Hydrological Sciences Journal
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/thsj20

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Version of record first published: 16 Dec 2011.

To cite this article: Christophe Tourenq, Mike Brook, Sandra Knuteson, Maral Khaled Shuriqi, Moaz Sawaf & Lisa Perry (2011): Hydrogeology of Wadi Wurayah, United Arab Emirates, and its importance for biodiversity and local communities, Hydrological Sciences Journal, 56:8, 1407-1422

To link to this article: http://dx.doi.org/10.1080/02626667.2011.631139

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Received 4 January 2011; accepted 23 August 2011; open for discussion until 1 June 2012

Editor D. Koutsoyiannis; **Guest editor** M.C. Acreman

Citation Tourenq, C., *et al*., 2011. Hydrogeology of Wadi Wurayah, United Arab Emirates, and its importance for biodiversity and local communities. *Hydrological Sciences Journal*, 56 (8), 1407–1422.

Abstract Wadi Wurayah, in the Emirate of Fujairah, United Arab Emirates, lies within the Hajar Mountain range by the Gulf of Oman. The climate of the area is influenced by climatic events originating in Africa, Eastern Europe-Siberia, and the Indian and Pacific oceans. Rainfall provides 18.7 hm^3 water annually, with an average of 2.24 hm^3 as runoff. Recharge from rainfall to the mountain ophiolite complex creates a unique hydrogeological system with permanent freshwater habitats that support a biodiversity unique in the country and the world. The freshwater habitats host, amongst others, two species of amphibians, one fish species and aquatic insect species new to science. Spring waters classified as magnesium bicarbonate, slightly alkaline, with temperatures from 22 to 28°C and an average pH of 8.3, meet physico-chemical standards for drinking and bottled water, but do not meet the bacteriological standards near places frequented by tourists. An active management of the human pressure on the whole wadi ecosystem is urgently needed.

Key words ophiolite; wadi; freshwater; biodiversity; Wurayah; United Arab Emirates

Hydrogéologie de l'Oued Wurayah, Emirats arabes unis, et son importance pour la biodiversité et la population locale

Résumé L'Oued Wurayah dans l'Émirat de Fujaïrah (Émirats arabes unis), est situé dans le massif de l'Hajar le long du Golfe d'Oman. Le climat de la région est influencé par des évènements météorologiques provenant d'Afrique, d'Europe de l'Est et de Sibérie, et des océans Indien et Pacifique. La pluie apporte un total annuel de 18.7 hm^3 d'eau avec en moyenne 2.24 hm^3 d'écoulement. La recharge de la nappe dans le complexe montagneux ophiolitique crée un système hydrogéologique unique avec des habitats d'eau douce permanents qui subviennent aux besoins d'une biodiversité unique dans le pays et dans le monde. Les habitats d'eau douce abritent notamment deux espèces d'amphibiens, une espèce de poisson et des espèces d'insectes aquatiques nouvelles pour la science. Les eaux de source classées comme riches en magnésium et bicarbonates, légèrement alcalines, avec des températures de 22 à 28°C et un pH moyen de 8.3, rentrent dans les normes physico-chimiques des eaux de boisson et embouteillées, mais ne sont pas aux normes bactériologiques près des lieux touristiques. La mise en place d'une gestion active de la pression anthropique sur l'écosystème de l'oued est impérative.

Mots clefs Ophiolite; oued; eau douce; biodiversité; Wurayah; Emirats arabes unis

ISSN 0262-6667 print/ISSN 2150-3435 online

http://dx.doi.org/10.1080/02626667.2011.631139
http://www.tandfonline.com

1 INTRODUCTION

Located on the northeast of the Arabian Peninsula, the Federation of seven sheikhdoms of the United Arab Emirates (UAE) encompasses about 83 600 km^2 with about 700 km of coastline on the Arabian/Persian Gulf (hereafter "Gulf") and the Gulf of Oman. Being at a meeting point between the Indo-Asian and the Afro-European regions, the UAE has a relatively rich biodiversity, although it is a hot and dry environment (Tourenq and Launay 2008).

The UAE hosts two of the "Global 200": the most biologically distinct terrestrial, freshwater and marine eco-regions in the world identified by the World Wide Fund for Nature (WWF): the Arabian Highlands and Shrublands and the Arabian Gulf and Sea. The Global 200 were selected for their species richness, endemism, higher taxonomic uniqueness, unique ecological or evolutionary phenomena, global rarity of habitats, intactness and representation (http://www.worldwildlife.org/wildworld; Olson and Dinerstein 1998).

The Gulf Cooperation Council countries (GCC), and the UAE in particular, have experienced tremendous development during the last decades due to an increase of wealth brought by oil and gas revenues. With the improvement of health and social welfare, the UAE population size has increased considerably (by 74.8% between 1995 and 2005; UAE MIC 2009). In the same period, the UAE natural and social environment has undergone dramatic changes with substantial development of infrastructure (roads, housing, industries, etc.) and agriculture (farms and forest plantations), and drastic modifications of lifestyle with the end of nomadism and the modernization of hunting and fishing (Gulf Research Center 2007).

The formidable coastal development initiated in Dubai during the last decade induced an increasing demand for cement, as well as building materials (rocks, aggregates, limestone, etc.). Given the pace of development in the country, raw materials for cement and building materials locally available in the country's mountains have been heavily exploited. Crushing and quarry licenses dramatically increased in the emirates of Sharjah, Ras al Khaimah and Fujairah to provide material on site rather than to rely on imports from overseas.

Fujairah is the only Emirate of the UAE Federation exclusively on the East Coast. It has a varied scenery consisting of mountains, alluvial plains and coastal habitats. However, with the saturation of the Gulf emirates' tourism and real-estate markets, developers have started to develop on the East Coast and the pressure is increasing on the natural habitats of Fujairah. The government of Fujairah, through the Municipality, decided to start targeting terrestrial areas for protection. Lying within a priority WWF Global 200 ecoregion (Ecoregion 127, Arabian Highlands and Shrublands), the Wadi Wurayah catchment area hosts a unique set of perennial freshwater habitats, in the form of springs, pools, riffles/streams and waterfalls (Rizk and El Etr 1997), and shelters a rich biodiversity of fauna and flora in an area of outstanding natural beauty that is already an established popular tourist attraction (Tourenq *et al*. 2009). The area was declared protected by decree in March 2009. This paper presents a synopsis of the hydrogeological features of Wadi Wurayah from the surveys initiated since 2006.

2 HYDROGEOLOGY

2.1 Location

The Wadi Wurayah catchment basin extends from Universal Transverse Mercator (UTM) 2815831.815 to 2800263.544 (North) and UTM 420127.757 to 430850.218 (East), between the towns of Kohr Fakkan (Sharjah Emirate) and Bidiyah (Fujairah Emirate) on the Oman Gulf coastline (Fig. 1). Located in the Shimayliyyah Massif, the catchment basin is flanked on its west side by the town of Masafi (Fujairah and Ras al Khaimah Emirate). It is part of the great Hajar Mountain range which parallels the East Coast of the UAE, extending from the Musandam Peninsula in the north to Oman in the south. The whole catchment is about 129 km^2 in area and has a maximum elevation of 956 m a.m.s.l. The catchment contains 371 separate streams of 301 km total length and the dendritic drainage branches from six main wadis. It comprises two main wadi branches, i.e. Wadi Ash Shamah subcatchment and Al Wurayah catchment proper, which both have large pools and waterfalls (Brook 2006).

