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The use of GIS and remote sensing for the assessment of waterlogging in the dryland irrigated catchments of Farafra Oasis in Egypt

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Abstract

This paper investigates the interplay of the hydrogeological characteristics, soil properties and recent land reclamation projects on the distribution of waterlogging and salinisation within the Farafra Oasis. The multi-temporal remote sensing data and field observations show that new reclaimed areas have been recently cultivated in distant areas from the old agricultural land. These new cultivations have developed widespread water logging, seepage channels and soil salinisation. Analyses of the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) showed that both old and new agricultural areas are located within same closed drainage basin. The fluvial channels of these catchments, which were developed during wet climatic pluvial have largely been obliterated by the prevailing aridity and often buried under aeolian deposits. However, the new cultivations have been developed on the fingertips of these fluvial channels, while the old fields occupy the low level playas. The soil of the new cultivated areas are mainly lithic with a high calcium carbonate content, thus limiting the downward percolation of excess irrigation water and therefore develop perched water table and seepage through the paleo-channels. The automatically extract drainage networks from DEM are resembling fluvial patterns and coincide with the seepage channels slowly heading toward old cultivation. The inactive alluvial channels and landforms have to be considered when planning for new cultivation in dryland catchments to better control waterlogging and salinisation hazard. It is highly recommended that newly developed seepage-channels have to be detected and intercepted before reaching old agriculture areas. Therefore, the "dry-drainage" concept can be implemented as the seepage water can be conveyed into a nearby playas reserved for evaporation.

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1 Introduction

One third of the world's land surface has been classified as arid or semi-arid and nearly half of the countries are directly affected in some ways by problems related to aridity (Simmers, 2003). However, soil and water resources of dryland are limited and poorly distributed, the growing demands for water and food production have initiated large scale reclamation projects in the surrounding of desert areas. Although, these development projects are intended to satisfy and maintain the human needs, they have neglected the impact of the hydrogeological setting on the landuse planning and management. The expanding agricultural is often dependent on the diversion of river water across different basins, for example the Tarim River in NW China (e.g. Huang and Pang, 2010), the "All-American Canal", which conveys water from Colorado River into the Imperial valley in Southeastern California (e.g. Houk et al., 2006). More recently, 5 billion m^3 of water is being conveyed from Lake Nasser into Tushka area in the southwestern desert of Egypt, in order to expand agricultural areas outside the realm of the delta and Nile valley and to alleviate these highly over-populated areas (El Bastawesy et al., 2008a). Notwithstanding, the agricultural development in the core of Saharan areas depending on non-renewable to limited groundwater resources, which are being depleted by over pumping (Marechal et al., 2006). Consequently, the disturbance of these areas hydrological balance and the irrigation of poorly drained soil has induced high perched water table, and thus developed waterlogging and salinisation (Bradd et al., 1997). Over time, if there is inadequate drainage, the depth to the water table will decrease and a shallow saline water table is likely to develop, and consequently, some irrigable lands are eventually abandoned (Williamson, 1998). In the presence of a shallow saline water table, crop production can suffer when salts accumulate in the soil surface through capillary action and/or directly as a result of waterlogging (Houk et al., 2006). Soil salinity negatively affects crop growth by increasing the osmotic potential of the soil solution, which decrease the ability of crops to extract water and thus decrease crop yield (Jones and Marshall, 1992; George et al., 1997).

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The problem of waterlogging and salinisation is of global extent; estimates suggest that the annual worldwide crop production losses associated with salinity on irrigated lands are around US$ 11 billion (Ghassemi et al., 1995). It is estimated that about 45 million ha (19 %) of the total irrigated land worldwide is severely affected by induced waterlogging and associated salinisation (Hoffman and Durnford, 1999). Annually, 1.0 to 1.5 million ha is additionally degraded by salinisation (Wichelns, 1999). For example, it is estimated that around 9.4 % of the quite recently reclaimed land in Western Australia is suffering from severe hydrological changes and extensive salinisation. Furthermore, this figure will be doubled within 25 yr, unless the complex hydrogeological processes are properly understood, and cost-effective farming management methods are also introduced (Bradd et al., 1997; George et al., 1997). It was also estimated that 30 % of the cultivated lands downstream of the Indus Basin are confronted with salinity and waterlogging problems. The new irrigation projects were introduced into the basin without adequate drainage systems; the seepage for unlined earthen canals and the percolation from irrigation fields have developed serious land degradation problems (Qureshi et al., 2008). In Egypt, the agricultural lands area is estimated to be about 8.2 million acre, i.e. 3.45 % of the state total area; with 5.7 million acre of old irrigated lands (in Delta and the Valley), 2.2 million a reclaimed and irrigated lands (in desert fringes and oases) and about 0.3 million acre of rain-fed cultivations (in Mediterranean coastal areas). The problem of saliniastion and waterlogging has rapidly increased after irrigation system was converted from basin to perennial following the construction of High Dam (Abul-Ata, 1977). Within 20 yr of the High Dam operation waterlogging and salinization had affected 28 % of farmland in Egypt and average yields in those areas had fallen by 30 % (Wichelns, 1999).

