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Assessment of waterlogging in agricultural megaprojects in the closed drainage basins of the Western Desert of Egypt

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Abstract. This paper investigates the development of waterlogging in the cultivated and arable areas within typical dryland closed drainage basins (e.g. the Farafra and Baharia Oases), which are located in the Western Desert of Egypt. Multi-temporal remote sensing data of the Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper (ETM+) were collected and processed to detect the land cover changes; cultivations, and the extent of water ponds and seepage channels. The Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) has been processed to delineate the catchment morphometrical parameters (i.e. drainage networks, catchment divides and surface areas of different basins) and to examine the spatial distribution of cultivated fields and their relation to the extracted drainage networks. The soil of these closed drainage basins is mainly shallow and lithic with high calcium carbonate content; therefore, the downward percolation of excess irrigation water is limited by the development of subsurface hardpan, which also saturates the upper layer of soil with water. The subsurface seepage from the newly cultivated areas in the Farafra Oasis has revealed the pattern of buried alluvial channels, which are waterlogged and outlined by the growth of diagnostic saline shrubs. Furthermore, the courses of these waterlogged channels are coinciding with their counterparts of the SRTM DEM, and the recent satellite images show that the surface playas in the downstream of these channels are partially occupied by water ponds. On the other hand, a large water pond has occupied the main playa and submerged the surrounding fields, as a large area has been cultivated within a relatively small closed drainage basin in the Baharia Oasis. The geomorphology of closed drainage basins has to be considered when planning for a new cultivation in dryland catchments to better control waterlogging hazards. The “dry-drainage” concept can be implemented as the drainage and seepage water can be conveyed through the inactive alluvial channels into certain abandoned playas for evaporation.

1 Introduction

The agricultural areas of the Saharan deserts are typically isolated, and mainly occur in small areas endowed by groundwater resources or ephemeral runoff of the surrounding mountains. Regionally, these limited groundwater resources of the drylands are being depleted by excessive pumping to cultivate the arable soils, as the demand for food production is increasing. Additionally, significant volumes of irrigation water are being transferred into the Sahara from the neighbouring perennial rivers. For example, 5 billion cubic meters of water will annually be conveyed from Lake Nasser into the Tushka area via a powerful pumping station and sets of artificial channels, in order to cultivate 2000 km^2 in the southwestern desert of Egypt (i.e. The South Valley Development Project) (El Bastawesy et al., 2008a). The main problem related to the large scale cultivation and irrigation of dryland areas is the development of waterlogging (Bradd et al., 1997). Over time, if there is an inadequate drainage system or considerable soil depth; a shallow perched water depth 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 (Jones and Marshall, 1992; George et al., 1997; Houk et al., 2006). Conventionally, waterlogging (i.e. excess soil moisture content) and soil salinity can be controlled through maintaining a net flux of salt away from the root zone and controlling the water table through 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).

Drainage networks, streams, catchment relief and drainage divides are important properties in the landscape, which significantly contribute to material flow (Burrough and McDonnell, 1998). Conventionally, the blue lines printed on most topographic maps represent these drainage networks, where continuous lines represent wet water courses and dashed lines seasonal ones (Chorowicz et al., 1992). The quality of these blue lines is dependent on the source of topographic maps and the level of expertise in portraying them. Furthermore, some of the ephemeral channels are expected to have been omitted during the production of these maps and many others may have spatial uncertainty, specifically in very low relief areas. The drainage networks of dryland catchments are often overlooked as the drainage channels are usually abandoned and inactive for long periods. Moreover, considerable areas of the dryland have been covered by aeolian deposits, and the buried drainage networks can only inferred by using Radar technologies and geophysical investigations (e.g. Blumberg et al., 2004; Paillou et al., 2009). Therefore, the traditional drawing of catchments and drainage networks from the available topographic maps, or the multi-spectral satellite images, can be fraught with a great deal of uncertainty. Thus, the automatic extraction of drainage networks and catchments from the digital elevation model (DEM) has widely been considered more objective in hydrological analysis than manual extraction (Tribe, 1991). The importance of the automatic delineation of drainage networks is well obvious in the Saharan desert areas; as the surface expression of the drainage courses is relatively poor and the quality of available topographic maps is questioned. Therefore, the mapping of surface drainage channels and catchment outlets can be derived with reasonable accuracy using the space-born DEM such as the Shuttle Radar Topography Mission (SRTM) DEM (e.g. Ghoneim and El-Baz, 2007; El Bastawesy et al., 2009). However, the accuracy and reliability of the hydrographic parameters simulation using DEM are known to be influenced by source, resolution and processing algorithms (Zhang and Montgomery, 1994; Wolock and McCabe, 1995). However, different sources and resolution of high quality DEM are expected to give highly correlated results (El Bastawesy, 2007). The various existing processing algorithms such as the D-8 (Mark, 1984), multiple flow direction algorithm (MFD) (Quinn et al., 1991) also have significant influence and result in relatively different network densities and distributions and catchments areas when applied on the same DEM sets (Desmet and Govers, 1996).