The primary wadi is 27.5 km long and the drainage is dendritic in shape. The upper reaches of the system have jagged mountain peaks with steep and narrow stream valleys. Further downstream, the relief generally flattens and wadis widen and have lower gradients. The wadi floodplain commences at the foot of the jebel ("*jebel*" is the Arabic word meaning mountain), downstream of the Wadi Wurayah recharge dam and comprises boulders, cobbles, gravel and sand of various grain sizes. The floodplain comprises a number of braided channels, which may

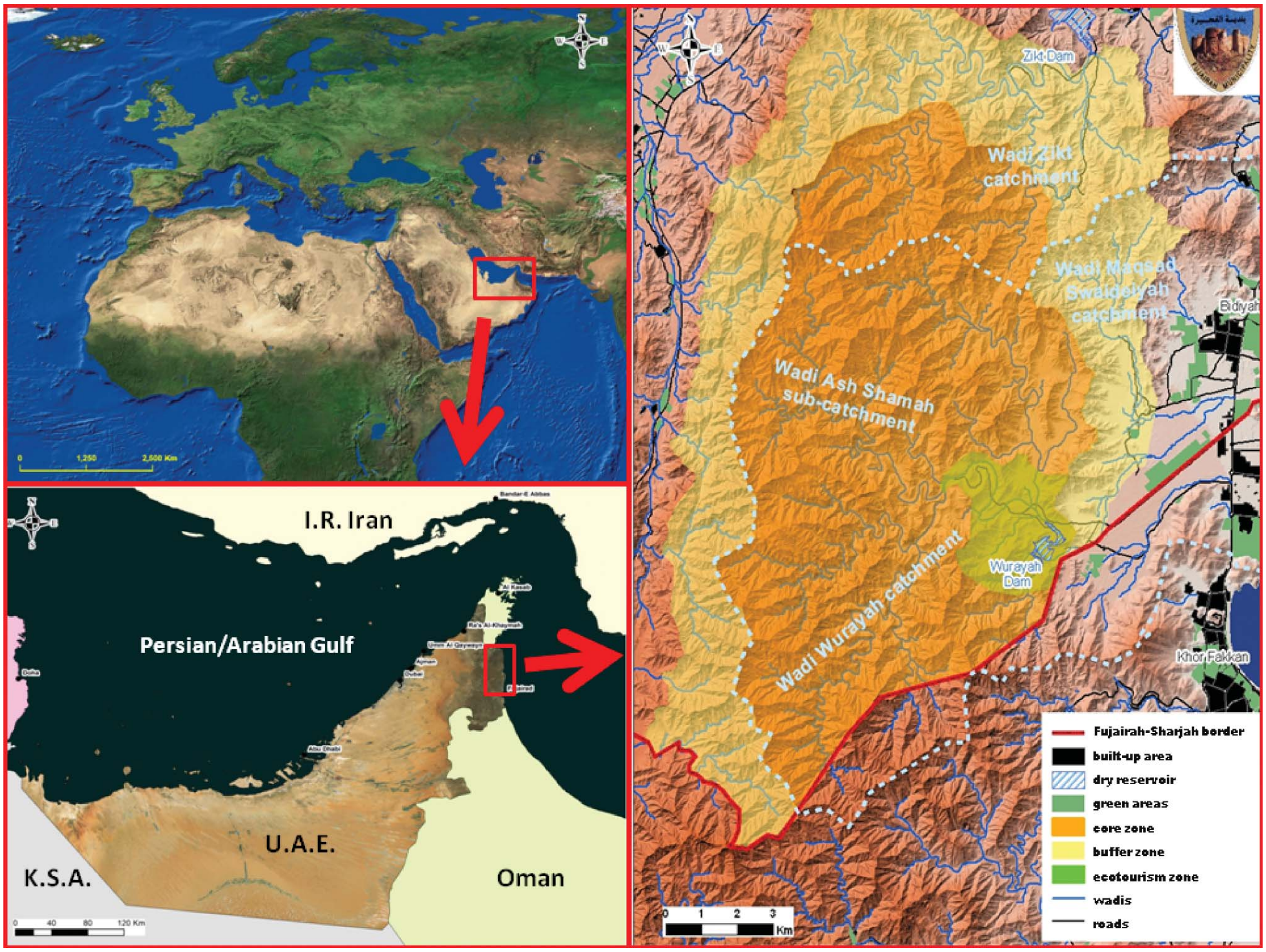

Fig. 1 Location of Wadi Wurayah catchment basin in the Arabian Peninsula (top left), the United Arab Emirates (bottom left) and with the Protected Area zoning (in dashed pale blue, right).

change direction and shape from one flood to the next (Brook 2006).

2.2 Climate

Generally, the current climate of the Arabian Peninsula, is mainly governed by the Hadley circulation, and modulated by several climate patterns such as the El Niño–Southern Oscillation (ENSO), the Indian Ocean Oscillation (IOO; or Indian Ocean Dipole, IOD, or Indian Ocean Zonal Mode, IOZM), the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO) (Kotwicki and Al Sulaimani 2009).

Air masses of four main origins seasonally influence the weather of the Arabian Peninsula and the UAE in particular: polar maritime, polar continental, tropical continental and tropical maritime. The aridity of the Peninsula is mainly due to its distance from the major rain-bearing systems, such as the North Atlantic depressions and the Indian Monsoon, and its exposure to continental air (Fischer and Membery 1998).

The general climate of the UAE can be described as hyper-arid (i.e. ratio of mean annual precipitation to mean annual potential evapotranspiration <0.05). Two main seasons are observed (Böer 1997): hot summers (May–September) and cooler winters (October–April).

During the summer, the weather system is characterized by cloudless skies, low humidity, very high temperatures (often exceeding 40°C), intensive surface heating, and dust transportation leading to hazy conditions: tropical continental air brings hot and very dry air from North Africa to the Arabian Peninsula, which becomes a stable high-pressure zone and source of tropical continental air itself (Fischer and Membery 1998). With the advent of the summer months, the Indian Monsoon system develops: a major cyclonic circulation forms around low-pressure centres, such as the central desert of the Arabian Peninsula (the Rub al Khali). However, these tropical maritime airflows influence only the southern part of the Arabian Peninsula, as the tropical continental air flows dominate the bulk of the region. The Indian Ocean Monsoon (IOM) seasonally affects parts of Yemen, southwestern Saudi Arabia, and coastal Oman. Thus, the Indian Ocean impacts on climate variability, notably throughout the IOD events, which can occur independently or be triggered by the ENSO (Schott *et al.* 2009).

During the winter (October–April), polar continental air from Central Asia brings dry and cool weather (down to 4°C), with a mean annual average of temperature around 27°C. The region is only occasionally affected by rain-bearing air movements: the polar maritime air masses from the North Atlantic that are a modification of the mid-latitude depressions that have already traversed North Africa and the Mediterranean (Fischer and Membery 1998).

Rainfall is erratic and unreliable and clearly influenced by orographic effects: the Al Hajar Mountains in neighbouring Oman, and the Jebel Hafeet in Abu Dhabi Emirate generate high rainfall incidents, especially during the winter months. Runoff in the non-vegetated, rocky mountains collects into wadis, which drain to lower lands, such as the gravel plains, eventually recharging the shallow alluvial gravel aquifers. The mean annual rainfall ranges from about 150 mm in mountainous areas to about 85 mm on the Gulf Coast, and much less in the central and western desert.

The climate of Wadi Wurayah reflects the hot, hyper-arid, mountain desert environment and the influence of the air masses mentioned above. Temperatures are highest during the period of April–October, and are coolest from November to March. In summer, typical daytime temperatures in the wadi can reach almost 50°C. Minimum atmospheric relative humidity (RH) values (< 10%) are recorded mainly during the summer between April and September. Maximum RH values (> 90%) are observed during winter (October–April) and correspond to night dew formation. According to Böer (1997), the catchment lies in a sub-humid bio-climatic zone and in an area that is the wettest in the UAE. It is not surprising, therefore, that the perennial waterfalls are unique to Wadi Wurayah.