Conventionally, water logging and soil salinity can be controlled through maintaining a net flux of salt away from the root zone and controlling the water table thorough drainage systems (Konukco et al., 2006). This can be achieved by the construction of artificial drainage infrastructures including both open surface drains and subsurface drainage pipes (Abdel-Dayem et al., 2007). The concept of "dry drainage" is also being

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used, in which parts of the available cultivated land are allocated as sinks to collected seeped excess-irrigation water to the fallow lands and thus preventing rising water table (Khouri, 1998). This system proved significance in controlling water logging in Indus basin in Pakistan, in Australia, and in rice-growing areas of West Africa (Konukco et al., 2006). Recently, the "bio-drainage" approach has also widely been used to combat soil slinisation and water logging, particularly in dry land areas. Certain plant species are capable of lowering the rising ground water tables and can be adopted as an alternative and cheaper strategy to control salinity (Zhao et al., 2004). The increasing expansion in agricultural areas and the developed widespread waterlogging and salinisation require time-effective and reliable remote sensing monitoring and observation, essentially to record changes and to anticipate further degradation. Thus, proper and timely decisions can be made to modify the management practices or undertake remedial actions that are most appropriate (Masoud and Koike, 2006).

The hydrogeological understanding of dryland setting from the catchment perspective is essentially required to fully comprehend how water logging and soil salinisation develop and outbreak in agricultural areas. The fluvial setting and hydrological processes of the dryland catchments are often overlooked as the drainage channels are usually abandoned and inactive for long periods, and may even be veneered and buried under aeolian deposits. The mapping of drainage channels and catchment outlets can be derived with reasonable accuracy using the available Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (e.g. Ghoneim and El-Baz, 2007; El Bastawesy et al., 2009). These derivatives are optimally integrated with soil properties, extent of cultivated areas, the fluvial and geomorphological setting of catchments to interpret the waterlogging and salinisation processes. This is to determine the most suitable remedial action to plan for an artificial drainage system, which should be uniquely compatible with hydrogeological setting of each catchment.

The concept of integrated catchment hydrological processes in dryland areas are often neglected when expanding agricultural development. As a result, the lack of understanding of soil, irrigation and drainage management within the study area has

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developed rapid land degradation. The current study aims to monitor and assess the water logging and salinisation hazard rapidly developed as a result of adding new cultivated areas in the higher fringes of old cultivated lands within the Farafra Oasis in the Western Desert of Egypt. The original landforms and geomorphology of catchments control the patterns of water logging and soil salinity hazards. The developed saline seepage pathways from new cultivation areas replicate the spatial patterns of fluvial channels. Thus water logging hazard can be better understood and thus mitigated by remote sensing and GIS mapping of the hydrological parameters, which must be considered to design the artificial drainage of agriculture fields.

2 Study area

Today, the hyper-arid core of the Great Sahara in Africa is one of driest places on earth currently receives less than 1 cm of rainfall per decade (Bornkamm and Kehl, 1989). Exceptionally, oases in the Sahara are endowed with plentiful discharge of groundwater that sustains human occupation as early as the Paleolithic. Where natural discharges from springs provided reliable perennial resources, which controlled both migration patterns and settlement of early populations (Hassan, 1997). Proxy data of archaeological studies, playa and palaeolake deposits, age dating techniques, and radar remote sensing data indicate that the Sahara has undergone several dramatic environmental changes in the Quaternary. Pluvial wet phases, which interrupted the long-term prevailing aridity of Sahara have developed fluvial channels, lacustrain deposits in local depressions, and more significantly have replenished the groundwater aquifers (Nicoll, 2004). Most of the evidences of preceding wet phases (i.e. paleodrainage) have largely been obliterated by the erosion and aeolian deposits (McCauley et al., 1982; Haynes, 2001; Pachur and Hoelzmann, 2000). Most of the paleodrainage has been buried under aeolian deposits, and have largely been detected by the Radar technology (e.g. Blumberg et al., 2004; Paillou et al., 2009).

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The depression of Farafra Oasis is located in the middle part of the Western Desert nearly at 650 km to the southwest of Cairo, it approximately covers an area over 10 000 km^{-2} (Fig. 1). Although, hyper-arid climate prevails the oasis and surrounding desert areas, playa deposits preserve paleoclimatic and archaeological evidences, which clearly depict Quaternary wet climatic phases that sustained early human occupations during the prehistory. Limited archaeological remains of the eighteenth dynasty and Roman periods are also found in the oasis (Hassan et al., 2000). In 1960, the population of the oasis was approximately just 1000 persons. Recently, unprecedented immigration from the Nile Valley and Delta was triggered following the construction of connecting networks of road and motivated by the staggering need for new land reclamation projects. These new projects are being developed on large tracts of soil mainly available in extensive playas, plains and outwash which are developed at the footslope of bounding scarps and on the floor of the depression. The water resources are mainly extracted from the deep Nubian Sandstone aquifer. Generally, the water is of reasonable quality, but there are growing concerns on the safe yield production of the aquifer given the non to limited recharge of the aquifers and the rapid developments of other mega-agriculture projects in other different parts of the Western Desert pumping the same aquifer (Thorweihe, 1990; Idris and Nour, 1990).

Traditionally, in the realm of almost flat topography in the Nile valley and Delta (i.e. old cultivation areas) the irrigation and discharge managements are largely dominated by land leveling techniques. In these old cultivation areas, artificial drainage networks and irrigation channels are arranged in alternating arrays trending from south to north as the main Nile flow direction. The open surface drainage and subsurface drainage systems are implemented on a large scale to sustain the irrigated agricultural and maximize crop yields (Abdel-Dayem et al., 2007). Large areas of the newly-reclaimed land in the desert areas have already been leveled and irrigated. But artificial drainage system have not yet developed, as it is generally believed that the natural drainage capacity of the deep sandy soil profiles is efficient to control rising soil water tables and salt accumulation in these areas. Unfortunately, this is not the case, remote sensing

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observations and field investigation show a large scale spread of water logging and salinization in the new agricultural areas in the Farafra Oasis. The digging of traditional more or less parallel and straight open drainage seems no effective to collect and control the widespread water logging in the farms.