The concept of integrated catchment management in dryland areas are often neglected when expanding agricultural development. The productivity of soils is increasingly affected by highly unfavourable drainage conditions, and improper farming and irrigation practices have caused widespread waterlogging (Khouri, 2003). As a result, the lack of understanding of soil, irrigation and drainage management can result in rapid land degradation. The current study aims to investigate the land cover changes of cultivated areas in typical dryland catchments, in order to assess the development and extent of waterlogging. The DEM-derived hydrological parameters are integrated with the multi-temporal remote sensing images in order to determine the relation of waterlogging patterns to the drainage networks, geomorphology and soil properties of the catchments. This is to determine the most suitable remedial action, which should be uniquely compatible with the inherited hydrogeological setting and characteristics of each catchment.

2 Study area

The long-term prevailing aridity of the Sahara was interrupted during the Quaternary by wet climatic periods (i.e. pluvial), which developed fluvial channels, lacustrine deposits in local depressions, and more significantly have replenished the groundwater aquifers (Nicoll, 2004). Most of the evidence of preceding wet phases and the alluvial channels have widely been obliterated by the erosion and aeolian deposits (McCauley et al., 1982; Haynes, 2001; Pachur and Hoelzmann, 2000). Typical dryland closed drainage basins in the Western Desert of Egypt (the depressions of Baharia and Farafra Oases), were selected to assess the interaction of different landforms, the hydrogeological setting and the agricultural management on the land degradation of cultivated areas.

The depressions of Baharia and Farafra Oases are located in the middle part of the Western Desert of Egypt, they are oriented in the northeast– southwest direction and approximately cover an area over 18 400 km^2 (Fig. 1). The Baharia depression is entirely surrounded by escarpments, but the Farafra depression is a closed basin with an irregular shape, where it is bounded by limestone 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. Geologically, the floor of the Baharia depression is underlain by the Nubian sandstone (e.g. Baharia Formation), which is assigned to the Upper Cretaceous and it is overlain by successions of chalk and chalky limestone (Khoman Formation) and the limestone of middle Eocene (El-Naqb Formation) (Awad, 1996). The limestone of lower Eocene (El-Naqb Formation and

