GROUNDWATER ATLAS OF ABU DHABI EMIRATE

Technical Report · December 2019

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GROUNDWATER ATLAS
OF ABU DHABI EMIRATE

هـيـئـة الـبيـئـة - أبـوظـبـي
Environment Agency - ABU DHABI

The Environment Agency - Abu Dhabi (EAD) was established in 1996 to preserve Abu Dhabi's natural heritage, protect our future and raise awareness about environmental issues.

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GROUNDWATER ATLAS
OF ABU DHABI EMIRATE

YEAR OF
ZAYED

"إن حماية البيئة يجب ألا تكون وألا ينظر إليها
كقضية خاصة بالحكومة والسلطات الرسمية فقط،
بل هي مسألة تهمنا جميعاً.

إنها مسؤولية الجميع ومسؤولية كل فرد في
مجتمعنا، مواطنين ومقيمين."

"We stress that conservation of the environment is not,
and must not be seen as, a matter only for Government
or officials. It is something that concerns us all.

This is a responsibility for all, every member of our
society, both nationals and other residents."

H.H. Sheikh Mohamed bin Zayed Al Nahyan
Crown Prince of Abu Dhabi Emirate
Deputy Supreme Commander
of the UAE Armed Forces
Honorary Chairman,
Environment Agency - Abu Dhabi

H.H. Sheikh Khalifa bin Zayed Al Nahyan
President of the UAE

H.H. Sheikh Hamdan bin Zayed Al Nahyan
Ruler's Representative in Al Dhafra Region,
Chairman, Environment Agency - Abu Dhabi

FROM THE CHAIRMAN

Message from His Highness Sheikh Hamdan bin Zayed Al Nahyan, Ruler's Representative in Al Dhafra Region and Chairman of Environment Agency - Abu Dhabi

For many years, groundwater was the only source of water available to our ancestors. Sourced from Aflaj (water channels), surface wells, springs and streams, it was used in the most sustainable manner. Over the past few decades, however, physical groundwater reserves have been depleted due to the rapid development of the Emirate, unsustainable irrigation practices in the agricultural and forestry sectors, and increased demand for freshwater as a result of population growth. We recognise the mounting pressures on our aquifers in conjunction with the ambitious development plans we have drawn for the future of Abu Dhabi, and are pursuing innovative solutions to protect this vital resource in the Emirate - to ensure sustainability and balance between development and the protection of our essential natural resources.

The Groundwater Wells Inventory and Soil Salinity Mapping Project, launched by the Environment Agency - Abu Dhabi (EAD) in October 2015, is the first phase of a long-term initiative aimed at the conservation of groundwater reserves in the Emirate of Abu Dhabi. This is geared to support the Emirate's sustainability, as well as the development of a comprehensive action plan for the management and reclamation of the farms affected by soil salinity. At present, groundwater accounts for 65% of the water consumed in the Emirate of Abu Dhabi, and is primarily used for agriculture, irrigation of forestry and afforestation. The expansion of the local agriculture sector and improvements in the standard of living have led to the irrecoverable consumption of water from non-renewable aquifers. Therefore, it has become more critical than ever before to preserve this precious and vital resource successfully, for both our present and future generations.

The Atlas is one of the most significant outcomes of the Groundwater Wells Inventory and Soil Salinity Mapping Project, which is an important and pivotal step in the Abu Dhabi Government's plan to improve the efficiency of the use of water resources and increase financial investment in the water management sector. The Atlas includes updated maps of the state of groundwater, its natural, chemical and biological properties, the calculation of groundwater reserves and the capacity of the aquifers in the Emirate - for the very first time. This will allow decision-makers to develop the necessary plans, policies and procedures for sustainable groundwater management and protection from pollution, founded in evidence-based scientific study.

On this occasion, I would like to extend my thanks and appreciation to His Highness Sheikh Khalifa bin Zayed Al Nahyan, President of the United Arab Emirates, and His Highness Sheikh Mohamed bin Zayed Al Nahyan, Crown Prince of Abu Dhabi, Deputy Supreme Commander of the UAE Armed Forces and Honorary President of the Environment Agency - Abu Dhabi, for their support, prudent guidance and continuous commitment to protecting the environment, and groundwater in particular.

It is our hope that this Atlas will enhance our partners' awareness around the state of groundwater in Abu Dhabi and provide them with accurate information on groundwater resources in the Emirate, as we develop plans to conserve, manage and use this important resource effectively and sustainably.

H.H. Sheikh Hamdan bin Zayed Al Nahyan
Ruler's Representative in Al Dhafra Region,
Chairman of Environment Agency - Abu Dhabi

FROM THE VICE CHAIRMAN

Message from H.E. Mohammed Ahmed Al Bowardi, Vice Chairman of Environment Agency - Abu Dhabi

Water is the basis of survival for all creatures. The earth is characterised by water, which is the source of life for everything. As part of the efforts of the United Arab Emirates to conserve its water resources, the Environment Agency - Abu Dhabi (EAD) in 2015 launched the first-of-its-kind inventory of all existing groundwater wells in the Emirate used across all sectors, including agriculture, forestry and entertainment.

As the authority mandated to protect the environment in Abu Dhabi, EAD holds a strategic priority to preserve our valuable groundwater resources and ensure its sustainability for future generations. The protection and preservation of groundwater resources is vital given that they are one of Abu Dhabi's non-renewable natural assets. Due to their use in planting and irrigation of forests and green areas, groundwater reserves have depleted rapidly - more than 20 times the natural recharge rate of aquifers.

This project to inventory all wells in Abu Dhabi was commissioned on the directives of His Highness Sheikh Hamdan bin Zayed Al Nahyan, the Ruler's Representative in Al Dhafra, and the Chairman of Environment Agency - Abu Dhabi (EAD). Groundwater should be utilised responsibly to ensure its sustainability for future generations, as well as to maintain public and private investment that relies on groundwater as a source of water. The information collected through this initiative has supported our efforts to develop the necessary plans for the integrated management of groundwater resources, to guide farm owners on how to maximise the economic and agricultural efficiency of their farms through the proper use of groundwater for irrigation.

The project contributed to the collection and documentation of the latest and most accurate data of existing wells in Abu Dhabi, including their type and status. It also recorded the current conditions of wells in the Emirate, along with their total number and use across various sectors. Morevoer, it helped identify those wells whose water is desalinated at desalination plants, as well as their number, location and methods of disposal of desalination exhausts.

All is data will be linked to a central database at EAD, and will be made available to researchers, groundwater users and decision-makers among other stakeholders. This will allow decision-makers to review, update and amend existing laws and regulations, as well as develop plans for integrated groundwater management.

This Atlas presents the analysis of the results of the Groundwater Wells Inventory project in the form of maps, graphs and images that detail the location, type, depth and use of wells in Abu Dhabi.

We hope that this comprehensive Groundwater Atlas - the first-of-its-kind for the Emirate of Abu Dhabi - will serve as an important reference for researchers and all those who wish to study the issue of groundwater in Abu Dhabi. It provides a summary of the history of the exploration and use of groundwater, lending important context to the current situation and state of this natural resource.

H.E. Mohammed Ahmed Al Bowardi
Minister of State for Defence Affairs,
Vice Chairman of Environment Agency - Abu Dhabi

FROM THE MANAGING DIRECTOR

Message from H.E. Razan Khalifa Al Mubarak - Board Member and Managing Director of Environment Agency - Abu Dhabi

Groundwater in Abu Dhabi is the key natural source of water in the Emirate, mainly used to irrigate agriculture, gardens, parks and afforestation projects. The irresponsible use of groundwater and the drilling of unlicensed wells has been identified as a major challenge towards the preservation of this vital and limited natural resource, placing a critical importance on the development of national groundwater conservation programmes.

Effective planning and regulation of the use of groundwater requires a comprehensive overview of the current conditions of wells in Abu Dhabi. For this purpose, EAD has introduced an initiative to locate and digitally record all groundwater wells to determine pumping quantities, water levels and quality.

The project, which lasted for 36 months and that was carried out in three main phases, included the inventory of existing groundwater wells in the Emirate of Abu Dhabi. In the first phase, all the wells were assigned a unified number during field visits that recorded pumping rates, groundwater levels, salinity, condition and the purpose for which each well is being used for.

The second phase included updates to available soil salinity and fertility measurement data. The soil samples were taken from a selected few of the 25,000 farms in the Emirate, and then analysed to identify the soil type, salinity and quality. This will help develop plans to determine the sustainability of these farms and classify them in terms of soil quality. This aims to drive investment to the agricultural sector, establish the best ways to manage these farms and discover the most suitable crops to maintain soil and water quality.

In its last phase, the project analysed all the water and soil data to produce an atlas of aquifers in the Emirate - the very first of its kind for Abu Dhabi. The study provides a summary of groundwater sources in terms of their quantity, quality, natural, chemical and biological property, location, depth and type. This information is displayed in the form of annotated maps, graphs, sections and images. The atlas will also include the results of the Well Inventory Project, detailing the location, type, depth and use of wells in the Emirate of Abu Dhabi.

This Atlas is a culmination of the efforts of a dedicated team of engineers, technicians, experts and specialists in the fields of water and soil at the Environment Agency - Abu Dhabi. I would like to express my appreciation to everyone for their outstanding contributions to this landmark publication. I am confident that this Atlas will serve as a valuable resource and reference tool for generations to come.

H.E. Razan Khalifa Al Mubarak
Managing Director,
Environment Agency - Abu Dhabi

FROM THE SECRETARY GENERAL - ACTING

Message from H.E. Dr. Shaikha Salem Al Dhaheri, Secretary General - Acting of Environment Agency - Abu Dhabi

About 50 years ago, Abu Dhabi's water needs were fully met from groundwater by using only traditional extraction methods. Today, groundwater still contributes to about 65% of the total use of water resources in the Emirate of Abu Dhabi, which is mainly used for irrigation purposes. Groundwater in Abu Dhabi is a scarce and non-renewable resource, and preserving this precious asset is one of the main priorities for the Government of Abu Dhabi. Over the past few decades, natural groundwater reserves have been depleted due to accelerated development, unsustainable irrigation practices in the agricultural and forestry sectors, and increasing demand for freshwater as a result of population growth.

Without accurate data it is difficult to develop and manage aquifers in the Emirate, which underscores the importance of this initiative to review, number, record and locate all existing groundwater wells in the Abu Dhabi. This information will be entered into the EAD central database that will help us determine, track and analyse the pumping quantities, groundwater levels and quality. This, in turn, will help the government to develop plans and initiatives for the sustainable management of groundwater to protect aquifers in the Emirate. This project aims to collect the necessary data in order to improve the efficiency of the use of water resources and drive more investment into the local water sector. The results of this project will provide the information needed to assist stakeholders in developing an integrated and effective water resource management plan. It will also help owners of farms and wells in reducing the financial waste resulting from drilling unproductive wells, improving overall agricultural efficiency and maximizing the use of groundwater for irrigation.

This initiative is an integral part of EAD's comprehensive and integrated groundwater management and regulation program to promote innovative and sophisticated solutions to address the increasing challenges facing non-renewable groundwater resources - in cooperation with both public and private partners in the Emirate of Abu Dhabi.

The outcomes of this project included the review of all groundwater wells in Abu Dhabi used to irrigate farms, forests and parks. Experts from EAD have conducted a series of field visits that saw each well assigned with a unique serial number, and have also recorded the volume of abstracted water, available water levels, quality, salinity, and purpose of extraction. They have also measured the soil salinity and quality through soil extraction and the analysis of soil samples from several farms in Abu Dhabi to create the first-of-its-kind groundwater atlas for the Emirate of Abu Dhabi.

This project and its outcomes were made possible by the tremendous efforts of EAD's technical team members, who in collaboration with our partners, have implemented this project over the past 36 months. Their contributions, which spanned planning to fieldwork and data collection, have been instrumental in the development of the atlas, in addition to the final reports of the project. I would like to express my sincere gratitude to the team for their hard work and dedication to this project.

This initiative, which was completed in the UAE's Year of Zayed, is in line with the vision of our founding father, the late Sheikh Zayed bin Sultan Al Nahyan, who advocated for the prudent, responsible and sustainable use of water resources. His values towards the protection of our natural resources continue to inspire and influence our long-term development goals. Guided by his environmental legacy, our nation has achieved great milestones in the conservation and management of our water resources, which have received wide international recognition.

H.E. Dr. Shaikha Salem Al Dhaheri
Secretary General - Acting,
Environment Agency - Abu Dhabi

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This Groundwater Atlas is result of the *Groundwater Wells and Soil Salinity Mapping of Abu Dhabi Emirate* project, which contributors are also authors of the Groundwater Atlas. The project was undertaken by a multidisciplinary team comprised from EAD and Dornier Consulting International. The strategic direction and high-level review process was overseen by the Technical Committee. The progress and implementation was monitored and supervised on a day to day basis by the Project Team.

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Abu Dhabi Municipality (ADM)
Abu Dhabi National Oil Company (ADNOC)
Al Ain Municipality (AAM)
Al Dhafrah Region Municipality (DRM)
Department of Municipal Affairs Abu Dhabi (DMA)
International Center for Biosaline Agriculture (ICBA)
Ministry of Climate Change and Environment, formerly: Ministry of Environment and Water (MOEW)
Statistics Centre Abu Dhabi (SCAD)
EAD Environmental Information Science & Outreach Management (EISOM)
EAD Environment Quality Sector (EQS)
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ABOUT THIS GROUNDWATER ATLAS

Established in 1996, the Environment Agency - Abu Dhabi (EAD) is committed to protecting and enhancing air quality, groundwater, and the biodiversity of our land and marine ecosystems. Through partnerships with other government entities, the private sector, NGOs and global environmental agencies, the EAD embraces international best practices, innovation and hard work to institute effective policy measures. They seek to raise environmental awareness, facilitate sustainable development and ensure environmental issues remain one of the top priorities of the national agenda.

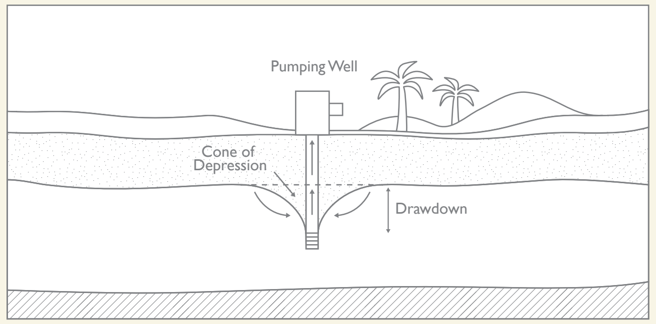
A thorough understanding of groundwater resources is essential for sustainable groundwater management. To gather this knowledge, the EAD initiated the project *Groundwater Wells Inventory* and *Soil Salinity Mapping for Abu Dhabi Emirate* to compile a comprehensive inventory of groundwater wells in the Emirate. Most of the groundwater resources are used for agricultural purposes. Data from farms, irrigation systems, and related soil salinity levels were gathered to study the impacts of irrigation water quality on agricultural land.

The *Groundwater Atlas of Abu Dhabi Emirate* presents the results and findings of this project. It further aims to give a comprehensive overview of the groundwater resources, its geological setting, quantity, quality, use, and management.

Coordinate system for all maps in this Atlas is UTM Zone 40N with WGS84 Datum. The maps included in this publication are not authorities on international or inter-emirates' boundaries.

Guide

This sketch will appear throughout the atlas, highlighting the subject of the respective page.




Arabian Gulf
Northern Emirates
Abu Dhabi City
Al Hayer
Sweihan
Al Khatim
Remah
Al Ain
Ghayathi
ABU DHABI EMIRATE
Al Araad
Al Wagan
Al Qua'a
Mizerah
Arrada
Himem
Saudi Arabia
Oman
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Kilometres
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Base Map Legend (for all Atlas Maps)
International Boundary
Inter-Emirate Boundary
Major Highway
Principal Highway

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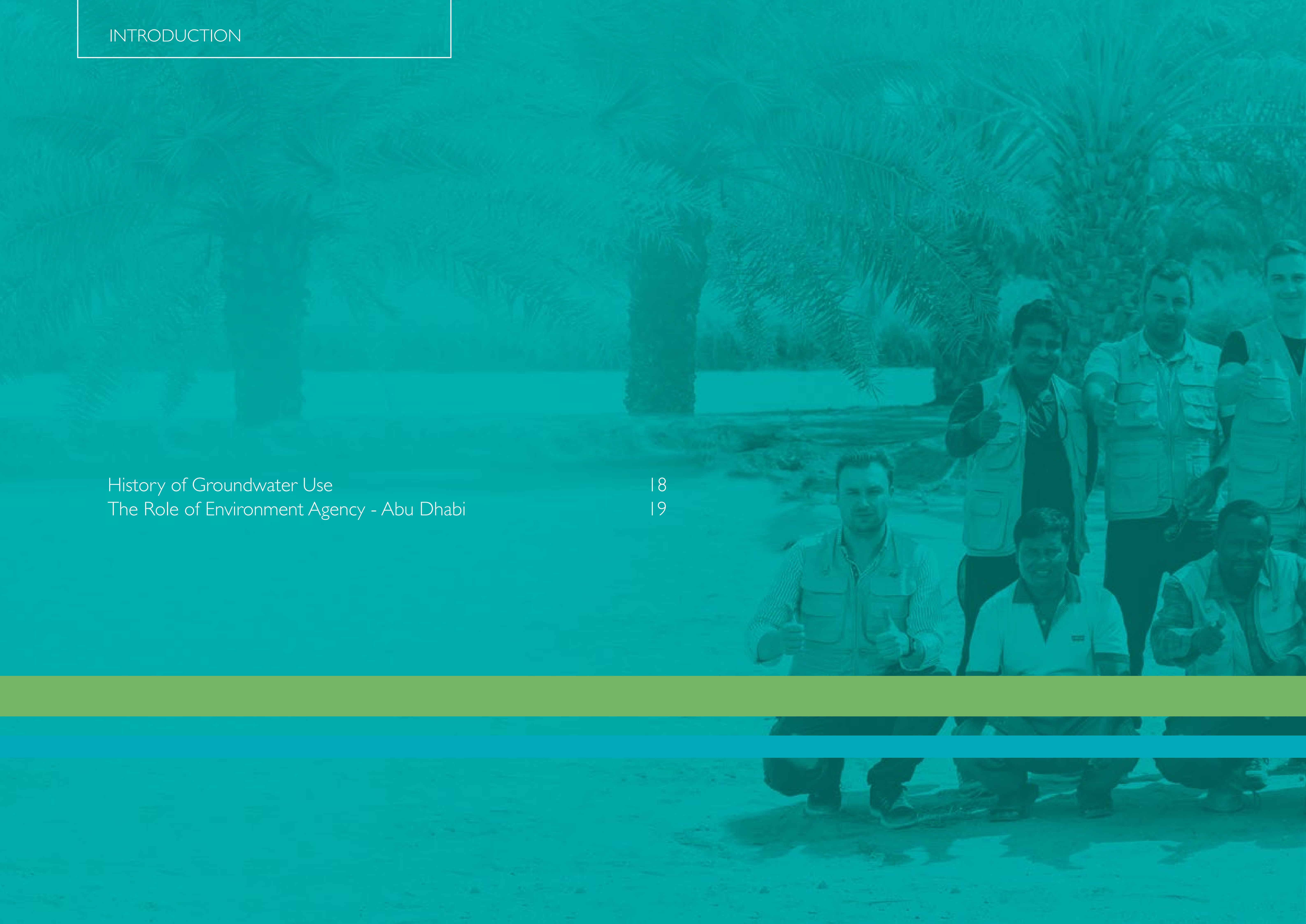


INTRODUCTION

Falaj in Al Ain Oasis

Aflaj are underground aqueducts that convey water from springs or wells to the demand areas by gravity flow. **The Al Ain Falaj is the longest in the Emirate - It is 15 km long.**

HISTORY OF GROUNDWATER USE

The first settlements in Abu Dhabi Emirate trace back to the Late Stone Age between 6,000 and 7,000 years ago. The semi-nomadic peoples that settled this land used oases like Liwa and Al Ain to establish agricultural hubs. Because of the unforgiving climate, survival depended on meticulous water management. Spurred by water scarcity, these early communities enforced strict punishments for anyone who intentionally or inadvertently jeopardised the essential water resources.

Around 3,000 years ago, in the late Bronze Age, the first Aflaj were developed in the Al Ain oasis. These underground aqueducts convey water from springs or wells to the demand areas by gravity flow. The groundwater use had an apparent social context: The maintenance of community-owned infrastructure was the responsibility of all shareholders. Governance systems ensured that the water was properly divided among the different users, and that the cleanest water at the entry point of the water into the oasis was available as drinking water for everyone. Springs and oases were places of flourishing community life and became targets of militant conflicts.

Water use was sustainable - essentially meaning that on a long-term average not more water was used then was naturally replenished. For millennia, the usage of water was governed by its availability. With the arrival of modern pumps and drilling techniques groundwater exploitation started. Water usage suddenly was governed by demand. Agricultural development provided food and income for the rapidly growing population. Irrigation needs of recreational areas and forests along the highways further increased groundwater abstraction. Well fields were constructed, which supported the drinking water supply from desalination plants until 15 years ago.

The Role of Environment Agency - Abu Dhabi

Founded in 1996, the Environment Agency - Abu Dhabi (EAD) cares about groundwater as part of its vision to protect and conserve the environment amidst the rapid socio-economic development of Abu Dhabi Emirate.

Understanding and monitoring the groundwater is the basis of any efforts to protect and sustainably manage the precious resource. Law and policy-making are essential to implement and enforce recommended measures. Milestones in groundwater legislation are Law no. 6/2006 and Law no. 5/2016. They state that groundwater within Abu Dhabi Emirate territory is property of the government. Responsible for management, organisation, and licensing the activities related to groundwater is the Environment Agency - Abu Dhabi (EAD). This comprises the setting of water quality standards, checking and inspecting wells, issuance of drilling permissions, and measurement and limitation of abstracted groundwater quantities. The activities are embedded in an overall framework to achieve sustainable groundwater management in Abu Dhabi Emirate.

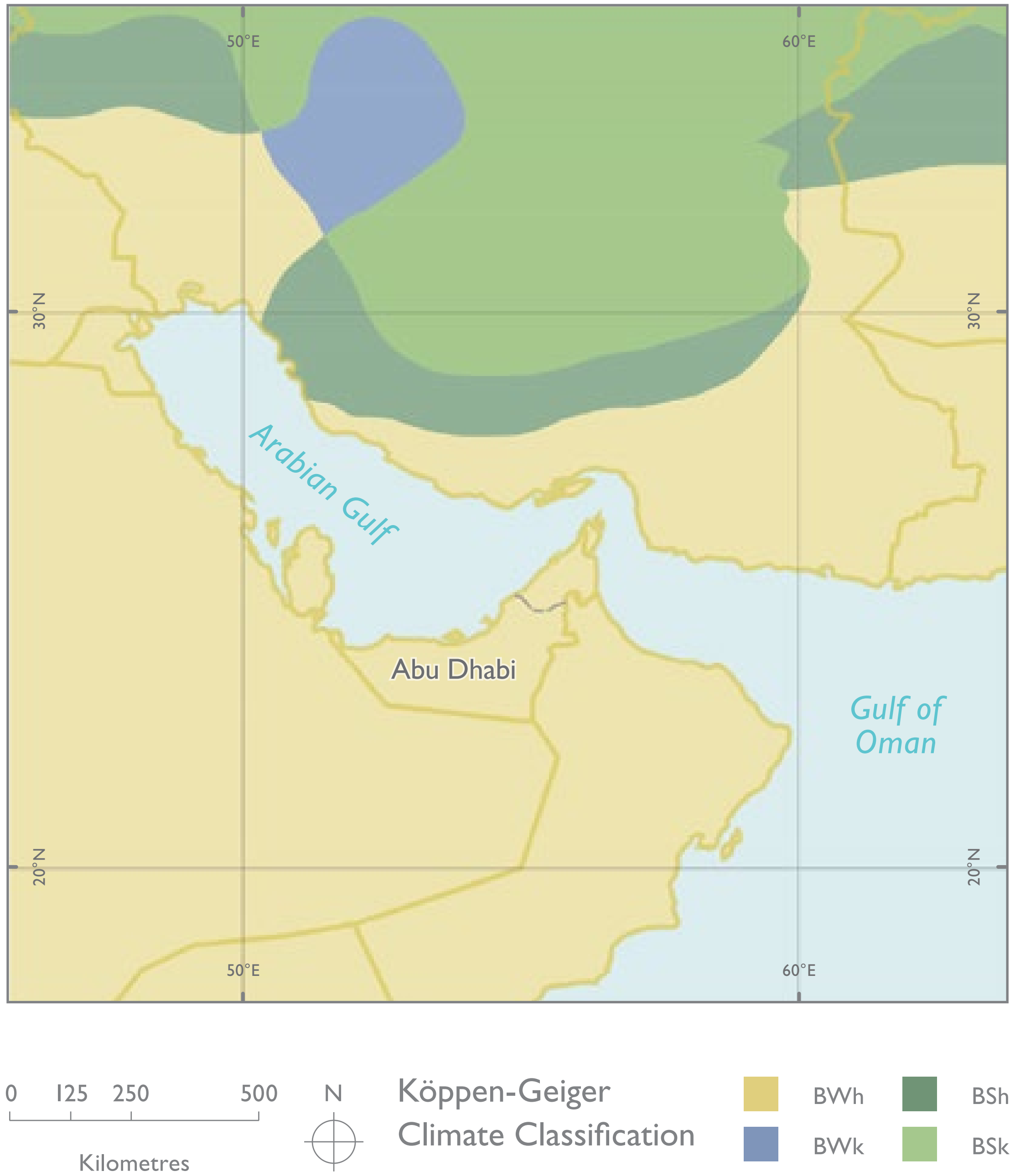
Still, 64% of all water used across the Abu Dhabi Emirate is groundwater; that is about 2 billion m^3/year. Agricultural and forestry sectors account for 95% of these abstractions. The EAD work in the groundwater sector aims to reduce the overall abstraction and to preserve the groundwater quality for many years to come. EAD educates groundwater users as well as the general public on groundwater related topics. Hopefully, the groundwater will remain the precious resource for the coming generations that it was for our ancestors.

Drip Irrigation System

CLIMATE & GEOMORPHOLOGY

CLIMATE & GEOMORPHOLOGY

Climate Classification



Köppen Climate Classification Coding Letters		
1st	2nd	3rd
B (Arid)	**W** (Desert)	**h** (Hot)
	S (Steppe)	**k** (Cold)

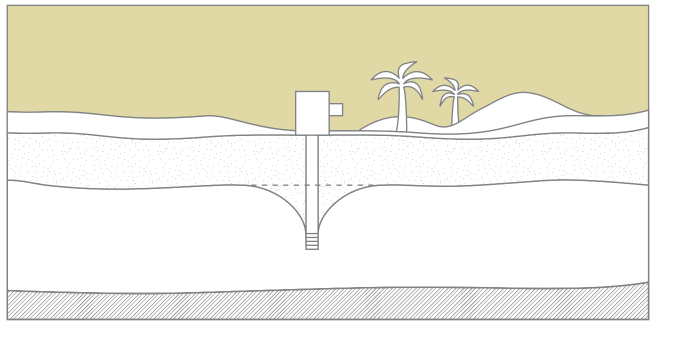
CLIMATE IN ABU DHABI EMIRATE

A hot and dry climate characterises the entirety of Abu Dhabi Emirate; however, climate differences are observed between east and west, and between coastland and inland. Highest rainfalls are recorded in the northeast around Al Hayar, where the annual average exceeds 100 mm. The proximity to the Hajjar Mountains leads to occasional torrential rains, mostly in April and November. The Liwa Desert hosts the highest average temperature. During the summer, average temperatures rise above 40°C, and daily highs reach over 50°C.

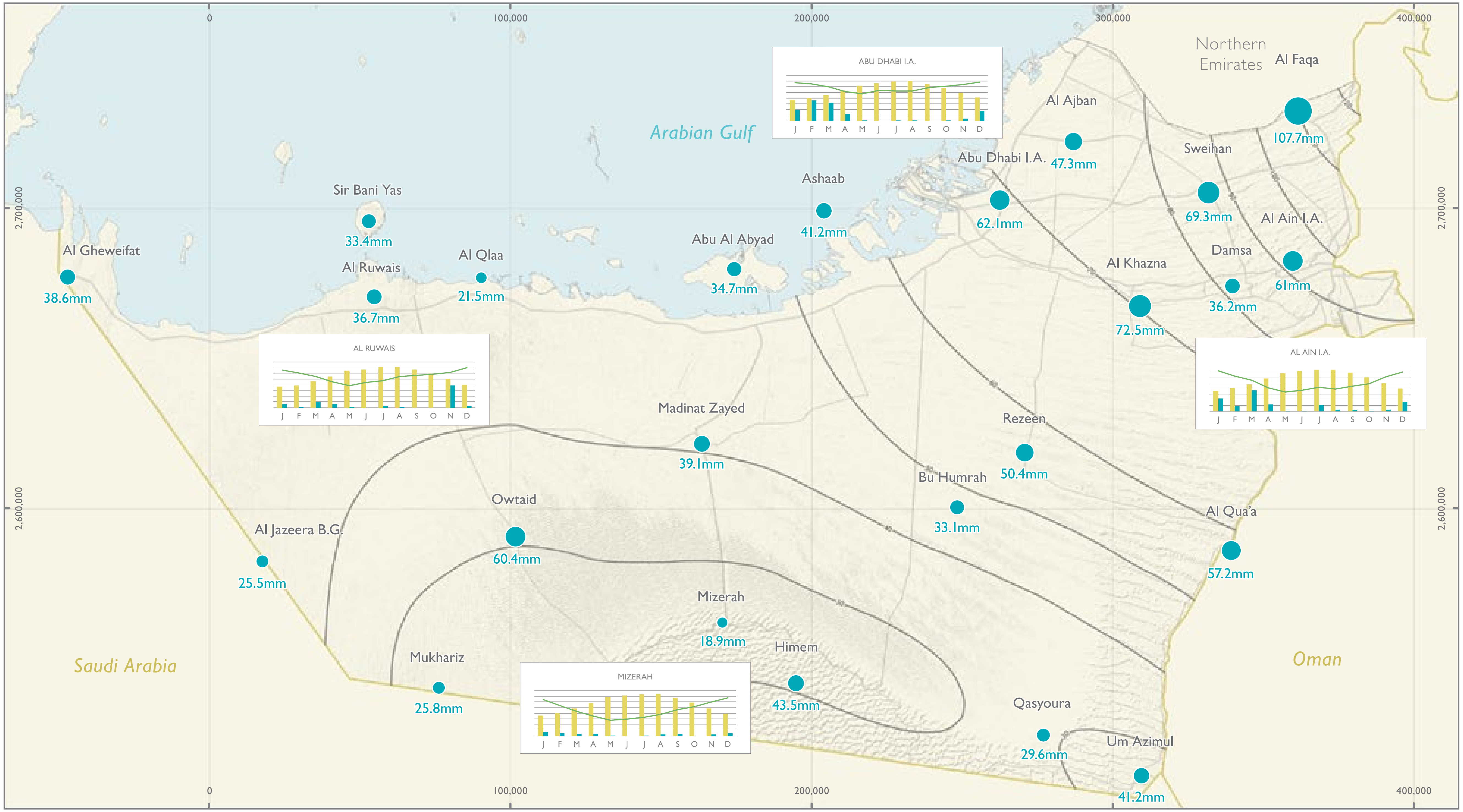
In standard climate classification (Köppen-Geiger), the climate in Abu Dhabi Emirate is characterised as BWh - arid (B), with assigned subgroups dry (W) and hot (h).

The aridity index (UNESCO) shows hyperarid (HA) conditions for the west and south of Abu Dhabi Emirate, and arid (A) conditions in the east and northeast. This reflects the huge negative balance between rainfalls of less than 100 mm/yr and the potential evapotranspiration of about 3,000 mm.

Climate in Abu Dhabi Emirate



CLIMATE IN ABU DHABI EMIRATE



Data Source: NCMS 2003-2016

GEOMORPHOLOGY

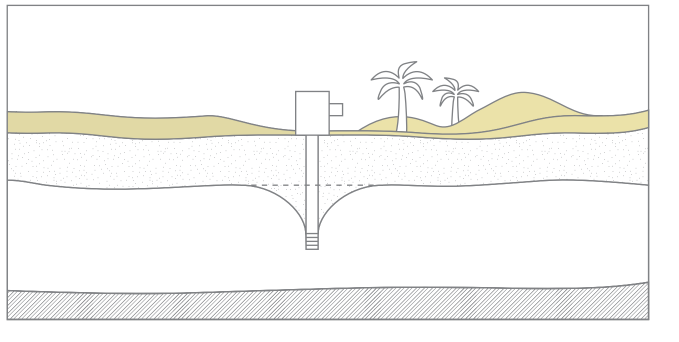
Geomorphology describes the characteristics of the earth's surface as it was formed by geologic and climate processes. Tectonic movements and sea level fluctuations have been the driving forces in the formation of mountain ranges, plains, and basins. Wind, rainfall, and hot and cold temperatures induce physical and chemical weathering, erosion, and accumulation of sediments. Various landscapes influence the water cycle by showing differences in runoff, evaporation and infiltration capacity of water. Therefore, geomorphology is essential to understanding the current formation of groundwater.

Rocks - The adjoining map shows the geologic upfolded calcareous rocks as part of the Hajjar mountains in the east. These rocks are surrounded by corresponding pediments as well as colluvial and alluvial fan deposits. Wadis transport the water and sediments from the mountains westwards onto the plains. Under the present climate, those deposits are barely visible on the surface because they are covered by aeolian (windborne) deposits. Rainfall in the Hajjar Mountains combined with runoff and infiltration along the wadis, contributes greatly to the groundwater recharge in the east of the country. Rock outcrops occur in the western fringe of Abu Dhabi Emirate, where tertiary limestones and dolomites, which are more resistant to erosion than the surrounding aeolian deposits, form elevated tablelands.