3 Geology and geomorphology

The Farafra depression is a semi-closed basin with an irregular shape, where it is bounded by the escarpments from the north, east, and west. The depression floor gradually rises southward and merges into the plateau that forms the northern escarpment for Dakhla and Abu Minqar Oases. The depression is mainly underlain by Palaeocene-Eocene sedimentary rocks, where the chalk of Upper Cretaceous (Khoman Formation) and Paleocene (Tarawan Formation) cover large areas in the north and the shale (Dakhla Formation) is mainly exposed in the south. Lower Eocene formations (El-Naqb and Farafra limestone) cap prominent escarpments (El-Azabi and El-Araby, 2000). However, major faults have outlined the western escarpment of El-Quss Abu Said Plateau and also along some other sectors of the northern escarpment. But the interplay between fluvial and karastic processes under changing climatic conditions since the Miocene has developed most of the current landforms. Chemical weathering and wind deflation have developed several small depressions (i.e. karst) on the main floor. Some of these depressions have been partially or fully filled by playas during the Quaternary wet climatic periods (Hassan et al., 2000). Generally, detailed mapping of the playas in the Western Desert is yet not available. However, more than 100 playas of different sizes were identified In Farafra depression from high resolution aerial photographs, and in total they cover about 440 km^2 (Embabi, 2004). Few playas are of large surface areas and they have been developed for agriculture. For example Al Gunnah playa, which is located at the northeast footslope of Kuss Abu Said Plateau, covers alone an area of more than 100 km^2 and it represents one of the oldest agricultural and settlement areas in the Farafra depression.

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Under the prevailing aridity, these widespread playas are exposed to wind erosion that scoured the former lake deposits and thus developed yardangs of various shapes and sizes, which stand as small residual hills above the surrounding playa floor. The eastern part of Farafra depression is covered by fields of sand dunes. These dunes generally extend southeast for about 200 km from the northeast corner of the depression to the northern escarpment of Dakhla depression. Interdune areas become wider southwards and eastwards and therefore, the decrease in sand supply dismantle the widely separated dune ridges into separate barchans before reaching the scarps of Dakhla depression (Embabi, 2004). Sand sheets also cover large surface areas in different places and have consequently obscured most of the fluvial channels developed at wetter climatic phases. Playas and sand sheets areas were recently engaged in a large scale development project including reclamation by land leveling, and digging of parallel irrigation and drainage channels. Tens of deep wells were drilled to tap the Nubian Sandstone aquifer for irrigation and other living purposes. The Nubian Sandstone aquifer is one of the largest groundwater aquifer in the Sahara, and it extends for over 630 000 km^2 in the Western Desert of Egypt, it represents the only source of water in the oases. The increasing demand for limited water and soil resources in the Western Desert, threats the processes of sustainable developments. Where the Nubian Sandstone aquifer is being over-pumped at a rate greater than the recharge, which may currently take place from deep aquifer layers or only have been replenished during pluvial times (Dabous and Osmond, 2001). This fossil groundwater is used in extensive cultivation projects across the Sahara. The impacts of intensive development on groundwater include excessive decline of water levels, depletion of aquifer storage, deterioration of groundwater quality and more important the salinisation and water logging hazards of the development projects. For example, the groundwater levels in Dakhla Oasis are gradually being lowered by a rate of 1 to 4 $m\,yr^{-1}$ as a result of over-pumping of the deep Nubain Sandstone aquifer for irrigation. Additionally, the productivity of soils is increasingly affected by high unfavourable drainage conditions and improper farming and irrigation practice have caused widespread water logging and

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salinisation of soils (Khouri, 2003). The rapid deterioration in land induced by spreading of water logging and salinization are detected and assessed using the following methodology.

4 Data and methods

Three Landsat TM and ETM+ satellite images for the Farafra depression, acquired in the years of 1984, 2001 and 2010, were obtained and processed to monitor the landuse changes. However, the ETM+ images acquired after May 2003 (except the nadir areas) are flawed with systematic missing scan lines (i.e. gaps) across the scenes. Fortunately, the area of interest in the Farafra Oasis is located in the flawless zone of the ETM+ images, and thus the analyses of muti-temporal images was not affected by the missing lines. Visual interpretation of the 1984 TM satellite image shows that the old agricultural fields are mainly developed on the floor of the playa depression, which is located at the north-eastern footslope of Kuss Abu Said Plateau (Fig. 2). Analyses of the ETM+ image of 2001 shows that totally new extensive areas of agricultural fields have been added to the southeast of old areas. Usually, the identification of waterlogging and soil salinisation can be achieved using either visual interpretation or digital analyses of bare and cultivated soil and vegetation index (Wildman, 1982). Equally these different methods require ground truthing and field verification. Waterlogging and excess soil moisture content can easily be detected on the satellite images as soil reflectance significantly decrease (in the visible part of the spectrum) in poorly drained and waterlogged areas than well-drained soil. However, selecting optimum satellite images is very crucial reflectance of soils and crops are varying at different stages of vegetation growth and irrigation status. Therefore, the visual interpretation is more reliable than digital analyses and classifications when multi-temporal satellite images covering the cultivated areas at different times. The Interpretation of the multi-temporal satellite images and field observations show that the new project area has developed a large scale water logging, ponds in low areas, and entailed by seepage areas heading to the “old” agriculture fields.

