and agriculture expansion took place in the study area during the period from 2009 to 2018, where the cultivated land was approximately doubled by 2.3 times in nine years (Fig 4). The field investigation reported that most of the reclaimed land in the study area is cultivated with olive based on the ground water supply and using the drip-irrigation system (Fig 5). The NDVI technique gave superior results for scattered vegetation from multispectral remote sensing images. It was obvious that most of the cultivated lands are distributed in the northern and northeastern parts of the study area (Fig 6), where the slope percent is less than 5% and the absence of sand dunes (Fig 3). On the other hand, some areas were reclaimed and cultivated in the middle, southern and southwestern parts of the study area, particularly, after 2009. These areas are mostly located in the sand dune region (Figs 3 and 6).

The resulted NDVI and MNDWI indicate that the increase in the cultivated land was associated with the formation and growing in areas under waterlogging conditions. The waterlogged area was approximately doubled by 21 times during nine years, where it increased significantly from 19 ha in 2009 to 393 ha in 2018 (Fig 4).

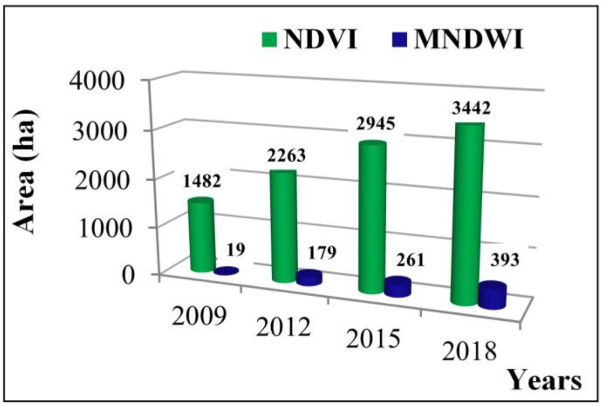

Fig.4. Area (ha) of NDVI and MNDWI.

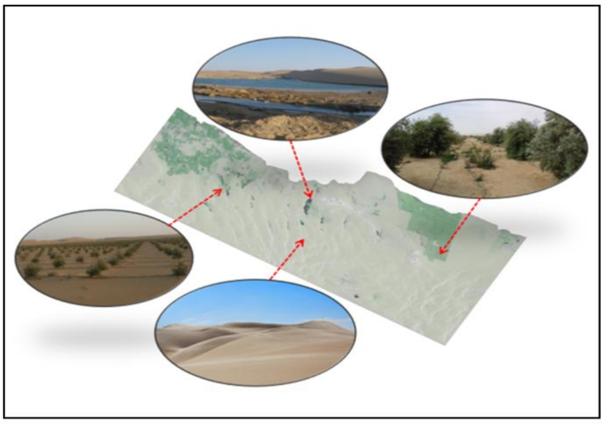

Fig.5. Different types of land use/cover.

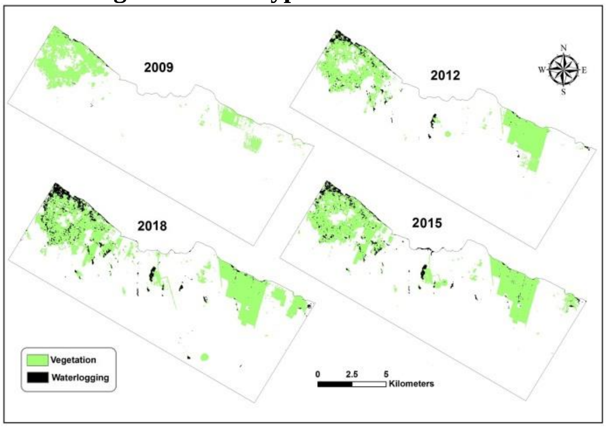

Fig.6. The spatial distribution of vegetation (NDVI) and waterlogging (MNDWI) in the study area.

In 2009, few areas existed under the waterlogging conditions, which mainly concentrated near the border of Lake Aghormy (Figs 6 and 1). After 2009 to 2018, the waterlogged areas spatially distributed and located in the northern and middle parts of the study area, where land reclamation and agriculture expansion were taking place (Fig 6).