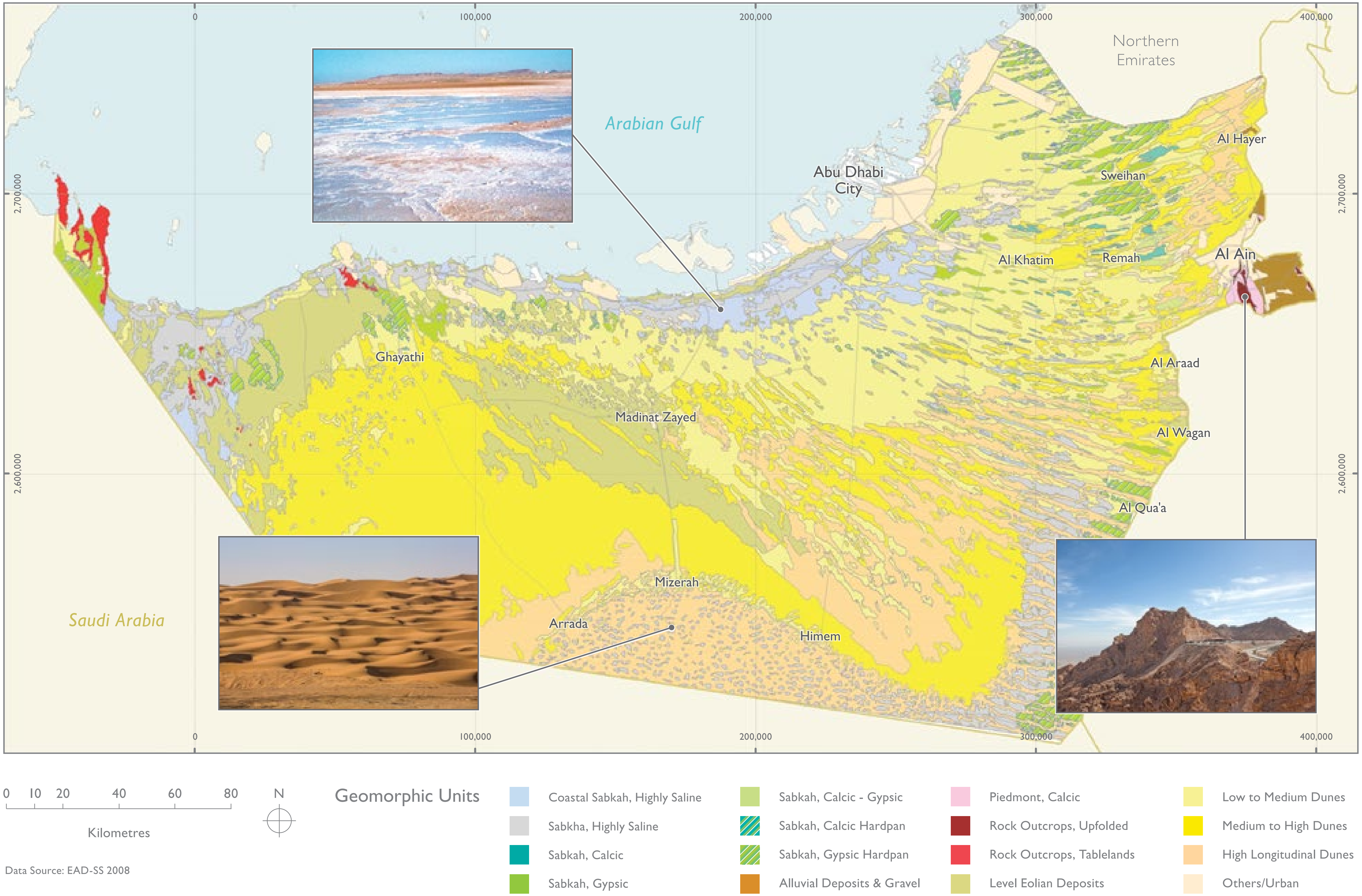
Sabkhas - In the coastal areas, sabkahs are formed where shallow groundwater and seawater were left behind by occasional flooding. The water creates a unique landscape as it evaporates and leaves behind salt, gypsum, and calcareous sediments at the surface. In the eastern and southern parts of the Emirate, inland sabkhas develop between dunes. Small depressions collect rainfall that quickly evaporates in the scorching heat, leaving behind gypsic and calcic hardpans. These hardpans restrict water infiltration into the subsurface.

Dunes - Windborne (aeolian) sediments cover the majority of the Emirate. In the adjoining map, these dunes are subdivided according to relief (level deposits, low to medium dunes, medium to high dunes, and high longitudinal dunes and barchans). The high longitudinal dunes and barchans, with the exception of some star dunes, follow an east to west pattern with long sweeping ridges and wide desert floors (sabkahs) between them. Wind patterns from a previous climate formed the dunes in this direction. Today, dunes are almost stationary, and their crests shift only according to the predominant northwest or southeast winds. The highest dunes appear south of the Liwa Crescent where the famous Moreeb dune has its peak. Despite their dry appearance, most dunes enhance groundwater recharge during occasional rainfalls. Thus, freshwater sits below the sand dunes as is the case around Madinat Zayed in the north of Liwa.

Geomorphology of Abu Dhabi Emirate



GEOMORPHOLOGY OF ABU DHABI EMIRATE



GROUNDWATER & AQUIFERS

GEOLOGY

The geological map shows the land surface and its defining rock and sediment features from different ages and types.

Quaternary sediments cover most of Abu Dhabi Emirate. They represent the youngest geological period (many dunes and coastal deposits are in the range of 10,000 years old - a blink of an eye in geological terms). Among them, the Abu Dhabi formation along the coast includes a range of marine and supratidal facies including coastal spits, bars, beach ridges, and lagoonal muds. The Rub Al Khali formation reflects the corresponding inland sediments, consisting of aeolian deposits (dunes). Older Quaternary sediments are up to 2.6 million years old and include Hili, Madinat Zayed, and Ghayati formations. They consist of fluvial sediments and cemented aeolian deposits (paleo-dunes).

Older rocks are hardly encountered at the surface. The geological profile (next page) shows their succession into the subsurface. During the Early Tertiary, between 66 and 34 million years ago (Paleocene, Eocene), Abu Dhabi Emirate was covered by a shallow ocean. Geological formations from this time like Umm Er Radhuma, Rus, and Dammam, reflect their prehistoric environment and are made up of limestones, dolomites, anhydrite, and shales. In the Middle and Late Tertiary periods, between 34 and 2.6 million years ago (Oligocene, Miocene, Pliocene), the uplift of the Hajjar mountains formed a deep basin at its foothills that collected thick layers of sediment. The interaction of uplift, basin evolution, and sea level changes led to the deposition of first marine (Lower Fars Group), and then terrestrial sediments (Upper Fars Group). The groundwater resources are stored in the rocks from Late Tertiary (Upper Fars Group) and Quaternary age.

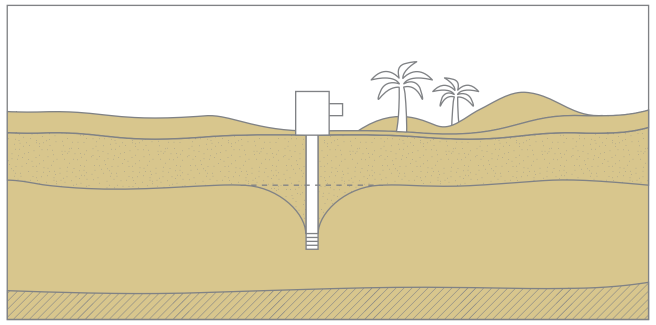
Salt domes and their associated rocks are the oldest rocks found in Abu Dhabi, dating back to the advent of life about 550 million years ago (Ediacaran). They are found at Jabal Dhanna, and on Sir Bani Yas and Dalma islands. Rocks from Paleozoic and Mesozoic ages (541 - 66 million years ago) do not crop out at the surface, nor do they contain usable groundwater resources. However, they do form the subsurface treasure chest containing the oil and gas resources of Abu Dhabi.

Sand Dunes Aerial View, Rub Al Khali Desert

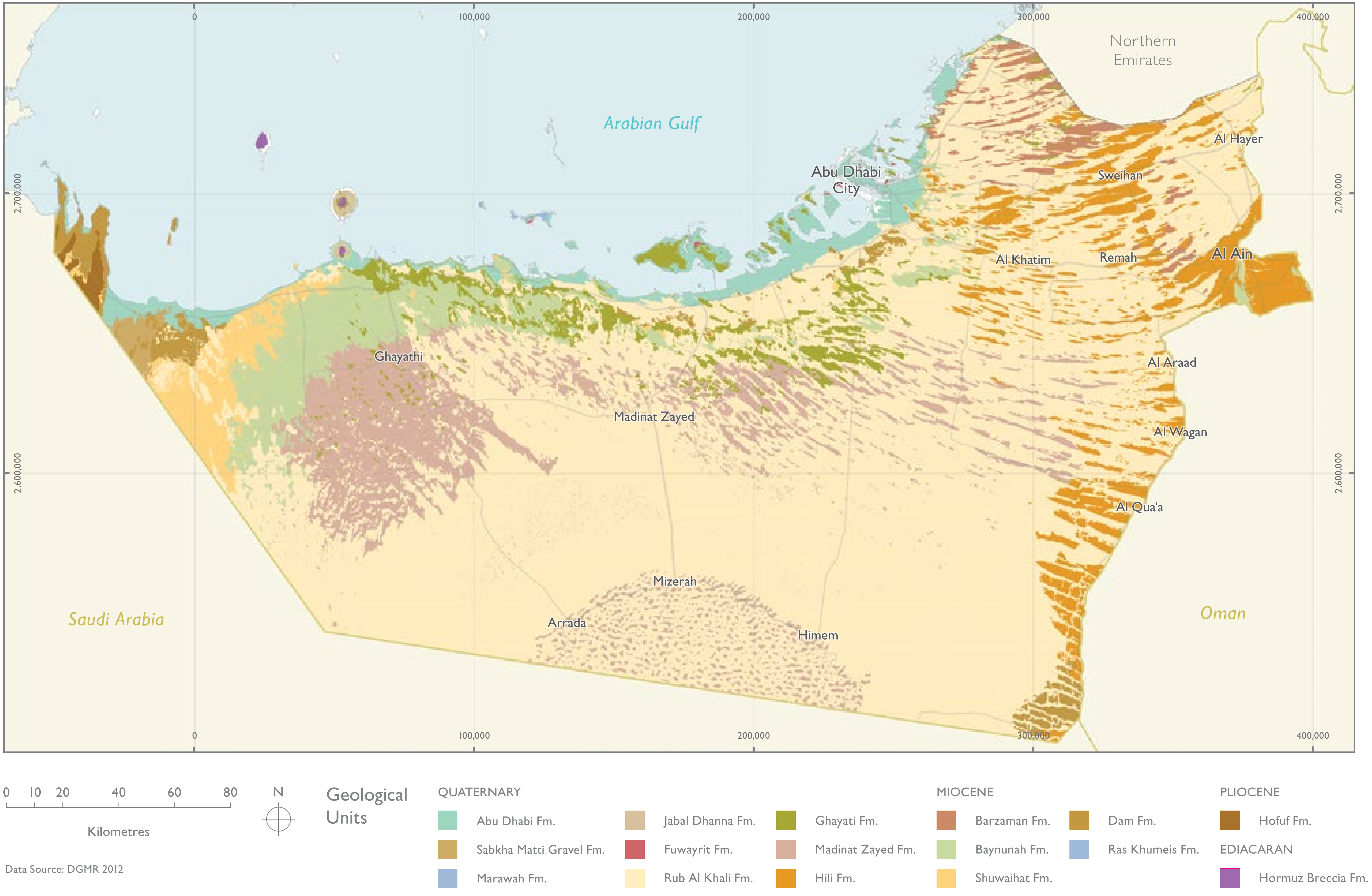
Geological Terms

Sediment (Clastic) - is a type of rock that consists of weathered pieces/grains of other rocks, which were transported and deposited.
Aeolian - transported by wind.
Fluvial - transported by water.

Geology of Abu Dhabi Emirate



GEOLOGICAL MAP OF ABU DHABI EMIRATE



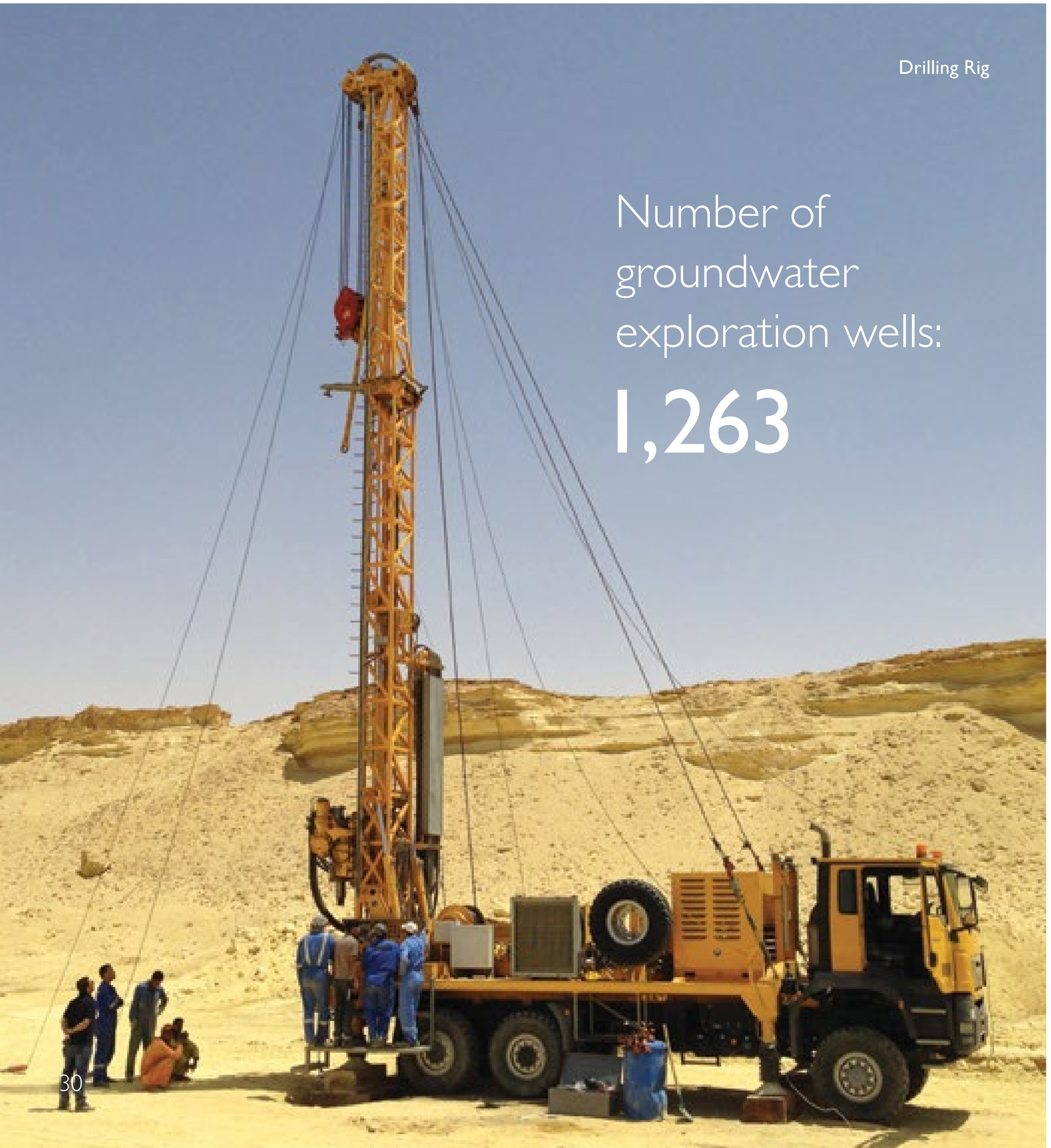
Data Source: DGMR 2012

GEOLOGY OF ABU DHABI EMIRATE

The search for water, especially drinkable water, leads to many new insights about rocks and soil. For over 20 years, EAD has lead efforts to explore the subsurface in order to find, quantify, and protect the groundwater resources. Numerous drilling campaigns have been conducted for that purpose, and more than 1,200 exploration wells have been drilled within Abu Dhabi Emirate.

Tectonically speaking, Abu Dhabi Emirate is part of the Arabian Plate. Over millions of years, sediments accumulated under remarkably stable conditions, reaching a cumulative thickness of more than 10,000 m. The uplift of the Hajjar Mountains east of the Emirate began about 30 million years ago, and is integral to understanding the current groundwater bearing uppermost strata. During this tectonic rise, a basin developed in the western foreland.

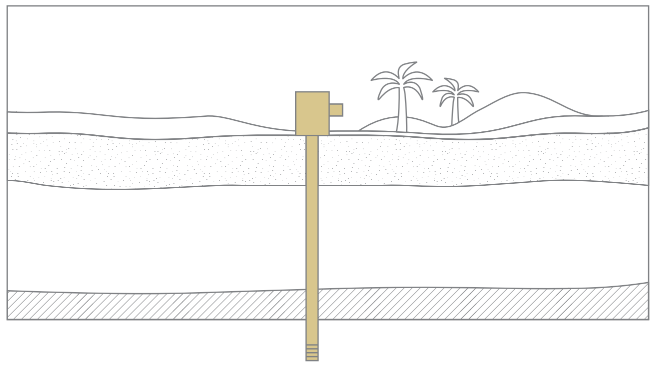
Near the Hajjar mountains in the northeast of the Emirate, the subsurface is tilted and fractured by the tectonic movements of the orogeny, and covered by a thin layer (20 - 100 m) of sediments from the Late Miocene to Quaternary age. It is these tilted layers that occasionally pinch through the surface, forming Jabal Hafit and other mountains of Abu Dhabi Emirate. A major north to south trending thrust fault marks the beginning of the foreland basin. The sediments of the Late Miocene to Quaternary age settle in the basin up to 400 m thick, and comprise mostly alluvial sediments such as conglomerates, sand, and claystones. Occasionally, marine limestones appear in the basin. The extent of the foreland basin approximately coincides with the area of Al Ain Region. The subsurface of Abu Dhabi and Al Dhafra Regions remains mostly unaffected by the mountain build-up in the east. The respective sediments here are 100 to 120 m thick, and show a more uniform grain size composition of sand and siltstones.



Drilling Rig

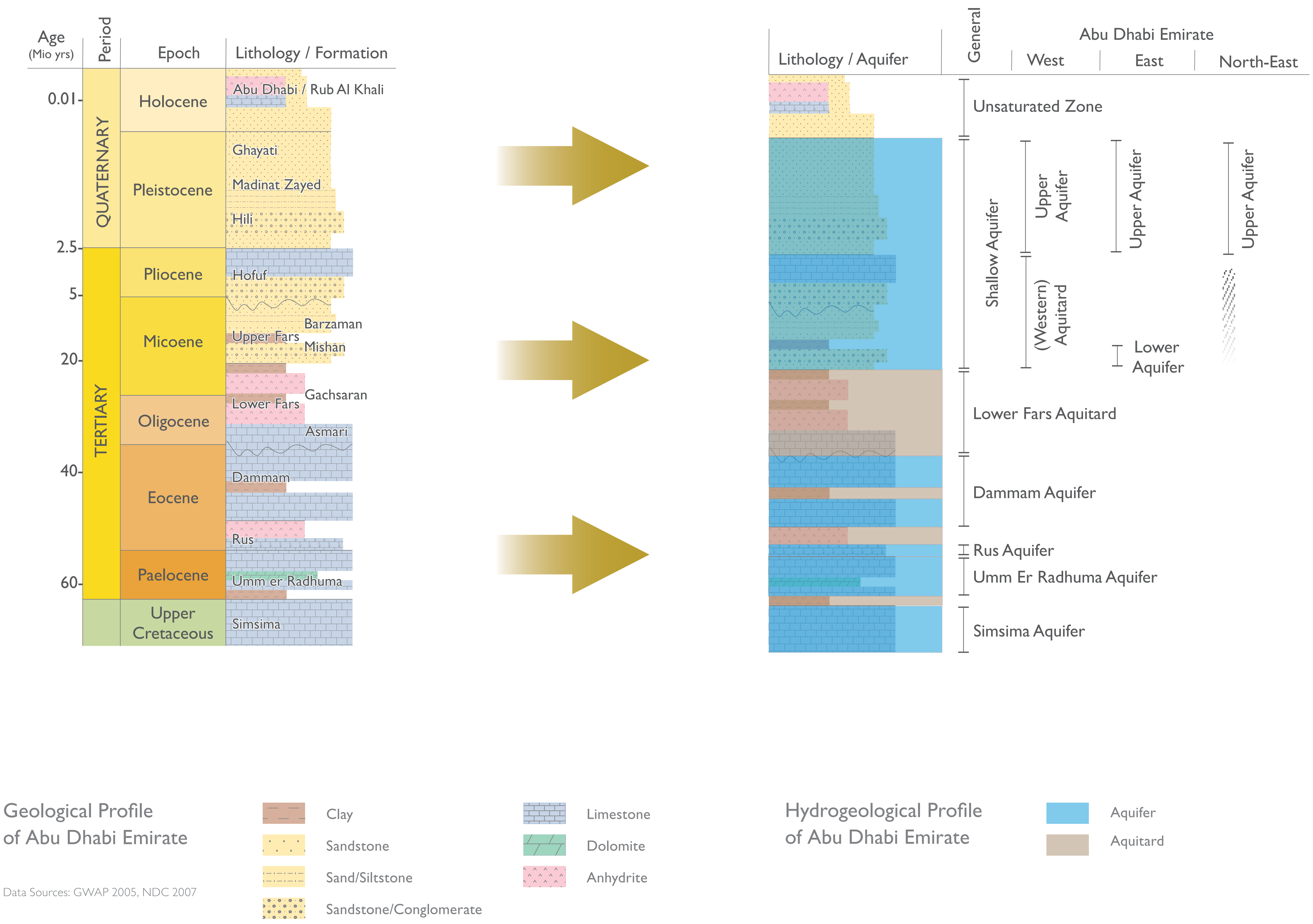
Number of groundwater exploration wells:

1,263



Boreholes with Geological Data

AQUIFERS AND AQUITARDS OF ABU DHABI EMIRATE



HYDROGEOLOGY

Hydrogeologists categorise the subsurface into aquifers - rocks which store and transmit water, and aquitards - rocks which inhibit or restrict the water flow.

In Abu Dhabi Emirate, the uppermost aquifer is the Shallow Aquifer. It is made up of sandstones and subordinate conglomerates, hence it is a porous aquifer. The Shallow Aquifer contains most of the usable groundwater resources. The underlying limestone aquifers are named for the rock formations they host, Dammam, Rus, Umm Er Radhuma, and Simsima. They contain mostly highly saline water (TDS>200 g/l) that far exceeds the salinity of seawater (TDS approx. 42 g/l). A notable exemption is an area east of Jabal Hafit, where high yielding wells with good groundwater quality have been drilled into Simsima aquifer.

Discharge of a Groundwater Well

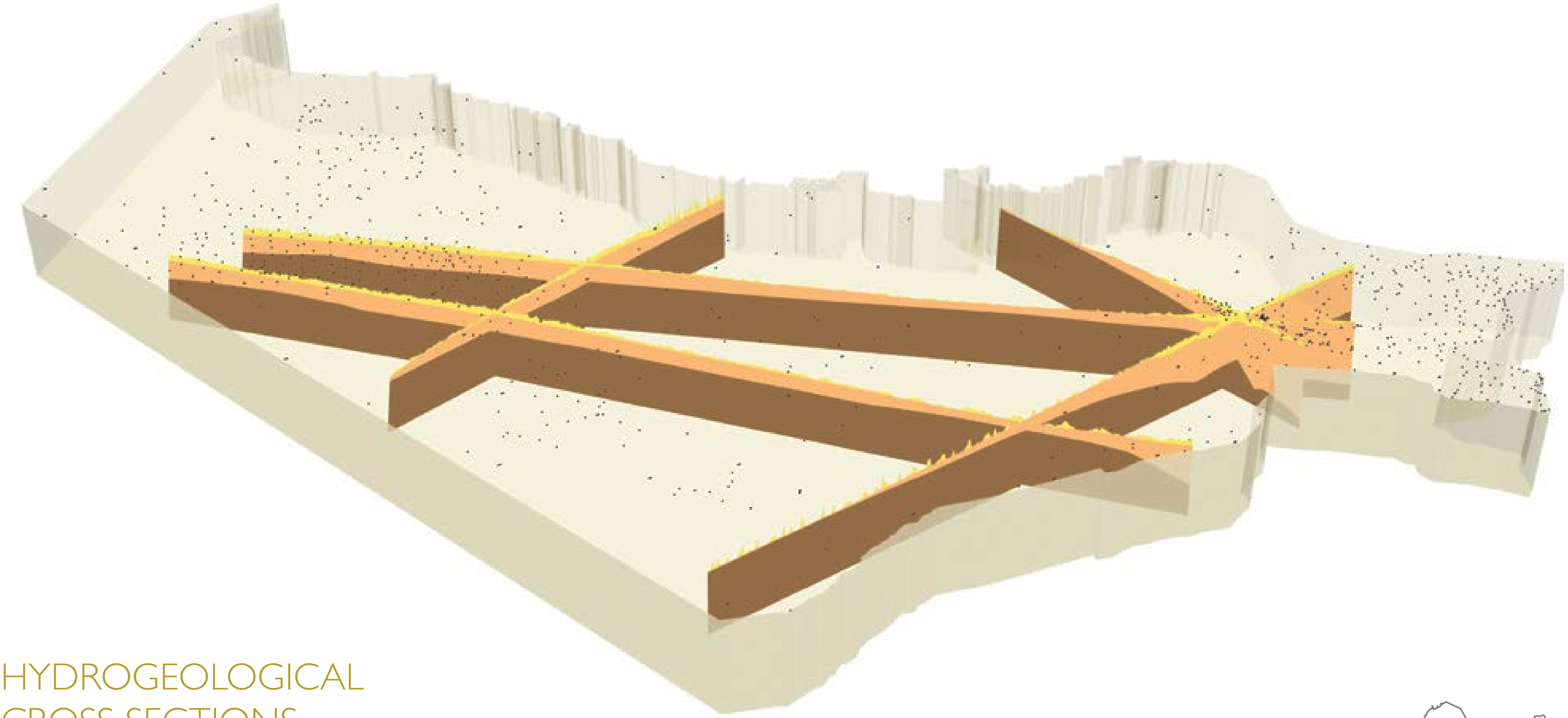
The Shallow Aquifer is an unconfined aquifer, which means that the water level in any given well will be the same level as it is in the aquifer. In contrast, the underlying limestone aquifers are mainly confined and their water level is delimited by an overlying, confining impermeable layer (e.g. clay or anhydrite). The water level in a well from these aquifers will rise according to its hydrostatic pressure. The only perennial spring in Abu Dhabi, Ain Al Faydhah, which is located south of Al Ain, discharges water from these limestone aquifers.

Below the vast dune areas of the Al Dhafra region, the Shallow Aquifer is mostly uniform, and can be up to 120 m thick. The prolific upper part (about 40 m sand), is known as Upper Aquifer and the lower part (about 80 m silt/sand) having a poor yield and water quality, is referred to as Western Aquitard.

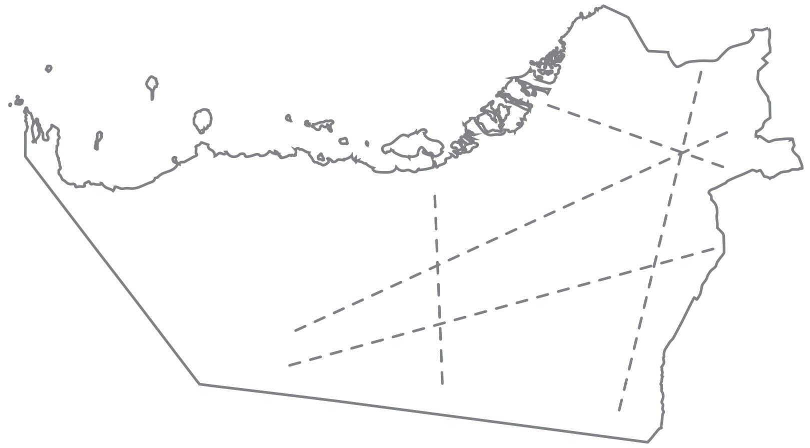
In the Al Ain region to the east, the thickness of the Shallow Aquifer increases to a maximum of 400 m. However, the uniform sand layers are interrupted by clay, silt, and conglomeratic sediments, causing only a small part of the actual thickness to yield significant amounts of groundwater. Often, water-bearing formations are hydraulically disconnected, meaning they have different groundwater levels and possibly a different water quality. This is the case around Remah and Wagan, where the two aquifers are called Upper Aquifer and Lower Aquifer.

In the Al Hayar region in the northeast, only the Upper Aquifer exists. Thrust faults drastically reduce the aquifer thickness to less than 100 m. Despite the reduced thickness, the aquifer yield can be very high in this area, because porous sand sediments provide favorable conditions for the groundwater flow.

Although there are differences in the aquifers from the east and the west of the Emirate, a shallow groundwater bearing layer is found nearly everywhere, as long as excessive pumping has not depleted the sources.



HYDROGEOLOGICAL CROSS SECTIONS AND BOREHOLES



0 10 20 40 60 80 N

Kilometres
Vertical Exaggeration 1:80

Hydrogeological Cross Sections

- Dune Cover
- Shallow Aquifer
- Aquitard / Lower Fars Formation
- Boreholes with Lithologic and Hydrogeological Data According to EAD

Data Sources: EAD 2017, GWAP 2005, EAD-WSI 2017

HYDROGEOLOGY OF ABU DHABI EMIRATE

The map shows the main hydrogeological units within the Shallow Aquifer. They differ in lithology, geological age, connection to the surface, and most notably by the underlying aquitard. The units reflect the change in the Shallow Aquifer in the west and the east of the Emirate, as described on the previous pages.

Unit SA_L - This unit comprises the Shallow Aquifer (as Upper Aquifer and Western Aquitard) that is unconformably underlain by the Lower Fars Formation as a basal unit. The aquifer consists mostly of aeolian sands that increasingly become dominated by silt closer to the bottom. The SA_L unit is the dominating hydrogeologic unit of the Al Dhafra Region.

Unit SA_U - This unit represents the Quaternary/Pliocene sand and gravel aquifer (Upper Aquifer) that is delimited by the bottom of the Upper Fars Formation. The Upper Fars Formation also contains water-bearing layers (Lower Aquifer). Wells in the Al Khazna and Remah areas tap either the Upper Aquifer only, or both the Upper and Lower Aquifer. Regionally, the Upper Fars Formation is regarded as an aquitard, though locally it contains water-bearing layers.

Unit SA_S - This unit delineates the coastal and inland sabkha areas. Active inland sabkhas appear patchy in interdunal areas, while the coastal sabkhas form a continuous stripe along the Arabian Gulf. In sabkhas, the groundwater level is close to the surface. Capillary ascent of the water and subsequent evaporation leads to the crystallisation of gypsum and salts, leaving the groundwater highly saline.

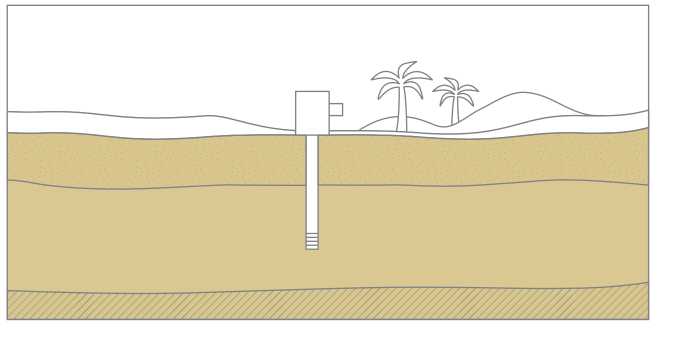
Unit SA_M - Unit SA_M represents the shallow sand and gravel aquifer that is overlaying the tectonically emplaced Early Tertiary and Late Cretaceous limestones and shales. Occasionally, limestone wedges pierce through the surface as ridges, and form small isolated groundwater reservoirs (**LRM** unit in the map). The SA_M unit represents a prolific aquifer with good groundwater quality, although it has a limited and undulating thickness due to its tectonically emplaced underlying stratum.

Unit SA_J - This unit comprises the shallow sand and gravel aquifer of the Al Jaww plain, situated east of Jabal Hafit. The aquifer is shallow (maximum thickness of 40 m), and covers the underlying basal units like a thin sheet. The basal unit is mostly the Lower Fars Formation, but consolidated Post-Fars sediments (Upper Fars and Pliocene Clastics) also occur.