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The DEM of SRTM (Fig. 3) was processed to automatically extract the drainage networks and sub-catchment boundary of Farafra depression in order to investigate the spatial relationship of agriculture fields and developed seepage channels in context of catchment hydrology. The hydrological analyses of DEM was carried out using the widely used D-8 algorithm embedded in ArcInfo software with some modifications in the filling of DEM step (El Bastawesy et al., 2008b). This method requires, first, that all the sinks (i.e. local depressions) of the DEM to be filled and raised in elevation to their neighbouring cells in order to ensure the flow continuity within the catchment to an outlet (Jenson and Dominique, 1988). The filling step of the DEM does not distinguish between naturally occurring sinks (i.e. playas), which is the case in Farafra depression and the artefacts resulting from the generation technique of DEMs. The main playas dotting Farafra depression were delineated by visual interpretation of satellite images and their relative low elevations to surrounding were assessed using the available DEM. Some of these playas are covered in parts by sand sheets and also cultivated. However, any given playa can be considered as terminals for surface flow and seepage from a fixed catchment area, the individual playas can be connected by over flow channels under certain hydrological conditions and thus their catchments are relaxed. Herein, playas were individually delineated and masked from the processing steps of DEM to locally entrap the surface flow in separate and terminal locations. Therefore, the contributing drainage networks and catchment area to the different terminal playas have been determined following the subsequent D-8 algorithm routine in ArcInfo as follow:

1. The terminal-masked DEM of Farafra depression was filled;
2. The flow direction of each cell into the lowest elevation cell of the surrounding eight cells was determined;
3. Once the route of flow is determined for each cell, it is possible to accumulate the number of upslope flow contributing cells (i.e. areas) and the flow pathways;

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4. Selecting a threshold of the minimum flow accumulation number is required to extract the fingertips of delineated channels and different catchments within the Farafra Depression (Fig. 4).

The automatically extracted drainage networks were overlaid ontop of the satellite images, which show the seepage pathways in order to investigate the correlation between the DEM-simulated hydrographic flow patterns and the emerging seepage patterns. This is to understand the control of geomorphology and landforms on dynamics of water logging and seepage and how to sustain newly developed agricultural areas. Furthermore, since the radar images are not available for the study area, the SRTM was displayed in panchromatic image to show the shallow-buried alluvial channels (Fig. 5). The SRTM uses a microwave signals of a 5.7 cm wavelength which is similar to the C-band of Radarsat-1 satellite that can penetrate upto 0.5 m in desert areas veneered by sands (Schaber et al., 1997; Ghoneim and El-Baz, 2007)

5 Mapping of soil and landforms

The soil map of the study area was extracted from the available soil map of Egypt (ASRT, 1982), the original nomenclature of soil order, suborders and great groups have been updated using the latest American Soil Taxonomy of USDA (2010). The ETM+ satellite image of 2010 was pre-processed, and enhanced using ENVI 4.7 software (ITT, 2009) to delineate the extent of agricultural developments, seepage and water ponds. The different landforms were initially determined from the satellite images and DEM following the methodology developed by Dobos et al. (2002) (Fig. 6). The digitized soil units were correlated and combined with the delineated landforms to define the dominant soil sets, which indicate the vulnerability to water logging and salinisation hazards. Accordingly, the optimum land use and soil management can be suggested.

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6 Results

Hydrologically, the Farafra depression is a closed drainage basin occupied by several playas; each is fed by a set of drainage channels. The surface channels that were formed during the Quaternary wet pluvial are often buried and veneered by sand sheets and cannot be fully traced from optical satellite images and available topographic maps. Therefore, the catchment parameters were automatically delineated from the available DEM using the D-8 method embedded in ArcGIS. The playas (i.e. natural sinks) were first delineated from the visual interpretation of satellite images and DEM values, then their locations were masked from the DEM thorough the consequent steps of extracting the drainage parameters. This is to enforce the drainages entrapment into these pre-defined natural sink holes to accurately map the constituting catchments of the closed drainage basins. The conventional filling of all sinks in the DEM leads to overestimation in catchment areas and errors in flow pathways, where the extracted channels may override exiting the local flow collection areas (playas) to only reach the lowest level playa at the footscarp of Kuss Abu Said Plateau. The old agriculture areas occupied the floor of three separate playas. The fringing mudflat of the old cultivation are gradually being reclaimed, However a huge project was recently established on the outwash plains in the southeast catchments of the study area. The newly cultivated catchments show severe water logging and salinisation that appeared after land levelling and irrigation (Figs. 7 and 8).

The construction of spaced, parallel open drainage channels to combat water logging seems not effective as lots of farms were abandoned, particularly in the lithic soils. The designed artificial drainage channels are intersecting with the natural buried channels only in some places. The natural drainage channels must be considered, excavated (if buried), and used to collect the excess water, which usually moves laterally toward channels as throughflow. The developed water logging is spatially associated with the neglected natural channels, and the detected seepage areas from the “new” agricultural areas is following these paths toward the local playas of these catchments

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(Fig. 9). The most recent satellite images shows that these seepage channels have partially filled the local playas with ponds, which are only at short distances from the old agricultural fields (see Fig. 2).

