Journal of Arid Environments 110 (2014) 19–29

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Estimating groundwater resources in remote desert environments by coupling geographic information systems with groundwater modeling (Erg Chebbi, Morocco)

Manuel García-Rodríguez [a, *], Loreto Antón [a], Pedro Martinez-Santos [b]

[a] Departamento de Ciencias Analíticas, Facultad de Ciencias, Universidad Nacional de Educación a Distancia (UNED), Paseo Senda del Rey 9, 28040 Madrid, Spain
[b] Departamento de Geodinámica, Facultad de Ciencias Geológicas, Universidad Complutense de Madrid (UCM), 28040 Madrid, Spain

ARTICLE INFO

Article history:
Received 19 November 2013
Received in revised form
21 March 2014
Accepted 27 May 2014
Available online 27 June 2014

Keywords:
Dune aquifers
Desert
Erg systems
Groundwater model
Khettara
Qanat

ABSTRACT

Groundwater resources are essential to underpin the daily life of communities in remote regions. Hydrogeological studies in these areas are complex, largely due to the absence of long water table records and to the difficulties involved in accessing some relevant locations. This hampers attempts to manage local resources. Devising cost-effective methods to explore these aquifers is important to understand how they work and to come up with adequate protection strategies. This paper deals with the joint application of Geographic Information Systems (GIS) tools and numerical groundwater models to explore groundwater resources in desert areas. The method is illustrated through its application to Erg Chebbi, a water table aquifer located in southern Morocco, which supplies drinking and irrigation water for local communities while also underpinning agriculture and tourism. The geometry of the aquifer was established based on existing cartography, GIS and a field survey. This led to the development of a steady-state numerical model. Modeling results suggest that the aquifer has been depleted by almost 30% due to groundwater extractions in less than 50 years. The average drawdown was found to be in the order of three meters. This corresponds to a total depletion in the order of 20–60 Mm^3.

1. Introduction

Ergs are best described as sand deserts. They are often found in sub-equatorial latitudes and may extend from hundreds to millions of square kilometers (Thomas, 1997). Ergs are frequently made up of wind-blown sands, and present a variety of unique landforms that range from aeolian ripples to dune complexes (Wilson, 1972; Lancaster, 1994). Surrounding areas are characterized by the presence of sand sheets, which are often originated and controlled by shallow water tables or local crusts (Loope, 1984; Kocurek and Nielson, 1986; Wilson, 1973). Barchan-type dunes are also found around the hardened land surface that surrounds ergs.

Due to their porous nature, ergs store moderate amounts of groundwater. The storage capacity of erg aquifers is generally limited by the high permeability of sands, which results in rapid drainage. In arid areas, ergs are often underlain by impervious basements. This results in shallow water tables, which constitute the only source of water for local communities. Understanding the hydrogeological behavior of these systems is essential to underpin human development (Fryberger et al., 1988; Gosselin et al., 2006; Barczuk and Dluzewski, 2006; Maman et al., 2011). Despite the local and regional importance of erg aquifers, there are relatively few papers in the literature dealing with them. This is attributed to the fact that most ergs are located in remote regions, which means that studies are costly and cumbersome to carry out.

Dune aquifers in desert environments are usually replenished by rainfall infiltration and by percolation from adjoining alluvial deposits (Jacobson and Jankowski, 1989). Recharge tends to be associated to storm events and concentrated in time. In most desert environments recharge is highly variable, and does not exceed 10% of rainfall (Chenini and Mammou, 2010). However, it can be significant whenever the effects of evaporation are offset, i.e. during storm events (Gosselin et al., 2006). Discharge naturally takes place through springs, oases and direct evapotranspiration from shallow water tables.

Erg Chebbi is a dune complex located in southeast Morocco (Fig. 1A). Since 2000, it is part of UNESCO's "Oases du Sud Marocain"

* Corresponding author. Tel.: +34 913987360.
E-mail addresses: manu.garo@ccia.uned.es (M. García-Rodríguez), lanton@ccia.uned.es (L. Antón), pemartin@ucm.es (P. Martinez-Santos).