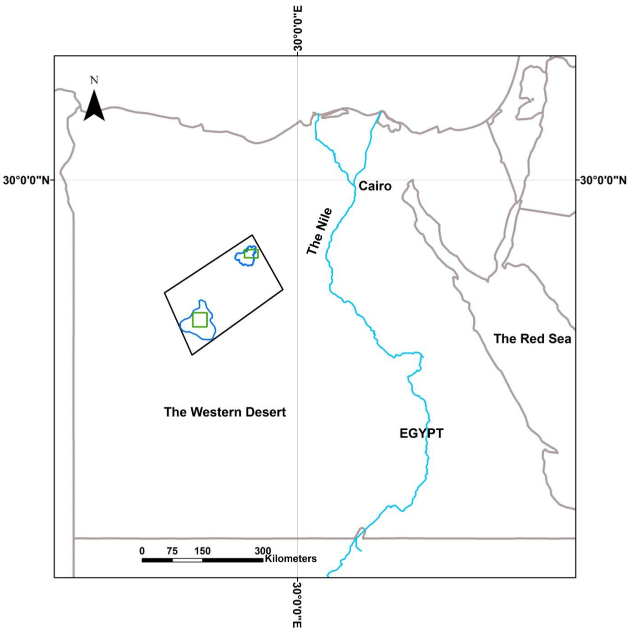

Fig. 1. Location map of the study area; the catchments of Farafra and Baharia depressions are outlined in blue, and the insets of satellite images are outlined by green boxes.

Farafra Formation) caps prominent escarpments surrounding the semi-closed depression (El-Azabi and El-Araby, 2000).

These depressions are composed of separate and interconnected local basins, which vary in size from several tens of meters up to hundreds of square kilometers in area (Embabi, 2004). For example Al Gunnah playa, which is located at the northeast foot slope of Al Quss 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 (Hassan et al., 2000). Recently, the Baharia and Farafra depressions as well as other oases in the Western Desert have undergone large scale development projects including reclamation by land leveling, and drilling hundreds of deep wells 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 (Dabous and Osmond, 2001). 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 parts of the Western Desert pumping the same aquifer (Thorweihe, 1990; Idris and Nour, 1990). These new irrigation projects are being developed on large tracts of soil mainly available in extensive playas, plains and outwash which are developed at the foot slopes of bounding scarps and on the floor of the depression of Farafra Oasis. However, large areas of the depressions have already been irrigated, but the drainage problems were ignored, 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, these hypotheses were not true and the cultivated areas have developed widespread waterlogging problems which are clearly visible in the field scale as well as on satellite images of moderate resolution such as the Landsat TM and ETM+.

3 Materials and methods

The identification of waterlogging on satellite images can be achieved using either visual interpretation or digital analysis of the Landsat spectral bands including: change detection techniques, ratios and vegetation index (Wildman, 1982). Equally these different methods require ground truthing, which are time and cost consuming. Water ponds can easily be detected on the satellite images as the reflectance of water is nearly zero in the reflective infrared bands (i.e bands 4 and 5 of the TM and ETM+), while the majority of surrounding land cover are of higher reflectance (Moore, 2000). Moreover, the dates of satellite image acquisitions are very crucial; as the reflectance of soils and crops vary at different stages of vegetation growth and irrigation status. The accuracy of delineated land cover classes, using the digital analysis algorithms embedded into software, can only be assessed when the multispectral data are calibrated by reference field data (i.e. training sets) which are not available for this area. Herein, the visual interpretation will be used as the available multi-temporal satellite images covering the cultivated areas are available only for few dates being separated by long periods of time. Four Landsat TM and ETM+ satellite images were collected for the Farafra and Baharia depressions (17 October 1984, 11 November 1989, 23 March 2003 and 30 September 2011); these images were acquired during the autumn and spring seasons in order to minimise the uncertainties of vegetation and cultivation reflectance during a single season. The study area was extracted from the available Landsat scenes. False colour composites of bands 7 (2.08–2.35 µm, shortwave infrared) 4 (0.76–0.90 µm near infrared) and 2 (0.52–0.60 µm visible green) displayed as red, green and blue respectively, were found to provide the best overall discrimination. These bands were also selected to minimise inter-band correlation, thereby maximising information content of the resulting composite image. Thereafter these images were further enhanced using the interactive stretching of histograms, then these images visually interpreted to detect the land cover changes and to map the waterlogged areas (Fig. 2).

The DEM of SRTM with 90 m resolution (Fig. 5) was processed to automatically extract the drainage networks and sub-catchment boundary for the studied areas in order to investigate the spatial relationship and aerial extent of agriculture fields and the catchment-drainage networks.