The current situation clearly indicates that the regional physiographic setting of soil was not comprehended, where adopting the same technique of farm management in the Nile Delta and the Valley may not be appropriate in the Sahara. The agricultural fields are mainly situated on depressions, footslopes, mudflats, outwash plains and playas landforms (Table 1). Most of the soils in these landforms are usually shallow (less than 0.5 m deep). These shallow soils are: Lithic Torrifluvents, Lithic Torriorthents, and Lithic Torripsamments. On the other hand, deep soils (from 1.5 to 1.7 m) are mainly represented by Vertic Torrifluvents and Typic Torrifluvents soils and occupied by the "old" cultivation. The calcium carbonate content is very high, particularly in the Typic Haplocalcids soils. This implies that calcic horizons in these soils can develop sub-surface hardpan, which encroaches the rapid development of water logging hazards. Additionally, saline soils (Typic Haplosalids) are of widespread distribution in different cultivated lands.

7 Discussion and conclusion

The regime of dryland catchments in different parts of the globe has been disturbed by the large scale and unprecedented agricultural development in these areas. This is mainly driven by the stress of population increase, economical growth and development. The huge surplus irrigation water whether conveyed from nearby river catchments, or pumped from underlying groundwater aquifer has slowly engaged the fluvial processes of these catchments. In some areas the role of fluvial channels (buried or exposed) were ignored in the planning and implementation of the mega-agricultural projects. This is clearly evident in the closed drainage catchments where all surplus irrigation water was gradually added to the shallow and perched water table and was logged on the surfaces of low-laying areas and in the channel courses themselves.

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Moreover, this can be recognised in trans-boundary drainage catchments, where regulations of using shared water resources are closely monitored, but the integrated fluvial processes and their impact on waterlogging and salinity developments in downstream are neglected.

Remote sensing data have been used as a rapid and efficient tool to monitor, assess and evaluate the progress of different land use and land cover changes (e.g. Palmer and Van Rooyen 1998; Shalaby and Tateishi, 2007). The planning for the Saharan new projects seems not preceded by sufficient multi-disciplinary integrated research on soil physiographic, catchment hydrology and their role on adopting certain irrigation and discharge strategies (e.g. Wichelns, 1999). It is of utmost importance to consider the context of catchment hydrological processes in planning for new cultivation projects in the Saharan soil. However the fluvial and hydrological processes of these catchments have been inactive for prolonged period under prevailing aridity. The irrigation of such soil has provoked a slow rate hydrological activities within the defunct channels. Therefore, the catchments have to be first determined and delineated using the available topographic maps or DEM and remote sensing data. Although, the delineation processes of surface drainage networks and buried channels depend on the availability of high resolution images, DEM and radar data. The quality of drainage networks extraction for the purpose of waterlogging management at the cultivated plots scale would increase by the availability of more precise DEM as such those produced by laser scanning or detailed field survey.

The understanding and mapping the distribution of soils units, particularly in the closed drainage catchment is also necessary to better manage the waterlogging problems. For example, the lithic soils are highly susceptible to waterlogging in low lying landforms (e.g. playas) than the developed on higher elevation such as footslope. Within each catchment only certain areas should be cultivated, the fluvial channels should be utilised for agriculture drainage, which must be conveyed into local non-developed playas. The system of reserving certain areas within the agricultural fields for seepage and collection of drainage water is known as the “dry-drainage” concept

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(Konukcu et al., 2006). This system is suitable to be implemented in the Saharan areas. The proportion of cultivated lands within each catchment, the irrigation water requirements, and evaporation from drainage ponds should be balanced, to prevent water logging and salinisation hazards.

In conclusion water logging and soil salinisation is the major threat facing inhabitation and development in the Saharan areas. Extensive water logging hazard has occurred as the geomorphologic setting was not considered when developing new agricultural areas. The playas and buried channels of closed drainage basins are the most vulnerable areas for water logging, particularly when the soil of higher surrounding areas is cultivated. It is recommended that constructed open drainage networks should coincide with the natural drainage system delineated using remote sensing and DEM analyses.

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Table 1. The main landforms and their associated soil classes in the Farafra depression.

Landform	Area (km^2)	Land use	Soil order				Soil set
			Entisol	Area (%)	Aridisol	Area (%)	
Depressions	474.29	Barren	Lithic Torriorthents Lithic Torripsamments	21.86 17.05	Typic Haplosalids	61.09	Complex
Foot slopes	1135.71	Barren	Lithic Torrifluvents Lithic Torriorthents Vertic Torrifluvents	23.42 36.98 25.62	Typic Haplosalids	13.98	Complex
Mud flats	223.07	Cultivated	Typic Torriothents Typic Torripsamments Vertic Torrifluvents	40.68 17.85 41.47	–	–	Complex
Outwash plains	1843.08	Cultivated	Typic Torriothents	100	–	–	Consociation
Peneplain	1345.795	Barren	Lithic Torriorthents Vertic Torrifluvents	83.97 16.03	–	–	Consociation
Playas	591.68	Cultivated	Lithic Torrifluvents Lithic Torriorthents Lithic Torripsamments Typic Torrifluvents Typic Torriothents Vertic Torrifluvents	7.14 28.91 2.92 16.05 1.25 19.98	Typic Haplocalcids Typic Haplosalids	15.54 8.21	Complex
Sabkhas	71.90	Barren	–	–	Typic Haplosalids	100	Consociation
Sand sheets	1860.86	Barren	Typic Torripsamments	100	–	–	Consociation
Wetlands	29.50	Barren	– –	– –	Typic Haplosalids Aquic Haplosalids	16.59 12.91	Consociation
Sand dunes	2337.94	Barren	–	–	–	–	–
Plateau	1149.5	Barren	–	–	–	–	–
Rock outcrops	183.95	Barren	–	–	–	–	–