The weather situations that give rise to rainfall in Wadi Wurayah can be summarized as (EWS-WWF and Fujairah Municipality 2006):

(a) During winter months (October–April), the majority of rainfall events is related to:
   - (i) cloud bands that migrate from the eastern coast of Africa, induced by well-defined upper troughs over the middle latitudes (provides 80% of all UAE rainfall); years with rare rainfall are associated with fewer such cloud migrations;
   - (ii) frontal systems that originate in the Mediterranean, when the Siberian high pressure shrinks northeastwards by late winter; these systems may have tracks across the Gulf Sea and such frontal systems give rise to rainfall and thunderstorms;
   - (iii) the southward advance of active westerly troughs over the southwestern part of the Arabian Peninsula that bring cold air masses, which meet and converge with relatively hot and humid air from the south; these situations lead to the most vigorous and unstable weather conditions, which often result in heavy rain.

(b) During summer months (May–September), rainfall can be associated with:
   - (i) clouds drifting from the Indian Monsoon over the Arabian Sea;
   - (ii) afternoon convective clouds due to orographic effects;
   - (iii) rare cases of the Inter Tropical Convergence Zone shifting northward over the UAE and causing overcast weather and thunderstorm activity;
   - (iv) the temperature contrast between land and sea (at the hottest time of the year), which may be large enough to produce what is known as a sea breeze front that may give traces of rainfall along the coast.

Precipitation patterns from four weather stations in the vicinity of Wadi Wurayah catchment show strong relations with the Pacific Decadal Oscillation, or ENSO events. For all El Niño years, the annual rainfall is above the average, especially during the 1990–1995 period, one of the longest-lasting El Niño periods ever recorded (Fig. 2).

2.3 Geology

The geology includes basic and ultra-basic igneous rocks as bedrock, including the world-famous Semail ophiolite suite. Lying on top of the bedrock are relatively thick deposits of old and recent alluvium, comprising boulders, cobbles, gravels and sands, laid down in a high energy fluvial environment. Whilst the former does contain some groundwater in fractures

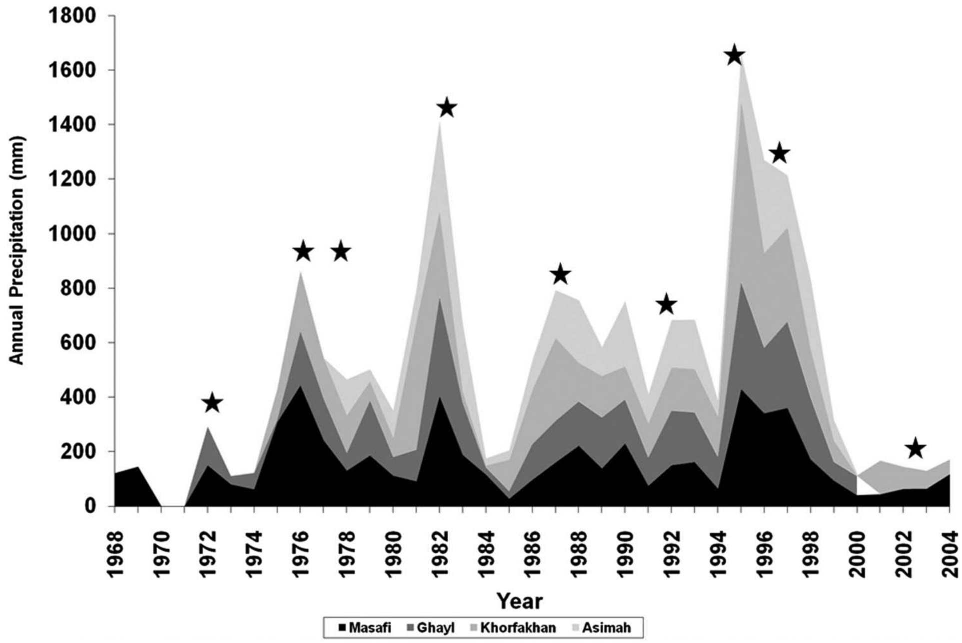

Fig. 2 Annual rainfall at four stations surrounding Wadi Wurayah, Fujairah, UAE for the period 1968–2004 (extracted from UAE Ministry Environment and Water data provided to authors 2005, Brook 2006). El Niño (ENSO) years for the period are indicated with a star. Data from 2000–2004 are shown only for Khor Fakkan and Masafi stations (illustrated in different shades of grey).

and cavities, it is the latter, Quaternary gravels that are the primary aquifer in the catchment, having an average permeability of about 5 m/d and a porosity of 10–15%. The ophiolite complex (bedrock) is cut by deeply incised wadis which have subsequently been filled with fluviatile deposits (UAE ME and BGS 2007a, 2007b, 2007c, 2007d).

The Upper Cretaceous to pre-Permian Semail ophiolite suite comprises mostly gabbros, ultra-basics and fine- to coarse-grained granite and granodiorite as minor intrusions. The upper parts of the catchment are mostly ultra basics, comprising peridotite, serpentinized peridotite and serpentinite, with locally banded magnesite. Thin chrysotile and calcite veins are common. Under extreme temperature, the calcite has transformed to marble. The serpentinite is generally highly fractured, and rock falls and minor avalanches are seen along contact planes. The lower part of the catchment contains complex zones of gabbro with intermixed ultra-basic rocks. The upper catchment wadis and lower wadi plains comprise wadi gravel deposits. These deposits comprise rounded gravel, cobbles and boulders, usually within a poorly sorted sand/silt matrix. In the vicinity of active wadis, the gravel becomes increasingly compact with depth. Thick gravel terraces are seen 2–3 km upstream of the Khor Fakkan–Masafi road and continue for a distance of 9–10 km into the catchment (Brook 2006).

These terraces are very compact and cemented with a shallow cover of loose boulders, cobbles, gravel and sand. The fluviatile deposits are boulders, gravel, sand and silt; these occur within the active wadis and in old undifferentiated terrace deposits and cemented wadi walls. The sediments spread out into an outwash fan downstream of the recharge dam. Structurally, the Shimayliyyah Mountains are part of a complex anticline system, which has been subject to thrusting and over-folding during emplacement of basic igneous crustal rocks. The catchment contains numerous structural lineaments trending mostly NNE–SSW and NW–SW, and these structures control wadi directions in the upper catchment. There are three major sets of faults in the region: NW–SE, NE–SW and N–S (Brook 2006; UAE ME and BGS 2007a, 2007b, 2007c, 2007d).

2.4 Hydrology

There are two types of aquifer present in the catchment: the ophiolite and the alluvium aquifers (W.S. Atkins 1993, Joudeh 1994, Rizk and El Etr 1997, Brook 2006):

(a) The ophiolite suite comprises igneous and ultra-basic rocks which form the bedrock (base) to the aquifer systems and are themselves not considered as a productive aquifer. For the most part of the catchment, the bedrock is covered with a thin veneer of gravels. Primary permeability of the bedrock is negligible, although fractures and cavities do provide some secondary permeability and some opportunity for groundwater storage. It is accepted that localized groundwater flow can occur within the bedrock, but it is considered that this is not significant regionally.

(b) Forming the alluvium aquifer, wadi deposits comprise both recent and old Quaternary gravels, which contain boulders, cobbles, pebbles, sands and gravels, of varying content and with varying degrees of cementation and compaction. Generally, the formation takes on the appearance of a moderately cemented conglomerate and is the predominant aquifer in the catchment. The thickness of the alluvium aquifer varies from a few metres within the narrow stream valleys in the upper reaches to 20–40 m within the middle and lower reaches. At about 3 km from the coastline, it is reported that the bedrock shelves steeply and alluvium thickness reaches 90 m or more. Data from 47 boreholes (W.S. Atkins 1993) show depth to bedrock varying from 6.6 to 96 m below ground level (b.g.l.) and the water table being at depths between 3.68 and 51.52 m b.g.l. The permeability of the gravel aquifer was tested and found to be between 0.1 and 163.3 m/d. Transmissivity of the gravel aquifer is very variable (18.3–615 m^2/d), depending on the degree of cementation, as is the storage capacity, but the effective storage of the wadi deposit is calculated at between 5 and 15%.