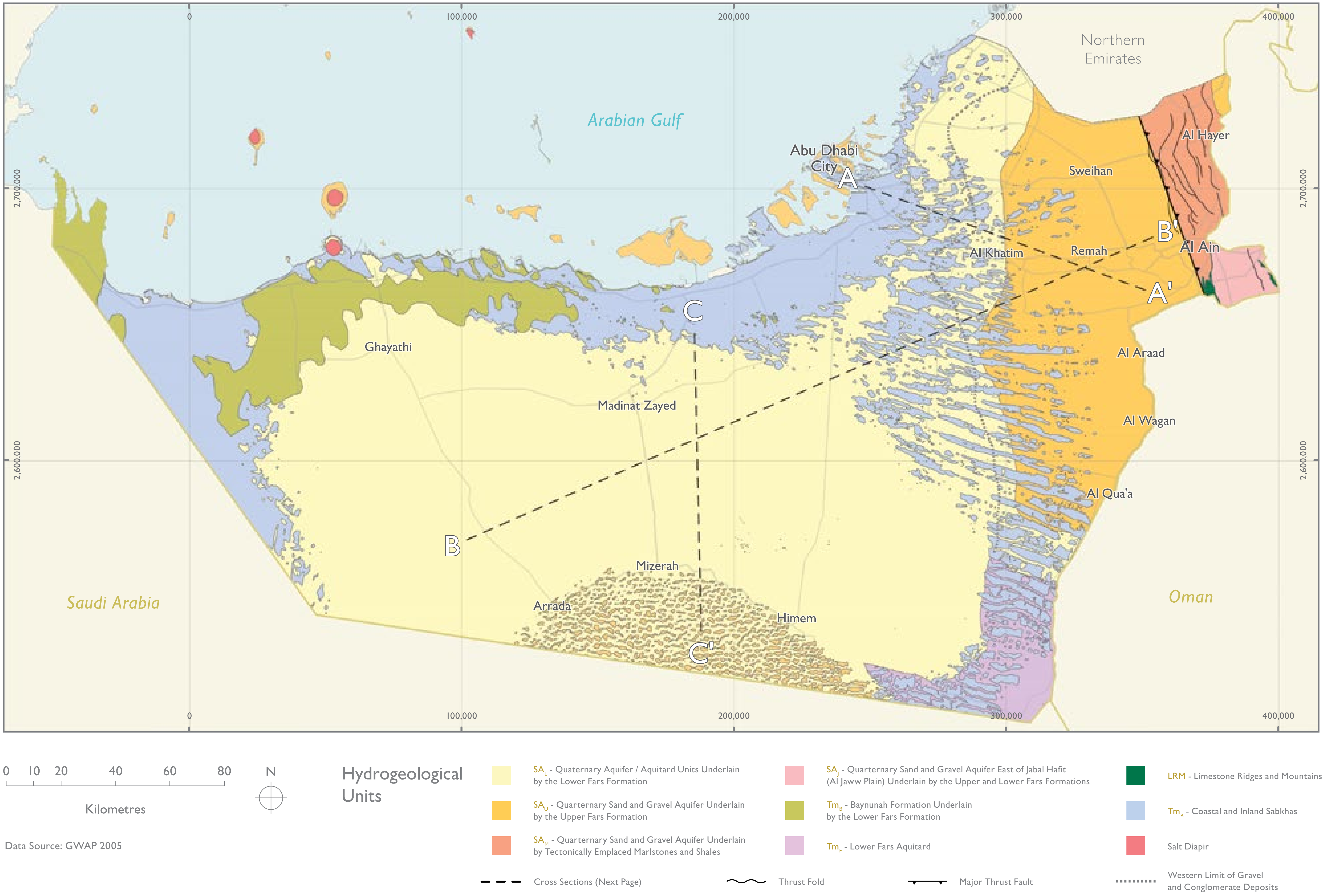
Unit Tm_B - Unit Tm_B delineates the Baynunah Formation, which consists of Upper Miocene fluvial sandstones with some conglomeratic layers. It forms small mesas along the coastal road between Abu Dhabi and Sila, where it is often found with a gypsiferous cap-rock that protects the underlying friable sandstone from erosion. It intersects with the SAL aquifer unit, and has similar hydraulic properties.

Unit Tm_F - This unit represents areas where the Lower Fars Formation, the main basal aquitard of the Shallow Aquifer, crops out or is found close to the surface. It is an aquitard unit.

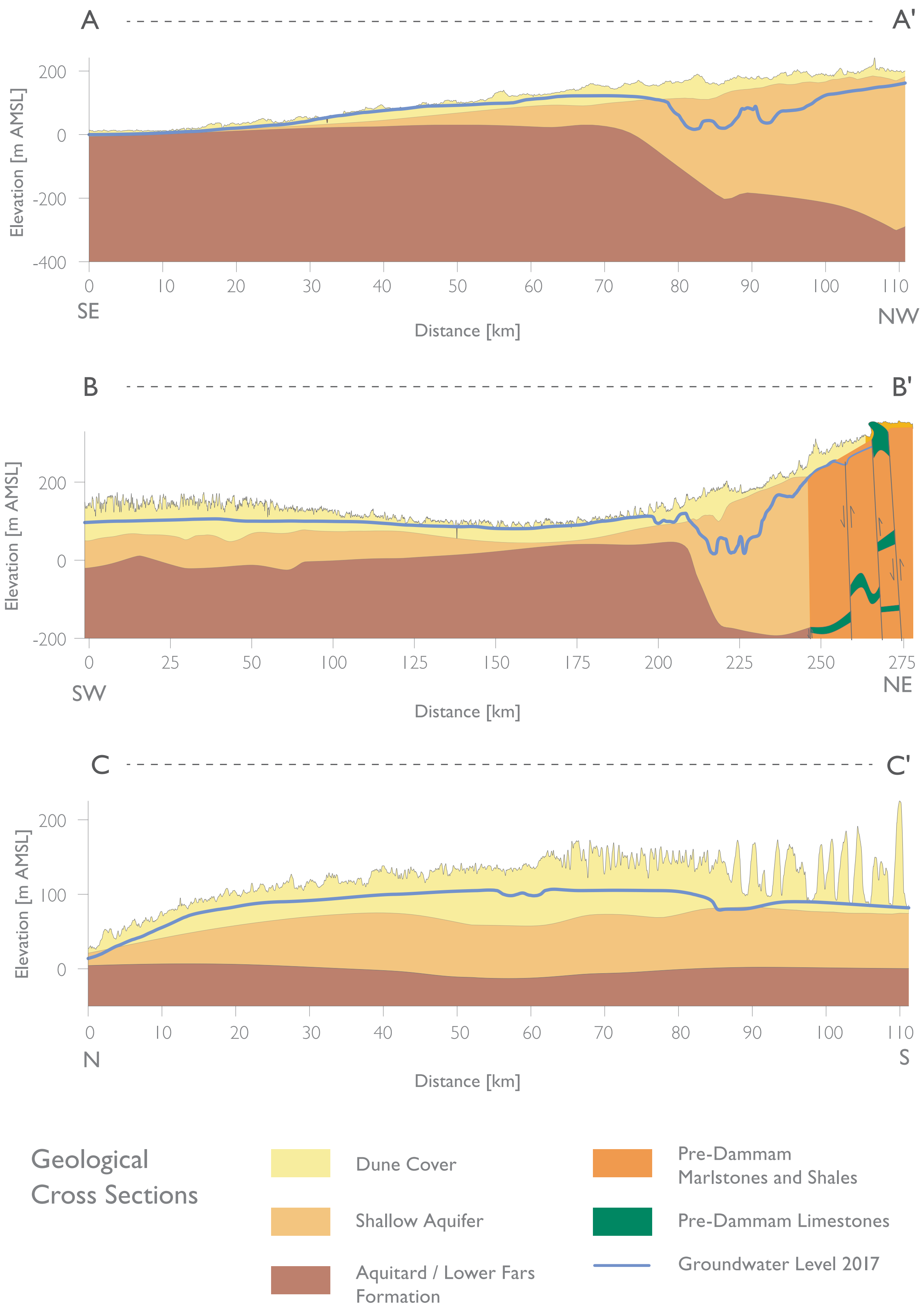
Hydrogeology of Abu Dhabi Emirate



HYDROGEOLOGICAL MAP



Data Source: GWAP 2005



SHALLOW AQUIFER

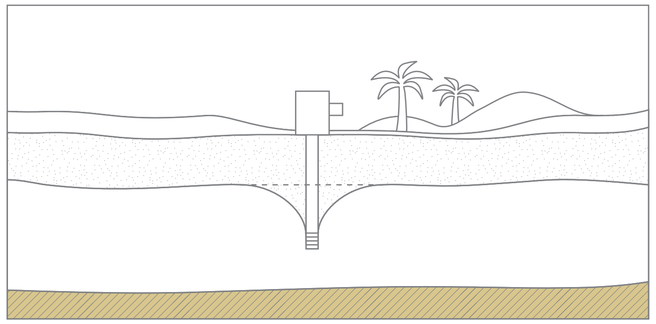
Almost all usable groundwater resources of Abu Dhabi Emirate are contained in the Shallow Aquifer. Though it varies strongly in thickness, groundwater quality, and yield, the Shallow Aquifer exists over almost the entire Emirate.

The map on the right shows the base of the Shallow Aquifer, formed by the Lower Fars formation. Clay and gypsum layers separate the groundwater resources of the Shallow Aquifer from the underlying, highly saline waters of the Dammam formation.

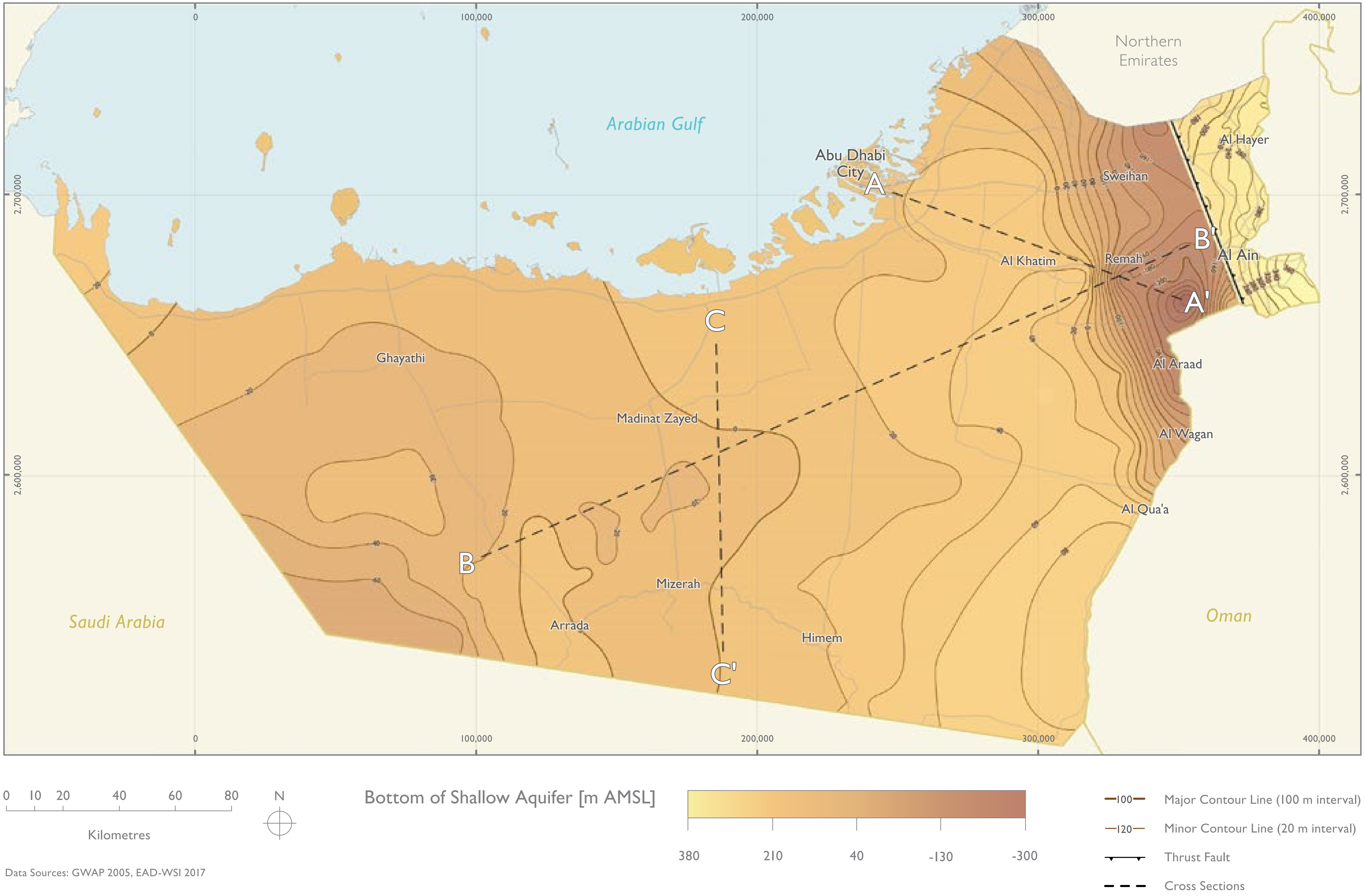
The cross sections on the left (their courses are indicated on the map by the dashed lines) show the shape of the Shallow Aquifer in different parts of the Emirate. Notably, the thickness increases in the very east, where the rise of the Hajjar mountains caused the subsidence of geological layers in its foreland. The centre profile shows the tectonic border of this basin, and the related, strongly reduced aquifer thickness further towards the mountains.

The groundwater level in the Shallow Aquifer shows considerable depressions in the areas of high abstractions. In the cross sections, they occur in the area of greatest aquifer thickness. Unfortunately, clay and silt layers limit the groundwater resources in the lower parts of the aquifer, hence the abstractions pose a serious threat to the available groundwater.

Bottom of Shallow Aquifer



BOTTOM OF SHALLOW AQUIFER



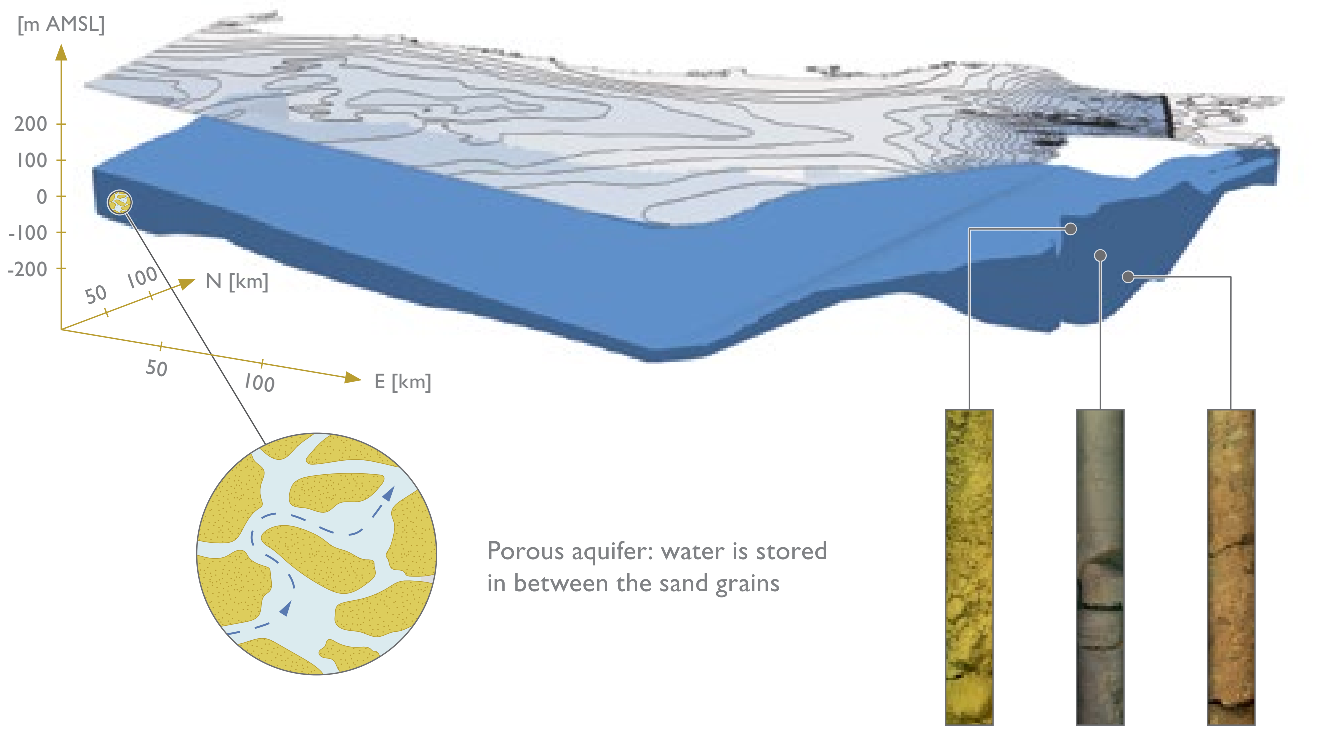
Data Sources: GWAP 2005, EAD-WSI 2017

HOW GROUNDWATER IS STORED

Groundwater is stored and flows in pores, along bedding planes, joints, and faults in rocks. An aquifer is a layer of gravel or sand, a sandstone or karstified (cavernous) limestone, or even a large body of rock, such as fractured granite that has sizable openings. In terms of stored volume, groundwater constitutes the most abundant supply of freshwater available to humans.

Groundwater is stored within rocks, rather than in between rocks. That is why rock properties, like lithology, porosity, and the amount and spacing of joints determine how much water can be stored. In sandstones, the volume of stored water might be 10% of the rock volume, or can reach up to 30% (1 m^3 sandstone then contains 300 l water). Limestones or volcanic aquifers usually store less water, between 1-5% of their volume.

The total amount of groundwater resources in an area is governed by the spatial distribution of rock properties, and by the aquifer's geometry (its extent and thickness). The aquifer thickness (as shown in the map) is defined by the distance between the groundwater level and the bottom of the aquifer. Abstraction from pumping wells lowers the groundwater levels, and in turn reduces the aquifer thickness, and ultimately diminishes the groundwater resources.

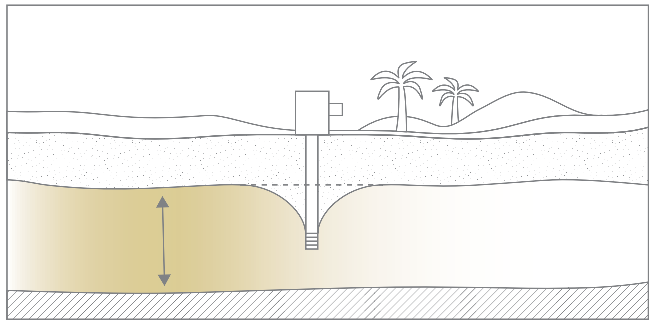


3D view of Shallow Aquifer

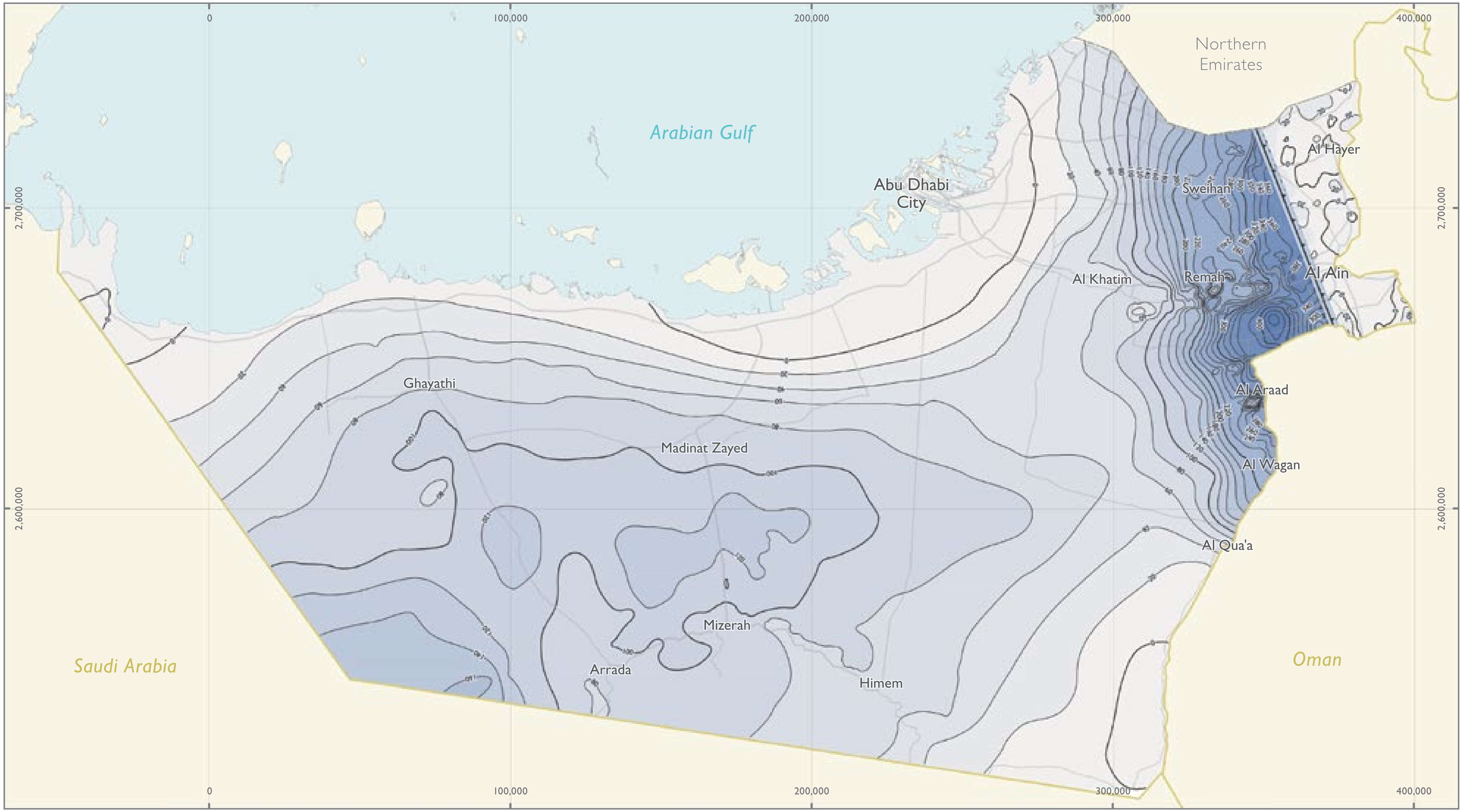
Aquifer comprises different lithologies

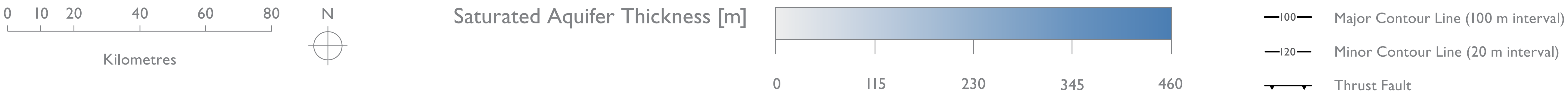
The Meaning of Aquifer - The word is taken from Latin, where "aqua" means "water" and "ferre" is "to bear". Accordingly, aquitard is derived from "aqua" and from "re-tard", which means "holding back".

Aquifer Thickness



SATURATED THICKNESS OF SHALLOW AQUIFER





Data Sources: GWAP 2005, EAD-WSI 2017

HYDRAULIC CONDUCTIVITY

Hydraulic conductivity is defined as the volume of water that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured at perpendicular to the flow direction. It indicates the ease with which water moves through the subsurface and is used to calculate rates of groundwater movement.

The hydraulic conductivity of a rock determines how well it transmits the groundwater. It is a basic hydrogeological rock property. The higher the hydraulic conductivity, the higher the groundwater flow rate through the rock.

Aquifers develop in a great variety of rocks - with sufficient time, and given that geological processes, such as tectonic movements or mineral dissolution by water, took place. The Hydraulic Conductivity of a rock is determined by its voids and spaces, and not by the rock material (lithology) itself. Hence, it depends mainly on the rock's fractures, bedding planes, and porosity, to determine how well the rock is able to act as an aquifer.

The map on the right shows the hydraulic conductivities of the Shallow Aquifer for selected wells in Abu Dhabi Emirate, as well as the geometric mean of those values for the respective aquifer zones.

Hydraulic conductivities around Madinat Zayed and the Liwa Crescent range mostly between 10 and 100 m/d: they are among the highest in Abu Dhabi Emirate. The homogenous unconsolidated sands of these areas provide the right conditions for a good aquifer. In the northeast of the Emirate, in Al Hayer and Al Ain, semi-consolidated sand and gravel layers have hydraulic conductivities of typically between 1-10 m/d. The lowest hydraulic conductivities are found around Remah, generally below 1 m/d.

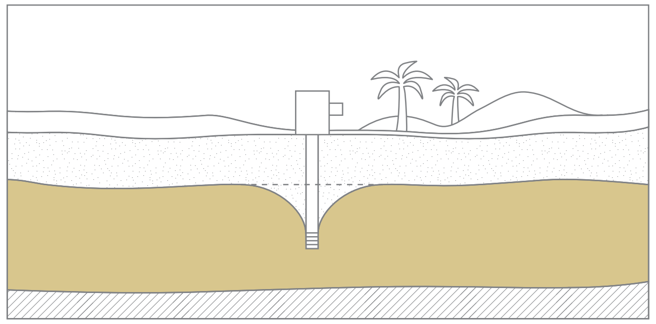
Unconsolidated dune sands in Liwa area

Definition of Hydraulic Conductivity

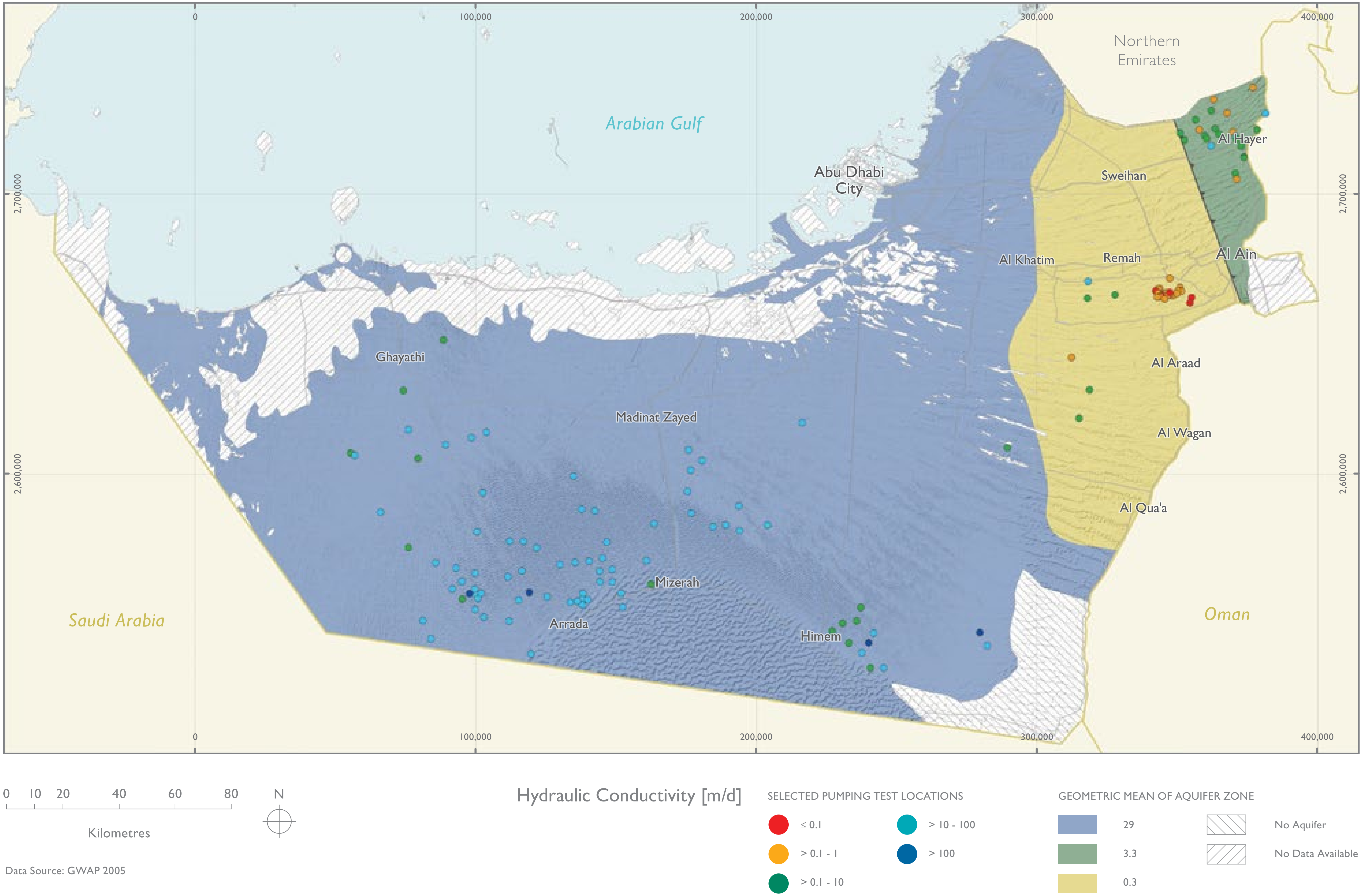
$$k = Q/(i \times A)$$

Where:
- **k:** Hydraulic Conductivity [m/d]
- **Q:** Flow [m^3/d]
- **i:** Hydraulic Gradient [-]
- **A:** Area [m^2]

Hydraulic Conductivity of Shallow Aquifer



HYDRAULIC CONDUCTIVITY OF SHALLOW AQUIFER



GROUNDWATER ORIGINS

Stable isotopes analyses show that there are at least two distinct sources of groundwater in Abu Dhabi Emirate.

Groundwater in the Al Ain and Abu Dhabi regions show an isotopic signature that reflects recent rainfall. Recharge occurs mainly in the Hajjar mountains in the east, from where the groundwater flows towards the Arabian Gulf. Groundwater in the Al Dhafrah region possesses a very different isotopic composition. The TDS-d cross plot reveals that this difference cannot be a result of secondary evaporation. It proves that groundwater in the Al Dhafrah region is paleo-groundwater and has a different origin than the groundwater in the other parts of Abu Dhabi Emirate. The $\delta^{18}O$- $\delta^{2}H$ cross plot shows a shift in slope for samples with high salinity in the respective regions. This shift is attributed to secondary evaporation, and is a strong indication of irrigation water return flow with high salinity to the aquifer.

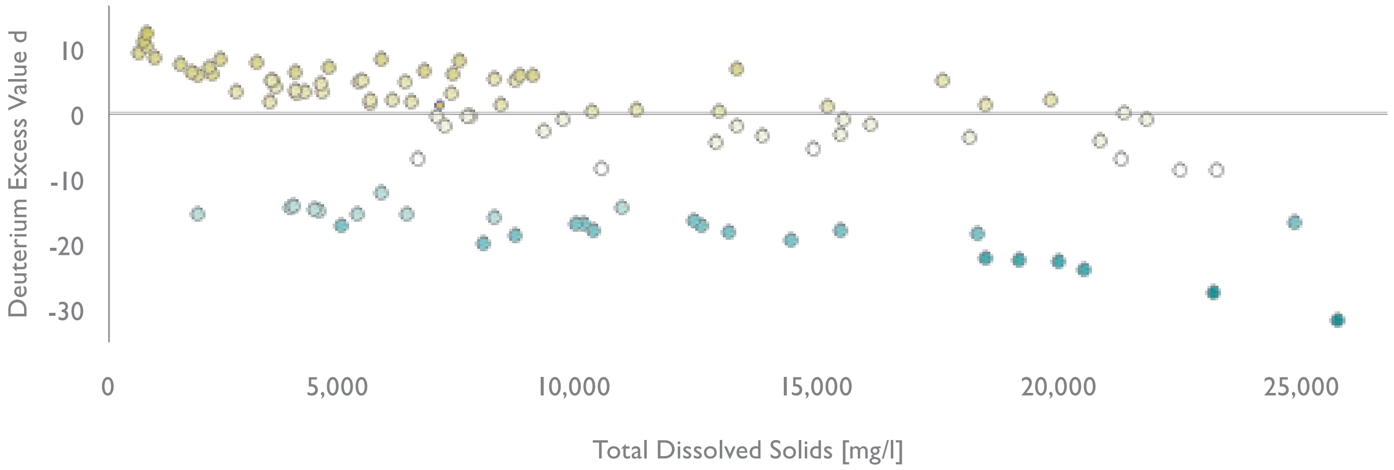
The Deuterium Excess Value

The deuterium excess value is an index of deviation from the global meteoric water line ($\delta^{2}H=8*\delta^{18}O+10‰$). It provides a simplified visualisation of the stable isotope information and correlates to the physical conditions of the oceanic source area of the precipitation.