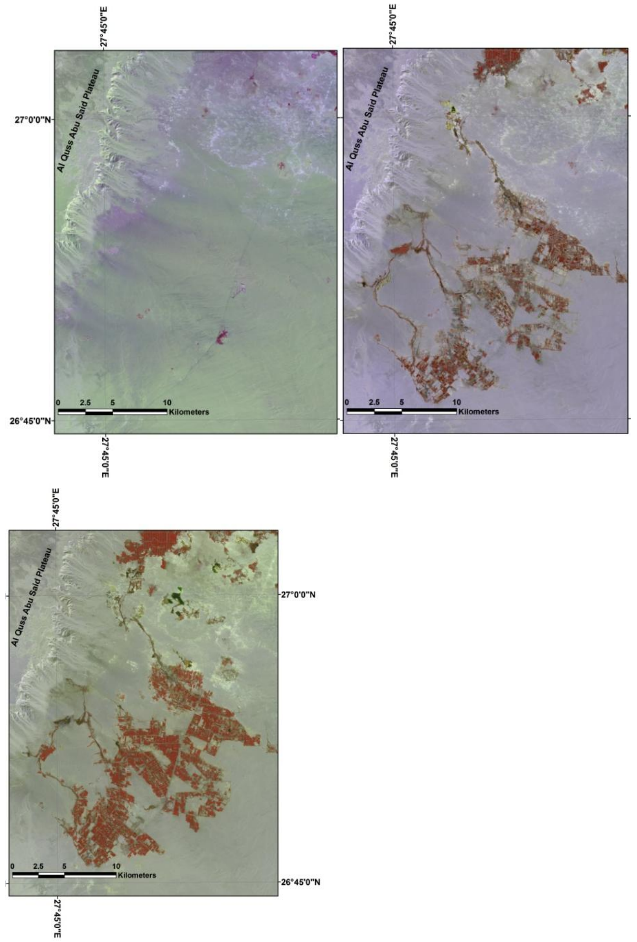

Fig. 2. The Landsat TM and ETM+ images for the Farafra Oasis, which show the extent of agriculture areas (red) in 1984 (top left), 2003 (top right) and 2011 (bottom). Note the development of seepage channels and water ponds (black) during the period of 2003 to 2011.

Fig. 3. Field photos show the development of waterlogging within the Farafra Oasis, and the growth of plant and shrub species distinctive to saline and waterlogged soil.

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). Therefore, it is important to adjust the flow directions to cope with the fact that the filling step of the DEM does not distinguish between naturally occurring sinks (i.e. playas), which is the case in the study area and the artefacts resulting from the generation technique of DEMs. The main playas dotting the area were delineated by visual interpretation of satellite images and their relative low elevations to the surrounding were assessed using the available DEM. The playas were masked from the processing steps of DEM to locally entrap the surface flow in separate and terminal locations. Therefore, the contributing drainage networks and sub-catchments of the different terminal playas have been determined following the routine application of the D-8 algorithm routine in ArcInfo as follow:

1. the terminal-masked DEMs were filled;
2. the flow direction of each cell into the lowest elevation cell of the surrounding eight cells was determined for the study areas;
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;
4. selecting a threshold of the minimum flow accumulation number is required to extract the channels and the catchments within the area.

The different landforms were initially determined from the satellite images and the DEM, and the ASRT (1982) soil map of Egypt following the methodology developed by Dobos et al. (2002) and the American Soil Taxonomy of