2.4.1 Surface water flow The runoff following a rainfall event provides low salinity and low temperature runoff, which infiltrates the fractured ophiolite and the recent and older wadi gravel and gravel terraces in the upper parts of the catchment. Runoff quickly finds its way downstream in flash floods, which also provide significant recharge to the alluvial aquifer in the mid part of the catchment, ultimately culminating in storage for the Wadi Wurayah recharge dam. Serving the dual purpose of preventing downstream flooding and enhancing the recharge to aquifers by storing the runoff so that it can be gradually released downstream for maximum recharge effectiveness, the dam was constructed in 1997 in the lower part of Wadi Wurayah. From 1997 to 2005, a total of nearly 9 hm^3 was captured from flood events. Three spillways were constructed at 2.5, 8 and 10.5 km downstream of the main dam to capture the main dam overflows (W.S. Atkins 1993, Brook 2006).

Undulations within the impermeable igneous bedrock are filled with shallow alluvium. Upstream of the contact spring waterfall, springs bring water to the surface both at the contact between bedrock and alluvium (Fig. 3(a)) and at the contact between cemented and uncemented gravel (Fig. 3(b)), the former acting as impermeable barriers forcing water into the wadi channels (Joudeh 1994). Fractures within the cemented gravels also produce springs. Combined flows from contact springs near the contact spring waterfall are approximately 2–3 L/s (Fig. 3(e)). Downstream of the contact spring waterfall, surface water forms continuous streams above saturated gravels (Fig. 3(c) and (d)). Main and contact spring waterfalls of Wadi Wurayah have flows of about 40–45 and 15–17 L/s for main and contact waterfalls, respectively. The main waterfall has a drop of about 8 m and is the highest, perennial waterfall in the UAE (Fig. 3(f)).

2.4.2 Groundwater flow Groundwater flows within the alluvium aquifer in a northeasterly direction within the wadi plain towards Wadi Azir and out to the coast. Groundwater levels in Wadi Wurayah catchment have been monitored by seven UAE Ministry of Environment and Water (MEW) observation wells (WUR-1 to WUR-7; Fig. 4). Years 1995–1997 had more than double the average annual rainfall, causing many flood events and, in 1998, groundwater levels were at their highest ever recorded. Since then, because of a period of generalized drought in the country, the long-term trend has been for levels to fall, Observation well levels have varied between 9 and 57 m b.g.l. between 1998 and 2005. Even though wells in or near the active channels respond instantaneously to wadi flow events—with water levels increasing by up to as much as 30 m (e.g. WUR-2 and WUR-4 in early 2005)—all wells, except WUR-7, located 1 km from the coast, show a general decline in groundwater levels by up to 34 m (range: 7–22 m on average) between 1998 and 2005 (Fig. 4). A recent study by Alhogaraty (2010) shows a decrease of 20 m between 2005 and 2009 in downstream groundwater levels (WUR-5).

Groundwater gradients in the upper wadi area are steep and range between 0.0123 and 0.0166. The sectional groundwater throughflow in the vicinity of well WUR-4 varies between 0.1 and 1.5 hm^3/year,

Fig. 3 Contact springs upstream of main waterfall (a) between bedrock and gravels, (b) between cemented and uncemented gravel, (c) and (d) flowing streams in between the main springs and contact waterfall, (e) contact spring waterfall, (f) main waterfall.

depending upon applied permeability and depth of groundwater flow. The groundwater flow patterns appear to undergo a major change approximately 3 km from the coast, where gradients are very flat and the groundwater level is very close to sea level (wells WUR-7 and WUR-6). Groundwater in the coastal zone is therefore susceptible to seawater intrusion if abstractions are excessive. It is estimated that groundwater recharge in the catchment is between 1.5 and 2.5 hm^3/year, suggesting that approximately 15% of the total catchment annual precipitation is converted to surface runoff and groundwater throughflow.

2.4.3 Water quality The quality of surface water in the upstream catchment is exceptionally good in terms of hydro-chemical parameters, and meets, from a chemical point of view, most of World Health Organization's standards for drinking water and also for bottled water (Table 1). Wurayah waters can be classified as magnesium bicarbonate, a type which is indicative of a recently recharged and active water resources regime, slightly alkaline with a mean pH value of 8.3 (range: 8.1–9.1). Average laboratory total dissolved solids (TDS) are 310 mg/L (range: 257–403). Average dissolved oxygen (DO) varies between 5.2 and 11.22 mg/L. The average nitrite concentration values in Wurayah surface waters of freshwater habitats did not exceed 0.02 mg/L, the average nitrate concentration value being 5.76 mg/L. Mean temperatures in pool habitats ranged from 22 to 28°C owing to their diverse physical nature and location.

However, as a consequence of the construction of the tarmac road in 1996 and the citation of the site in UAE tourist and off-road guides, the site has increasingly gained considerable recognition. Unfortunately, the increased number of tourists visiting the site has resulted in a considerable degradation with tagging

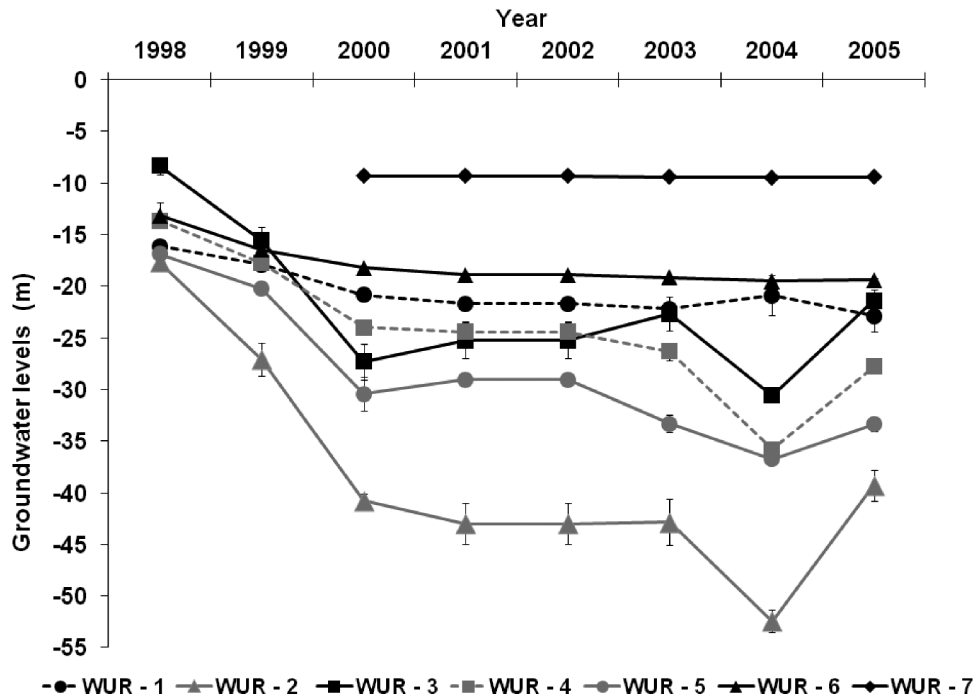

Fig. 4 Groundwater levels (± SE) of seven monitoring wells (WUR) in Wadi Wurayah catchment basin (extracted from UAE Ministry Environment and Water data provided to authors, 2005, Brook 2006).