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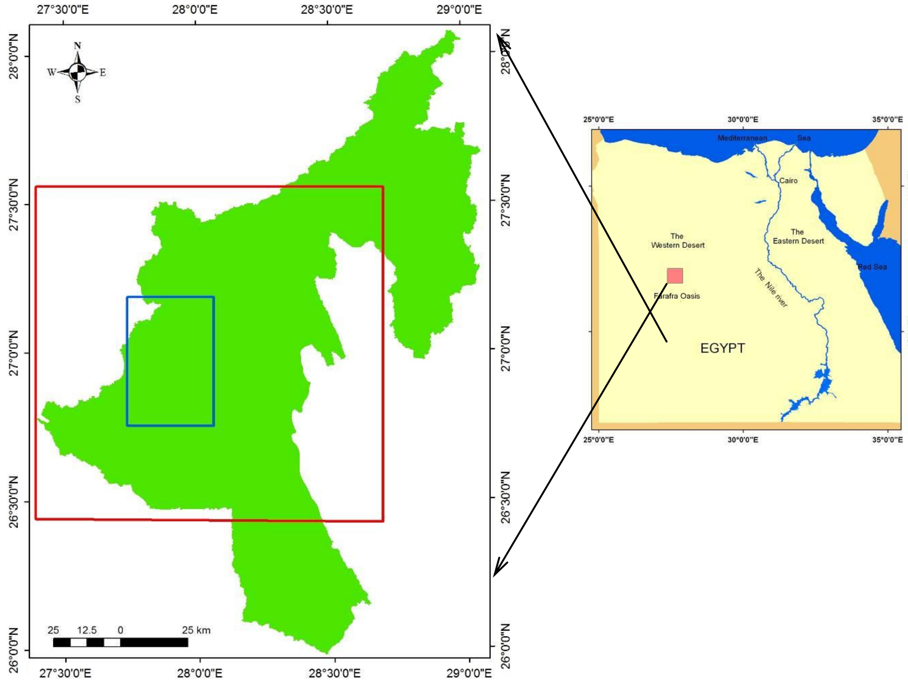

Fig. 1. Location of the Farafra Oasis on Egypt map (right). Solid green area outlines (Figs. 3 and 4), red box outlines (Fig. 5), blue box outlines (Figs. 2 and 8).

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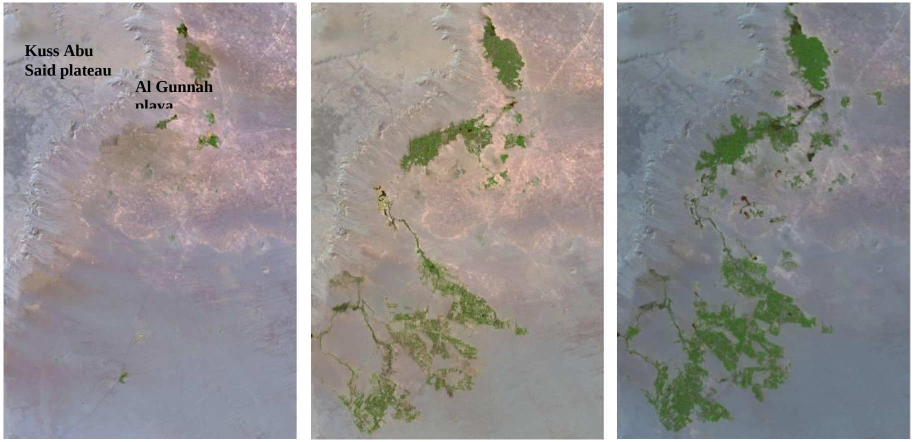

Fig. 2. The Landsat TM and ETM+ images for the Farafra Oasis show the extent of agriculture areas (green) in 1984 (left), 2001 (middle) and 2010 (right). Note the development of seepage channels and water ponds (black) during the period of 2001 to 2010.

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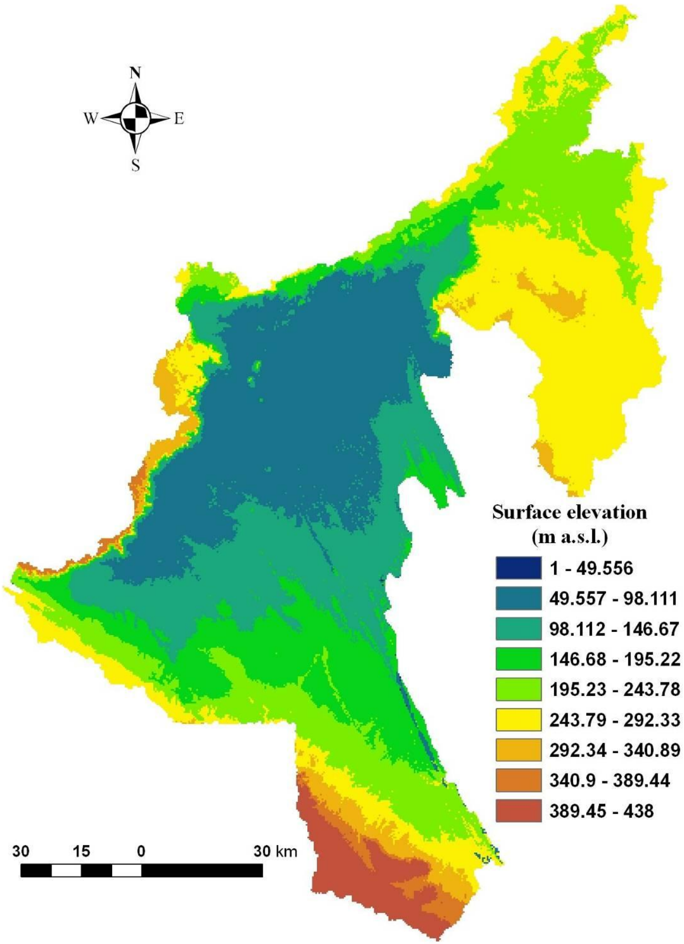