The relationship between DEM and NDWI

To determine the causes of waterlogging development in many parts of the study area, a spatial relationship was investigated between the DEM and MNDWI-2018. This relationship was examined through assigning two transects passing onto the waterlogged areas and the DEM (Fig. 7). The first transect (AB) extends transversely from north to south in the far western part of the study area, where many waterlogged regions are existed. In contrast, the second transect (CD) extends longitudinally from west to east along the study area at the boundaries of the sand dunes, where many waterlogged areas are also existed. For the "AB" transect, the development of the waterlogged areas was most likely due to the continuous increase in the surface water level of Lake Aghormy. Thus, the continuous increase in the lake surface water level will probably decreases the water table level in the northwestern part of the study area (Fig. 8). These results go along with findings for other areas in the oasis reported by Hasan (2016). On the other hand, the waterlogged areas south of the "CD" transect were mainly developed due to the trapping of the agricultural drainage water and well- water overflow between the sand dune formations (Fig.9).

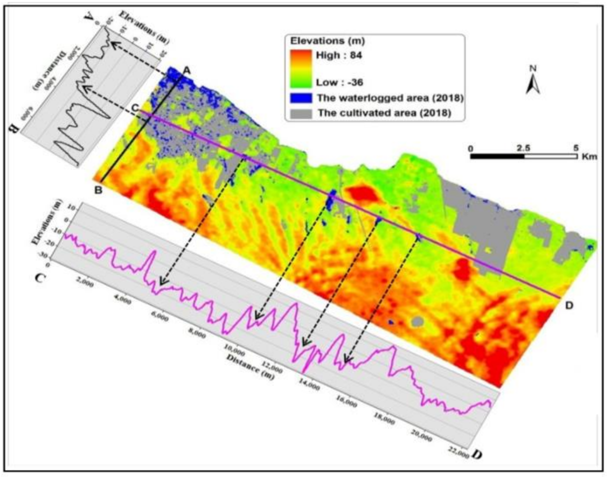

Fig.7. The spatial relationship between DEM and waterlogging.

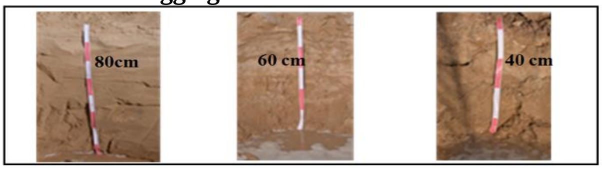

Fig. 8. The water table level at different locations on the "AB" transect.

Fig. 9. Trapping of the drainage water and well-water overflow by sand dunes.

Future plan for management of the waterlogging problem

Locally, to solve the waterlogging problem in the investigated area a future strategy was proposed. In this strategy, a surface drainage network was suggested, which includes: 1) establishment of a main drain at the Northern border of the study area, right on the South borders of Lake Aghormy and Lake Zeitun (Figs 10 and 1). This drain will prevent the lakes water intrusion into the water table of the study area and, consequently, it will increase the water table level from the soil surface. This strategy was successfully followed in different areas of the low laying land that adjacent to Lake Siwa (Hasan 2016). 2) Drilling transverse drains in the study area, which should be connected to the main drain to discharge the free water in the waterlogged areas developed in the sand dune region, where water stream runoff can be followed as guidance for the drainage network design (Fig 10).

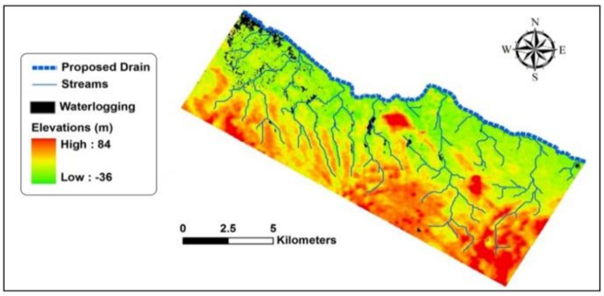

Fig 10. A suggested surface drainage network.

CONCLUSION

The agricultural expansion and waterlogging problem East of Siwa oasis were detected and mapped by using a time series of Landsat images. The application of remote sensing indices such as NDVI and MNDVI provided reliable information about the land use and land cover conditions in the investigated area, which could help in the sustainable land management. During the period from 2009 to 2018, the study area witnessed an obvious expansion in the agricultural land through desert reclamation, where the cultivated land area was approximately doubled by 2.3 times in nine years. In contrast, the waterlogged area remarkably increased by 21 times during the same period, where it extended from 19 ha in 2009 to 393 ha in 2018. The development of the waterlogging problem in the study area was regarded to the continuous increase in the surface water level of Lake Aghormy as well as the trapping of the agricultural drainage water and well-water overflow between the sand dune formations. Therefore, this study recommended a strategy to mitigate the waterlogging problem in the investigated area, which will enhance the drainage conditions and consequently it will limit the growth of waterlogged areas.