(painting) of the rocks, continuous and widespread litter deposits and burning of native vegetation during the last couple of years. Graffiti is prevalent around the main waterfall pool, although this is predominantly an aesthetic problem; the aerosol paints used are toxic and the cans are usually discarded in the area when empty. A large input of organic items of rubbish, including food and sewage, can increase nitrates and phosphates in the water, therefore enhancing algae growth and leading to eutrophic conditions, a decrease in dissolved oxygen and the extirpation of the unique aquatic fauna.

High concentrations of coliform bacteria, of animal faeces origin, but also *Escherichia coli* originating from human faeces, have been found in the waters of wadis in the region that are heavily frequented by tourists (Motalleebi and Knuteson 2008). Using the same methods as Motalleebi and Knuteson (2008), the most probable number (MPN) in 100 ml water was determined. Analysis showed that the bacteria concentration was higher than the WHO authorized levels for public beaches, swimming pools and drinking water (Table 2; WHO 2003, 2006). Faecal coliform bacteria, at levels up to 50 times greater than the WHO standards for minimum levels for public beaches and pools, were found in all pools nearby the Al Wurayah waterfall. Feral goats, dogs and wildlife could be one source of the faecal contamination. Lower levels of bacteria in the upper pools, compared to the lower pools used by tourists, suggested that bacterial contamination in the lower pools is of human origin. As no bathroom facilities exist near these areas, human faeces are a source of contamination through shedding of microbes or accidental release of faecal materials while bathing (WHO 2003, 2006). *Escherichia coli* were found in most of the pools of the area. Although not all of these bacteria are pathogenic, they indicate the possible presence of other microbes found in faeces that are pathogenic and may cause diseases such as gastroenteritis or diarrhoeal diseases (WHO 2003, 2006).

Information on groundwater quality has been obtained from an earlier study (W.S. Atkins 1993), laboratory analyses supplied by the Emirates Pure Spring Water Company which abstracts groundwater in the coastal plain, and a recent work by Alhogaraty (2010). During the 1993 survey, the total dissolved solids (TDS) of groundwater at depths of between 10 and 50 m b.g.l. (excluding the coastal plain) varied from 211 to 320mg/L in monitoring wells WUR-3 and WUR-5, respectively. Ten years later, from samples taken between December 2002 and June 2003, Al-Matari (cited in Alhogaraty 2010) shows TDS concentrations in monitoring wells WUR-3 and WUR-5 of between 119 and 278 mg/L, respectively. The TDS values of water samples collected from

Table 1 Physical-chemical parameters from Wadi Wurayah surface waters samples collected in January 2006 (EWS-WWF and Fujairah Municipality 2006).

Site ID	pH	Total hardness[(a)] (mg/L)	Conductivity (mS/cm)	TDS[(b)] (mg/L)	Chloride (Cl) (mg/L)	Bicarbonate (HCO_3) (mg/L)	Sodium (Na) (mg/L)	Calcium (Ca) (mg/L)	Magnesium (Mg) (mg/L)	Nitrate (NO_3) (mg/L)	Fluoride (F) (mg/L)	Nitrite (NO_2) (mg/L)
Main spring	8.1	170	n.d.	306	73	103	n.d.	n.d.	n.d.	3.4	< 0.01	< 0.01
LF1 first pool	8.1	229	n.d.	360	59	162	n.d.	n.d.	n.d.	5.0	< 0.01	< 0.01
Main waterfall	8.4	192	n.d.	362	74	170	26	12	39	1.0	< 0.01	< 0.01
RF1-1	8.3	203	n.d.	350	83	162	31	9	43	3.0	< 0.01	< 0.01
RF1–2	8.2	236	n.d.	368	83	171	30	15	48	2.0	< 0.01	< 0.01
RF1–3	8.5	247	n.d.	403	84	213	30	15	50	1.5	< 0.01	< 0.01
LF1-1	8.3	165	453	278	45	127	8	14	36	8.0	< 0.01	< 0.01
LF1–3	8.4	166	466	278	45	127	8	11	29	7.8	< 0.01	< 0.01
LF1–5	8.3	170	466	289	46	131	8	11	34	7.8	< 0.01	< 0.01
LF1–6	8.9	151	n.d.	257	48	102	6	11	33	4.6	< 0.01	< 0.02
LF1–8	8.5	162	n.d.	275	48	120	6	4	31	5.3	< 0.01	< 0.01
LF1–9	8.1	180	450	277	44	150	7	12	36	6.4	< 0.01	< 0.01
LF1–10	8.1	188	438	267	45	140	8	13	37	6.0	< 0.01	< 0.01
LF1–11	8.2	193	463	284	49	159	7	14	38	5.3	< 0.01	< 0.01
LF1–12	8.2	191	451	274	47	155	7	14	38	6.0	< 0.01	< 0.01
LF1–14	8.2	200	475	292	47	169	7	16	38	5.0	< 0.01	< 0.01
LF1–15	8.2	193	492	301	46	175	8	16	37	5.0	< 0.01	< 0.01
LF1–18	8.4	194	493	303	47	159	6	14	38	5.0	< 0.02	< 0.01
LF1–19A	8.4	196	491	301	46	167	6	14	39	5.0	< 0.02	< 0.02
LF1–19B	8.4	195	501	306	47	171	7	14	38	5.0	< 0.01	< 0.01
LF1–20	8.2	193	507	311	54	171	8	14	38	5.0	< 0.01	< 0.01
LF1–22A	8.6	185	486	298	47	159	6	15	35	5.0	< 0.02	< 0.01

[(a)]Total water hardness is defined as the sum of Ca^{2+} and Mg^{2+} concentrations expressed as mg/L of $CaCO_3$. Water is classified according its hardness into soft water (<60 mg/L), moderately hard water (61–120 mg/L), hard water (121–180 mg/L) and very hard water (>180 mg/L).
[(b)]TDS: total dissolved solids is a measure of the combined content of all inorganic and organic substances contained in a liquid in molecular, ionized or micro-granular (colloidal sol) suspended forms.

Table 2 *Escherichia coli* and faecal coliform concentrations in Wurayah water waterfall pools (WU, WF and WL) in March 2008 (Knuteson *et al*. unpubl.). (BD: below lower detection of 4/100 ml). World Health Organization standard for drinking and bathing water are 0/100 and 100/100 ml, respectively (WHO 2003, 2006).

Site ID	Description	Faecal coliforms (/100 ml)	*E. coli* (/100 ml)
WU-1	Upper flowing pool	689	BD
WU-2	Upper flowing pool	875	4
WU-3	Upper flowing pool	1313	BD
WU-4	Upper stagnant pool	4480	BD
WF-1	Waterfall flowing water	1462	4
WL-1	Lower inner pool	7945	64
WL-2	Lower outer pool	3266	49

wells tapping the shallow aquifer at greater distances downstream of the dam site (WUR-5) are higher than those located near the dam (WUR-3), indicating a recharge from the dam reservoir (Alhogaraty 2010). Groundwater quality generally deteriorates downstream, as the extended residence times allow water to dissolve more salts from the gravel deposits. However, in the study area, this process is accelerated by the salt water intrusion from the Gulf of Oman into the eastern gravel aquifer due to the intensive pumping activities to meet increasing irrigation and domestic water needs of the villages and cities of the coast (Murad and Krishnamurthy 2004). Alhogaraty (2010) reports TDS concentrations of up to 345 and 891 mg/L, respectively, in downstream monitoring wells WUR-6 and WUR-7 in 2009, corresponding to increases of 42 and 31%, respectively, since 2005. In 2009, the calculated groundwater dissolved salts—KCl, NaCl, $MgCl_2$, $MgSO_4$, $Mg(HCO_3)_2$, $Ca(HCO_3)_2$—were 42 and 23% for wells WUR-6 and WUR-7, respectively (Alhogaraty 2010). As a consequence, the Emirates Pure Spring Water Company experienced high TDS values for the last decade (1415 mg/L in January 2006) and had to desalinate the water before bottling it.