Fig. 3. SRTM DEM of the catchment area.

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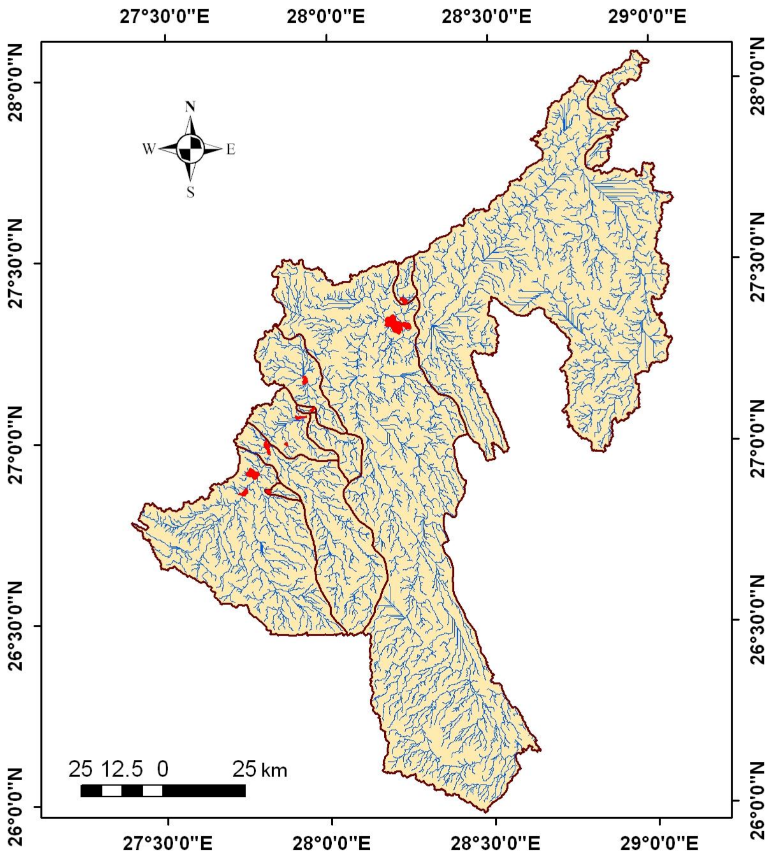

Fig. 4. The automatically extracted drainage networks (blue lines) and sub-catchment boundaries (thick brown lines) from the DEM in Fig. 3. The terminal playas of these subcatchments (solid red areas), are partially submerged by water on the most recent satellite images, and their DEM-elevation levels are lower than surrounding surfaces.

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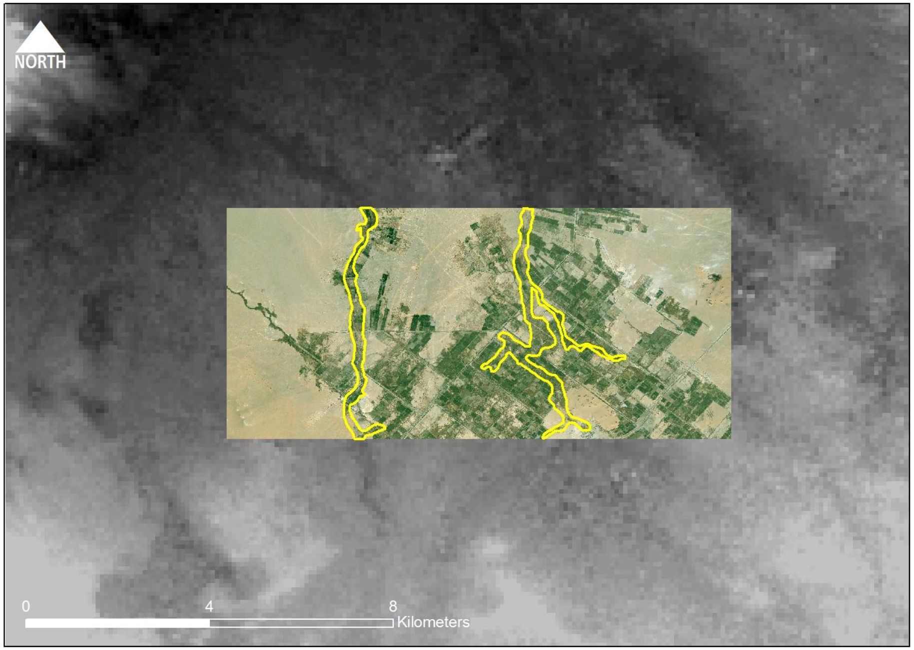

Fig. 5. A panchromatic SRTM images shows the shallow-buried alluvial channels (dark tones) underlying some of the cultivated plots, as shown (outlined yellow lines) ontop of the satellite image.