Although this strategy may be effective in solving the waterlogging problem within the study area, the surface water level in the lakes continues to rise, causing waterlogging and soil salinization of the most fertile and valuable lands in the oasis. This requires the concerted efforts of the government and the private sector to broadly solve the drainage problem in Siwa oasis through establishment of a general strategy for the oasis development. This strategy may include one or both of the following proposals: i) Reuse of the agricultural drainage water in the forestation of sand dune and tree fencing, which reduces the risk of sand storms and dune movement in the oasis, or ii) Transfer of the lakes' extremely saline water outside the oasis.

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تحديات الإدارة المستدامة للأرض بواحة سيوة: مشكلة غدق التربة في الأراضي الصحراوية المستصلحة حديثا

أسامة راضى محمد عبد القوى
قسم الاراضى والمياه - كلية الزراعة (الشاطبى) – جامعة الاسكندرية

تعتبر مشكلة غدق التربة من المشاكل التى تعيق تحقيق الادارة المستدامة للارض، ولمعالجة تلك المشكلة يجب ان يتوافر عنها معلومات دقيقة ودورية، حيث تساعد تطبيقات تقنيات الاستشعار عن بعد فى امكانية رصد وتحديد الارضى المتأثرة بالغدق وبالتالى وضع الحلول المناسبه لها. تهدف هذه الدراسة الى :1) رصد وتحديد مساحات الاراضى الزراعية وكذلك الأرضى المتأثرة بالغدق فى الاراضى الصحراوية المستصلحة حديثا بشرق سيوة، وذلك باستخدام بيانات وتقنيات الاستشعار عن بعد. 2) اقتراح خطة مستقبلية لحل مشكلة غدق التربة فى منطقة الدراسة. تم الاستعانة بأدلة الاستشعار عن بعد لتحقيق اهداف الدراسة مثل دليل الغطاء النباتى *NDVI* والدليل المعدل للمياه *MNDWI* حيث استخدمت أربع صور للقمر الاصطناعى الامريكى لاندسات والتى تغطى المنطقة، هذه الصور التقطت فى السنوات 2009، 2012، 2015، 2018. نتائج دليل الغطاء النباتى اوضحت ان الاراضى الزراعية تضاعفت بمقدار 2.3 تقريبا خلال تسع سنوات وهى الفترة من 2009 حتى 2018. هذه الزيادة ترجع الى المشاريع الخاصة لاستصلاح الاراضى بواحة سيوة. فى المقابل، وجد ان الزيادة فى الرقعة الزراعية بمنطقة الدراسة كانت مصحوبة بظهور وانتشار مساحات معتبرة من الاراضى المتأثرة بالغدق. حيث اوضحت نتائج دليل المياه ان مساحة الاراضى المتأثرة بالغدق ازدادت من 19 هكتار فى عام 2009 الى 393 هكتار فى عام 2018، وأن ظهور مشكلة الغدق هى نتيجة لارتفاع منسوب المياه فى بحيرة أغورمى بالاضافة الى تجمع وانحصار مياه الصرف الزراعى ومياه الابار بين تجمعات الكثبان الرملية. خلال هذه الدراسة تم اقتراح استراتيجية لمعالجة الاراضى المتأثرة بالغدق والتى تعتمد على فكرة انشاء مصرف رئيسى على الحدود الشمالية من منطقة الدراسة والجنوبية من بحيرة أغورمى بحيث يقلل من مستوى الماء الاراضى فى المنطقة المدروسة، علاوة على ذلك انشاء بعض المصارف العرضية فى المنطقة والتى يجب ان تتصل بالمصرف الرئيسى مما يساعد على تفريغ المياة المخزنة بين تجمعات الكثبان الرملية. هذه الشبكة من المصارف سوف تساعد على حفض مستوى الماء الارضى وتحسين ظروف الصرف وحل مشكلة غدق التربة.