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Assessment of groundwater and soil quality degradation using multivariate and geostatistical analyses, Dakhla Oasis, Egypt

Alaa A. Masoud [a,*], Mohamed M. El-Horiny [a], Mohamed G. Atwia [a], Khaled S. Gemail [b], Katsuaki Koike [c]

[a] Geology Department, Faculty of Science, Tanta University, 31527 Tanta, Egypt
[b] Geology Department, Faculty of Science, Zagazig University, 44519 Zagazig, Egypt
[c] Department of Urban Management, Graduate School of Engineering, Kyoto University, 615-8540 Kyoto, Japan

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ABSTRACT

Salinization of groundwater and soil resources has long been a serious environmental hazard in arid regions. This study was conducted to investigate and document the factors controlling such salinization and their inter-relationships in the Dakhla Oasis (Egypt). To accomplish this, 60 groundwater samples and 31 soil samples were collected in February 2014. Factor analysis (FA) and hierarchical cluster analysis (HCA) were integrated with geostatistical analyses to characterize the chemical properties of groundwater and soil and their spatial patterns, identify the factors controlling the pattern variability, and clarify the salinization mechanism. Groundwater quality standards revealed emergence of salinization (*av.* 885.8 mg/L) and extreme occurrences of Fe^{2+} (*av.* 17.22 mg/L) and Mn^{2+} (*av.* 2.38 mg/L). Soils were highly salt-affected (*av.* 15.2 $dS\,m^{-1}$) and slightly alkaline (*av.* pH = 7.7). Evaporation and ion-exchange processes governed the evolution of two main water types: Na–Cl (52%) and Ca–Mg–Cl (47%), respectively. Salinization leads the chemical variability of both resources. Distinctive patterns of slight salinization marked the northern part and intense salinization marked the middle and southern parts. Congruence in the resources clusters confirmed common geology, soil types, and urban and agricultural practices. Minimizing the environmental and socioeconomic impacts of the resources salinization urges the need for better understanding of the hydrochemical characteristics and prediction of quality changes.

1. Introduction

Development of agriculture and urban areas has demanded rapid use of groundwater and soil resources, which requires suitable assessment and prioritization of measures for their sustainable use. Indeed, overuse of groundwater and soil without proper management has caused serious environmental issues, especially in arid areas (Hereher and Ismael, 2015). Typical issues include a declining groundwater table, which induces intense soil salinization and enhances shallow aquifer salinity, leading to deteriorated quality and productivity of affected resources. Such a chain of environmental issues has occurred in the Dakhla Oasis, southern Egypt, where rapid development of agriculture has greatly increased the use of groundwater (Sefelnasr et al., 2014). Similar to other arid areas, mineral dissolution and transport by groundwater flow are the main factors leading to development of saline land and water, which manifests in the formation of terminal salt lakes, dry salinas, and areas of saline seeps and scalds in lowlands (Salama et al., 1999). Uptake of water and concentration of salts are enhanced through evaporation of saline groundwater at or near the ground surface, evapotranspiration by plants, hydrolysis of minerals during the weathering processes, and leakage of water between aquifers and confining beds. Waterlogging and water flow affect chemical and physical soil properties by oxidation/reduction, clay movement, salinity and sodicity, sulfidic condition, and water erosion (Salama et al., 1999). These processes induce severe land degradation problems, particularly when they act together in downslope topography as in the Dakhla depression. Clarification of such hydrogeochemical processes is vital for the water and soil resources sustainability.

Salinization has occurred in many deserts in Egypt and led to great degradation of soil resources; therefore, salinization has been widely studied (Masoud and Koike, 2006; Masoud, 2014a).

* Corresponding author.
E-mail address: alaa_masoud@science.tanta.edu.eg (A.A. Masoud).

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Salinization has had harmful impacts on numerous productive areas, including infertility in arid and semi-arid regions, and associated adverse socio-economic and environmental implications (Knapp and Baerenklau, 2006; Ielpo et al., 2017). In affected regions, evapotranspiration generally surpasses precipitation, after which regular percolation of rainwater through the soil is hampered. In addition to natural phenomena, irrigation of soil with low permeability using salt-laden water leads to a slow, but progressive and excessive accumulation of salts in soils (Eynard et al., 2006). This accumulation drastically changes soil physical and chemical properties, which directly impacts soil salinity and pH levels, leading to reduction in the productivity of plants. Moreover, extreme saline and pH conditions commonly result in nutrient toxicity and/or deficiency (Gould and Walker, 1999).

Degradation of the groundwater quality in salinized soil areas is also a severe environmental issue that originates from complex interactions of groundwater chemical properties with soil and rock compositions, hydrometeorology, topography, drainage system efficiency, anthropogenic activities, and other artificially imposed conditions (Kim et al., 2005). Effective management and sustainability of water necessitate that spatial variations in groundwater quality and its controlling factors be understood. In many areas of the Dakhla Oasis, the shallow groundwater is of poor quality and contains high levels of salts, and its use for irrigation significantly alters soil physical and chemical properties and hinders crop growth (Ghoubachi, 2001).