3 BIODIVERSITY

3.1 Flora

Wadi Wurayah hosts about 300 plant species (EWS-WWF and Fujairah Municipality 2006, Al Hamoodi unpublished). So far, no aquatic macrophytes have been recorded in the area, the only aquatic vegetation being algae in the form of diatoms, thin films of epilithic algae on rocks and gravel to fine filamentous, green algae in the riffles, and floating mats of brown algae in static pools. Wadi Wurayah is nevertheless characterized by its flora associated with the presence of temporary and/or permanent freshwater sources, such as: *Arundo donax*, *Nerium oleander, Saccharum ravennae*. Considered as rare in the UAE (Western 1989, Jongbloed 2003), the water-dependent Southern Cattail (*Typha domingensis*) has been identified in one location so far. The unique Orchidaceae found in the UAE, *Epipactis veratrifolia* lives in association with the fern *Onychium divaricatum* in moist and shady areas, mostly near contact springs. The plant species in Wadi Wurayah are characteristic of an arid mountain habitat, mostly an association of *Acacia tortilis*, *Lycium shawii*, with several woody perennials such as *Euphorbia larica* and *Tephrosia apollinea*. Woody perennials, namely *Convolvulus virgatus*, *Lycium shawii*, *Boerharvia elegans* and *Heliotropium* spp. and trees, such as *Moringa peregrina*, are found on slopes and plateaux. In wadi beds, one finds *Ficus cordata* and *Ziziphus spina-christi*. In addition to their importance for conservation, *Moringa peregrine* and *Ziziphus spina-christi* have an important cultural value in the UAE, as they supply nectar for the wild Asian Dwarf Honey Bee (*Apis florea*), which produces precious honey (Western 1989, Jongbloed 2003). In May 2009, *Grewia erythraea* Schweinf (Family Tiliaceae), a rare tree from the Hajar Mountains in Oman and UAE, was discovered in the area. Abandoned date palms (*Phoenix dactilifera*) in the lowest wadi elevations are signs of old nearby settlements (EWS-WWF and Fujairah Municipality 2006, Tourenq *et al.* 2009).

3.2 Fauna

Twelve species of wild mammals of the total of 20 observed or believed to exist in the UAE Hajar Mountain range, were recorded within the Wadi Wurayah National Park (Tourenq *et al*. 2009), including species considered endangered internationally, such as the Arabian Tahr (*Arabitragus jayakari*), the Arabian Leopard (*Panthera pardus nimr*) and the Mountain Gazelle (*Gazella gazella cora*), (IUCN 2010). Species of national conservation concern, such as Blanford's Fox (*Vulpes cana*), the Caracal Lynx (*Caracal caracal schmitzi*) and Gordon's Wildcat (*Felis silvestris lybica*), are present as well. Alongside the Jebel Hafeet massif in Al Ain, Abu Dhabi Emirate (Aspinall *et al.* 2005), Wadi Wurayah is one of the only two places in the UAE where the Arabian Tahr survives due to the presence of permanent freshwater. Escaped, or released in the wild after the introduction of motorized vehicles in the UAE, feral domestic goats (*Capra aegagrus hircus*) and feral donkeys (*Equus africanus*) are also regularly observed (Tourenq *et al.* 2009).

Seventy-four species of birds in total have been recorded within the Wadi Wurayah area so far (Tourenq *et al.* 2009). Of these, 5% are considered endangered worldwide by IUCN and 25% are of conservation concern for the UAE, such as the Egyptian Vulture (*Neophron percnopterus*), Lappet faced Vulture (*Torgos tracheliotos*), Bonelli's Eagle (*Hieraaetus fasciatus*), Barbary Falcon (*Falco pelegrinoides*), Lesser Kestrel (*Falco naumanni*) and Houbara Bustard (*Chlamydotis macqueeni*) (Javed 2008). Fifty-nine percent of the species recorded in the Wadi Wurayah region are known, or thought to be, present during the breeding season in the area (Tourenq *et al.* 2009).

A total of 15 species of reptiles and amphibians have been recorded in the area. Of interest are six species that are endemic to the mountains of the UAE and northern Oman: Blue-tailed Lizard (*Omanosaura cyanura*), Bar-tailed Semaphore Gecko (*Pristurus celerrimus*), Banded Ground Gecko (*Bunopus spatalurus hajarensis*), Gallagher's Leaf-toed Gecko (*Assacus gallagheri*) and the Omani Carpet Viper (*Echis omanensis*). The regional endemic amphibians: Arabian Toad (*Duttaphrynus arabicus*) and the Dhofar Toad (*Duttaphrynus dhufarensis*) are present as well (Gardner 2005, Egan 2007, Tourenq *et al.* 2009, Papenfuss *et al.* personal communication).

Three of the 18 species of freshwater fish found the Arabian Peninsula are present in eastern and southern parts of the UAE and in northern Oman: *Garra barreimiae*, *Cyprinion microphthalmum muscatensis* and *Awaous aeneofuscus* (Feulner 1998). Classified "Vulnerable" by IUCN (2010), *Garra barreimiae* is the only native fish species present in Wadi Wurayah (Tourenq *et al.* 2009).

A total of 74 terrestrial invertebrate families have been identified so far, belonging to 12 different orders: Diptera (flies), Hymenoptera (wasp, bees) and Coleoptera (beetles) represented the most diverse order of invertebrates in Wadi Wurayah (Tourenq *et al.* 2009). Coleoptera, Hemiptera (bugs), Odonata (dragonflies), Trichoptera (caddisflies), Platyhelminthes (flatworms), Nematodes (roundworms), Annelids (segmented worms), and Gastropoda (molluscs) are thriving in permanent freshwater habitats. To date, nine species of Odonata (dragonflies) have been observed in Wadi Wurayah, the waterfall pool has one of the only three records of *Tramea basalaris* and the only record of the Bloody Darter dragonfly (*Crocothemis sanguinolenta*) for the whole UAE (Reimer personal communication, Feulner *et al.* 2007). An arthropod fauna inventory by van Harten (2008, 2009, 2010, 2011) has so far revealed 55 species of arthropods new to science discovered in Wadi Wurayah. Five of these new species are Ephemeroptera (mayflies), namely: *Nigrobaetis arabiensis, Cheleocloreon soldani, Cloeon arenorum. Choroterpes (Choroterpes) pacis*, and *Caenis malzacheri*. Ephemeroptera are water-dependent for most of their life as larvae, very pollution-sensitive and are used as indicators of good water quality worldwide.

4 IMPORTANCE OF THE WADI FOR LOCAL POPULATIONS

Being populated since the Neolithic period (10 000–3000 BC), and located at the crossroads between Asia and Africa, the Fujairah Emirate is very rich in archaeological and historical sites of national and international importance (Ziolkowski 2002). Old settlements from the Third Millennium BC (3000 BC) and collective graves from the Second Millennium BC (2000 BC) were found on the northern vicinity of the Wadi Wurayah National Park and in Bidiyah, respectively. A number of sites from the Iron Age (1300–500 BC) and rock art carving (petroglyph) sites were identified in the mountains (Bithna, Wadi Asimah, and Wadi Awhalla) and on the coast (Dibba and Qidfa). The most ancient mosque of the UAE, dating from 1446 AD, is located in Bidiyah (Ziolkoswki 2007a, 2008). In 2007, Ziolkowski identified two pre-Islamic tombs in Wadi Wurayah National Park, similar to examples found all over the East Coast (Wadi Saqamqam graves) and on the plain of Kalba (60 more graves), that seem to be of a Late pre-Islamic date (i.e. post-300 BC to *ca*. 500–600 AD). Artefacts collected in the wadi were also identified as 15–18th century AD porcelain and pottery fragments, comparable to material dated from the 14–17th centuries AD (Ziokolwski 2007b). So far, 29 previously uncharted archaeological sites, from pre-Islamic tombs and Islamic graveyards to old settlements, were mapped in the Wadi Wurayah catchment basin. However, since an extensive settlement continued without interruption for several thousand years until recent times (the last Beduin family to camp during the winter in Wadi Wurayah left the area in 1981), the dating of some of the sites in Wadi Wurayah is difficult without further archaeological investigations and proper excavations.