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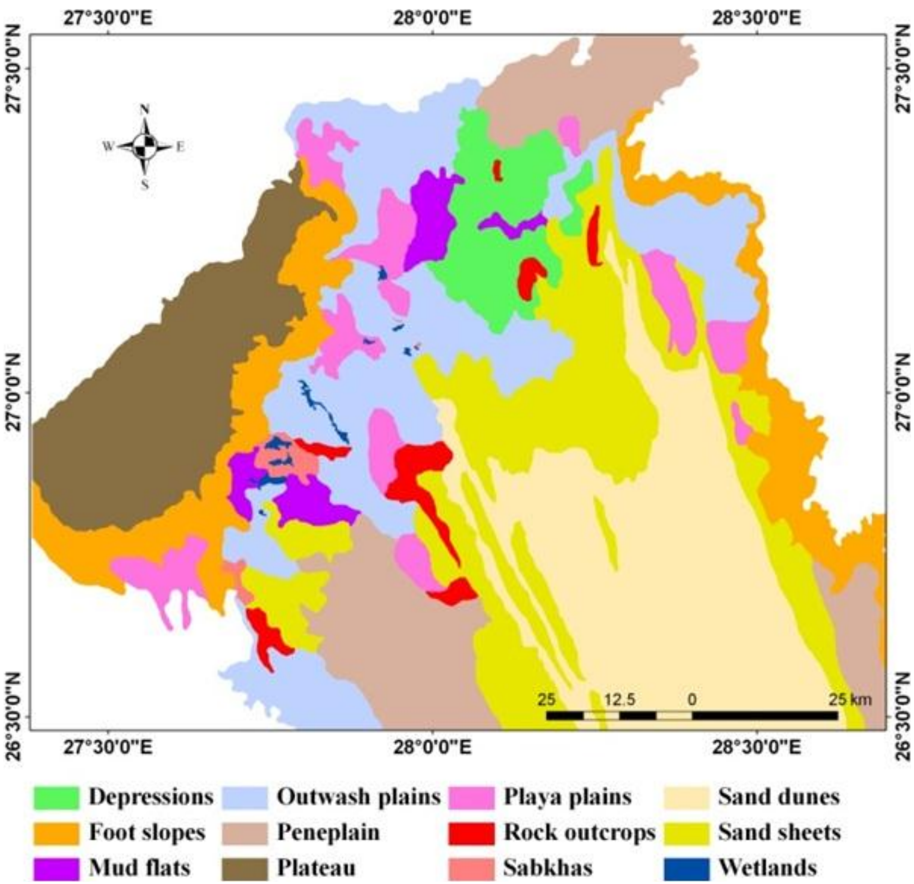

Fig. 6. Map shows the main landforms delineated from the satellite images and DEM for the Farafra Oasis. These units were preliminary checked for accuracy in the field.

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Fig. 7. Field Photo shows the developed water logging in the low laying playas.

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Fig. 8. Field photo shows the developed sodic patches in seepage channels and the growth of associated halophytes. The eastern scarp of Kuss Abu Said Plateau appears in the horizon.

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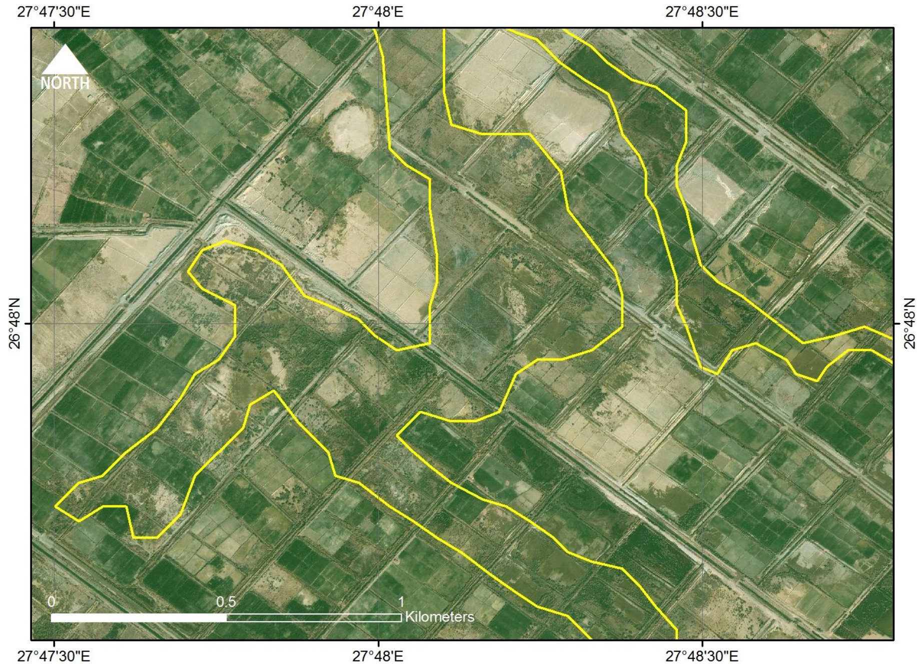

Fig. 9. Shows new the developed waterlogging marked by stressed cultivated plots and dark saturated soil, note the abundance of waterlogged plots ontop of the alluvial channels outlined by yellow lines (see Fig. 5).

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