Although the connection of groundwater and soil salinization has been observed as above, the individual salinization mechanisms, factors controlling groundwater and soil chemistry variations, and their intimate relationships are not well understood (Ebraheem et al., 2004). This study employed a combination of multivariate and geostatistical analyses to clarify these relationships to enable sustainable agriculture and population growth. Specifically, factor analysis (FA), hierarchical cluster analysis (HCA), semivariography, and kriging were used to evaluate groundwater and soil chemistry data, with a special emphasis on the relationships between groundwater and soil chemistries and between major and trace element concentrations. Several multivariate methods have been used for assessment and classification of hydrochemical data (Masoud and Koike, 2006; Masoud et al., 2016), and these are also commonly applied in the classification of soils (Ielpo et al., 2017). Additionally, geostatistics has been an effective tool for mapping spatial variations in water and soil chemistries (Kurunc et al., 2016; Takoutsing et al., 2017). Application of these methods can help prevent and mitigate salinization worldwide in arid and semi-arid regions with similar physiographic and environmental conditions as the Dakhla Oasis. Moreover, the results of this study will help decision makers maintain and improve groundwater and soil quality. The prime objective of the research is to investigate and document the factors controlling groundwater and soil quality degradation and their inter-relationships in the Dakhla Oasis (Egypt).

2. Study area

The study area is located in the eastern part of Dakhla Oasis (Fig. 1) and covers an area of approximately 530 km^2 (22.8 × 23.3 km). The Dakhla Oasis is a natural depression located in the middle Western Desert of Egypt, which has a hot and dry climate with almost no annual rainfall, a high rate of evaporation, and strong solar irradiation (Ismael, 2015). The area is defined as a hyper-arid region (UNEP, 1997). Although there were about 520 springs and ponds in the region, most have dried out recently, and those that remain only yield water through use of electric pumps (Sefelnasr et al., 2014).

The study area is composed of three main geomorphological units, a high plateau in the north, a depression in the middle, and a structural plain in the south (Fig. 2). The high plateau bounds the Dakhla depression to the north and is characterized by a wide rough surface and a precipitous escarpment dipping northward. The depression is a lowland formed by geodynamics and erosion, which contains different landforms represented by the alluvial terraces, piedmont flats, and residual hills. The structural plain originated from merging of the Dakhla depression into an extensive elevated plain sloping northward.

The ages of exposed rocks in the study area range from Late Cretaceous to Quaternary (Conoco, 1987) (Fig. 2). The Upper Jurassic–Campanian sequence, which is termed the Nubia sandstone, is composed of sandstone and claystone that directly overlies the basement rocks and is subdivided into different rock units with ascending age order, the oldest being Six Hills, Abu Ballas, Sabaya, and Maghrabi, and the youngest the Taref Formations (Fig. 2). The Mut Formation, which formed during the Campanian transgression, consists of variegated shale, siltstone, and claystone and extensively covers the Dakhla depression with varying thickness. Quaternary fresh deposits to eolian sediments, including sand dunes and alluvial, playa, and inland sabkha deposits, are of continental origin (Ebraheem et al., 2004) and widespread on the depression floor.

The aquifer system of the Nubian sandstone is composed of different water bearing formations with confining layers that are laterally and/or vertically interconnected. Productive aquifers are formed in the Taref (top), Sabaya, and Six Hills sandstone (bottom) formations (Fig. 2). Hydraulic head patterns and flow directions are easily affected by the unmanaged groundwater extraction, because they drive the dryness of the shallow wells, deepen the groundwater table, and makes extraction economically unfeasible (Kato et al., 2014). The effective porosity of the Taref sandstone aquifer is 28% in the top part, but decreases with the depth because of decreasing sand content and increasing cementation by Fe^{2+} and Mn^{2+} (Ghoubachi, 2001). The transmissivity is estimated to be 400 m^2/day in the east Dakhla depression and increases to about 550 m^2/day in the west with increasing sand content. Meanwhile, the average hydraulic conductivity of the Taref aquifer reaches 6.76 m/day at the maximum thickness of 110.45 m (Ghoubachi, 2001). In contrast with the average thickness of the Sabaya aquifer, 275 m, the Six Hills aquifer is thicker than 1000 m and becomes thick in general towards the west and south (Ebraheem et al., 2004). This increase in the thickness is mainly attributed to the fault throw enlarging towards these directions. The piezometric surface data of the Taref, Sabaya, and Six Hills aquifers in the Teneida and Mut areas are 118 m, 111 m, and 135 m above the mean sea level (a.m.s.l.), respectively (Gad et al., 2011). The water level data collected from the Taref shallow aquifer ranges from 129 m (a.m.s.l) at well no. 58 in the extreme southern peripheries of the depression to 84 m at well no. 26 in the central part (Fig. 3). Following these lowering in the topography and aquifer, the groundwater table tends to deepen from the high lands to the depression center and accordingly, the groundwater flows along this direction.

Acute, recent deterioration of the groundwater and soil quality have adversely impacted the agricultural activity in the study area. Salinization and extreme occurrence of Fe^{2+} and Mn^{2+} have imparted and limited the sustainable use of the resources, and salinity-induced mass death of palm trees has become apparent (Fig. 4a). Because of the cyclic seasonal evaporation of the irrigation water in the southern area, salt content has increased in the newly reclaimed sand land (Fig. 4b), which has led to the formation of thick salt crusts near the middle depression (Fig. 4c). Drainage water seeps to lowland regions in the depression, forming artificial canals and inducing salinization around their margins (Fig. 4d &e).