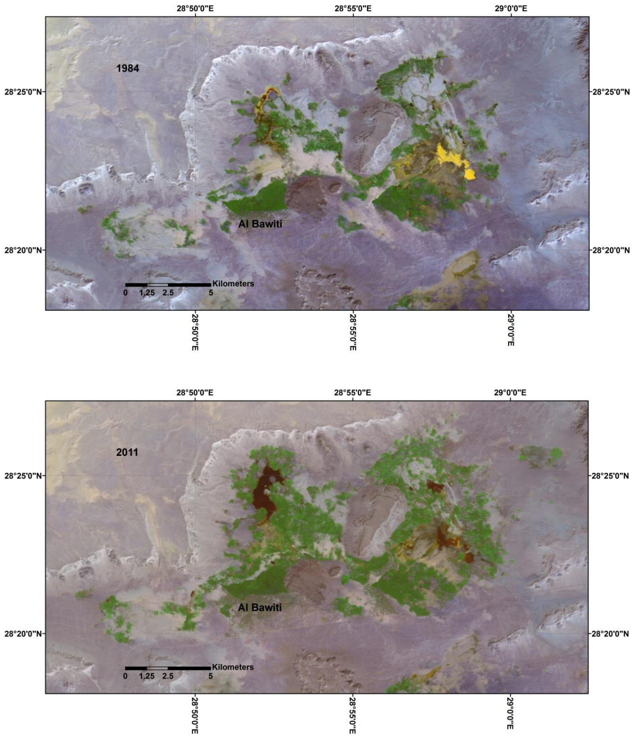

Fig. 4. The land cover changes within the Baharia Oasis between 1984 and 2011. Note the development of water ponds (black) on the low lying playas (yellow), and also note that the green colours represent the cultivated areas.

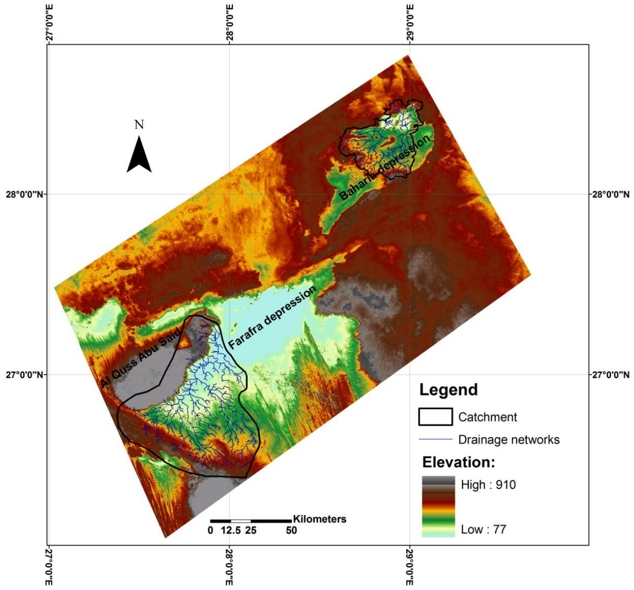

Fig. 5. The SRTM DEM and the automatically extracted drainage networks for the cultivated catchments within the study area.

USDA (2010). The digitized soil units were then correlated and combined with the delineated landforms to define the dominant soil sets, which indicate the vulnerability to waterlogging (Fig. 6).

4 Results

In the Farafra Oasis, the Landsat TM satellite image of 1984 (path 178/row 41) shows that agricultural fields are of small areas (6.5 km^2) and mainly concentrated on the floor of Al Gunnah playa (i.e. the village of Qasr Al Farafra), which is located at the north-eastern foot slope of Al Quss Abu Said plateau. The 1984 Landsat TM image (path 178/row 40) shows that the agricultural areas are larger than their counterparts in the Farafra Oasis, and the fields are also spatially distributed in three separate areas (i.e. the villages of Al Bawiti, Mandisha and Al Zabu). The fields are located in the periphery of playa surfaces which are partially occupied by water bodies and wet sabkhas (i.e. saline soil). The satellite images of 1989, 2003 and 2011 show that a considerable area to the south-eastern area of Al Gunnah playa in the Farafra Oasis has been cultivated. Field investigation showed that several irrigation and drainage channels have been developed through these parcels and the main irrigation method is bordering; the field is subdivided into smaller levelled parcels being separated by low raised levees. Extensive tracts of uncultivated soils are waterlogged and have supported the growth of diagnostic species of saline soils. Moreover, certain parcels in the cultivated strips were also abandoned and are indicated by saturated soils and the growth of saline species (Fig. 3). Concurrently, the satellite images for the Baharia Oasis showed the significant increase of agricultural areas, but the water ponds occupying the main playa near Al Bawiti have notably expanded over large surface areas and several fields in their surroundings have been submerged (Fig. 4).