As in most of the areas of the Hajar Mountains along the Indian Ocean coast, local tribes were herding their livestock (goats) and producing milk, meat and skins in the mountains during the winter months and then bringing them back to the coastal plains, where people spent the hottest season (April–October), trading, looking after palm plantations and fishing. This nomadic lifestyle survived until the end of the 1970s, when the country's oil boom resulted in sedentarization and easier access to amenities and housing. Presence of permanent water resources in Wadi Wurayah allowed a light variety of agriculture (date palm cultivation) in some areas. Agricultural activities, mostly dates, mango (*Mangifera* sp.) and *Citrus* sp. trees, are currently concentrated in the downstream part of the wadi, near the coast.

In addition to medicinal plant collection, the ancient tradition of wild honey collection is still practiced today in the area. Honey hunters start their quest after the winter rains (December–March) when the vegetation is blooming, seeking honey combs of the wild Asian Dwarf Honey Bee (*Apis florae*) in caves and trees, to extract the highly-prized honey (sold at around US$ 200 a litre). Found in tropical regions from Southeast Asia through to India, Pakistan and southern Iran, *Apis florae* is less productive than the Western or European honey bee (*Apis mellifera*) and not domesticated for honey production (hence the high price of the honey). The traditional honey hunting activity in the UAE has been sustainable until now and quite controlled by the local communities themselves. From September to April, honey hunters delicately take the honeycomb from colonies in natural caves/bushes/trees. Using sticks, they carefully prop the brood comb (with the queen) up again in the same position against the natural support so that the bee colony survives.

So far, Wadi Wurayah has been subject to little groundwater extraction. Networks of man-made channels, known locally as *falaj,* have been used in the region for millennia (Al Tikriti 2002, Al Suleimani *et al.* 2007) to collect groundwater, spring water and surface water and transport it, by gravity, to demand areas (habitations, plantations). However, despite the presence of permanent water and evidence of settlements, no *falaj* system has been found in Wadi Wurayah. Within the catchment, water extraction activity is currently restricted to the downstream part of the catchment basin for agriculture, and municipal well fields supplying the main towns of Khor Fakkan and Bidiyah and the Emirates Pure Spring Water Company bottled water factory near Bidiyah. A small dam has been constructed above the main waterfall to divert the surface flow into a 3-m-diameter concrete caisson which then feeds by gravity into a pipeline down the wadi to the area of agriculture. However, the system installed some 15–20 years ago is now out of order, destroyed by the successive floods.

5 GENERAL DISCUSSION

The particular hydrogeology of Wadi Wurayah catchment basin allows a peculiar wildlife, of national and international conservation concern with flagship species, such as the Arabian Thar, the wadi fish *Garra barreimiae* and the orchid *Epipactis veratrifolia*, to survive in a harsh arid environment. So far, the area is known to host about 44% of terrestrial plant species (approximately 300 of 688), 42% of terrestrial mammal species (20 of 48), 26% of terrestrial reptile species (14 of 53), 17% of bird species (74 of 435), and the only two amphibian species recorded in the country (Tourenq and Launay 2008, Tourenq *et al.* 2009). New discoveries are expected in the near future, especially regarding the invertebrate fauna. The presence of the 29 archaeological sites, including uncharted pre-Islamic tombs, shows that Wadi Wurayah has a tremendous potential for further archaeological investigation, exhibition and conservation of national cultural heritage.

With the official declaration of protection in 2009 by Local Decree, the local government committed to conserve this remarkable cultural heritage, biodiversity and one of the last intact natural freshwater habitats in the country. In November 2010, Wadi Wurayah catchment basin was declared as a UAE Ramsar site, highlighting local authorities' intention for the conservation of the ecological character of the site and sustainable use of the freshwater habitat and its resources. Although the Ramsar listing does not ensure protection, the area joined the list of sites in the world recognized as of "international importance" (Ramsar Convention Secretariat 2006).

Nevertheless, the Wadi Wurayah area is under considerable pressure. Interviews with local residents indicated a general decline of 72% in sightings of the flagship mammal species: Arabian Leopard, Caracal Lynx, Mountain Gazelle and Arabian Tahr in Wadi Wurayah over the last 15 years (EWS-WWF and Fujairah Municipality 2006). Such observed decline is probably due to several factors, including:

overgrazing, water overexploitation, habitat fragmentation and urbanization, introduction of non-native species, habitat degradation poaching and persecution, and mining.

Since the beginning of the 1980s, Wadi Wurayah area has no longer been exploited by goat herders, but domestic goats and donkeys have escaped, or were released into the wild, and become feral over time. Overgrazing was previously not identified as the primary threat for Wadi Wuaryah ecosystems. Because of the extirpation of the native wildlife (gazelles and thars), feral goats have now become an essential part of the diet of the few Arabian leopards and caracals in the region, and are the most observed ungulate in the Wadi Wurayah National Park (Jongbloed *et al.* 2001; EWS-WWF and Fujairah Municipality 2006). The number of feral donkeys is low (less than five individuals) in Wadi Wurayah and concentrated in the lower parts of the surveyed area (EWS-WWF and Fujairah Municipality 2006). By now, feral livestock populations may have reached an equilibrium in relation to predators, climate and water availability. However, observations on native vegetation seedlings indicate a recurrent grazing pressure. The decline of predators due to human persecution could have had a knock-on effect on vegetation, through enhancing the expansion of feral livestock, leading to overgrazing. Studies on the feral populations of goats and donkeys are urgently needed to identify: (a) the grazing pressure by feral goats and donkeys, and (b) the predator–prey dynamics between feral livestock and carnivores within the Wadi Wurayah ecosystem and the competition with native wildlife for foraging resources.

Over the last 30 years, the UAE has experienced extraordinarily rapid economic development, coupled with sharp population increases and the development of large agricultural and forestry sectors, substantially supported by government subsidies. Between 2003 and 2005, the population of the emirate of Fujairah alone has grown by 42% (Government of Fujairah 2008). As in all of the country, this demographic expansion and the infrastructure coupled with it, has resulted in increasing pressure on the existing water resources. In mountainous areas, the *falaj* system has been replaced by the construction of dams and mechanically-dug wells. Because of the topography, the deterioration of the water situation in the lower catchment and coastal plain of Wadi Wurayah will not have a hydrological impact on the surface water and groundwater resources of the mid-upper catchment. The perennial surface waters of Wadi Wurayah seem to be safeguarded against any over-exploitation of water resources in the lower parts of the same catchment. However, the groundwater level situation downstream is increasingly worrying and could have social and economic repercussions on local populations in the near future. The decreas in groundwater level of 20 m between 2005 and 2009 in the study area is enhancing saline water intrusion from the Gulf of Oman, into the fresh groundwater within the aquifer (Alhogaraty 2010). Coupled with extensive periods of drought, excessive groundwater pumping is one of the main factors behind the serious groundwater level drop within the study area and, the UAE in general. The country is subject to very high evaporation rates (2–3 m/year) and the natural recharge of groundwater from rainfall is less than one tenth of groundwater exploitation. Prevented from accessing the increasingly deteriorated fresh groundwater, the UAE population relies more and more on desalination for drinking and agriculture purposes (Brook *et al*. 2006).