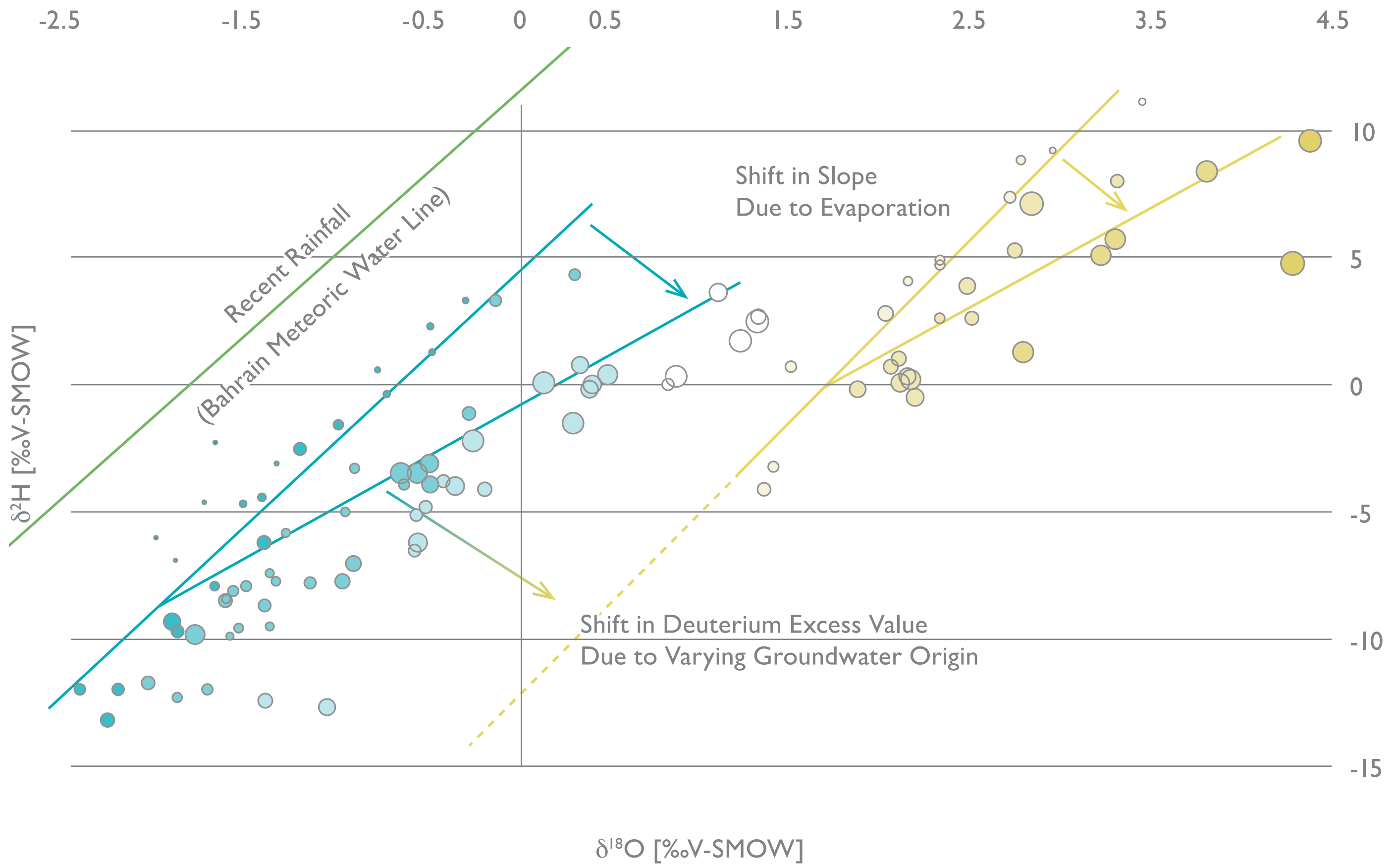
How can Stable Isotopes be used to Identify the Source of the Groundwater?

Evaporation and precipitation drive the global water cycle. Slight differences in vapour pressure between lighter and heavier isotopes lead to an increased evaporation of lighter isotopes and increased precipitation of heavier isotopes. These fractionation processes lead to patterns in the global rainfall that reflect the origin of the precipitated air mass and subsequently, the origin of the groundwater.

Deuterium Excess - TDS Relation of Groundwater Samples

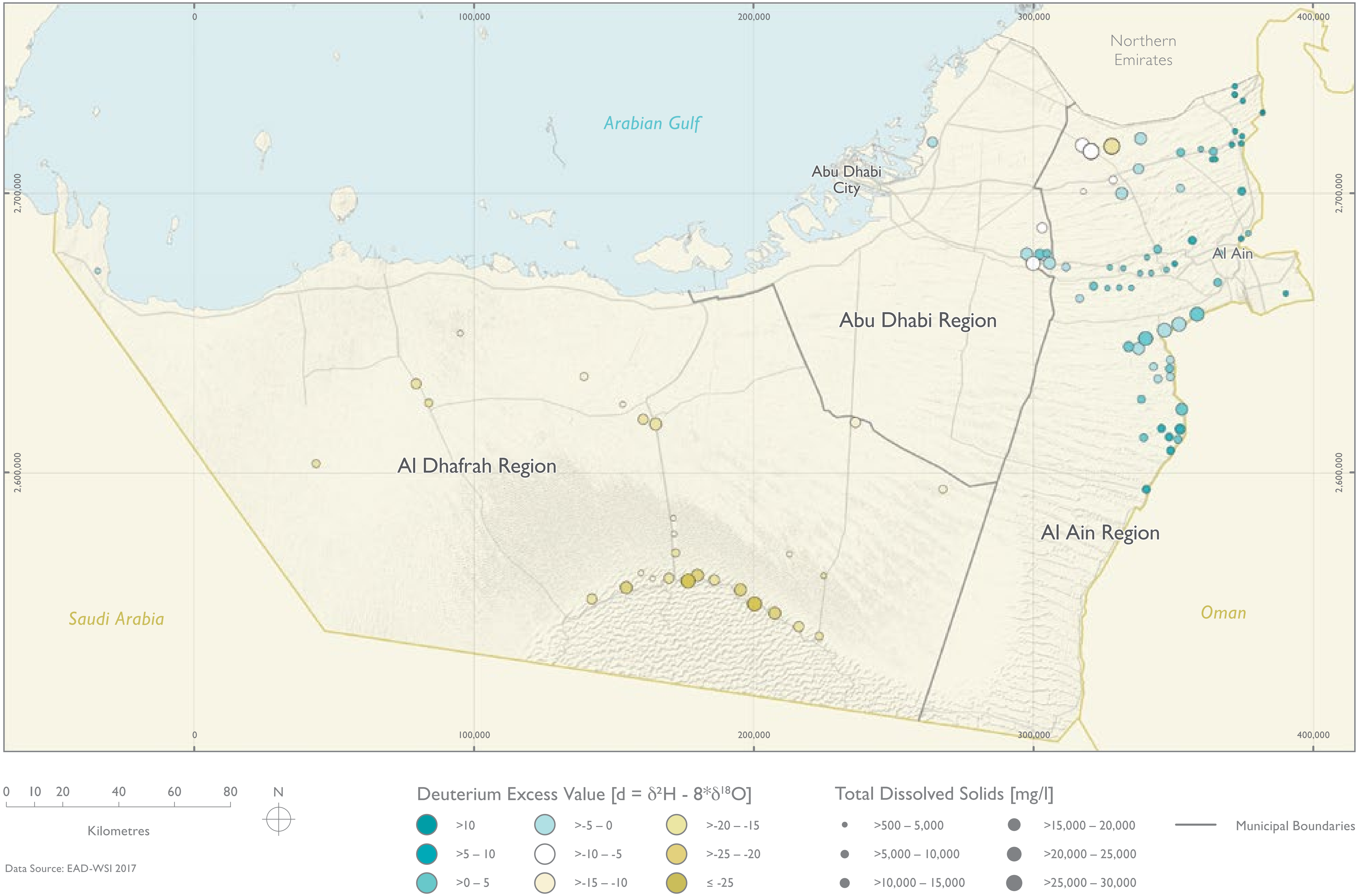


$\delta^{18}O$ - $\delta^{2}H$ Cross Plot of Groundwater Samples



*Note - Map legend also applies to graphs

STABLE ISOTOPES IN GROUNDWATER



Data Source: EAD-WSI 2017

JOURNEY FROM ROCK TO WATER

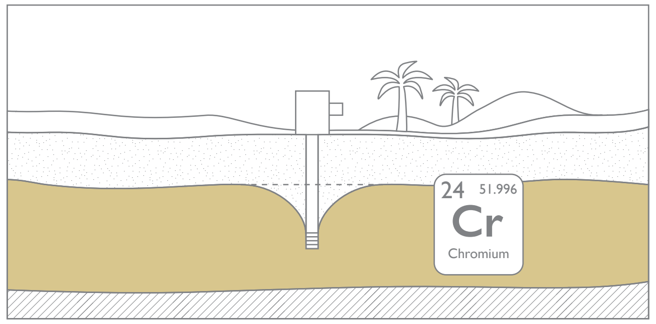
The Hajjar Mountains east of the Emirate are mainly made up of mafic and ultramafic rocks that contain olivine, pyroxene, amphibole, and biotite. These minerals have a dark colour, and contain a wide range of heavy metals (iron, chromium, nickel, selenium, etc.).

Today, these minerals are found throughout Abu Dhabi Emirate. Over time, weathering and erosion of the Hajjar Mountains led to the deposition of sedimentary rocks. This process creates the sand sheets and alluvial plains that characterise Abu Dhabi Emirate. When the mountain climate turned arid, wind, rather than rain and rivers, became the dominant force that shaped the surrounding geology. Wind blows mineral grains out of the mountain range across the Emirate. Moreover, wind also erodes the sedimentary rocks that were previously deposited and distributes these mineral grains.

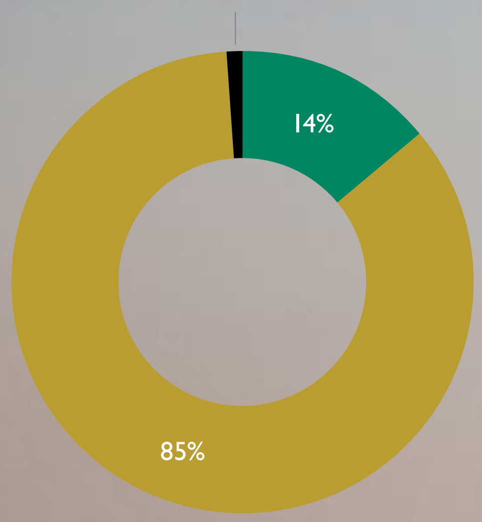
As groundwater flows in the aquifer it takes up heavy metals and other trace elements. Hydrochemical conditions determine how much of these constituents can be dissolved. Their solubility strongly depends on pH, redox (Eh), and temperature (T) of the groundwater. Chromium is one reason why most groundwater in Abu Dhabi Emirate is not suitable for domestic water supply (if left untreated). About 85% of the sampled groundwater exceeds the respective guideline value* (less than 0.05 mg/l). For agricultural irrigation, however, chromium is of no concern. Of the samples, 99% are in line with EAD regulations (less than 1 mg/l).

Aerial View of the Hajjar Mountains

Heavy Metals in Groundwater

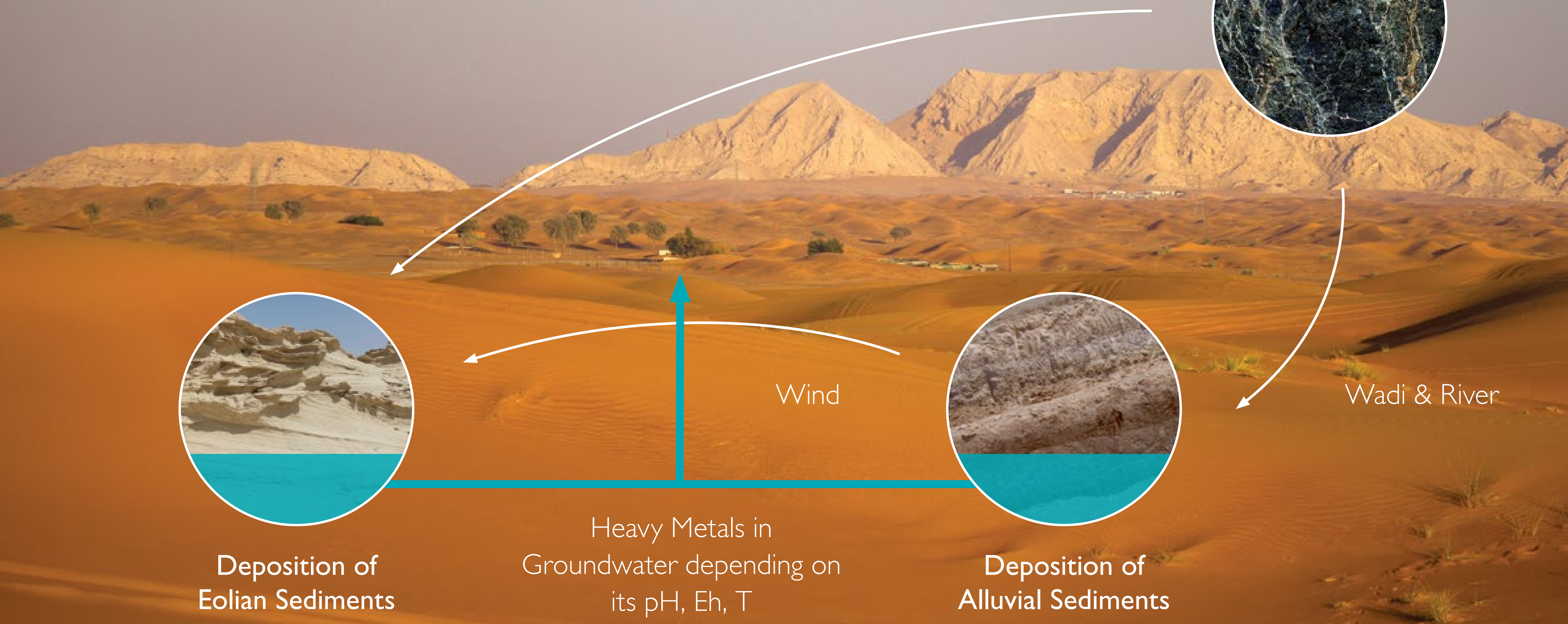


* EAD Recommendations for Groundwater Use Quality Guidelines, 2017/EAD-EQ-PR-TR-06



Chromium Concentration in Groundwater

- Below Guideline Value for Domestic Non-Potable Water (<0.05 mg/l)
- Below Guideline Value for Agricultural Irrigation but exceeding Guideline Value for Domestic Non-Potable Water (>0.05 mg/l to 1 mg/l)
- Exceeding both Guideline Values (>1 mg/l)

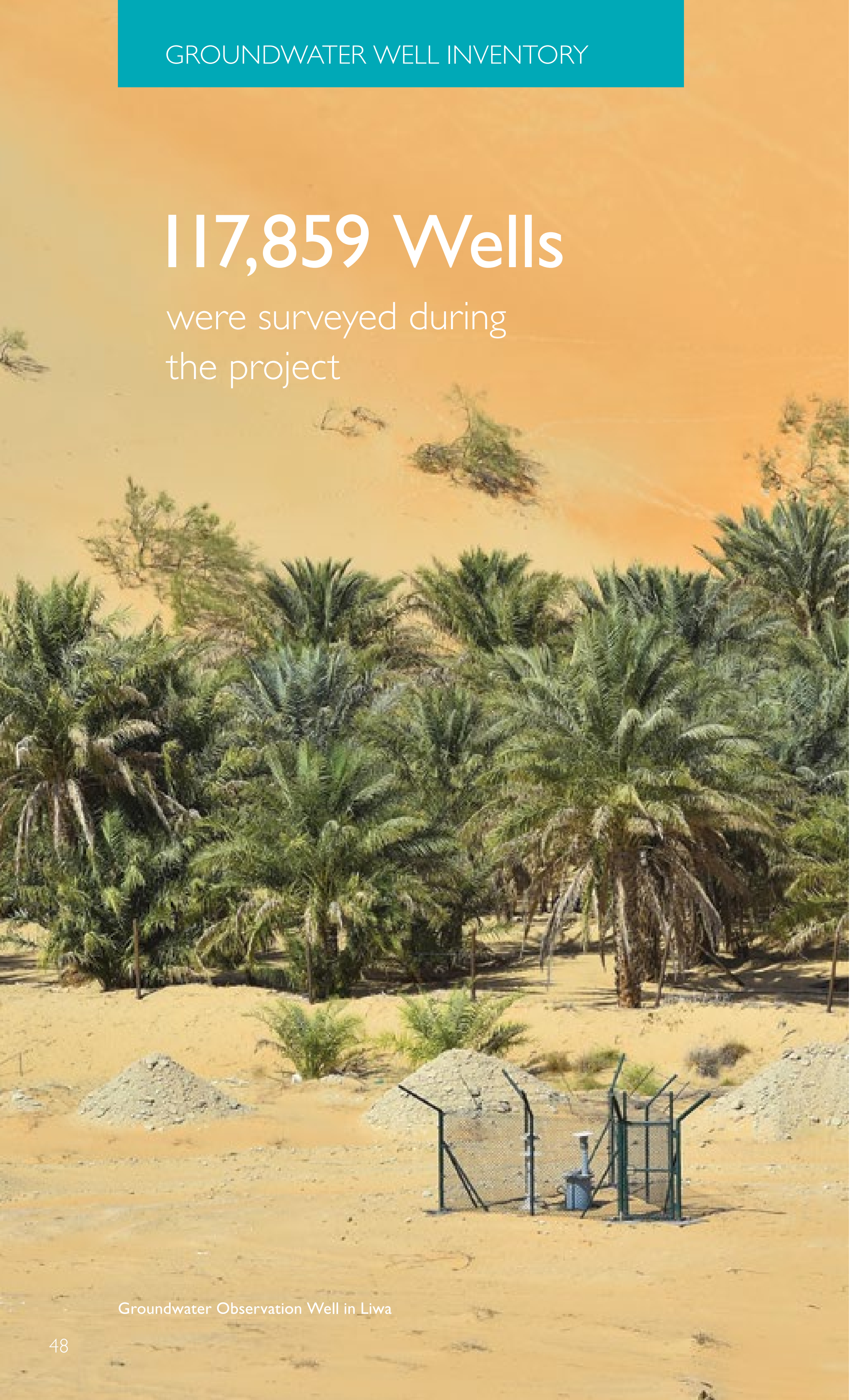


Data Source: EAD-WSI 2017

GROUNDWATER WELL INVENTORY

117,859 Wells

were surveyed during the project



Groundwater Observation Well in Liwa

THE PROJECT

Abu Dhabi Emirate stretches from As Sila to Al Ain, and from Liwa to As Sheib. About 120,000 groundwater wells were estimated to exist within the Emirate; their location, condition, use, and purpose remained largely unknown until recently.

This changed in October 2015, when the *Groundwater Wells Inventory and Soil Salinity Mapping for Abu Dhabi Emirate* project undertook the challenging task of cataloguing every well in the Emirate. This effort covered a span of three years in which each well's parameters were closely recorded, measurements were conducted, and water samples taken. This extensive well inventory forms the basis for effective management and protection of groundwater, and provides the key for sustainable use. The data also provides insight into water quality, the volume of groundwater abstractions, and the temporal development of groundwater levels. The bulk of groundwater wells in Abu Dhabi Emirate supply irrigation systems. For this reason, the impact of irrigation on farm soils and their salinity were closely examined in the project. The collected soil samples from 4,000 farms show how groundwater quality and farm soil management impact the soil salinity.

The project was executed in three phases:

- Phase 1 took two and a half months and comprised the mobilisation of survey teams, equipment procurement, and the development of work procedures.
- Phase 2 ran just over two years and included well inventory, farm survey, and water and soil sampling and analyses.
- Phase 3 took one year and comprised data evaluation, compilation of water and soil databases, creation of thematic maps, reporting, and the preparation of this groundwater atlas.

The following pages detail the project's tasks and methods, and present some of the equipment used. Throughout this *Groundwater Atlas of Abu Dhabi Emirate*, the results of the project are presented through maps, supporting graphs, and statistics.

The Groundwater Well Inventory

Throughout the duration of this project, 117,859 wells were surveyed. It took sixteen field teams working for two years to complete the job. Two supervisors, a groundwater technician and an assistant, guided the teams by organising work plans and survey routes, arranging equipment, and collecting and controlling the data quality.

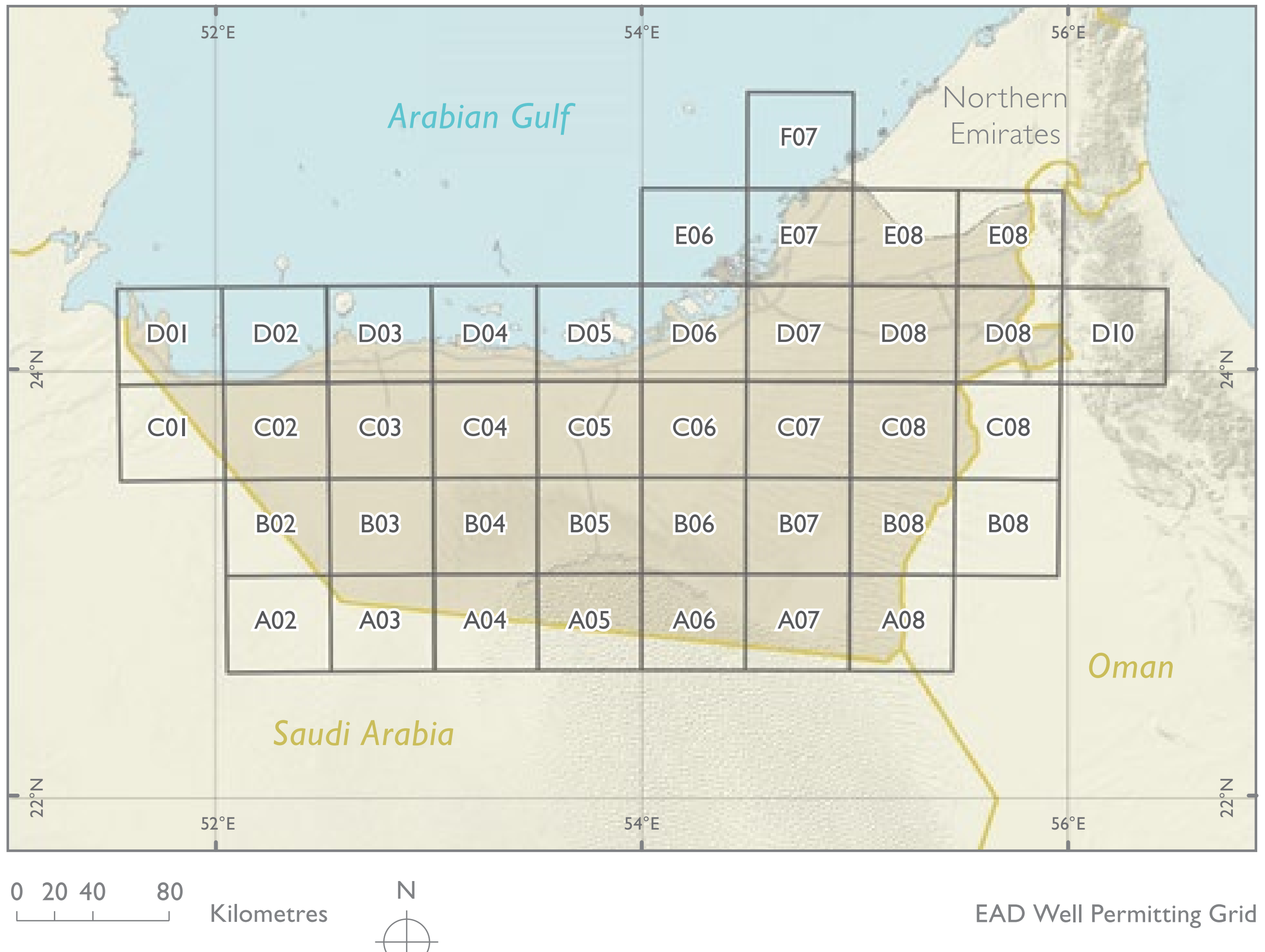
The majority of wells are located on farms and in forests with the exception of some remote desert locations. Special teams with experienced staff and special equipment were assigned to these remote desert locations, where off-road driving capabilities and extensive safety measures were essential to the survey's success.

For each surveyed well, more than 100 parameters were recorded. These parameters included coordinates, depth, diameter, and casing material of the well. Additionally, the use and operational status of the wells were assessed. Where possible, groundwater level, salinity, temperature, and pH were also measured. The teams recorded pump operation time, well discharge, and selected farm data at each of the wells.

Well-ID and Plates

Wells dug since 2005 with permission from the EAD received a metal plate with a well-ID. These plates were mounted at the well casing or foundation, and displayed the well-ID. The majority of the wells catalogued by the field teams did not, however, have a well-ID because they had been either dug before 2005 or without EAD permission. During the inventory, the teams assigned these unregistered wells a well-ID and mounted a metal plate.

The assignment of well-IDs followed EAD's standard code where the Emirate is divided into grid cells, each 50 x 50 km in size, named by rows (letters A to F) and columns (numbers 01 to 09). The well-ID has three components starting with two letters indicating the Emirate (e.g. AD), followed by the respective grid cell (e.g. D09), and ending with a 5 digit number (from 00001 to 99999).



EAD Well Permitting Grid

Groundwater Level Measurement Campaign

Groundwater levels fluctuate as a result of both natural and human-induced reasons such as rainfall, groundwater abstraction, and water network losses amongst other factors.

For mapping accuracy, it is important to measure groundwater levels in individual wells within a short span of time. This ensures little variation from environmental and human-induced factors. To accomplish this, groundwater level measurement campaigns are conducted that take water level readings in a short period of time. Within the framework of the *Groundwater Wells Inventory and Soil Salinity Mapping* project, such a campaign was carried out from the end of November to the beginning of December 2017. During this two week interval, 149 groundwater levels were measured across the Emirate.

The location of the measured wells was determined by high-accuracy differential GPS measurements. The differential GPS data determined the exact position of the wells within a few centimetres. In comparison, standard GPS measurements have an accuracy of several metres. The water level depth is always measured in the sampling process on the field. Accurate well elevation references are essential to correlate the groundwater levels between wells.

The groundwater level data obtained during the groundwater level measurement campaign were instrumental in developing the Groundwater Level map presented later in this atlas.

Groundwater Level Measurement on a Farm in Liwa

Groundwater Quality Investigations

The dissolved substances in water determine its quality. These substances consist of, but are not limited to, minerals, metals, gases, and organic compounds. Aside from these, the microbiology (bacteria) is also an important parameter for determining water quality. There are strict guidelines for the concentration of these substances in drinking and irrigation water for health reasons. Water quality is determined by natural processes as well as human activity. Mineral composition of the water-bearing rock largely influences the natural groundwater quality. A large portion of the irrigated water (commonly around 25% in the UAE) flows back through the subsurface and into the aquifer which can easily alter the groundwater. The irrigation water carries fertilisers, pesticides, and a potentially high salinity with it. Water losses from wastewater pipelines seep into the groundwater as well.

Within the framework of the *Groundwater Wells Inventory and Soil Salinity Mapping* project, a comprehensive sampling and analysis campaign was conducted to assess the state of groundwater quality in the Emirate. It consisted of:

- 1,000 Analyses - Major constituents, physiochemical and organoleptic parameters, alkalinity, and total dissolved solids
- 250 Analyses - Trace elements: aluminium, chromium, bromide
- 100 Analyses - Pesticides, insecticides, herbicides, halogenated hydrocarbons, PAH
- 100 Analyses - Isotopes: Deuterium, Oxygen, Tritium
- 100 Analyses - Microbiology: coliforms, enterococci, total bacteria count

Quality control and assurance is of the utmost importance in such campaigns. Sampling had to follow strict guidelines to avoid any alteration of the water samples. A Standard Operation Procedure (SOP) was developed that included:

- Materials, types, and size of equipment (e.g. sample bottles, hoses, filters, gloves)
- Handling procedures (e.g. cleaning and disinfection of equipment, sample storage times, temperatures, transport to laboratory)

A Chain of Custody sheet documented responsibilities during sampling, transport, and analysis as well as defined the procedure for shipping the samples. Within this procedure, the selected laboratories had to conform to required international standards.

6,000 metres

of soil profile have been augered by hand

Soil Sampling with Auger

The Farm Soil Salinity Survey

Inadequate rainfall, high salt content of irrigation water, and saline groundwater are causing one of the greatest challenges for agriculture in the Abu Dhabi Emirate - soil salinity. More than 80% of irrigated land in Abu Dhabi Emirate is affected by high salinity, which affects negatively the productivity of crops. Worldwide, every day some 2,000 ha of farm soil is lost due to salt-induced degradation.

The EAD conducted an extensive survey on over 4,000 farms in order to investigate the impact of irrigation water quality on soil salinity levels. More than 3,900 soil samples were analysed in the field in order to map the levels of salinity. On 100 farms the EAD established a long-term soil salinity monitoring programme to provide the baseline level, monitor changes and identify trends of soil salinity in agricultural areas. These selected farms are distributed across the varying agricultural soils within Abu Dhabi Emirate, and represent different crops, farm sizes, groundwater and irrigation sources, soil types, and landscapes.

The survey resourced available satellite imagery, farm administrative information from DMA, soil data from Abu Dhabi Soil Information System, and Land Cover data for farm selection and field orientation. Soil samples were collected from four depth intervals down to 150 cm in depth using hand augers. Field soil investigations included measurements of pH and Salinity (EC) at four depths intervals. Soil classifications, salinity measurements and farm parameters (e.g. crops grown, hectarage, irrigation system type/condition, water sources, and irrigation water quantity and quality) were also recorded. Samples for laboratory analysis were taken at 10% of the farms for the regular parameters EC, pH, major cations, and SAR. Additionally, irrigation water was sampled.

Farm in Al Khaznah

Handheld GPS and Data Logger

Electrical Water Level Meter

Ultrasonic Flow Meter

Hydrochemical Sampling

How to record all well data?
This electronic handheld device is used for GPS positioning, data recording, and photo documentation.

How to know that the measurement tape reached the groundwater level?
Contact with water will cause the orange light on the Electric Water Level Indicator to blink and a small alarm to go off.

How much water is pumped?
Without even seeing the water, the Ultrasonic Flow Meter will determine the water flow by detecting the reflection of ultrasonic waves.

How is the Water quality?
On-site pH, electric conductivity, and temperature are measured. Protective clothing ensures a representative groundwater sample for laboratory analysis.

Field Survey Equipment

Accurate field measurements require both state-of-the-art measurement devices and rugged, reliable tools. They are essential companions for field teams during their work on farms, forests, and sand dunes.

On-site Farm Soil Analysis:

The **Auger**, a manual drilling device, collects samples from up to 1.50 m. **Munsell Colour Charts** and the **Sieve** are used for soil classification. **Soil-water Suspensions** are prepared to analyse soil salinity and pH.

Soil Sampling Equipment

Groundwater Level Measurement

Inspection of Irrigation Systems

Assessment of a Groundwater Well

Capacity Building

EAD prioritises developing excellence and leadership skills among their employees, as wells as transferring their knowledge and best-practices to partnering organisations and authorities.

In line with this value, EAD conducted trainings within the *Groundwater Wells Inventory and Soil Salinity Mapping* project for their staff and project stakeholder staff alike. Their goal focused on building a greater capacity and understanding in both the theoretical and practical spheres of environmental management.

Throughout the project, EAD junior hydrogeologists and soil experts received on-the-job experience, as they worked closely with the consultant in the field surveys and contributed to the study.

In the field, training began with an introduction to field survey planning and data dictionary development. Training sessions developed proficiency and understanding in:

- Well and farm attributes
- Land use attributes
- Usage of GPS-Data-Collection System
- Spatial coverage and track logging
- Applying registration plates
- Groundwater sampling for hydrochemical analysis
- Soil salinity sampling

In the office, training developed advanced GIS mapping and related database skills, such as:

- Groundwater well inventory (data compilation and interpretation)
- Groundwater mapping processing
- GIS and satellite imagery processing
- Assessment of the farm/soil salinity inventory, mapping and monitoring, and development of soil salinity maps

Measurement of Hydrochemical Field Parameters

GROUNDWATER WELL STATUS

The status of wells can be operational, disused, backfilled or have exploration or observation purposes. An operational well is capable of producing water, meaning a pump is installed and can be switched on. If a well has nothing installed, or does not clearly indicate that it is functional, it is a disused well. When disused, it is important that the well is backfilled in order to reduce the risk of groundwater contamination.

In the past, exploration wells were drilled in order to investigate geology and groundwater resources of the subsurface. Observation wells have a small diameter, and are used to monitor groundwater level and groundwater quality. Generally, these wells have no significant pumping capabilities. Most of the wells in the Emirate of Abu Dhabi are disused; a result of a decade of groundwater abstraction which left many wells collapsed or dry.

Less than half of all wells in the Emirate are operational. Out of the non-operational wells non-operational wells, only 5.7% are backfilled. Groundwater has been closely investigated in the last decades, but the total number of exploration and observation wells is minimal: They account for just over 1% of all wells in the Emirate.

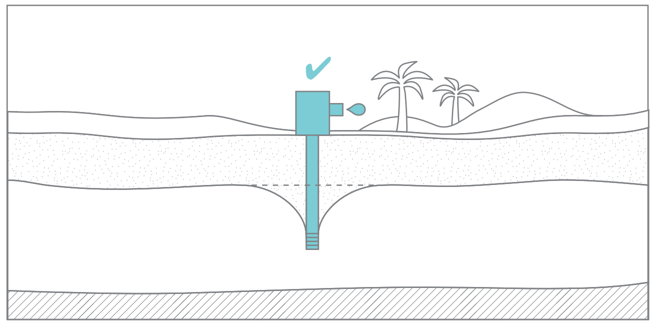
Unused and open wells are a great hazard. Recent reports document several cases of injury or death from children falling into these wells. Unused wells also have been used as garbage disposals or places to discard deceased animals. To prevent these unfortunate occurrences in the future, open and unused wells need to be properly closed. The majority of disused wells are only poorly closed or semi-professionally backfilled. These wells are still a danger to the population as well as the groundwater. A properly closed well will be filled with sterile local soil to the top and sealed with a bentonite and cement cover. This backfilling procedure prevents groundwater contamination and improves the overall groundwater quality. And most important, it improves the safety of people, especially of children, by preventing accidental falls.