http://dx.doi.org/10.1016/j.jaridenv.2014.05.026
0140-1963/

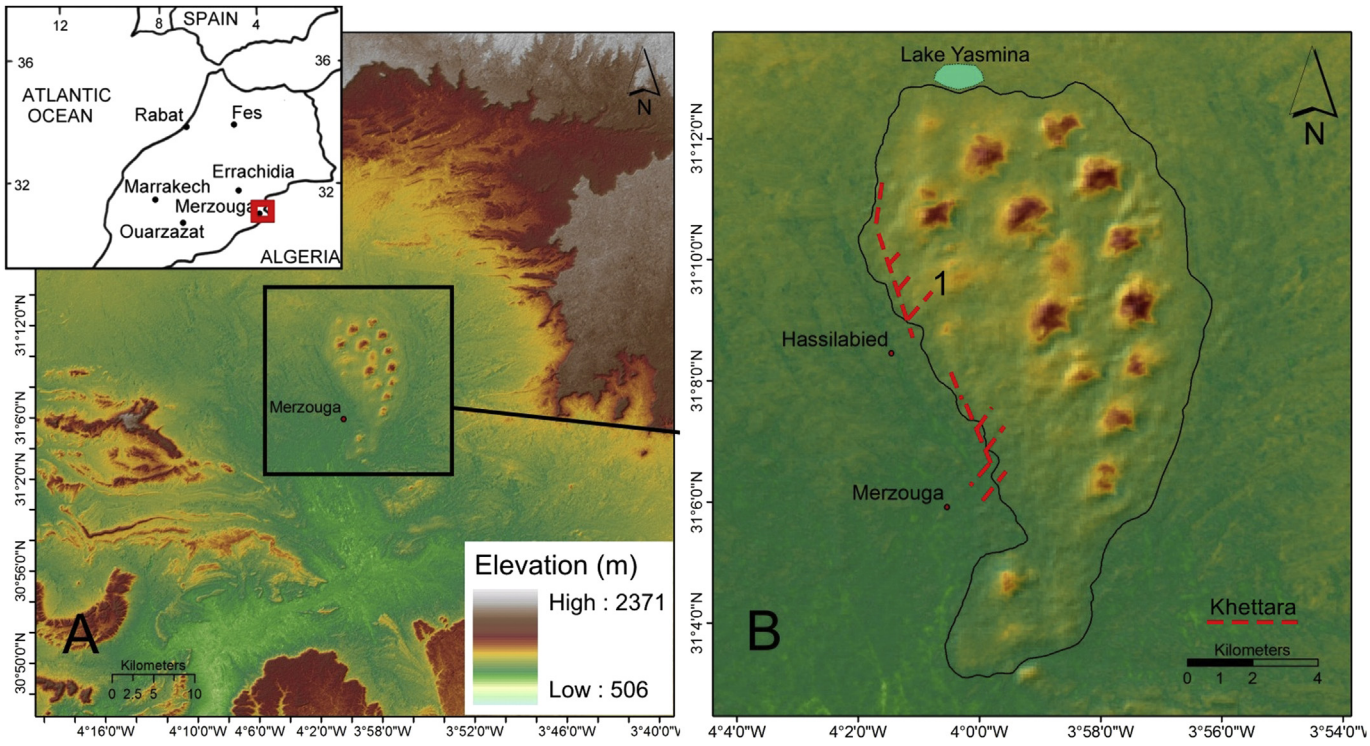

Fig. 1. Geographical setting. (A) Satellite image showcasing the general location of Erg Chebbi. (B) Map of Erg Chebbi representing large dunes, perimetral sand sheets and schematic layout of the main khettaras.

Biosphere Reserve. From the hydrogeological standpoint Erg Chebbi is best described as a shallow water table aquifer (García-Rodríguez et al., 2008a).

For decades, its groundwater resources have been tapped by human communities. These are located in the peripheral areas of the system. Groundwater is typically accessed by groundwater galleries (khettaras) and shallow wells (Fig. 2). Khettaras are gently sloping tunnels used to tap and convey shallow groundwater (Beaumont, 1989; Honari 1989). For practical purposes khettaras are best described as horizontal wells. They are originated in ancient Persia, where they were named "qanats", but spread all the way to China and Western Europe following the path of Islamic expansions. Thus, khettaras are known as "kanerjing" in China, "kiraz" in Afghanistan, "foggara" in Algeria and parts of southern Europe or "viajes" in central Spain (AMED, 2008; Ben Brahim, 2003; Lightfoot, 1996a). Khettaras capture groundwater by creating a preferential drainage path below the water table. Qanats can be several kilometers long (Martinez-Santos, 2013). Water flowing into the galleries is led by gravity to outlets located at lower points, where people can use it. Vertical shafts connect the gallery with the ground surface (Fig. 2B). These are typically located 10–25 m apart, and serve several purposes. For one, shafts contribute to keep the galleries straight while they are being built and to facilitate maintenance access during the operational stage. Also, shafts are capped for safety and to prevent contamination. If aquifer capacity is sufficient and the construction is adequate, khettaras provide continuous water flow for long periods of time (Martinez-Santos and Martinez-Alfaro, 2012).

Since the late 1960s, about 260 khettaras (1700 km) have been abandoned in the Taffilalet region – where Erg Chebbi is located – due to dropping water tables (Escriche, 2010). Nowadays, approximately 300 khettaras remain operational. These amount to approximately 1200 km in length, and irrigate 12,750 ha (Lightfoot, 1996b; AMED, 2008). This demonstrates how mounting pressures derived from a growing population are generating unwanted effects on the environment.

The Hassilabied and Merzouga khettaras, currently operational, were built in the 1960s. During the 1960s, these towns experienced

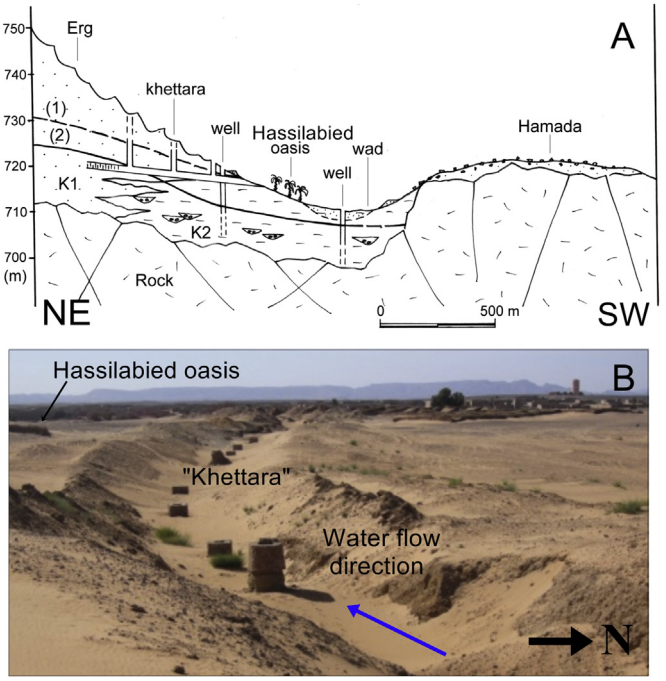

Fig. 2. (A) NE–SW hydrogeological cross-section of the Hassilabied area (García-Rodríguez et al., 2008a). Surface number [1] represents the water table under natural conditions whereas number [2] corresponds to 2008. (B) Picture of the khettara represented in the cross-section.