The Wadi Wurayah area has been progressively encroached during the last decade. Agricultural and urbanized lands have extended into the eastern part, downstream of Wadi Wurayah National Park; a road and even a power line are currently being built south of the catchment basin. The construction of infrastructure (buildings, roads, etc.) and the nuisance (heavy vehicle traffic, dust, noise) associated with it, in addition to aesthetic impacts on the natural habitats, can have irremediable consequences on the hydrology of the wadi ecosystems. It induces a supplementary stress to the remaining, arid mountain, fragile wildlife populations, increases the risk of pollution from rubbish left behind, and enhances the penetration of feral animals (goats, dogs, cats, rats, etc.) and of humans in the mountain area. Built for groundwater recharge and protection from floods, dam reservoirs may controversially provide additional habitats that are colonized by aquatic vegetation, invertebrates, amphibians, fish, etc. In arid lands, permanent artificial water bodies play a social and economic role as they become popular tourist attractions, in addition to water resources and security advantages. However, unlike the nearby Wadi Shih Reservoir, most of the reservoirs in the region, such as the Wadi Wurayah Dam reservoir, are dry and their construction has necessitated the intake of construction material close-by and the building of access roads. Because it is increasingly seen as a lucrative activity, the ancient honey gathering tradition could become less sustainable one day. This activity is also threatened by quarrying and overexploitation of freshwater resources, impacting on the habitat from which the Asian Dwarf Honey Bees extract pollen and nectar.

Up to the early 2000s, Wadi Wurayah was free of alien species, except for some feral dogs and cats scouting rubbish and litter in areas frequented by tourists. In 2007, the Red-eared Slider (*Trachemys scripta* spp.) and in 2008 the Mozambique Tilapia (*Oreochromis mozambicus*) were discovered in some pools of Wadi Wurayah (Tourenq and Shuriqi 2010, Tourenq *et al.* 2011). Both species have been nominated amongst the 100 "World's Worst" invaders by the Invasive Species Specialist Group of the IUCN (http://www.issg.org/database). As the waterfall pool where tilapias fish were introduced has the only record of the Bloody Darter dragonfly (*Crocothemis sanguinolenta*) for the whole UAE (Feulner *et al.* 2007), immediate removal of alien fish was organized by local authorities and EWS-WWF (Tourenq *et al*. 2011). In the same period of time, a plant originating from South America with invasive potential, the Green Aloe (*Furcraea foetida*), was removed manually from the wadi. Introduced in the country in the 1980s, the Common Mynah (*Acridotheres tristis*), also one of the 100 "World's Worst" invaders (http://www.issg.org/database), has increasingly encroached the upstream part of the Wurayah catchment basin. Benefiting from the expansion of urbanization and agricultural development, the Red Fox (*Vulpes vulpes arabica*) has expanded its range in the UAE. It is now one of the most common mammals observed in the wadi. Because of their regular incursion into farms and urbanized areas to scavenge or predate on livestock and poultry, red foxes and feral dogs are the object of continuous persecution (shooting, poisoning and trapping) that, in turn, also affects native species such as Caracal Lynx, Gordon's Wild Cat and Blanford's Fox. The presence of invasive and feral species in the catchment basin is enhanced by the continuous dropping of litter by tourists.

Although few people stay overnight or go beyond the spots that can be reached by four-wheel-drive vehicles, the area is under considerable tourist pressure as it is one of the only places in the Fujairah Emirate that has permanent freshwater pools. In addition to the presence of faecal bacteria in water samples from the pools, in a two-day cleaning operation in 2008, a total of 158 kg of litter was collected in the vicinity of the main popular tourist spot after a weekend. Over 94 kg of the litter (= 59%) would have been recyclable if disposed of properly. The highest single value was for glass (47% of the litter), much of which was broken, posing a risk to animals and visitors. There was also large number of batteries. Toxic acids in the batteries are very harmful when they start to corrode the metal casing and leach out into the environment, spoiling groundwater and soils forever. The degradation of the water quality and the environment and the proliferation of invasive and feral species could be easily reduced if a proper litter disposal system and warning signs, as well as a proper indication and enforcement of fines, were organized for visitors.

Despite the UAE Federal Law 24 of 1999 updated in 2006 on environment protection and the Fujairah Law Decree 2 of 2009 for the creation of Wadi Wurayah Mountain National Park, hunting and poaching still occur in the Wadi Wurayah area. On the basis of a social survey (EWS-WWF and Fujairah Municipality 2006), officially declared hunters represented only 8% of the people interviewed, of whom only 17% admitted to still hunting today (mostly feral goats, Arabian Tahr, Mountain Gazelle and Sand Partridge). Honey collectors may often carry a gun and hunt as the occasion arises. Hunting and poaching by non-residents is also suspected. The hunting and poaching occurs mostly during summer (May–September), which is the period when wildlife visits the few permanent water sources; therefore, their behaviour is more predictable and they are more vulnerable. Because of their potential threat to domestic livestock, carnivores are as highly targeted.

In 2008, there were 76 crusher establishments, representing 40% of the industrial labour force of the Fujairah Emirates alone, according to the *Fujairah Statistics Yearbook* from the Statistics and Planning Department of the Government of Fujairah (2008). To our knowledge, there are no current projects of quarrying in Wadi Wurayah. However, since 2006, new quarries have been opened north of the catchment area (Wadi Zikt) for a nearby coastal development. The increasing development of the coast, and therefore the growing need for building materials, makes this threat still pending.

As the first official mountainous protected area of the country, the main objective of Wadi Wurayah National Park was the conservation of permanent freshwater resources and subsequently the unique cultural and natural heritage linked with it. After its official declaration, the main current challenge is to put in place and implement the proper management structure.

Since the availability of groundwater and surface water of high quality is the key to sustaining the rich biodiversity of the area, we recommend:

1. the development of a regular surface water monitoring programme;
2. the development of a regular groundwater monitoring programme;
3. a climate monitoring to get accurate local rainfall data and investigate its relationship with global climate events (e.g. El Niño/La Niña phenomena);
4. the investigation of the ground and surface water resources use;
5. the development of a water resources database for all water related information; and
6. the development of a methodology to estimate the catchment water balance.

The involvement of both federal and local authorities is imperative to the promotion of a sustainable use of the area.

Acknowledgements The authors are grateful to Ms Razan al Mubarak, director, EWS-WWF, Eng. Mohammed al Afkham, director, and Eng. Ali Kassim, Head of the Environment Protection and Development Department of the Fujairah Municipality for their constant support. Eng. Aseela Al Mualla, and Dr Wafa'a Yaser Abdelqader, Head and chief of Fujairah Municipality Food and Environment Laboratory of Fujairah Municipality graciously analysed the water samples. Mohamed Sager Al-Asam, and Mr. Ahmed Saif Al Matri, Head of the Water Resources Section from the Ministry of Environment and Water in Dubai provided invaluable data, information and reports on the hydrogeology of the area. We thank Dr Anthonius "Tony" van Harten for sharing information on arthropod fauna or the wadi and Dr T. Papenfuss, Museum of Berkeley, California, and T. Pierson, University of Georgia, USA, for their discovery of *Assacus gallagheri*. The members and chairs of the Emirates Natural History Groups from Al Ain (Rob Reimer, Brian Holms), Dubai (Gary Feulner), and Abu Dhabi (Dr Drew Gardner), have been an extraordinary support by providing information and technical assistance. The Wadi Wurayah project has been graciously sponsored by HSBC Bank Middle East, Bridgestone, and children from Jumeirah English Speaking School and Raffles Dubai.

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