EAD Groundwater Monitoring Well

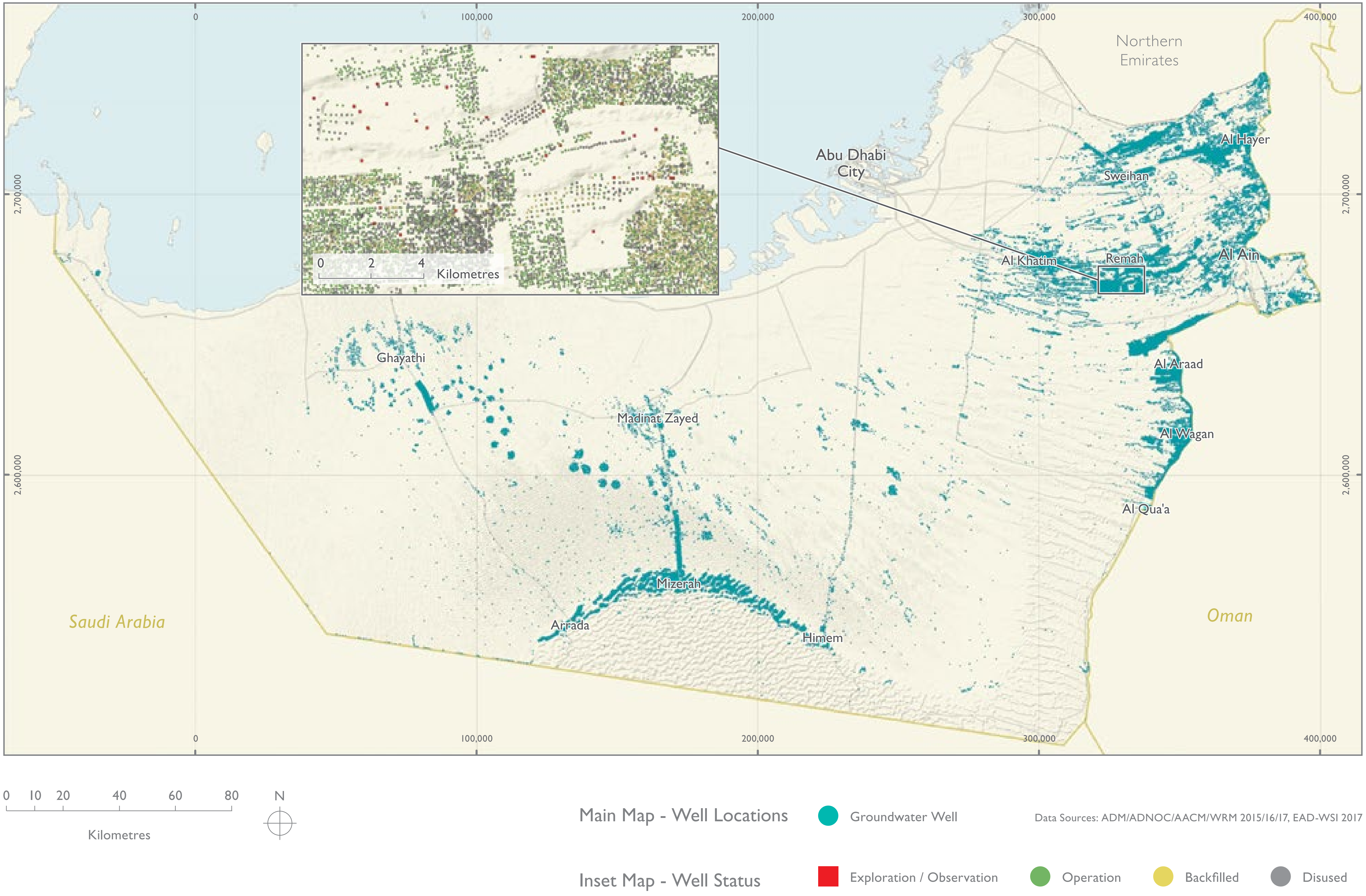
Operational Well


Disused Well

Groundwater
Well Status



LOCATION AND STATUS OF GROUNDWATER WELLS



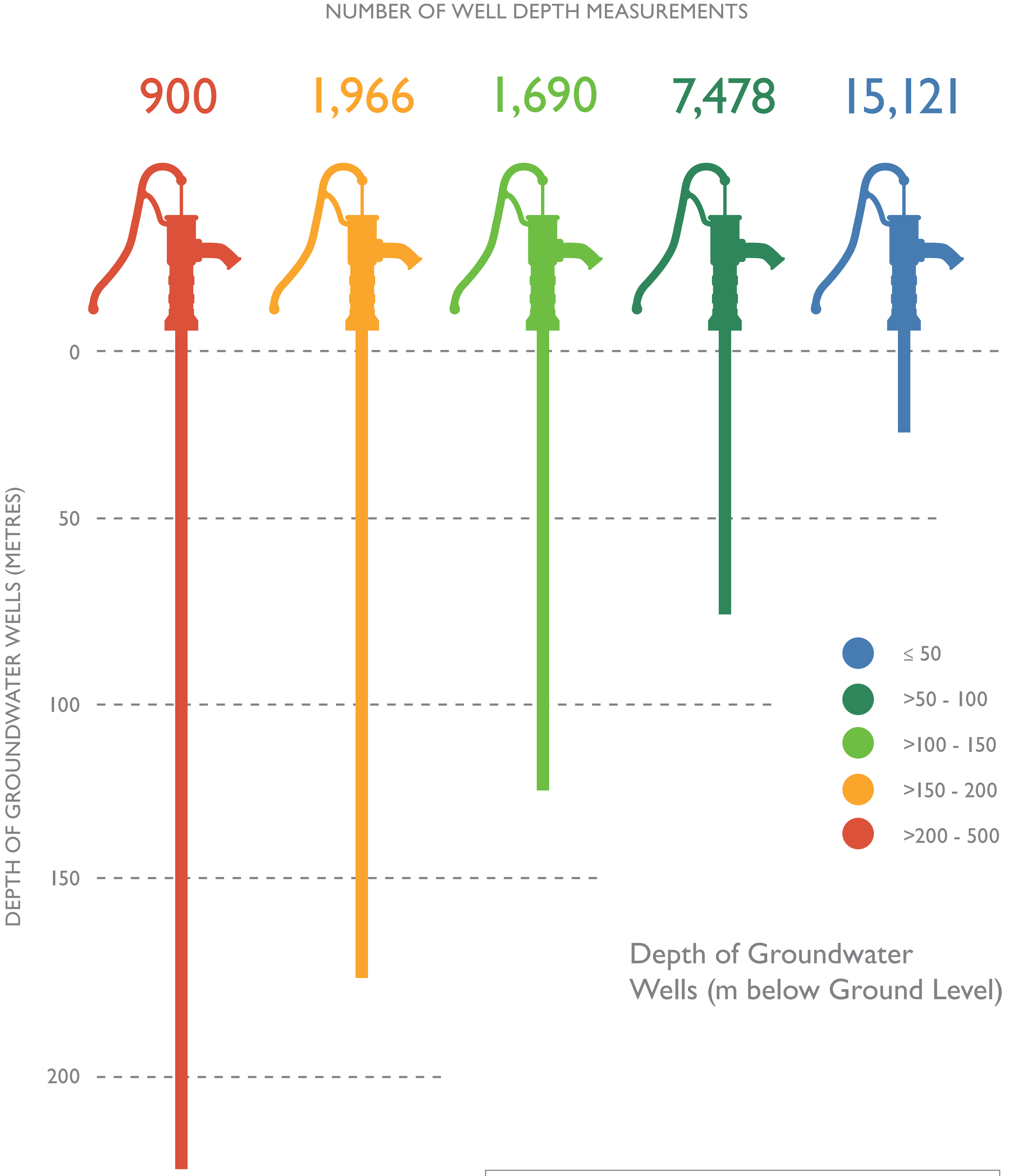
GROUNDWATER WELL DEPTH

The depth of each individual well depends on the groundwater level: the deeper the groundwater level, the deeper the well must be. Most of the shallow wells are found close to the coast, in the Liwa Crescent or around Al Ain where groundwater sits close to the surface.

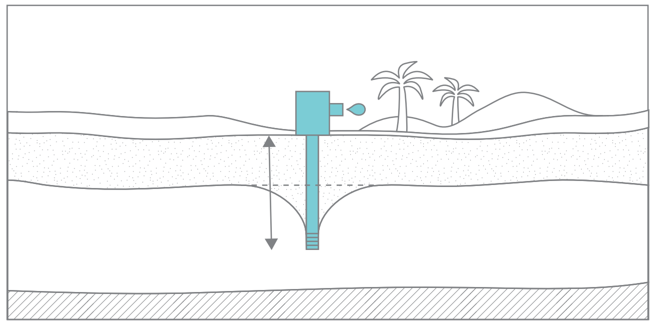
Deeper wells are located in the Remah area and around Al Araad. In these regions the water level dropped dramatically in the last 20 years (more than 200 m in some areas). As a result, the wells in these regions fell dry and new wells were necessarily drilled deeper to adapt to the change. The majority of wells are drilled in places where the groundwater is easily accessible at a depth of 50 m or less, hence, wells for irrigation are usually shallow. In contrast, well fields are drilled to make best use of the available water resources both in quantity and in quality. They are frequently drilled deeper than corresponding wells for agricultural irrigation. This point is best exemplified in the well fields of the Bu Hasa area.

Exploration wells constitute another category of wells. Their primary purpose is the exploration of the underground, rather than water abstraction. These wells must reach great depths in order to provide the necessary information. If the information proves useful, these exploration wells are often converted into groundwater monitoring stations or wells for regional water supply.

More than 50% of all measured wells in Abu Dhabi Emirate are less than 50 m deep.

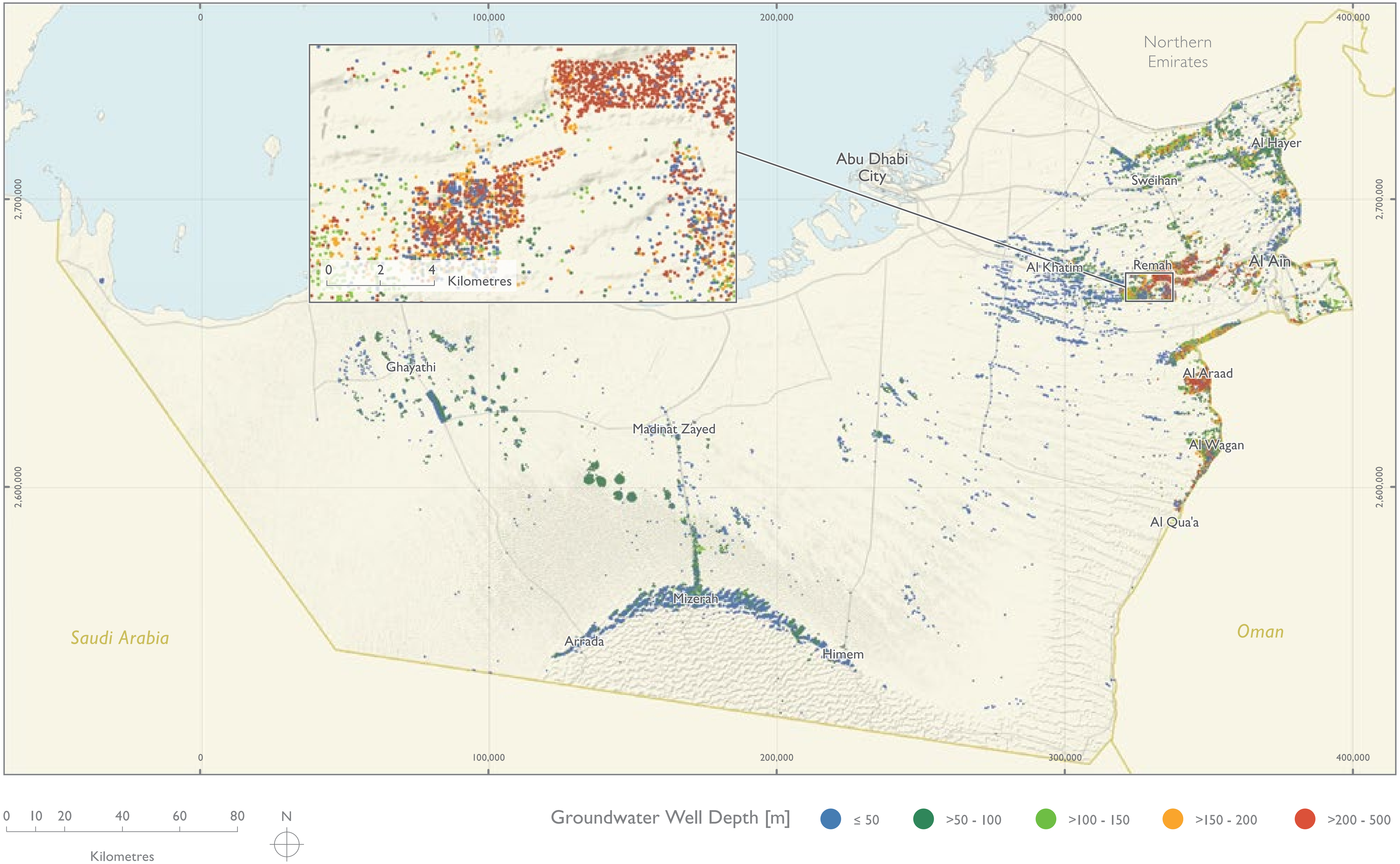


Depth of Groundwater Wells (m below Ground Level)



Groundwater Well Depth

GROUNDWATER WELL DEPTH



Data Sources: ADM/ADNOC/AACM/WRM 2015/16/17, EAD-WSI 2017

GROUNDWATER WELL USE

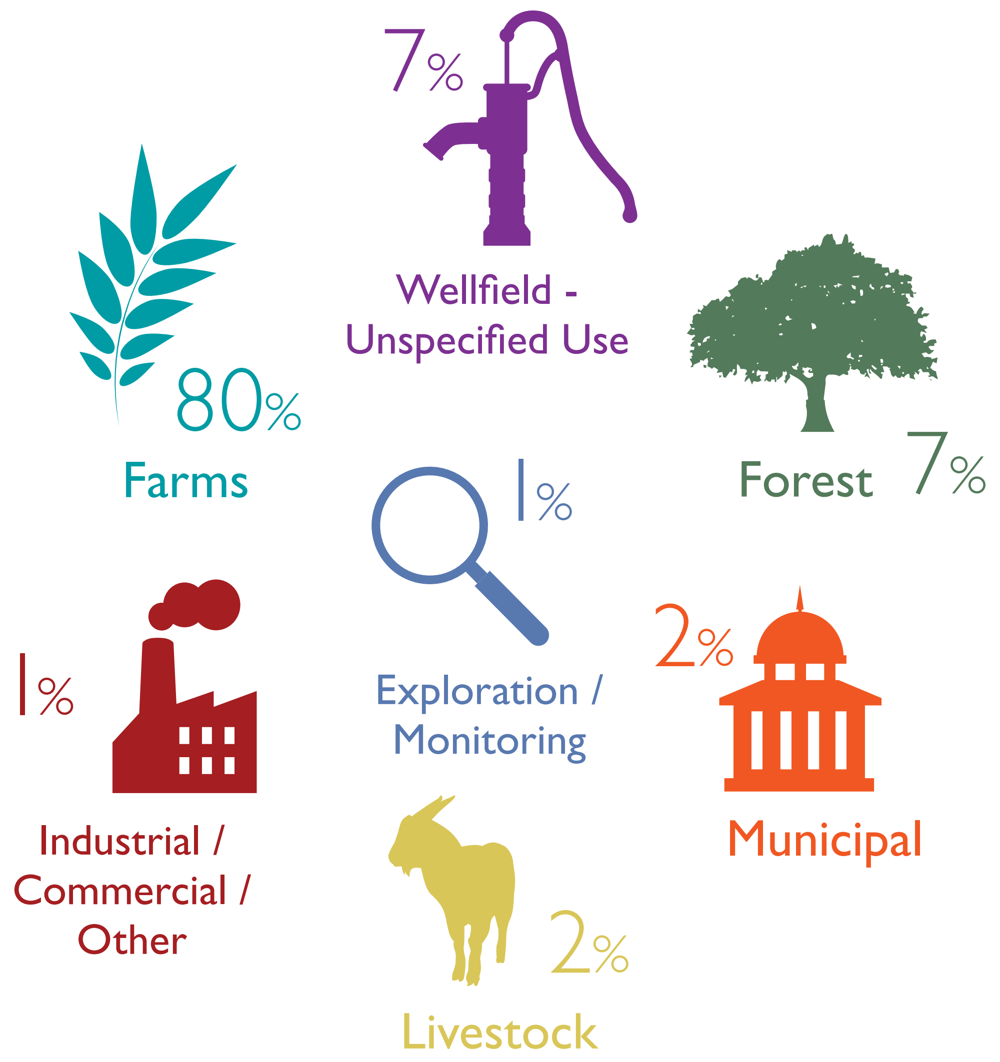
Groundwater in the Emirate of Abu Dhabi is used by a variety of consumers. The distribution of consumers indicates that the majority of groundwater wells supply farms in places such as Liwa, Remah, or Al Arad. The second largest consumers of groundwater are forest wells which are mostly located in Al Khatim and north of Ghayathi. The well fields are mainly located in the north Sweihan, Madinat Zayed and Ghayahi area.

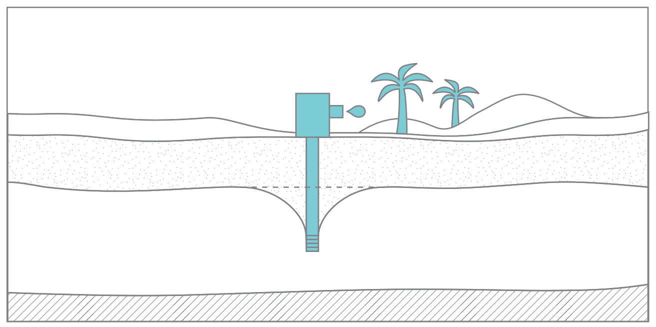
Farm wells are often simply constructed and are either drilled or dug. Depending on the yield of the aquifer and the demand for water, several wells might be constructed on a single farm. Forests are found scattered along the roads of Abu Dhabi Emirate. Planted for beautification purposes and to create a comfort micro-climate, forests usually host much bigger and more productive wells in order to supply the trees adequately with water. Forests stretch several kilometres along roadsides and usually house more than one well.

Wells in well fields are mostly constructed with a larger diameter and a proper well design in order to maximise efficiency. In the past, they were used for drinking water supply, but few are still operational because drinking water is now supplied entirely by seawater desalination plants. However, some of the well fields have been repurposed to provide water for irrigation or livestock on surrounding farms.

89% of the wells are used for agriculture and forest irrigation

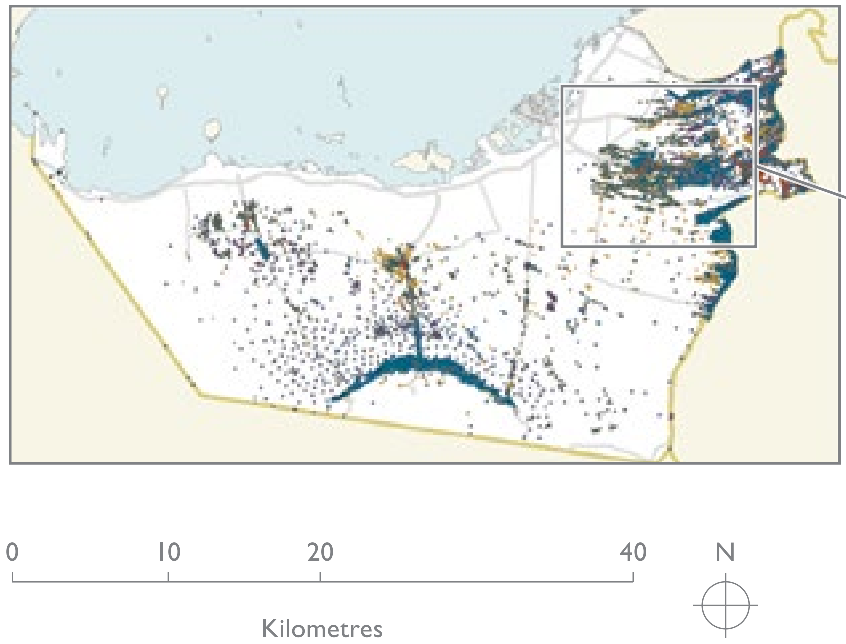
Groundwater Well Use



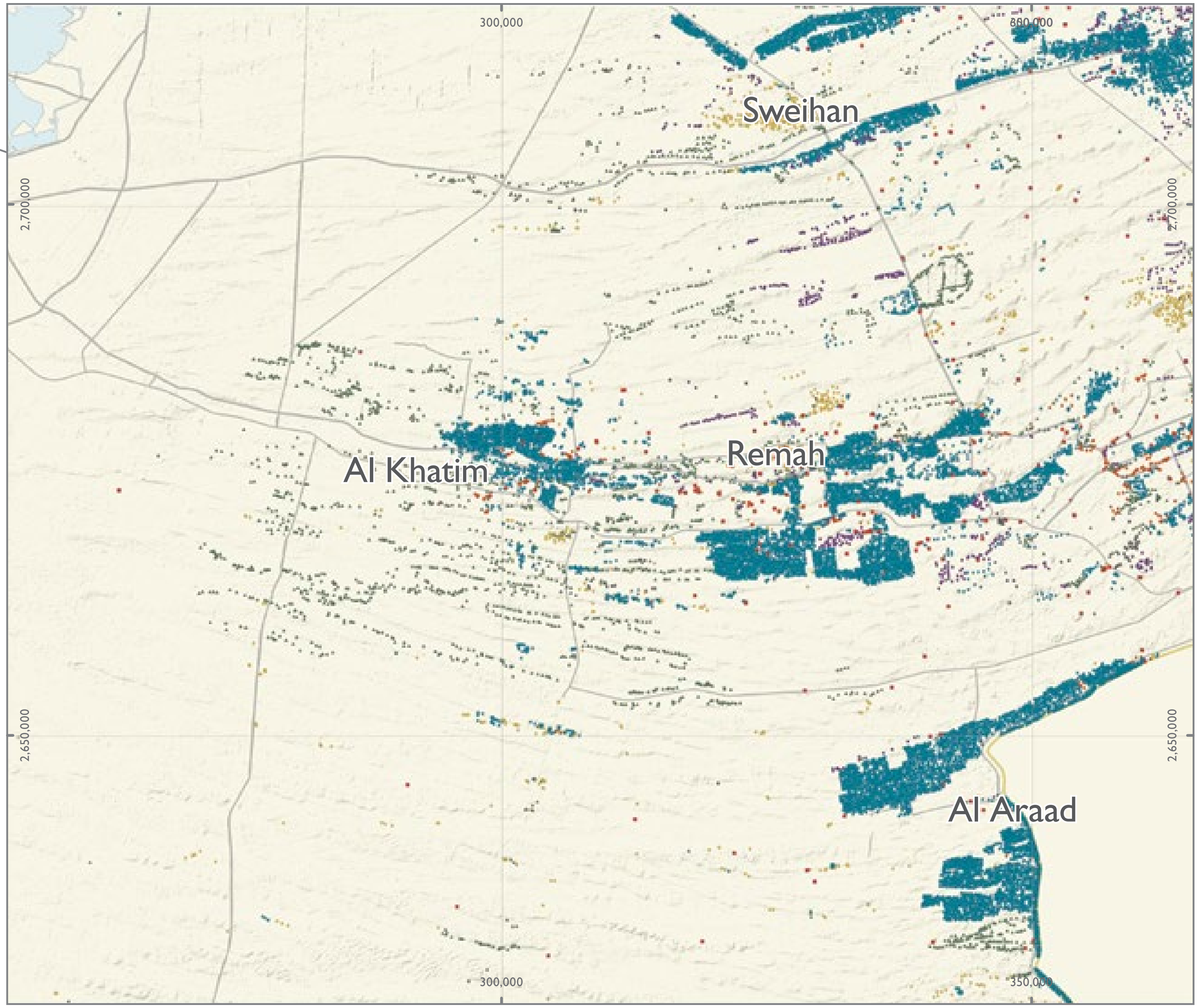


Groundwater Well Usage

GROUNDWATER WELL USE (OPERATIONAL WELLS)



Forest in Abu Dhabi Emirate



Groundwater Well Use

Exploration/Monitoring · Farm · Municipal · Wellfield - Unspecified Use · Forest · Livestock · Other

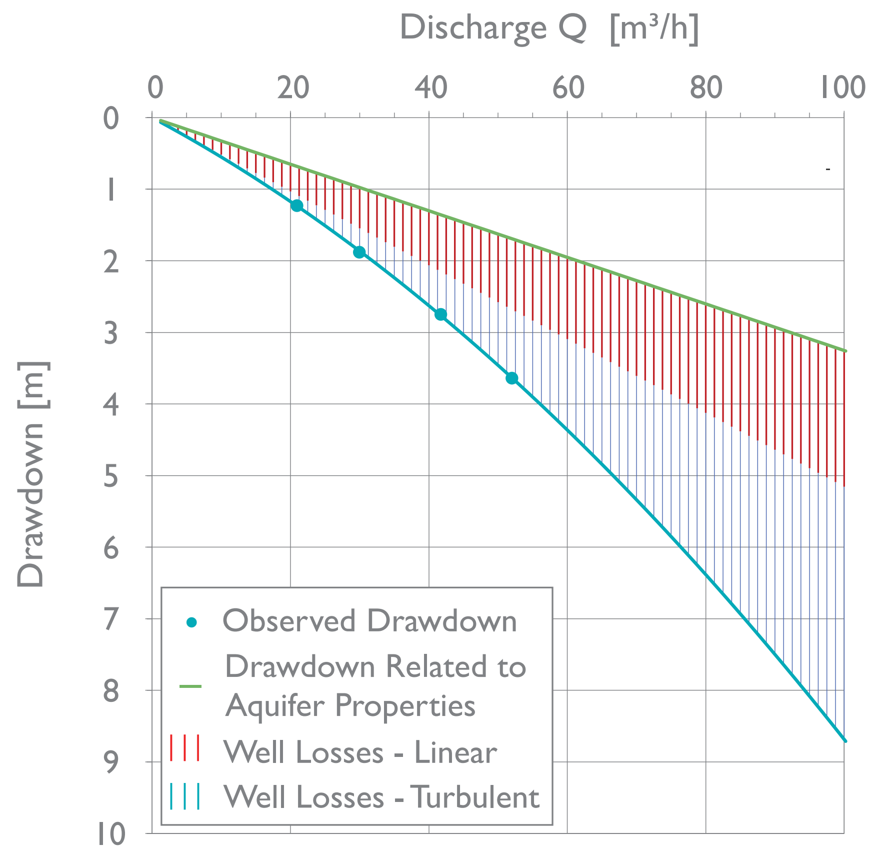
Data Sources: ADM/ADNOC/AACM/WRM 2015/16/17, EAD-WSI 2017

GROUNDWATER WELL PERFORMANCE

Each well yields a different amount of water, which depends on the well design and construction, but most importantly on the aquifer that is tapped. Hydrogeologists conduct pumping tests in order to determine the aquifer and well properties. In these tests, the water is pumped from the well, so that the pump rate and the corresponding drawdown of the water level can be measured.

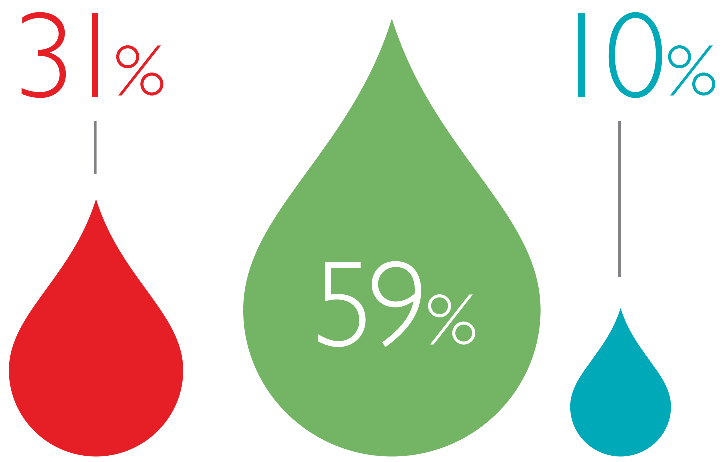
The hydraulic conductivity determines how much water flows through a unit of rock under a certain hydraulic gradient. Specific yield and specific storage are aquifer parameters that characterise how much water can be stored and released from the rock. Specific capacity is the ratio of groundwater discharge to water level drawdown. The value integrates both aquifer and well performance. As the aquifer properties do not change (except maybe for the groundwater level), it is often used to investigate the well performance over time. Clogging and bio-fouling reduce the available groundwater abstraction rate over the life-span of a well. Specific capacity measurements serve as an indicator for a successful well rehabilitation. The map shows the distribution of specific capacities among wells in Abu Dhabi Emirate and corresponding aquifer productivities. The highest specific capacities are found in the very northeast, in the Al Shweib area. Wells with high specific capacities are found around Liwa, too, which alludes to a high aquifer productivity in the area.

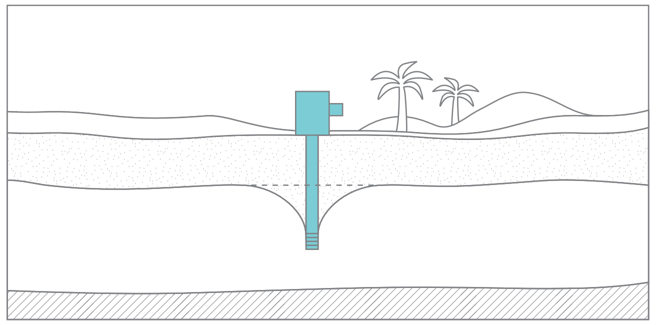
Well Performance Curve



Specific Capacity of Groundwater Wells [m²/h]

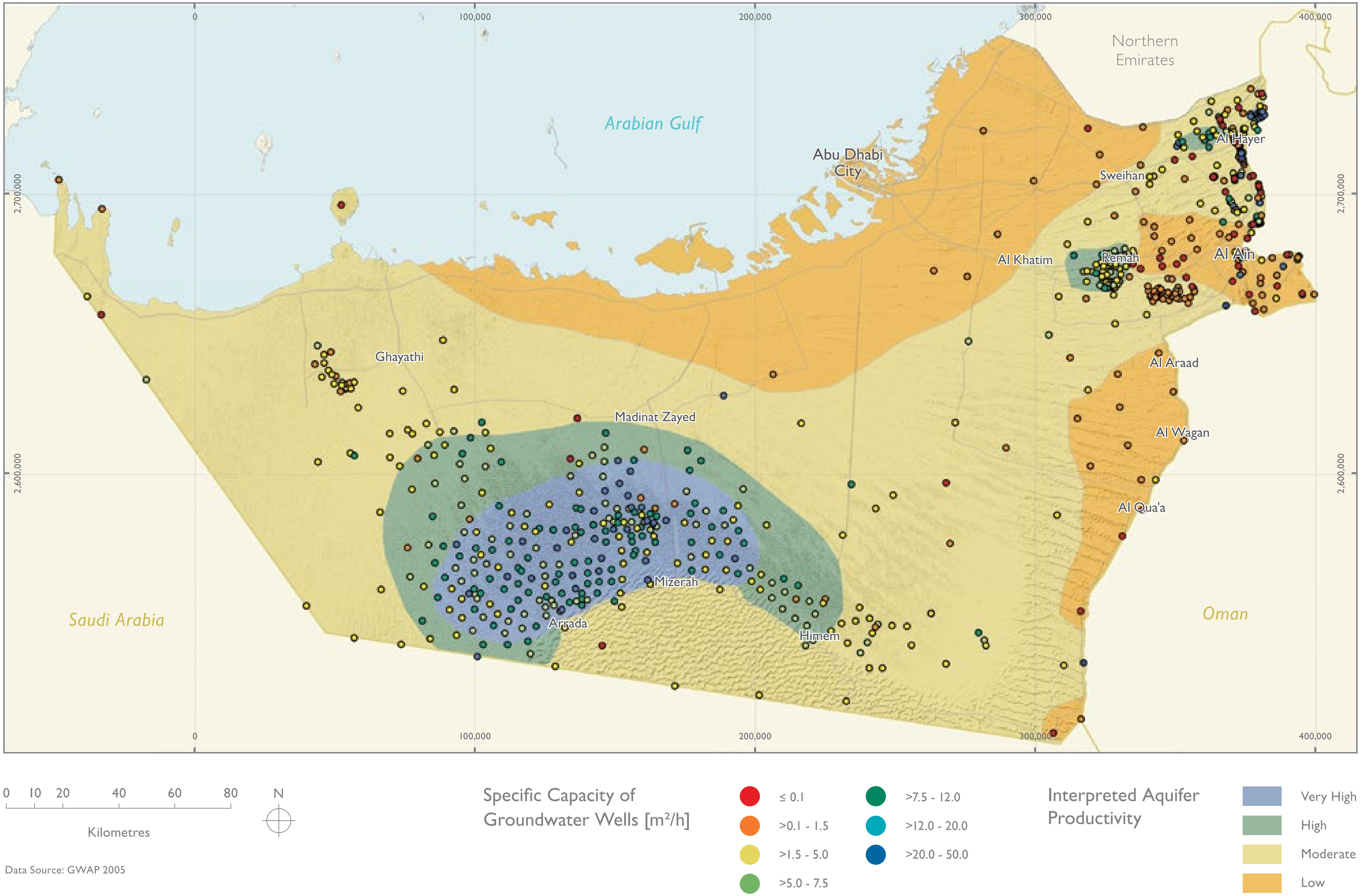
Low (≤1.5)
Moderate (>1.5 - 12)
High (>12 - 50)





Capacity of Groundwater Wells

AQUIFER PRODUCTIVITY AND SPECIFIC CAPACITY OF GROUNDWATER WELLS



Data Source: GWAP 2005

GROUNDWATER WELL DISCHARGE

Groundwater abstraction for agricultural or human use makes a significant impact on groundwater resources. As water is pumped from a well, it causes a drawdown of the aquifer water level nearby. An accumulation of several wells and their drawdown can impact the groundwater resources permanently. Because heavy pumping leads to groundwater depletion, it is environmentally wise to avoid wasteful groundwater consumption.