The interpretation of satellite images and field observations showed that the cultivation of large areas in closed drainage basins has developed extensive tracts of waterlogging and water ponds on the low playa surfaces. Most of the waterlogged areas are distributed in a unique pattern resembling channels of drainage basins. Although most of drainage networks of the Farafra and Baharia depressions (which were formed during the Quaternary wet pluvial) are of poor surface expression due to the prevailing aridity, and they are now buried by sand sheets. The automatically extracted drainage networks from the DEM are in coincidence with the extent of seepage and waterlogging pattern within the new cultivated fields in the Farfara Oasis. This correspondence indicates that the SRTM is suitable to delineate the poorly expressed drainage networks of the desert areas. Additionally, it implies the significance of selecting optimum locations for agricultural development. These shallow alluvial channels remained dry and inactive for long periods, until they revived hydrological activates by the irrigation of fields developed on its soil and surroundings. The channels are being saturated

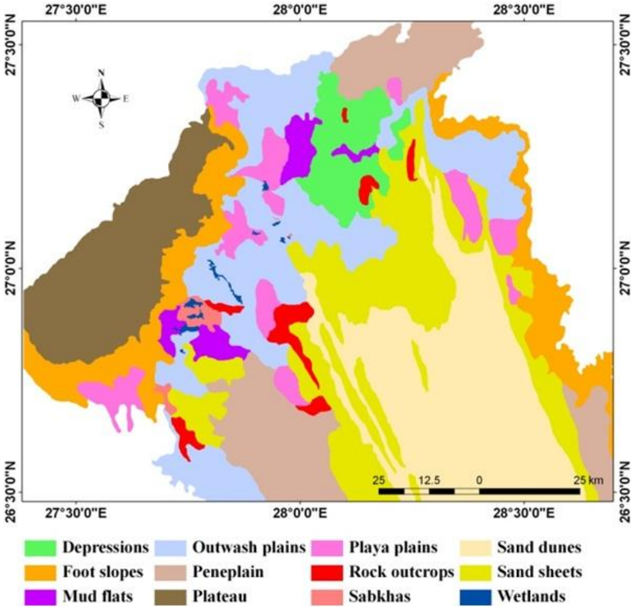

Fig. 6. Map shows the main landforms delineated from the satellite images and DEM for the Farafra Oasis. These units were checked for accuracy in the field.

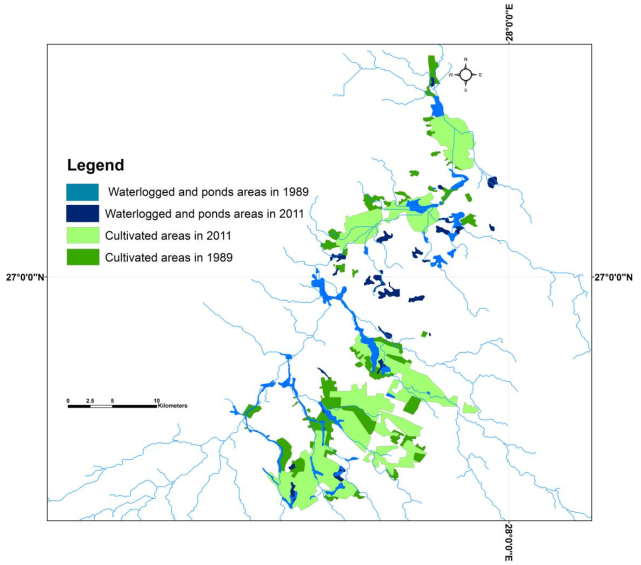

Fig. 7. The extent of cultivations and waterlogging areas in the Farafra Oasis.