The map depicts the total amount of water abstracted in each agricultural centre of Abu Dhabi Emirate. The Liwa Crescent abstracts the most groundwater, followed by Al Wagan and Remah abstraction centres. High groundwater abstraction rates in these areas are due to the dense population of farms that rely on groundwater for irrigation. Forest wells are primarily located outside the agricultural groundwater abstraction centres, with the exception of Al Khatim/Al Khazna's large number of forestry wells.

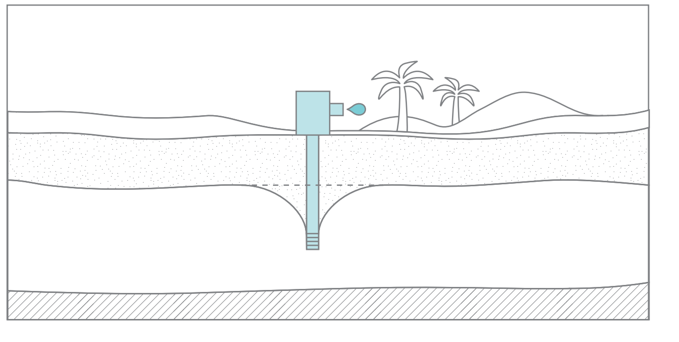
The total groundwater abstraction in the Emirate of Abu Dhabi was 2.1 km³ in 2017. Agricultural irrigation uses about 82 per cent of the abstracted groundwater and forests account for about 12 per cent of the total annual groundwater use. EAD aims to monitor and reduce these groundwater abstractions.

Groundwater Modelling supports decision making in regard to limitation of abstraction rates, and helps to assess and mitigate the consequences of groundwater depletion. Within this framework, a reliable prognostic tool of future groundwater abstractions is needed, which accounts for, among other things, the impact of policy making and the changes in groundwater quality and availability.

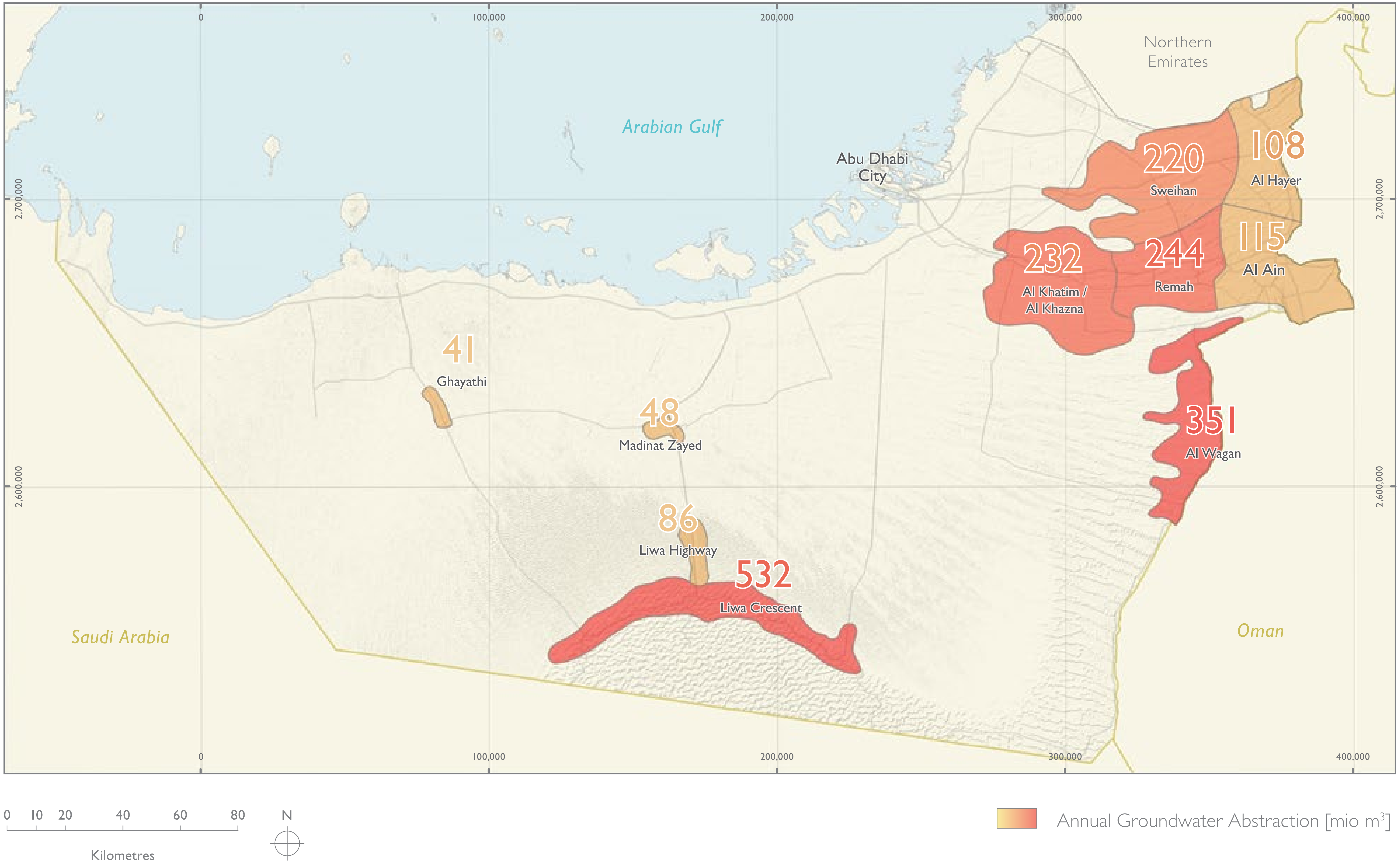
Agricultural Abstraction Center	Annual Groundwater Abstraction [mio m³] 2017	Number of Operational Wells
Liwa Crescent	532	9,633
Al Wagan	351	8,737
Remah	244	6,981
Al Khatim / Al Khazna	232	4,175
Sweihan	220	5,640
Al Ain	115	3,290
Al Hayer	108	4,453
Liwa Highway	86	1,289
Madinat Zayed	48	762
Ghayathi	41	874
Outside of Abstraction Centre	113	2,649

Region	Annual Groundwater Abstraction [mio m³] 2017	Number of Operational Wells
Abu Dhabi	166	3,161
Al Ain	1,113	30,473
Al Dhafrah	810	14,849

Annual Groundwater Abstraction



ANNUAL GROUNDWATER ABSTRACTION 2017



Data Source: EAD-WSI 2017

GROUNDWATER FLOW SYSTEM

GROUNDWATER FLOW SYSTEM

Installation of a Data Logger

Groundwater Monitoring Wells

Fenced EAD Monitoring Well

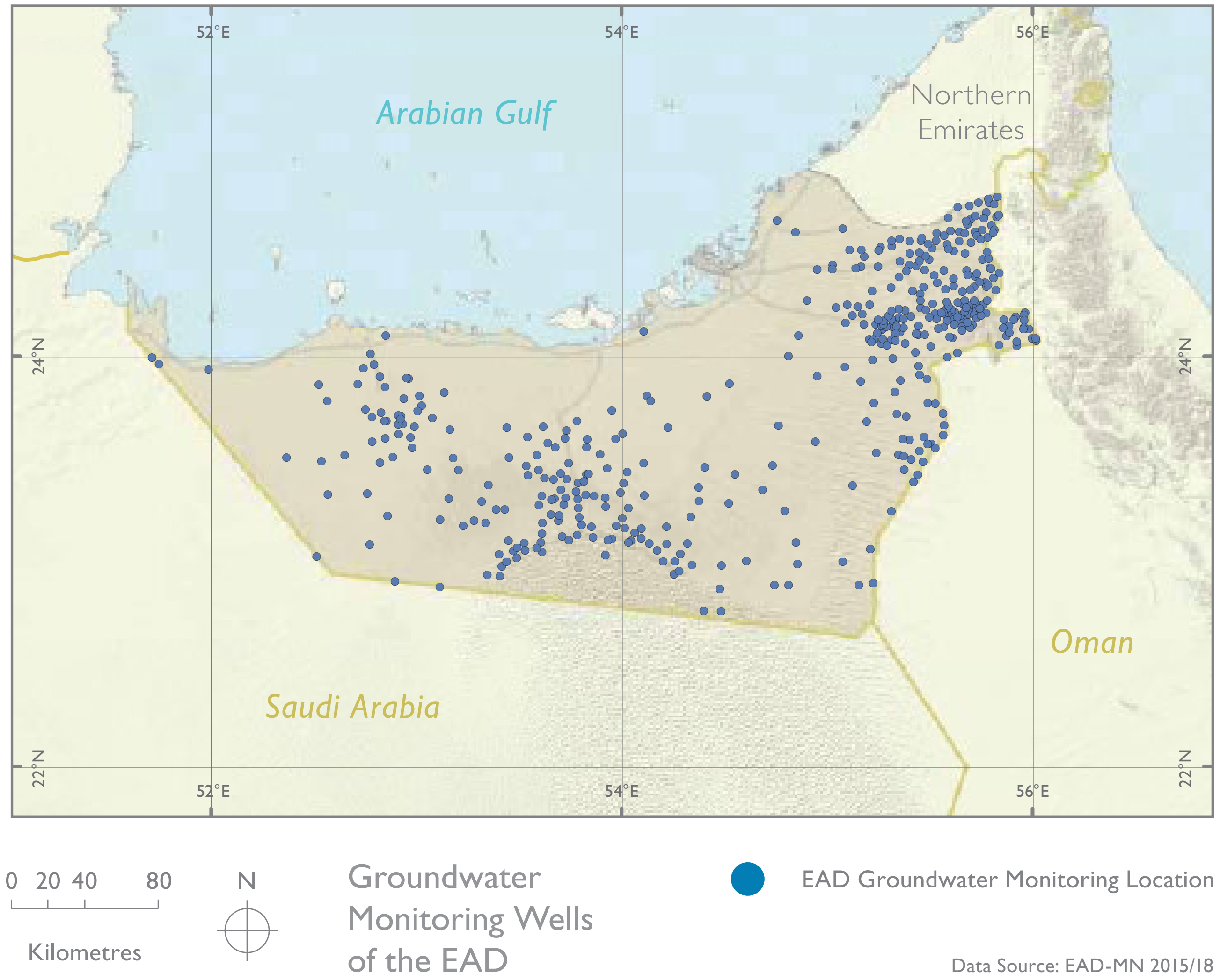
GROUNDWATER MONITORING NETWORK

Sound data is the bedrock for beneficial environmental decision making. To guide policy-making, the EAD operates an extensive groundwater monitoring network, comprised of 452 wells that supply essential data. These wells provide the key to understanding how groundwater quantity and quality changes over time.

Wells are visited in monthly, quarterly, and yearly intervals, and water samples are collected at several selected wells for further laboratory analysis. At every site, the standard parameters were recorded, including groundwater level, electrical conductivity, and temperature. The compiled data draws a comprehensive picture of the state of groundwater resources in the Emirate.

To prevent damage to the wells, EAD erected fences around them and posted signs bearing its logo. These precautions protect the wells and raise public awareness for the groundwater monitoring programme.

From its humble beginnings over two decades ago, the groundwater monitoring network has come a long way to become the state-of-the-art network it constitutes today. The scorching heat and high humidity affect the lifetime of data loggers, cables, and probes, making routine maintenance essential to overcoming the harsh environment. Wells are frequently covered by sand dunes or washed away by the rare torrential floods.



Data Source: EAD-MN 2015/18

452 Wells

comprise the EAD Groundwater Monitoring Network supplying essential data on the state and development of groundwater resources

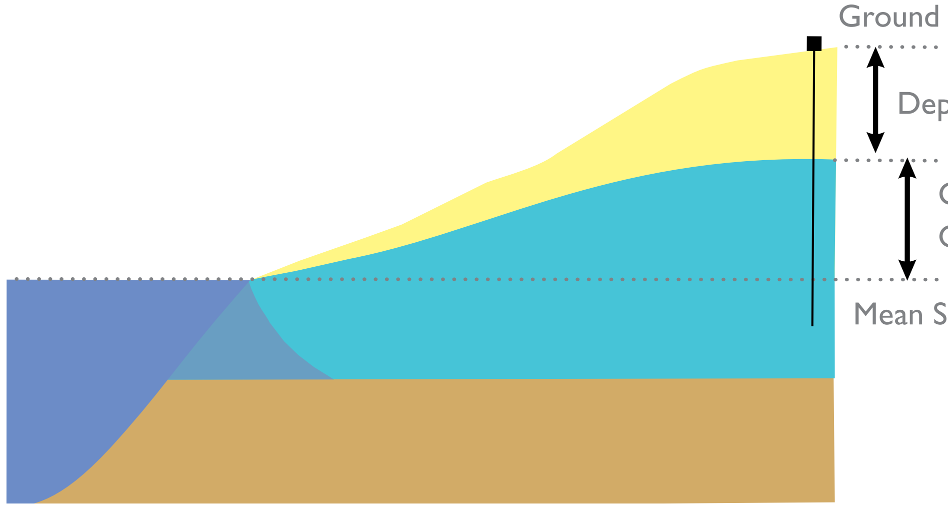
GROUNDWATER LEVEL

Generally, the groundwater level follows the natural declination of the ground level. The highest groundwater levels are located in the northeast of Abu Dhabi Emirate near the Hajjar Mountains (400 metres above sea level). Throughout the Emirate, the groundwater level declines until it reaches sea level along the coast. The Groundwater Level map also reveals an area of high groundwater levels in the central part of the Emirate, north of the Liwa Crescent. This groundwater mound acts as a water divide and is formed from water of low salinity. All water north of the mound flows towards the Arabian Gulf, while the groundwater south of it flows towards the south.

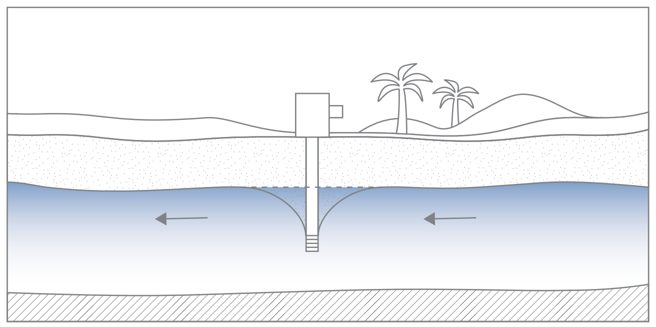
Continuous and large groundwater abstractions have a strong impact on groundwater levels. The aquifer is drained, and groundwater levels decline in a wide area around the wells. In Abu Dhabi Emirate, groundwater levels are lowered around agricultural areas, because of groundwater abstraction for crop and fodder irrigation.

Groundwater flows from areas of high groundwater levels to areas of lower groundwater level. This general rule is based on the assumption of uniform groundwater densities. In reality however, varying salinities and varying temperatures influence the density of the groundwater. To account for this effect, the measured groundwater levels in the project were converted into reference freshwater levels. These take into account the density of the groundwater column and depict the true piezometric surface. The density of groundwater in Abu Dhabi Emirate varies between 994 kg/m^3 and 1,248 kg/m^3.

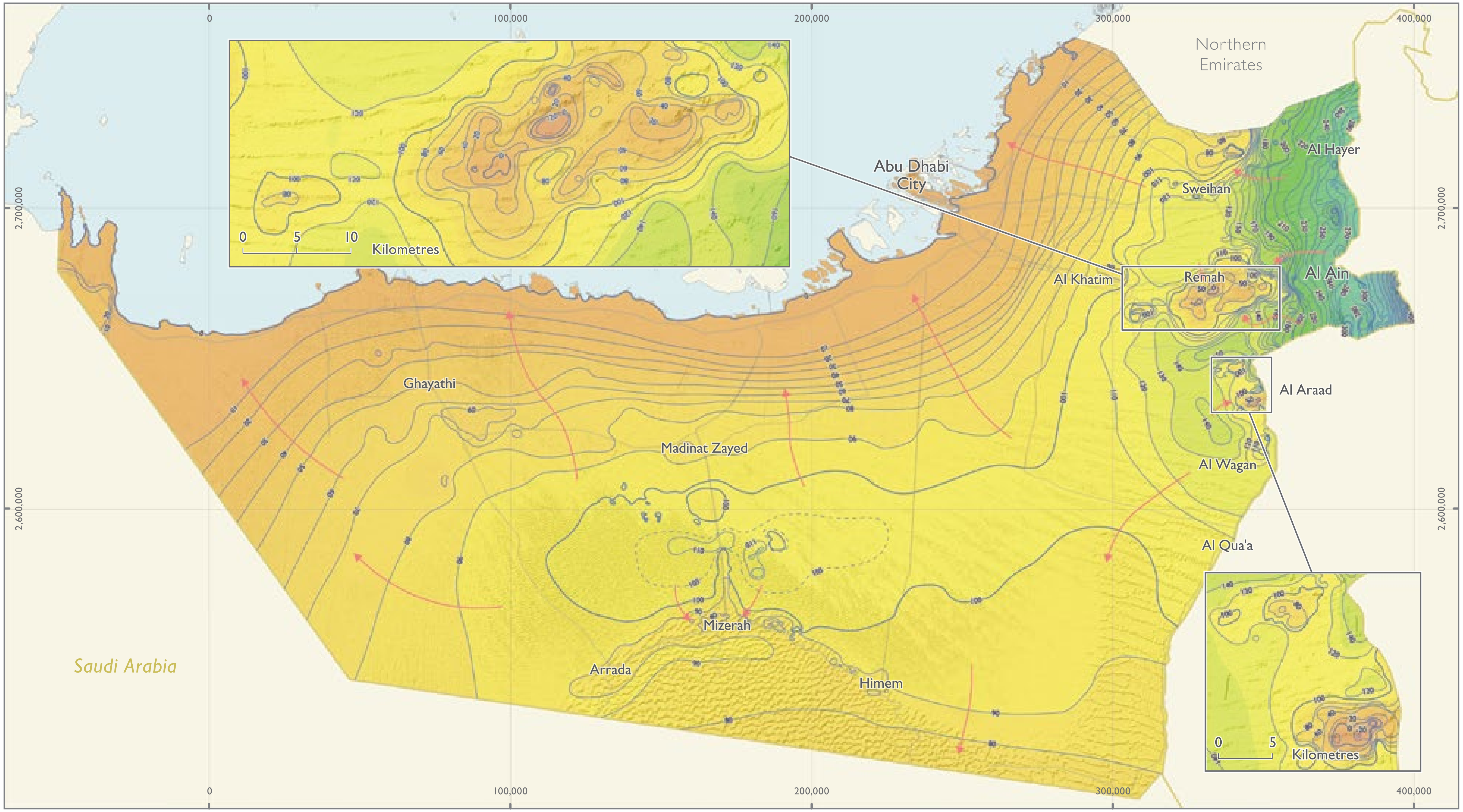
More than **31,000** groundwater levels were measured during the well inventory.



Groundwater Level



GROUNDWATER LEVEL 2017



0 10 20 40 60 80
Kilometres
N

Water Level [m AMSL]

400 290 180 70 -40

Major Contour Line (100 m interval)
Minor Contour Line (10 m interval)
Contour Line of Special Interest (5 m interval)
Groundwater Flow Direction

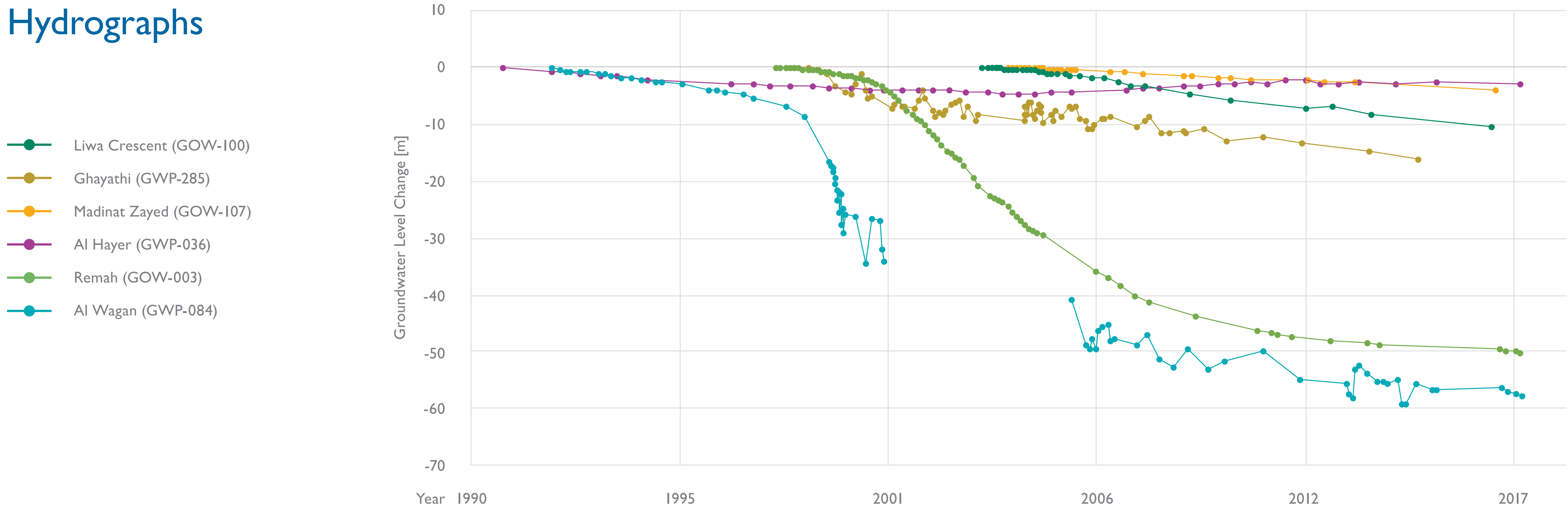
Data Sources: EAD2017, GWAP 2005, EAD-WSI 2017

GROUNDWATER LEVEL CHANGE

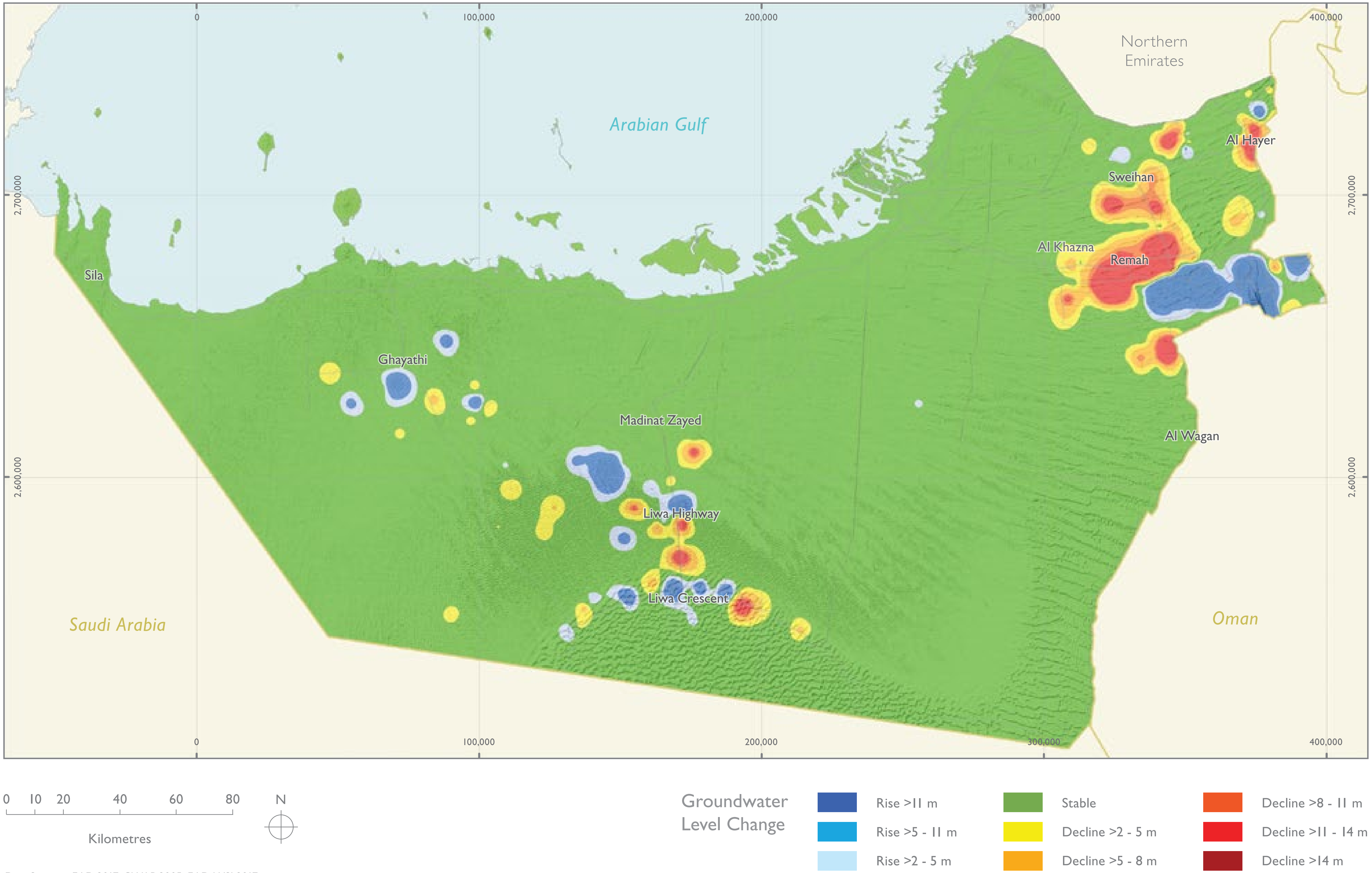
Changes in the groundwater level of Abu Dhabi Emirate are closely linked to agricultural activity. Areas with a strongly declining water table coincide with the areas of highest groundwater abstraction for agricultural irrigation.

The areas around Remah and Al Wagan illustrate this best. In the course of 25 years, the water level in groundwater monitoring wells has dropped by more than 50 m (see Hydrographs). The map shows the groundwater level change between 2005 and 2017. While yellow and red areas face a continued decline of groundwater levels, in blue areas a relative rise is observed. This relative rise is mainly attributed to a small reduction in agricultural activity and shut-down of well fields. Though between 2005 and 2017 the groundwater level slightly increased in these areas, an absoulte drawdown prevails, compared with the natural state. True rising of the water table takes place only in the vicinity of Al Ain, where losses from the water network and excessive landscape irrigation leads to rising water levels above the natural state.

Hydrographs



GROUNDWATER LEVEL CHANGE (2005-2017)



Data Sources: EAD 2017, GWAP 2005, EAD-WSI 2017

GROUNDWATER FLOW

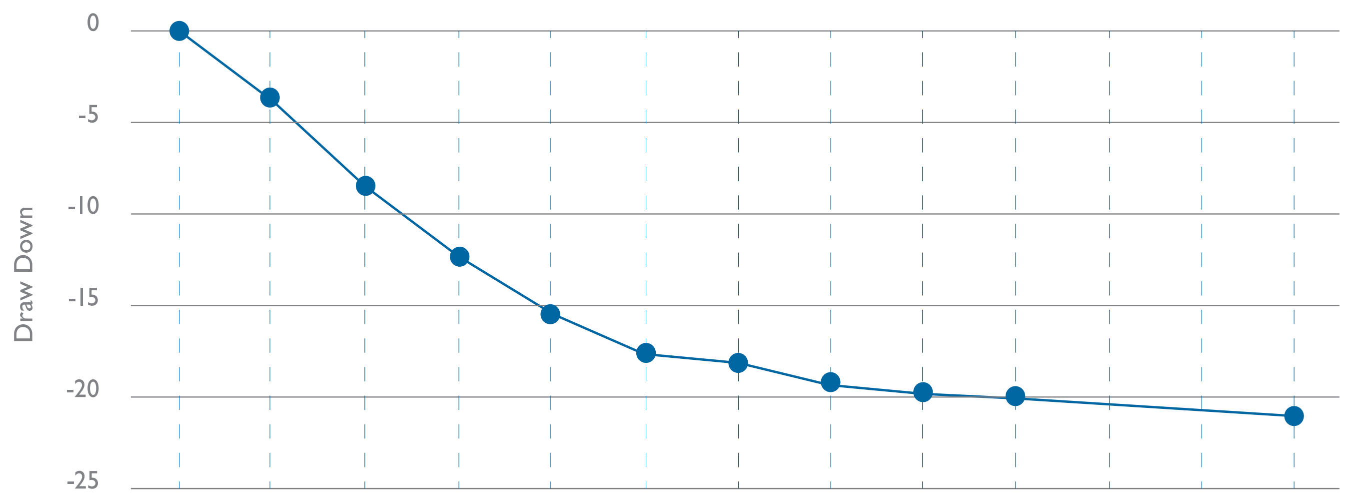
Groundwater flow follows the gradient of the groundwater level from the area of recharge to the receiving water body. In Abu Dhabi Emirate, most of the groundwater flows from the Hajjar Mountains on the Omani border, towards the Arabian Gulf.

The groundwater surface shows significant depressions in areas with high agricultural groundwater abstraction. These depressions are caused by many years of agricultural irrigation supplied by groundwater. The depressions are most prominent around Remah, where the groundwater level is more than 150 metres lower than the surrounding groundwater level. This cone of depression is so deep that it disrupts the natural groundwater flow from the Hajjar Mountains towards the sea.

Cone of Depression

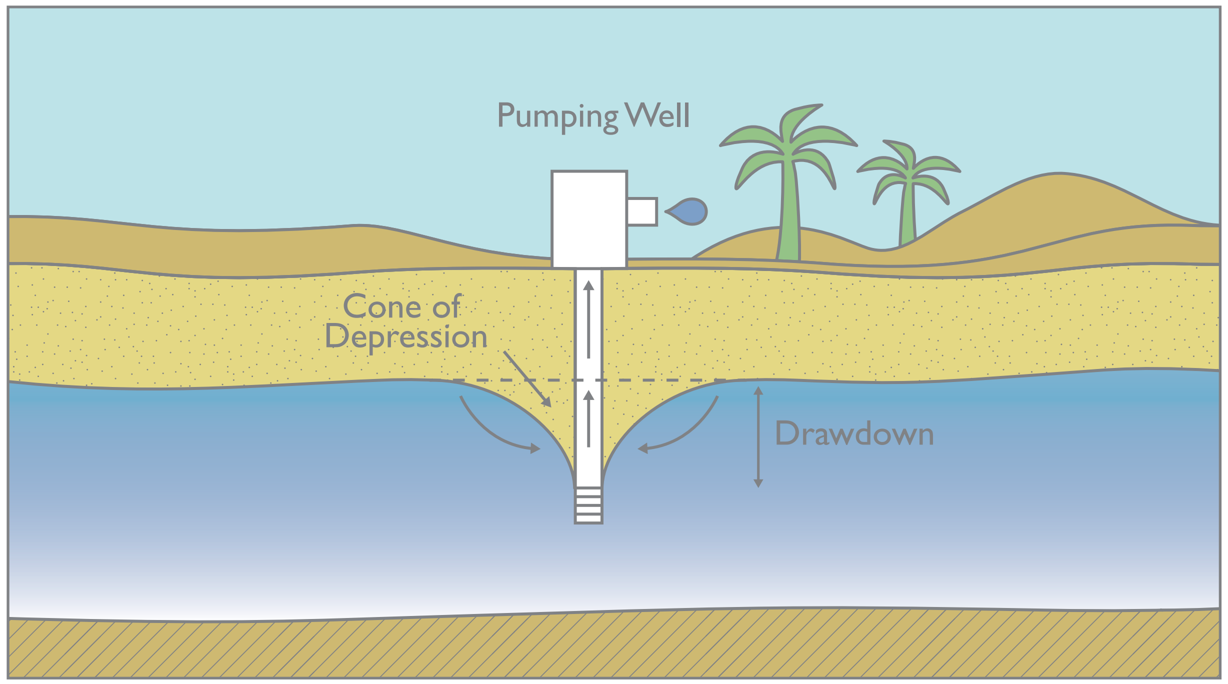
Abstracting groundwater leads to a depression of the groundwater surface around the well (the cone of depression). The gradient in water level between the cone of depression and the ambient aquifer leads to water flowing from the surrounding aquifer into the well. Once pumping stops, the cone of depression will fill up with water from the aquifer until the water levels equalise again. When pumping takes place over an extended period and the cones of depression from many abstraction wells overlap, the groundwater flow cannot compensate the pumping and a regional depression in the water level forms.

Drawdown in Observation Well GOW-003 (Remah)

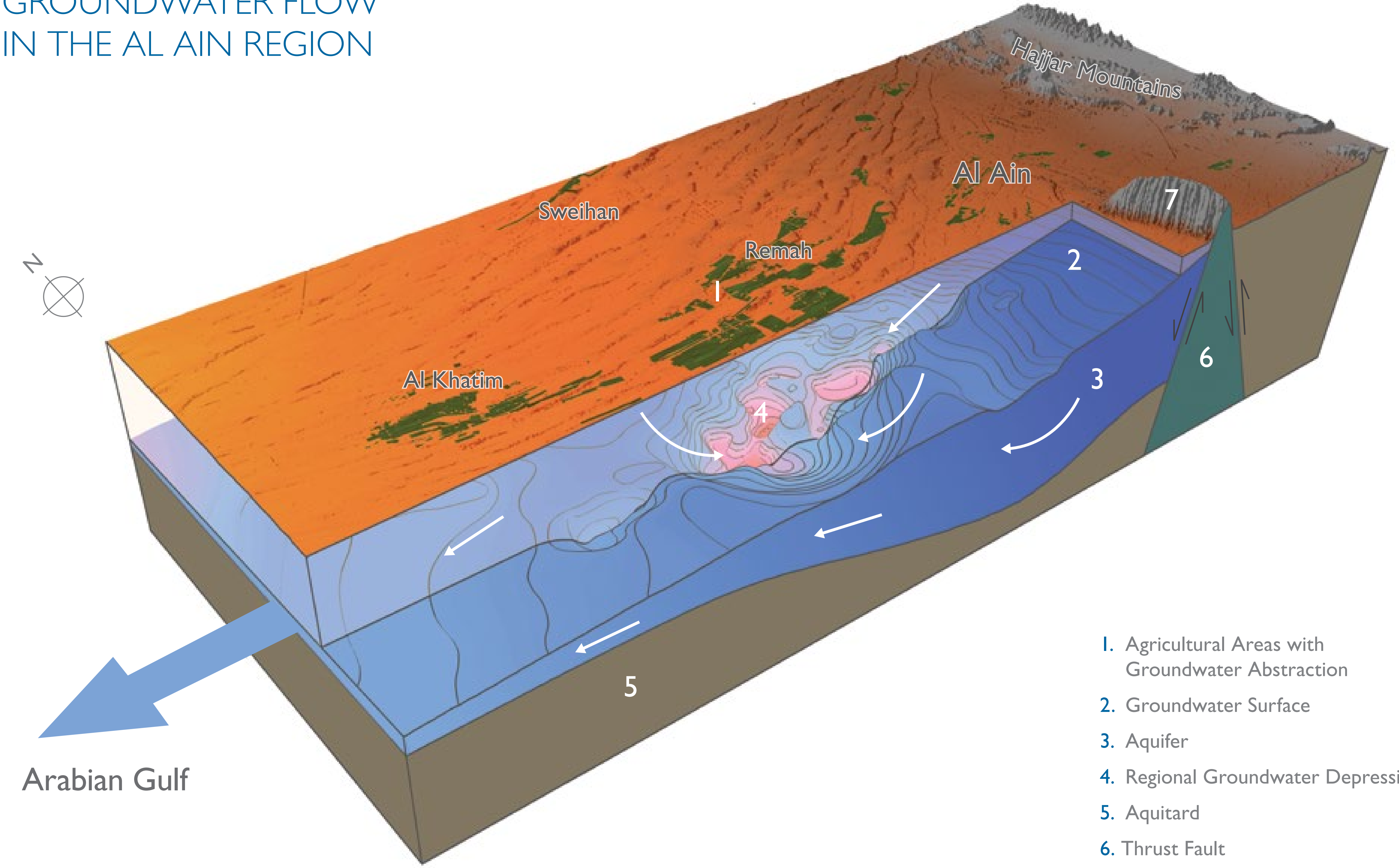


Year	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
GOW-003	0	-4.05	-8.53	-12.54	-15.57	-17.82	-18.29	-19.54	-20.11	-20.33	-	-	-21.30

Diagram: Cone of Depression



GROUNDWATER FLOW IN THE AL AIN REGION



1. Agricultural Areas with Groundwater Abstraction
2. Groundwater Surface
3. Aquifer
4. Regional Groundwater Depression
5. Aquitard
6. Thrust Fault
7. Jabal Hafit

Groundwater Level in a Dug Well

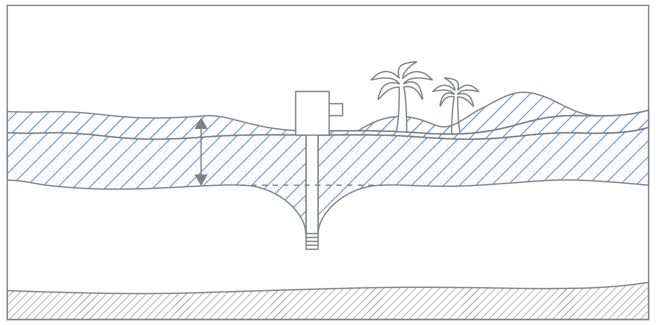
DEPTH TO GROUNDWATER

The Depth to Groundwater map primarily reveals the geomorphological features and regional depressions in the groundwater table.

Distinguishing geomorphological features of this map are the large sand dunes of the Rub Al Khali Desert in the south of Abu Dhabi Emirate and Jabal Hafit in the east of the Emirate.

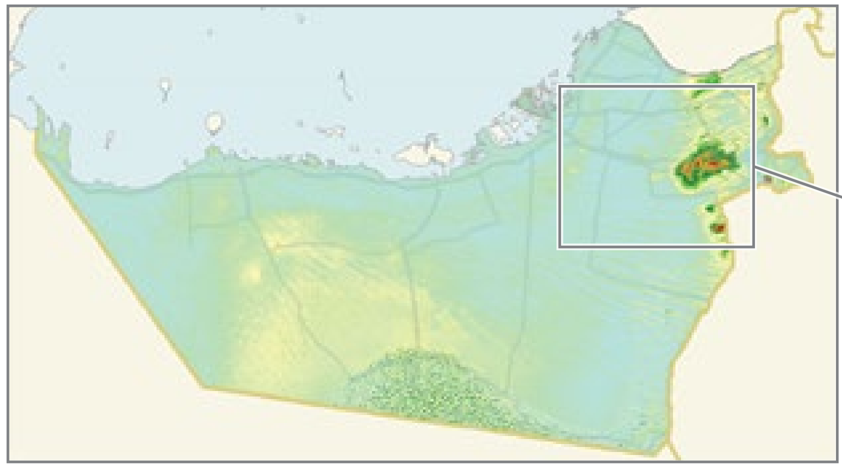
Most prominent however, are the groundwater depressions under the agricultural areas of Remah, Al Araad, and north of Sweihan. The groundwater table in these regions has declined steadily over the last decades and now reaches lows of 200 metres below ground level; a result of the intense abstraction of groundwater. However, in most other regions of the Emirate, the phreatic groundwater table sits at depths less than 50 metres. Near the Arabian Gulf, groundwater is found at a depth of just a few metres, providing a staunch contrast to the eastern part of Abu Dhabi where water might only be found at over a hundred metres depth.

In Remah, Al Araad, and north of Sweihan the water level dropped dramatically during the last decades. In some places more than 200 m.



Depth to Groundwater Level

DEPTH TO GROUNDWATER LEVEL

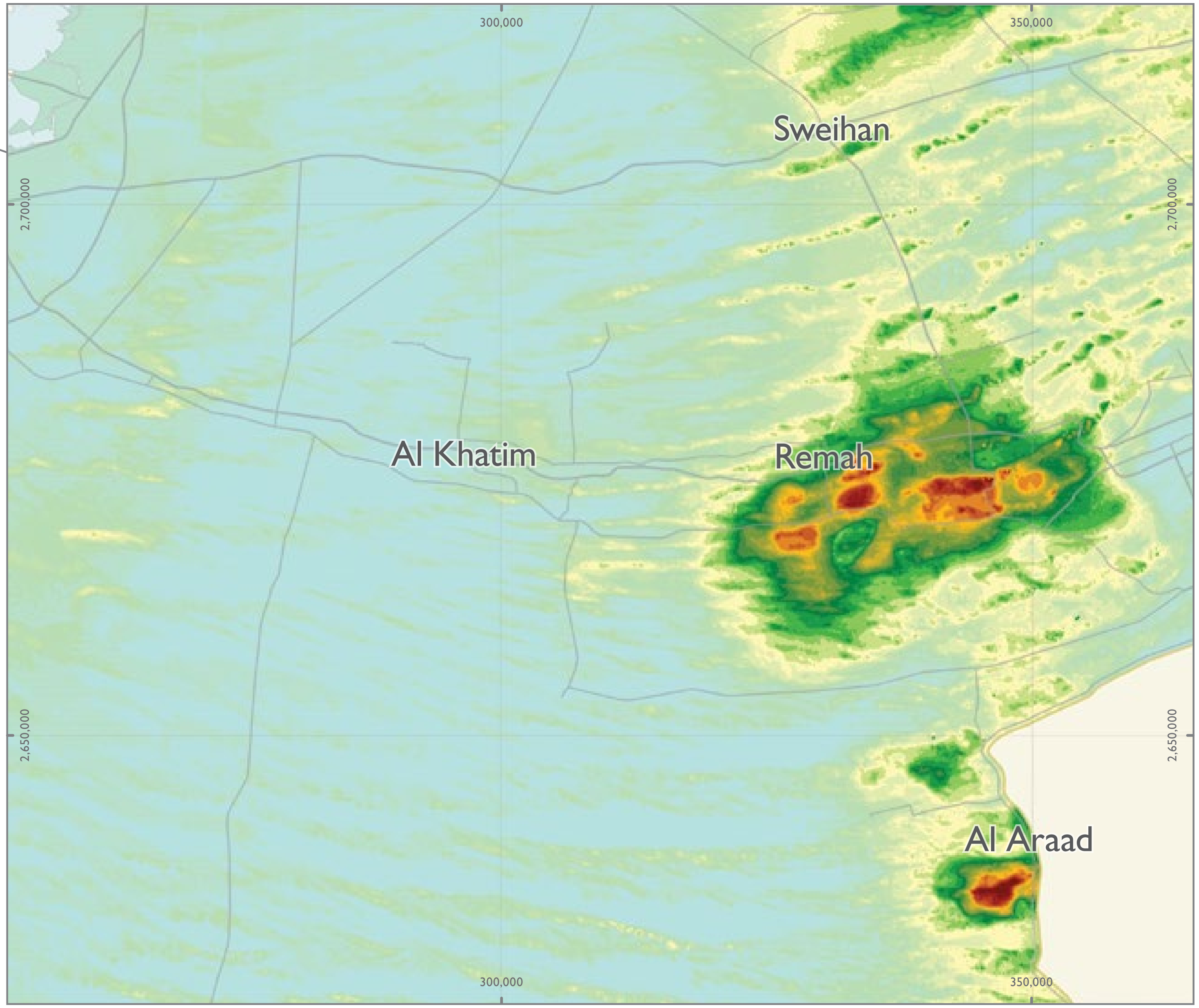


0 10 20 40

Kilometres

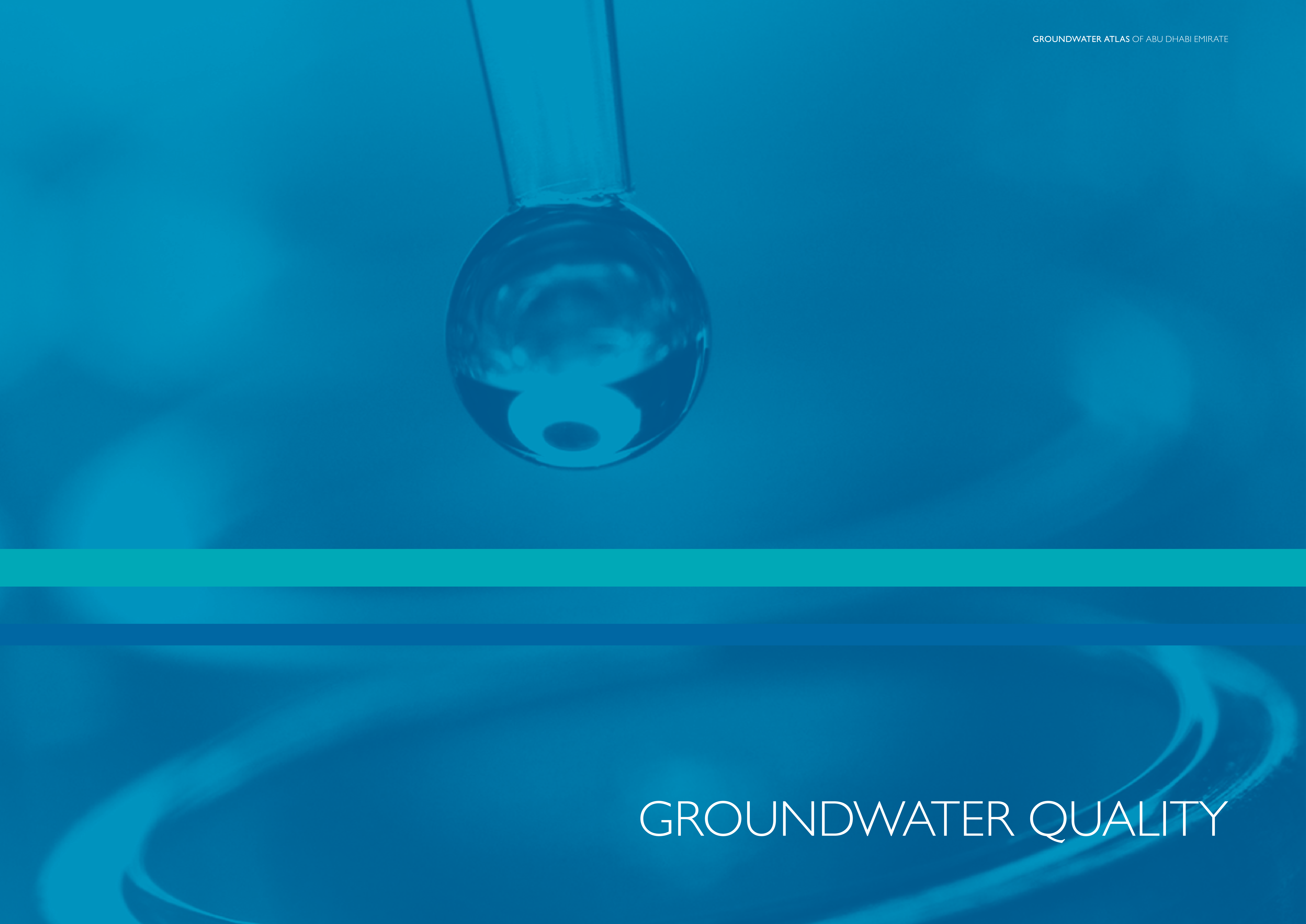
N

Groundwater Level Measurements



Depth to Groundwater Level [m]

Data Sources: ASTER 2011, EAD-WSI 2017



GROUNDWATER QUALITY

GROUNDWATER SALINITY

The usability of water is primarily determined by the concentration of Total Dissolved Solids (TDS). Rainfall has a very low TDS, often less than 100 mg/l. As the rainwater infiltrates the underground and is stored in the pores of the water-bearing aquifer, it dissolves some of the minerals from the host rock and consequently becomes more salty. Sodium chloride, gypsum, and calcium carbonate are the main minerals that are dissolved in groundwater, leading to an increased salinity.

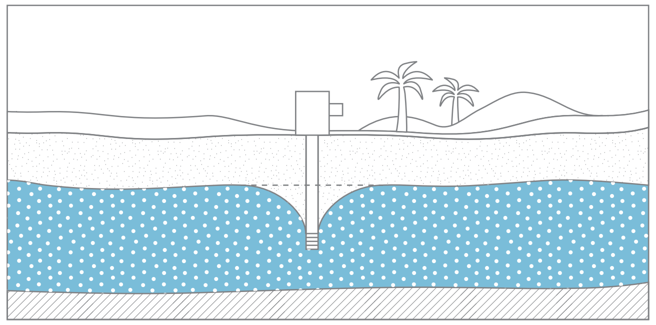
Two areas of freshwater with low mineral content are found in Abu Dhabi Emirate:

In the northeast, rainfall from the Hajjar Mountains recharges the aquifer and slowly flows towards the Arabian Gulf. The longer the water remains in the aquifer, the more time it has to dissolve minerals and interact with the rocks: In general, the water gets more saline as it flows towards the sea.

Another area of low salinity is found north of Liwa, where recharge from rainfall is minimal and the resulting groundwater is older. Most of it entered the aquifer thousands of years ago, in a time with a more humid climate. Very slow groundwater flow, uniform sandy lithology, and a distinct vertical salinity gradient in the aquifer have kept the uppermost groundwater fresh for centuries.

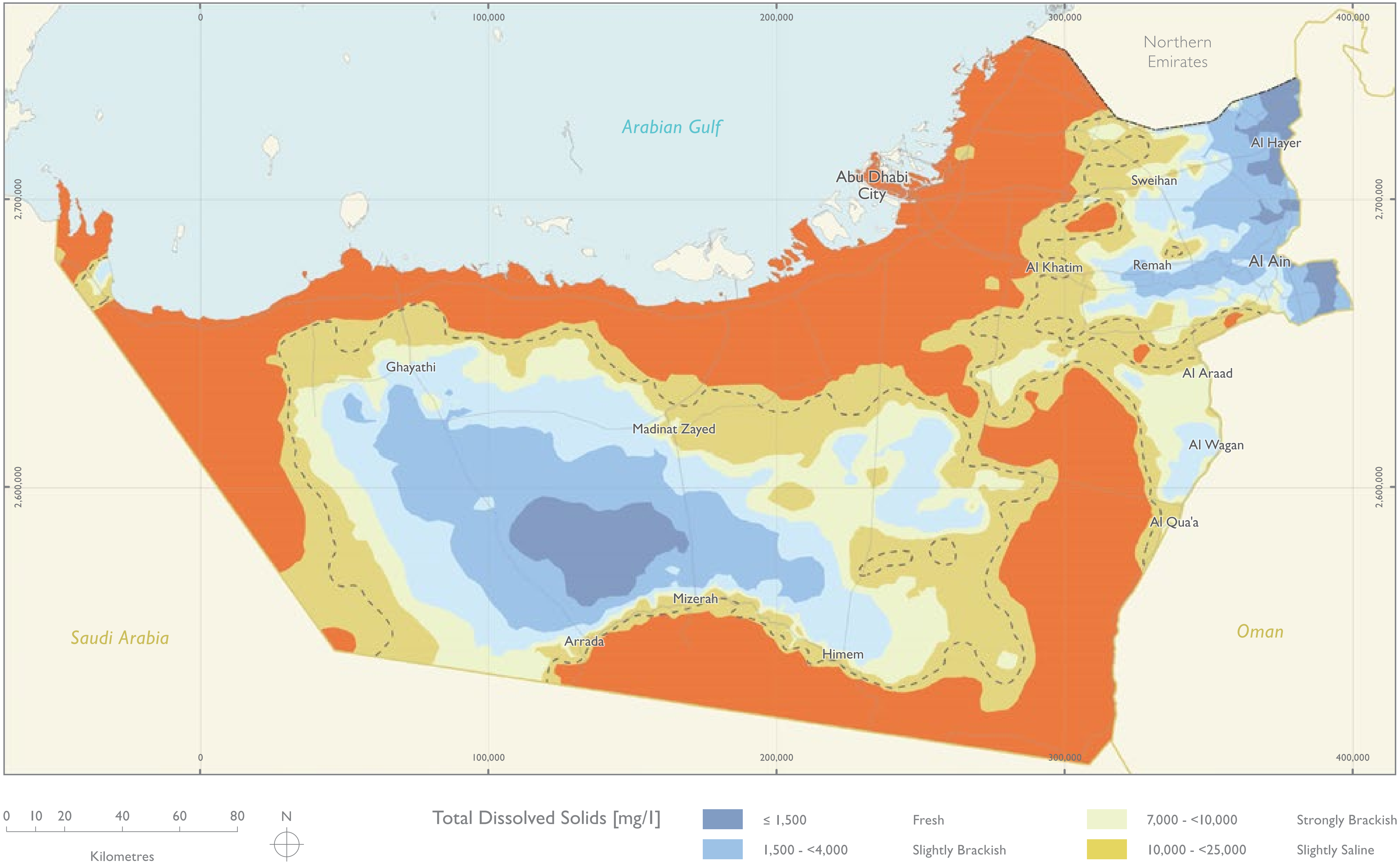
Along the coast in the west, as well as in the southeast, the groundwater table is very shallow. In these sabkha flats, the groundwater comes close to the surface and some of it evaporates. The dissolved minerals stay behind and lead to a further salinisation of the groundwater. Water in these regions can be as salty as 140,000 mg/l; that is more than three times as salty as the water of the Arabian Gulf.

Electrical Conductivity Measurement



Groundwater Salinity

GROUNDWATER SALINITY (2017)



Data Sources: EAD-WSI 2017

GROUNDWATER QUALITY

The classification of groundwater quality is often related to overall mineralisation, which can be expressed as the concentration of total dissolved solids (TDS). The seven most common ions (major ions) largely determine the TDS value. However, minor constituents such as phosphate, boron, fluoride, and metals like iron, manganese, zinc and others, also have an effect on groundwater quality. Even in small concentrations, they restrict groundwater use and affect human health. They appear in quantities of nanograms, and up to a few milligrams per litre.

To ensure groundwater quality, Environmental Agency - Abu Dhabi (EAD) set thresholds for the maximum concentration for each constituent.* These thresholds are among the strictest worldwide. The acceptable value differs between groundwater intended for domestic use, irrigation, or livestock supply. EAD regularily samples wells across the Emirate to monitor the groundwater quality.

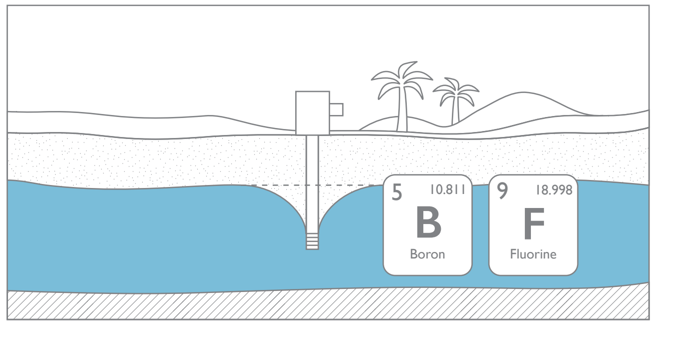
Both natural processes and human activities affect the groundwater quality. The minor constituents are helpful for tracing the natural groundwater evolution and determining the causes of groundwater pollution. For instance, elevated boron and phosphate concentrations are related to the inflow of fertilisers from irrigation water or detergents from wastewater into the aquifer.

Elevated fluoride concentrations are often naturally present. Fluoride occurs in pyroxene minerals of alluvial sediments, which originate from weathered rocks in the Hajjar Mountains. Low calcium content in the groundwater (typical for sandy aquifers in arid climates) leads to the solution of fluoride from rocks into the water.

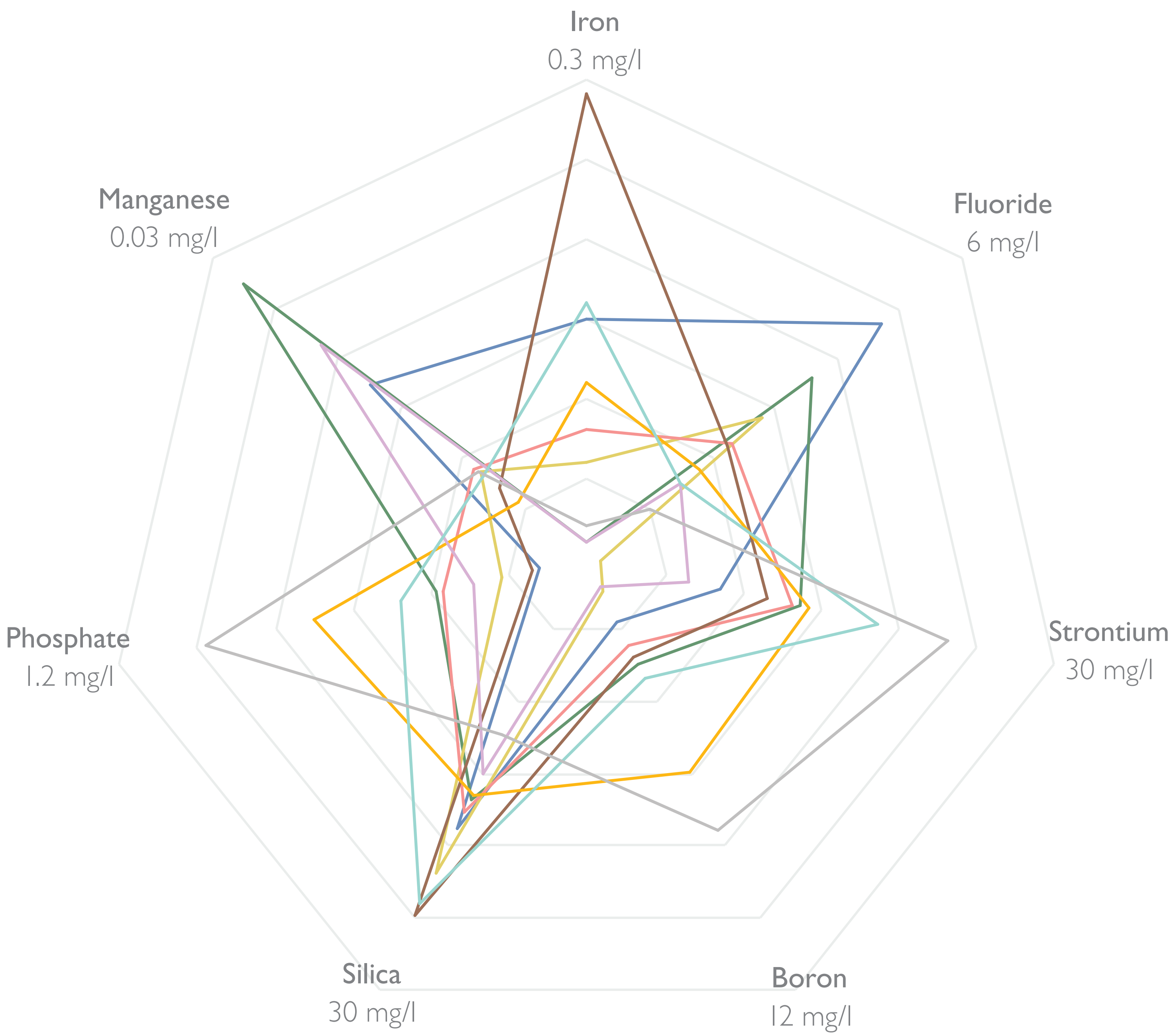
Every aquifer has a fingerprint of minor constituents concentrations, as shown in samples from the Liwa area in the radar graph to the right. This helps to distinguish groundwater from different aquifers even if their total mineralisation is similar.

The major ions (the most common ions) dissolved in groundwater are:
With a positive charge - calcium, magnesium, sodium and potassium
With a negative charge - chloride, sulphate, bicarbonate

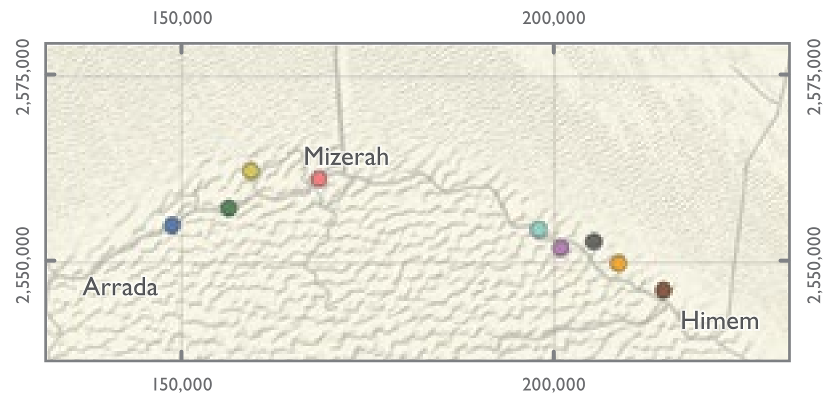
Minor and Trace Elements in Groundwater



* EAD Recommendations for Groundwater Use Quality Guidelines, 2017/EAD-EQ-PR-TR-06

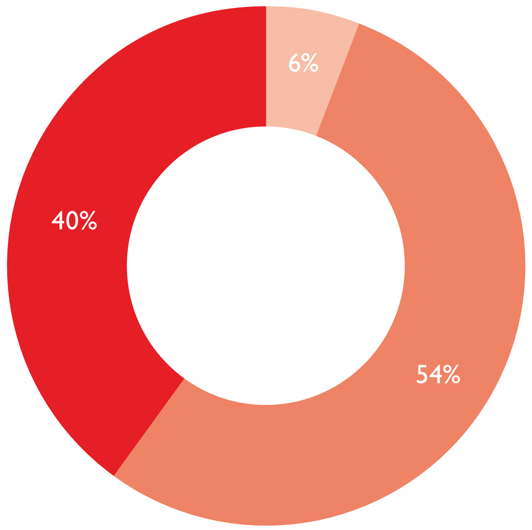


Selected Samples from the Liwa Crescent



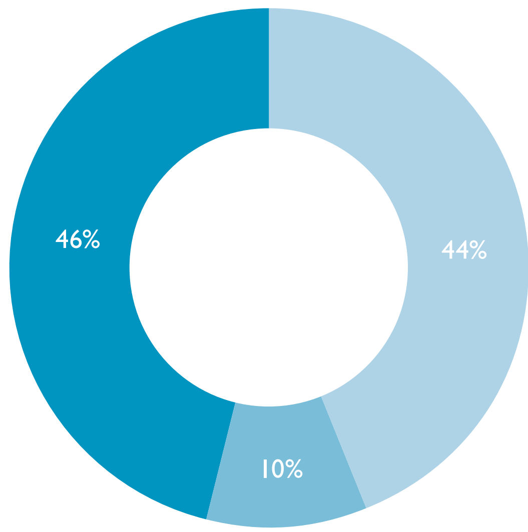
Data Source: EAD-WSI 2017

Boron Concentration in Groundwater Samples



- Below Guideline Value for Agricultural Irrigation (<0.5 mg/l)
- Below Guideline Value for Domestic Non-Potable Water but exceeding the Guideline Value for Agricultural Irrigation (>0.5 mg/l to 2.4 mg/l)
- Exceeding both Guideline Values (>2.4 mg/l)

Flouride Concentration in Groundwater Samples



- Below Guideline Value for Domestic Non-Potable Water (<0.4 mg/l)
- Below Guideline Value for Agricultural Irrigation Water but exceeding the Guideline Value for Domestic Non-Potable Water (>0.4 mg/l to 1 mg/l)
- Exceeding both Guideline Values (>1 mg/l)

GROUNDWATER POLLUTION

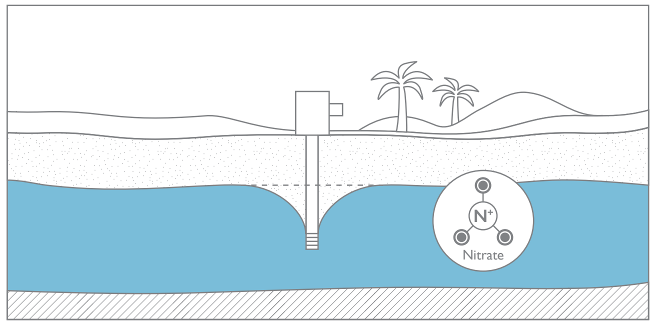
Compared to other water resources, groundwater is well protected from inadvertent or deliberate pollution. However, if close to the surface, groundwater may be impacted by (waste)water network losses, landfill seepage, or return flow from irrigation water.

The map on the right shows the nitrate content which gives some indication about the groundwater vulnerability. High nitrate concentrations rarely occur naturally, and usually originate from fertilisers which are washed into the aquifer together with the irrigation return flow. Where shallow groundwater levels are prevalent under agricultural areas (e.g. Liwa), nitrate concentrations are high. This is a clear indicator that irrigation return flow has reached the aquifer. In contrast, areas with deep groundwater levels (e.g. Remah and Al Wagan) have lower nitrate concentrations, because irrigation return flow never reached the aquifer, and nitrate had time to degrade along the flowpath.

Abu Dhabi Emirate threshold* for nitrate concentrations in domestic non-potable water is 45 mg/l. 40 per cent of all groundwater samples show concentrations above this value, signaling the magnitude of surface water's impact on the groundwater. However, high nitrate concentrations are of minimal concern for agricultural irrigation. One of EAD's major strategic objectives is to protect groundwater resources and ensure its quality. This is accomplished by establishing groundwater protection zones, enforcing high environmental standards in the construction sector, continually monitoring groundwater quality, and regulating groundwater abstractions, among other things.