with excess irrigation water, which seeps through the subsurface soil layers and gradually encroaches the downstream areas (Fig. 7). The movement of seepage water downstream along these courses has resulted in the accumulation of surface ponds, particularly in the cultivated low areas located in the course of these saturated channels. In 1989, the total cultivated area in the Farafra depression was approximately 143 km^2, and it increased to 190 km^2 in 2011. During the same period, the waterlogged and pond areas have increased from approximately 22.7 km^2 to 36.1 km^2. On the other hand, the total cultivated area in the Baharia depression is much smaller than their counterparts in the Farafra depression (in 1984 only 40.9 km^2 were cultivated, and increased to 95.5 km^2 in 2011). But the resulting waterlogging and land degradation is more pronounced, as the playas near Al Bawiti are almost covered by water ponds and several surrounding cultivated areas have been totally submerged. The areas of water ponds have increased from 0.3 to 4.7 km^2 during the period from 1984 to 2011. Indeed, the accuracy of these measurements is affected by the spatial resolution of the Landsat satellite images and the quality of discrimination of different land covers.

The current study shows that the interaction of regional physiographic settings of soil, hydrological settings and geomorphology of the cultivated areas in the dryland were not fully understood. The agricultural fields in the Saharan oases are mainly developed on the floors of depressions, mudflats, and outwash plains (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 subsurface hardpan, which supports the rapid development of waterlogging hazards. Sets of open ditches were constructed in the cultivated areas to control the developed waterlogging. The construction of spaced, parallel open drainage channels to combat waterlogging is a widely used technique in the Nile Delta and Valley, but the adoption of this technique in the Farafra depression seems to be ineffective. The designed open-drainage channels are locally intersecting with the waterlogged buried channels, but considerable areas still affected by waterlogging particularly those associated with the neglected buried channels. Alternatively, the main natural drainage channels themselves must be considered and used to collect the excess water, which usually moves laterally toward channels as through flow.

5 Discussion and conclusions

The agricultural megaprojects taking place within the depressions of the Western Desert of Egypt have neglected the impact of defunct-fluvial channels and the catchment geomorphological parameters on land degradation. The cultivation of considerable areas within the dryland closed drainage basins have developed widespread waterlogging particularly in the areas underlain by shallow soil and buried fluvial channels. The planning for the Saharan new projects appears not to be preceded by sufficient multi-disciplinary integrated

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	—	—	—	—	—

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 a prolonged period under prevailing aridity. The irrigation of such soil has re-activated the hydrological processes within these defunct channels.

The mapping of soils units and their relation to the fluvial channels is also necessary to better manage the waterlogging problems particularly in closed drainage basins. For example, the lithic soils are highly susceptible to waterlogging in low lying landforms (e.g. playas) than the ones developed on higher elevation such as foot slope. 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 (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 methods, and evaporation from drainage ponds should be balanced, to prevent waterlogging. This system proved significance in controlling waterlogging in Indus basin in Pakistan, and in rice-growing areas of West Africa (Konukco et al., 2006). Recently, the “bio-drainage” approach has also widely been used to combat waterlogging, particularly in dryland 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 require time-effective and reliable remote sensing monitoring and observation, essentially to record changes and to anticipate further degradation. 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). 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 use of advanced techniques for irrigation (i.e. dripping and sprinkling) as can maximize the benefit of saving limited water resources and reduce the development of harmful waterlogging.

In conclusion waterlogging is the major threat facing the development of the Saharan areas. Extensive waterlogging 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 waterlogging, particularly when the soil of higher surrounding areas is cultivated. It is recommended that the management strategies for waterlogging should consider the natural existing drainage system when planning for the distribution of farmlands to minimise the need for artificial drainage to control subsequent waterlogging. The value of remote sensing, and DEMs of different sources and resolutions is highly appreciated in the dryland environments; as the essential topographic data, field observations and in situ collected data are very limited. The integration of these multi-source data and their interpretation can enable us to better understand the complex processes of land degradation, thus improving the management of limited water and soil resources with the fragile dryland.

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