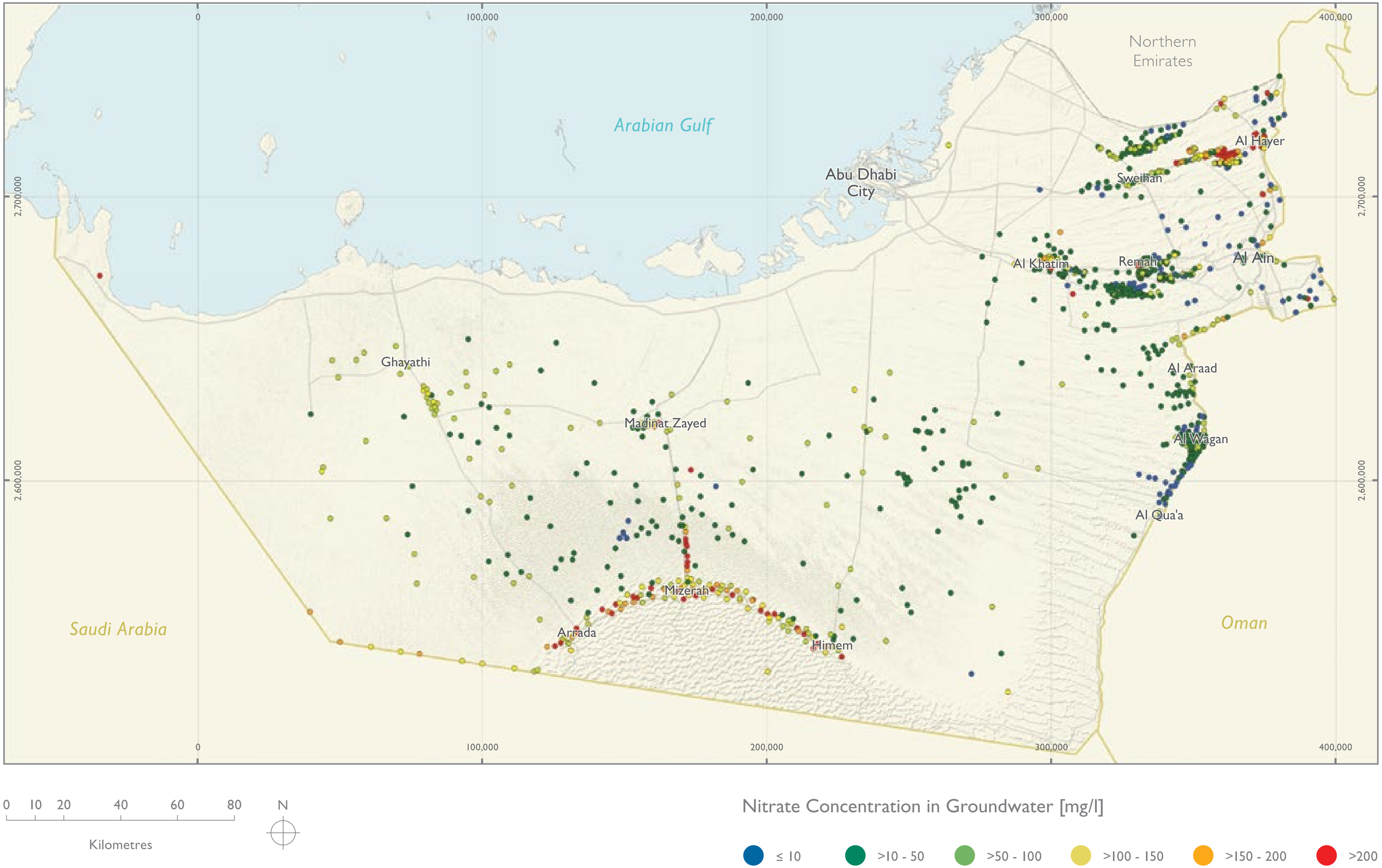
* EAD Recommendations for Groundwater Use Quality Guidelines, 2017/EAD-EQ-PR-TR-06

Date Palm Irrigation



Nitrate in Groundwater

NITRATE IN GROUNDWATER



Data Source: EAD-WSI 2017

GROUNDWATER MANAGEMENT

GROUNDWATER MANAGEMENT

GROUNDWATER BUDGET

In its natural state, the inflows and outflows of the groundwater resources are balanced, meaning that as much water that enters the aquifer system will also flow out. Any fluctuation to this balance alters the amount of stored groundwater (more inflow will increase the resources, more outflow will decrease them).

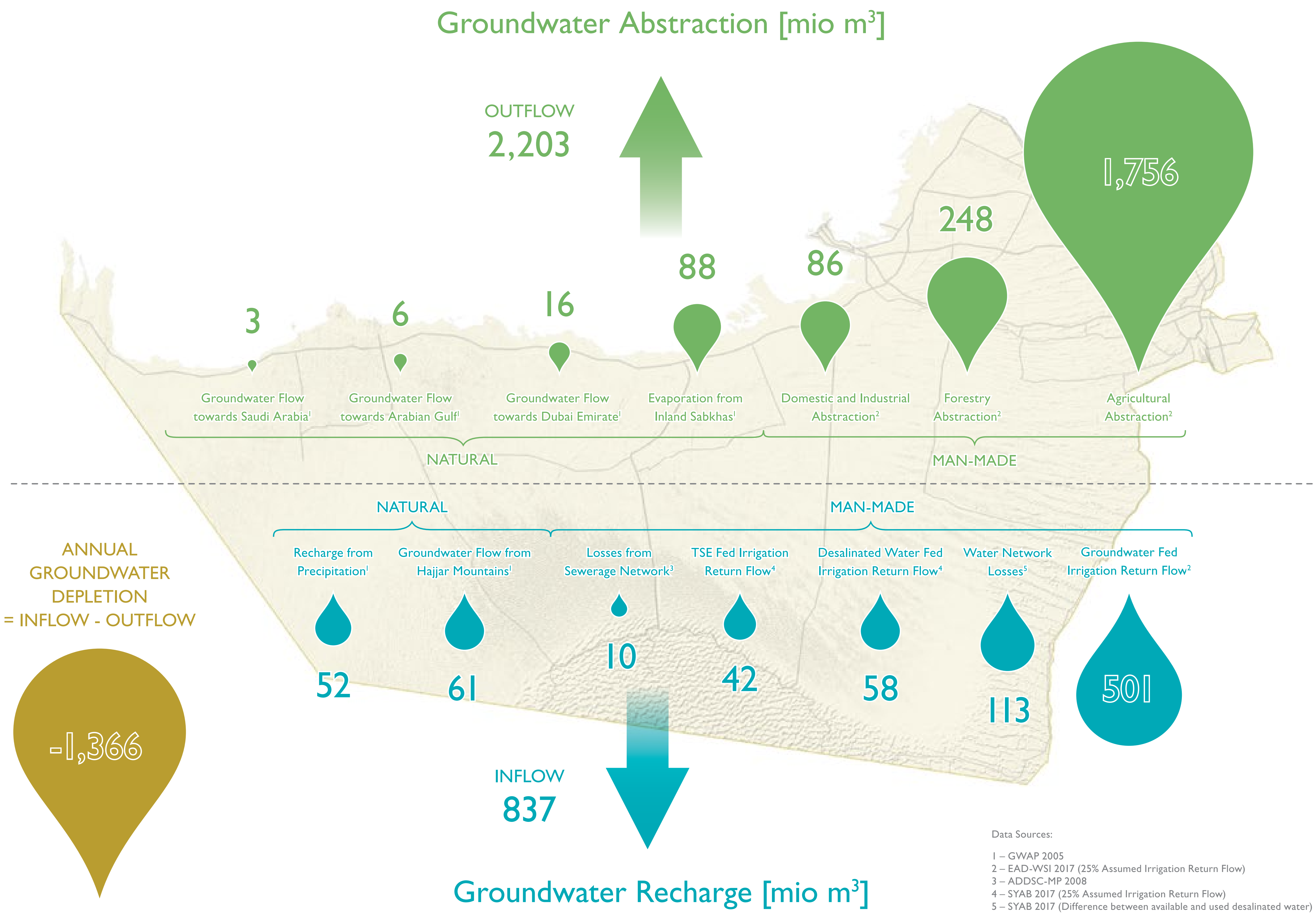
The current state of the groundwater budget of Abu Dhabi Emirate is shown in the map to the right. The vast amount of groundwater abstraction for agricultural and forest irrigation, leads to much higher outflows than inflows. The groundwater resources are depleting every year by more than 1 km^3. Man-made inflows exceed the natural inflows by far, and help reduce the groundwater depletion. However, they pose a real threat to natural groundwater resources. Irrigation return flow carries fertilisers and pesticides from the surface into the aquifer, and losses from Treated Sewage Effluent (TSE) pipelines also cause quality deterioration in the aquifer. In short, the manmade inflows diminish the overall quality of the natural groundwater resources.

It remains EAD's largest challenge in groundwater management, to establish a sustainable practice for the use of the groundwater resources. This challenge requires a serious analysis of the groundwater budget on a local scale in order to implement a customised solution. This includes:

- Monitoring and overall reduction of groundwater abstractions
- Establishing protection zones for good quality groundwater resources
- Enhancing natural recharge

In close cooperation with the agricultural sector, EAD began reducing irrigation water abstraction by shifting crop patterns, updating irrigation technology, and introducing best-practice farm management techniques. The growing habit of re-using TSE for irrigating farms and forests helps reducing groundwater abstractions.

Groundwater Cistern on a Farm



Data Sources:

1 – GWAP 2005
2 – EAD-WSI 2017 (25% Assumed Irrigation Return Flow)
3 – ADDSC-MP 2008
4 – SYAB 2017 (25% Assumed Irrigation Return Flow)
5 – SYAB 2017 (Difference between available and used desalinated water)

Falaj in Liwa Oasis

GROUNDWATER RESOURCES

Groundwater is a rare and precious resource, which needs the most careful vigilance and stewardship.

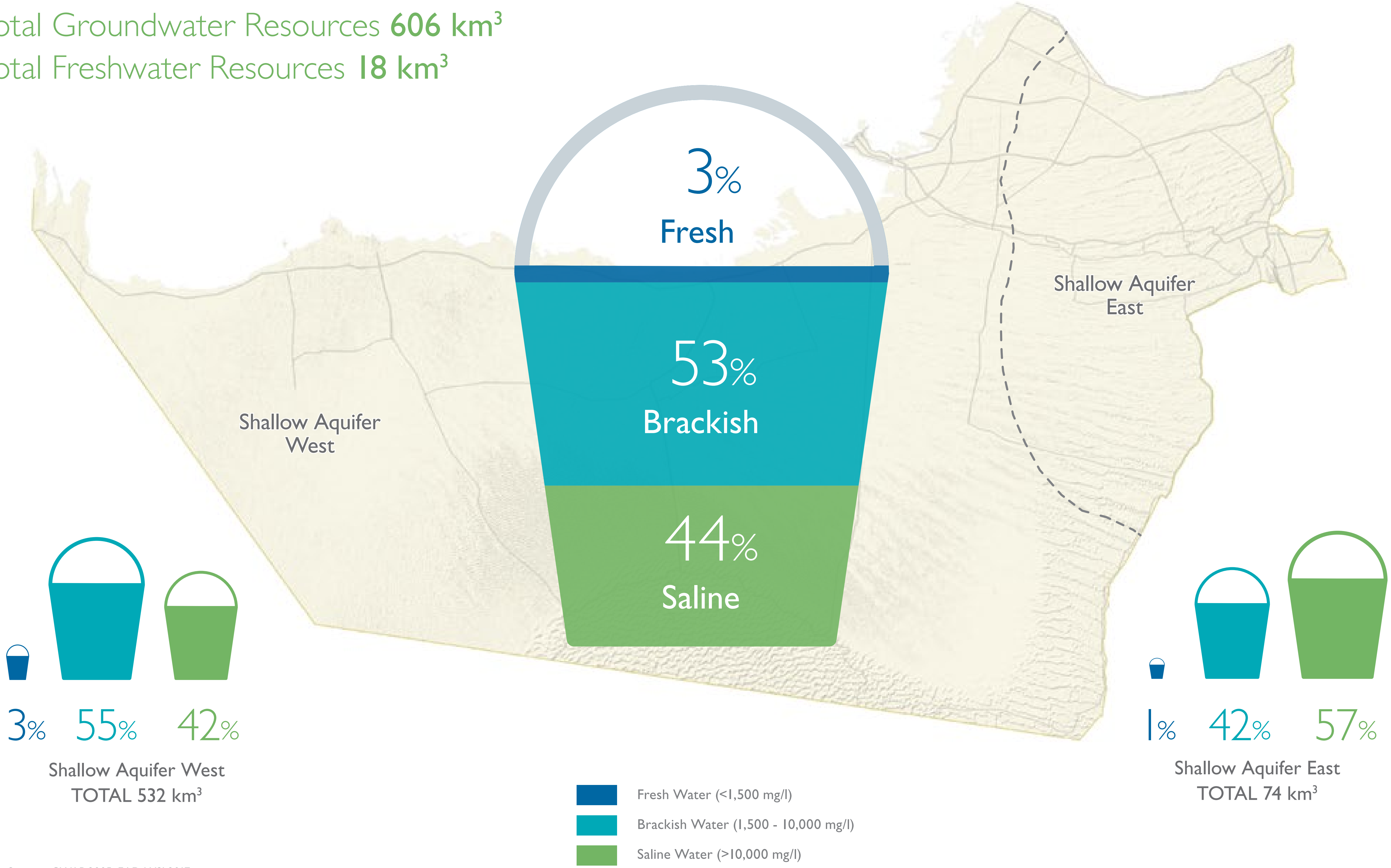
Groundwater is in many areas the only water resource available. It is essential for sustaining wildlife in remote areas and forms the basis of agricultural practices and food production in Abu Dhabi Emirate. The groundwater resources of Abu Dhabi Emirate are under stress: a low natural recharge rate and high groundwater abstractions lead to a decline of groundwater levels in many places and to the depletion of groundwater resources. Groundwater pollution also contributes to the reduction of usable groundwater resources: fertilisers, pesticides, wastewater, and brines from small farm desalination units enter the aquifer and deteriorate the groundwater quality, leaving it unusable in worst cases. In its natural condition, the groundwater stored beneath our feet is of varying quality. In the Shallow Aquifer, almost half of the groundwater (44%) is classified as saline water unsuitable for any use. 53% is brackish water, which can be used to some extend for agriculture. Only 3% of all groundwater stored in the Shallow Aquifer is of freshwater quality (TDS < 1,500 mg/l).

It is these freshwater resources that are most under threat and which need the most protection. EAD responds to this challenge by:

- Building a comprehensive understanding of groundwater resources.
- Achieving reduced groundwater use and improving agricultural sector productivity, together with other sector authorities.
- Identifying groundwater protection zones and 'red zones' of heavy groundwater abstraction, where furtheruse (e.g. drilling or rehabilitation of wells) is restricted.

GROUNDWATER RESOURCES

Total Groundwater Resources **606 km³**
Total Freshwater Resources **18 km³**



Data Sources: GWAP 2005, EAD-WSI 2017

SWSR Well Field

Monitoring and Sampling Well

STRATEGIC WATER STORAGE AND RECOVERY IN LIWA

Desalination plants supply today's drinking water demand in Abu Dhabi Emirate. Groundwater is used for agriculture and other purposes, but generally is not of drinking water quality. The Strategic Water Storage and Recovery project (SWSR) was established to ensure drinking water supply for Abu Dhabi Emirate in cases of emergency, if a shortage in desalinated water production occurs.

In the dune sands north of Liwa, the Shallow Aquifer provides a natural safe place to store drinking water in the subsurface. Surplus water from seawater desalination plants is used to build up the storage. The drinking water infiltrates into the aquifer and there replaces the native groundwater: a 'drinking water bubble' is created, well protected beneath the surface.

At any point in time, over 300 wells are ready to pump drinking water for the population from a depth of up to 80 m. Once the water is pumped from the aquifer, is enters the regular water supply network and is brought to consumers via reservoirs, pipelines, and pump stations across Abu Dhabi Emirate.

The ambitious Strategic Water Storage & Recovery (SWSR) project was realised by Abu Dhabi Water and Electricity Authority, its subsidiary Transco, and EAD. It provides Abu Dhabi Emirate with a safe drinking water supply for up to 90 days if needed. While it is a common practice worldwide to store water in an aquifer (e.g. to enhance water resources or overcome seasonal water shortages), the SWSR Liwa stands out in its size and its vision to ensure a safe water supply for millions of people.


Aerial View of a SWSR Well Field in Liwa


Pumping Station and Storage Tank


Infiltration Basin

FARM SOILS & IRRIGATION

FARM SOILS & IRRIGATION

LAND COVER

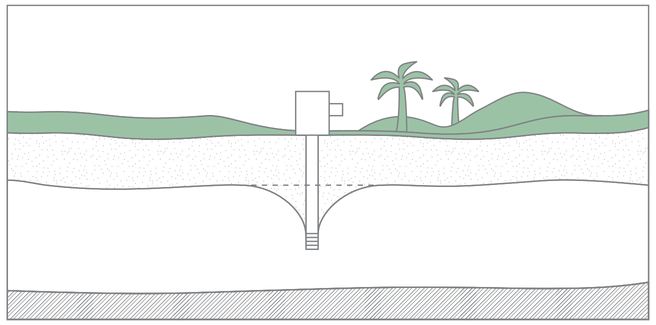
The rapid socio-economic development of the Emirate in the last decades has altered the land surface. Urbanisation, agricultural land cultivation, and forest plantations had a tremendous impact on the landscape.

Despite such rapid development, more than 90% of Abu Dhabi Emirate is still covered by barren land. Dunes, sand sheets, gravel plains, sabkhas and coastal areas are still largely untouched by human activity. Urban, commercial, and industrial areas are mostly contained to the two largest cities, Abu Dhabi and Al Ain. They cover more than 3% of the entire Emirate area, and are continually growing.

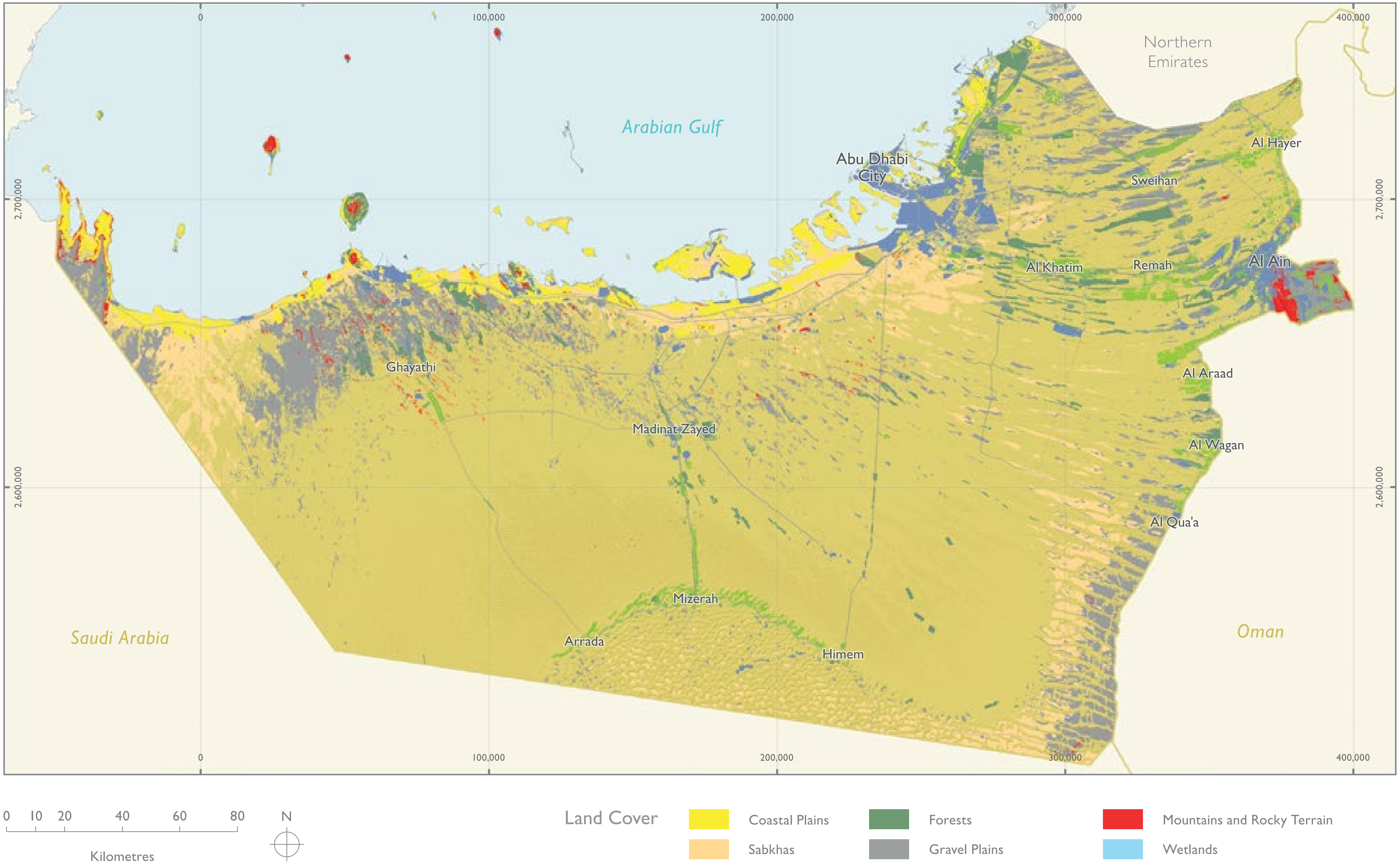
Farmland accounts for about 140,000 ha of the land cover (2%), and forests encompass 145,000 ha (2.4%) of land. These forests were originally planted to curb desertification, protect roads and residential neighbourhoods from dune sands, and improve the micro-climate. Mountainous terrain and wetlands cover a limited amount of the Emirate. However, these terrains are among the most impressive, providing important animal habitats and places for human recreation.

More than 18 million trees were planted
with the ambitious vision to green the desert.

Landcover in
Abu Dhabi Emirate



LAND COVER



Land Cover

Coastal Plains	Forests
Sabkhas	Gravel Plains
Farmland	Sand Sheets and Dunes
Mountains and Rocky Terrain	Wetlands
Urban, Commercial and Industrial Areas	

Data Source: EAD-HM 2016

SOIL CLASSIFICATION

The Soil classification map of Abu Dhabi Emirate is based on the Extensive Soil Survey conducted in 2008, providing a baseline and reference on soil information in Abu Dhabi. Within the current Soil Survey, 4,006 farmland soil profiles are additionally described and classified, and a long-term monitoring of farm soils is being established. The soil profile data from augering, together with the field analysis of EC and pH is used for soil classification according to the United Arab Emirates Keys to Soil Taxonomy 2014. The Soil taxonomy hierarchy comprises Order, Suborder, Great Group, followed by Subgroups and Phases. The map shows the Great Group levels of Abu Dhabi Emirate soils. The farmlands that were mapped during the current survey are highlighted.

Aridisol - Soils of a dry climate

Calcids - Soils with a secondary calcic layer h (Hot)

HC: Haplocalcids - typical soils with a calcic layer

PC: Petrocalcids - soils with a hardened calcic layer within 100 cm of the soil surface

Gypsids - Soils with a secondary gypsic layer

HG: Haplogyopsids - typical soils with a gypsic layer

PG: Petrogypsids - soils with a hardened gypsic layer within 100 cm of the soil surface

CG: Calcigypsids - soils with a calcic layer overlying a gypsic layer

Salids - Highly saline soils (ECe> 30 mS/cm)

AS: Aquisalids - highly saline soils (ECe> 30 mS/cm), where the groundwater level is within 100 cm of the soil surface

HS: Haplosalids - typical highly saline soils (ECe> 30 mS/cm)

Entisol - Soils without distinct profile

Orthents - typical non-sandy soils of recent origin without profile development

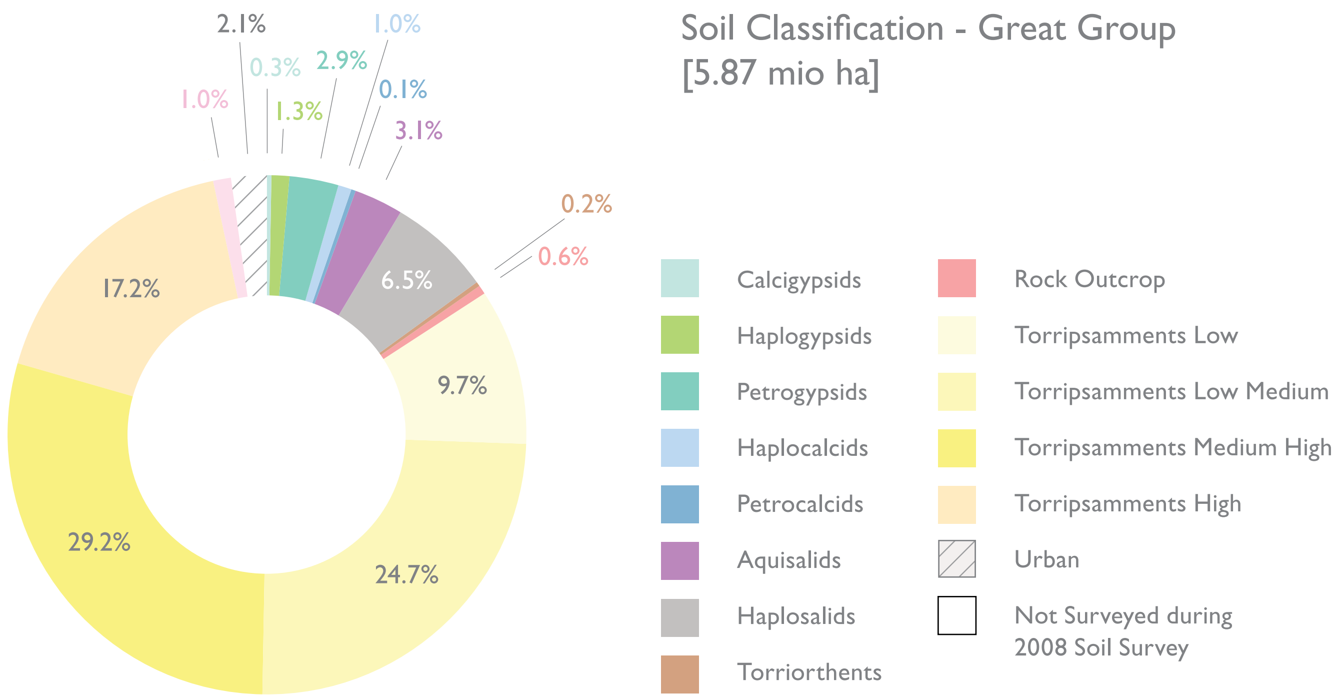
TO: Torriorthents - loamy and gravelly soils on recent hillslope and river deposits

Psamments

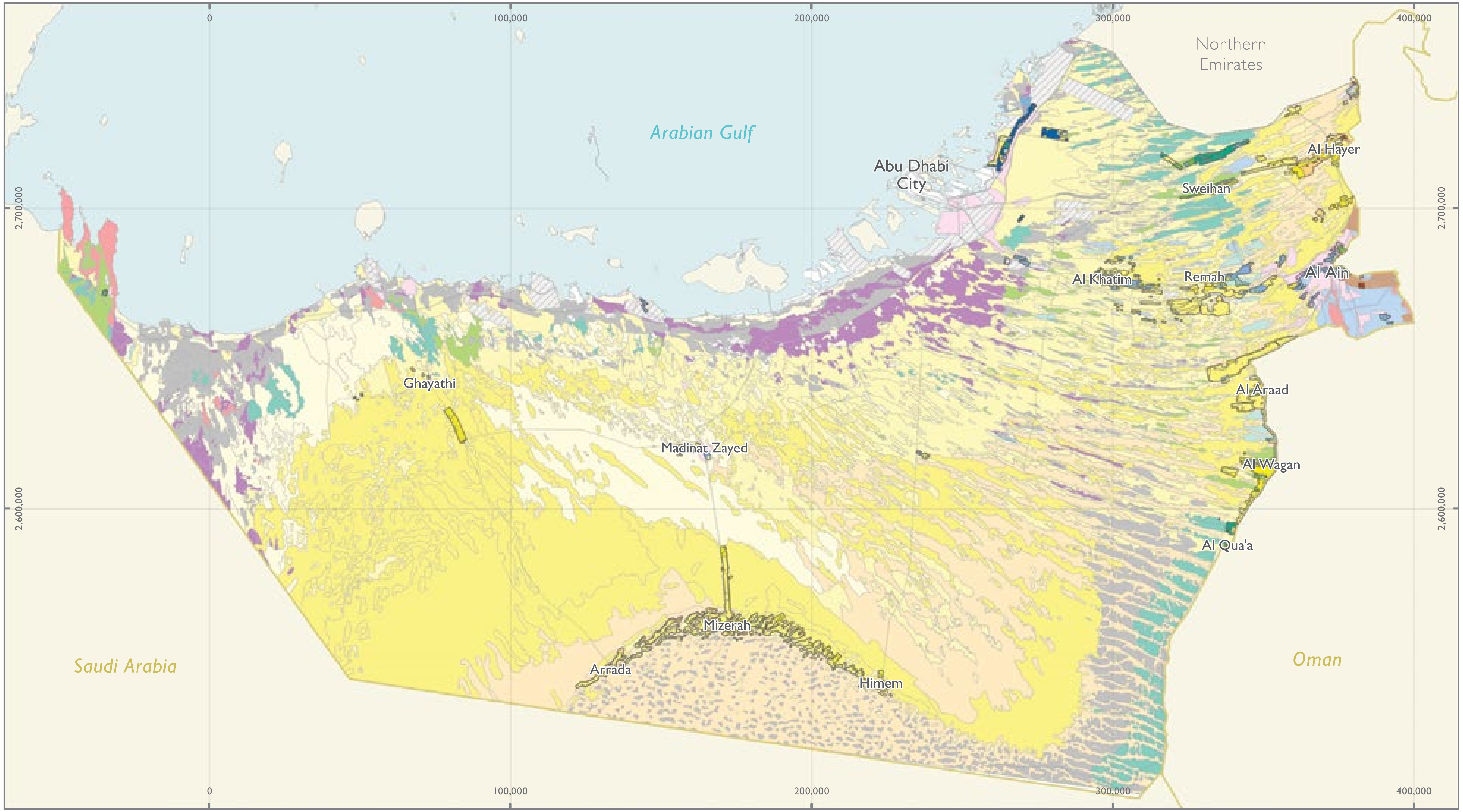
TTP: Torripsamments - sandy soils without differentiation, varying relief from low to high

RO: Rock outcrops - areas without soil cover

Soil Classification on a Farm in Al Khaznah



SOIL CLASSIFICATION - GREAT GROUPS



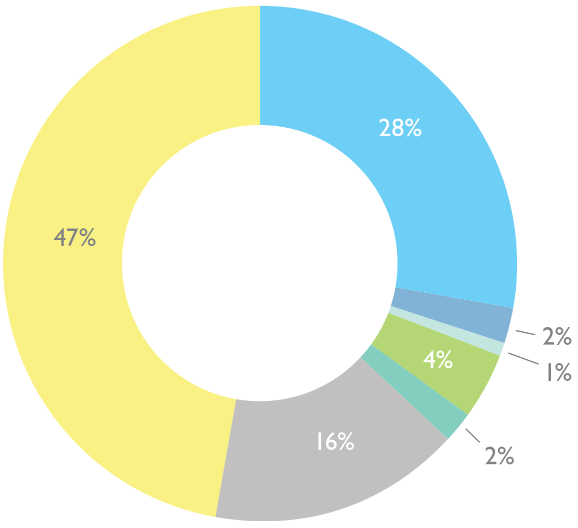
0 10 20 40 60 80 Kilometres

N

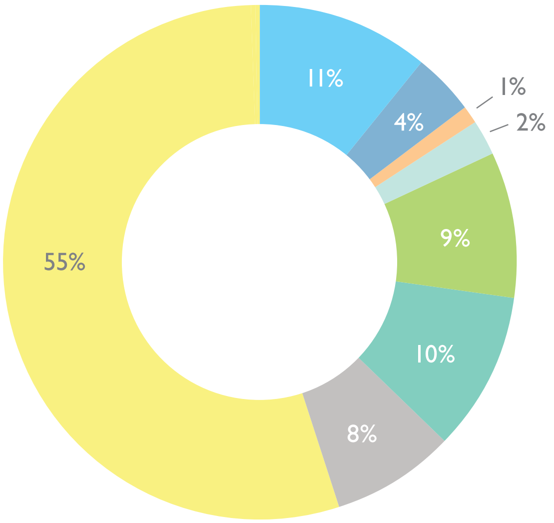
Data Sources: DMA 2015/16, EAD-SS 2008, EAD-WSI 2017

Great Groups

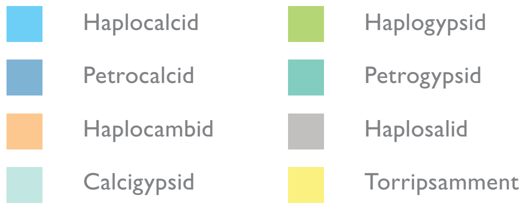
- Calcigypsids
- Haplogypsids
- Petrogypsids
- Haplocalcids
- Petrocalcids
- Aquisalids
- Haplosalids
- Torriorthents
- Rock Outcrop
- Torripsamments Low
- Torripsamments Low Medium
- Torripsamments Medium High
- Torripsamments High
- Urban
- Not Surveyed during 2008 Soil Survey
- Area Surveyed During the EAD Well Inventory Project

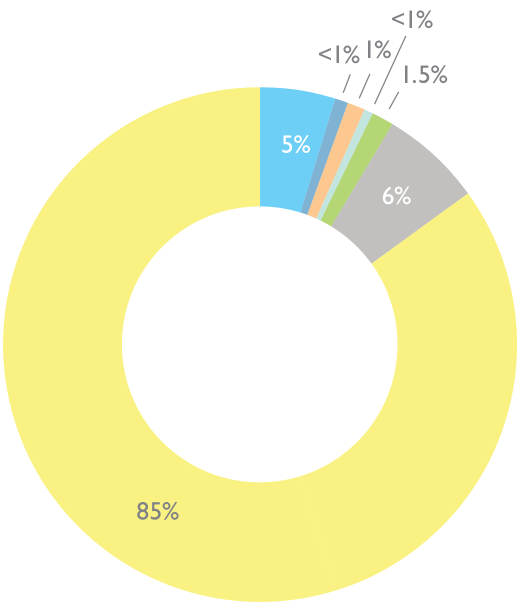


Soil Type Agricultural Areas,
Abu Dhabi Region, 1,254 Profiles



Soil Type Agricultural Areas,
Al Ain Region, 1,994 Profiles





Soil Type Agricultural Areas,
Al Dhafra Region, 759 Profiles

SOIL CLASSIFICATION OF FARM LANDS

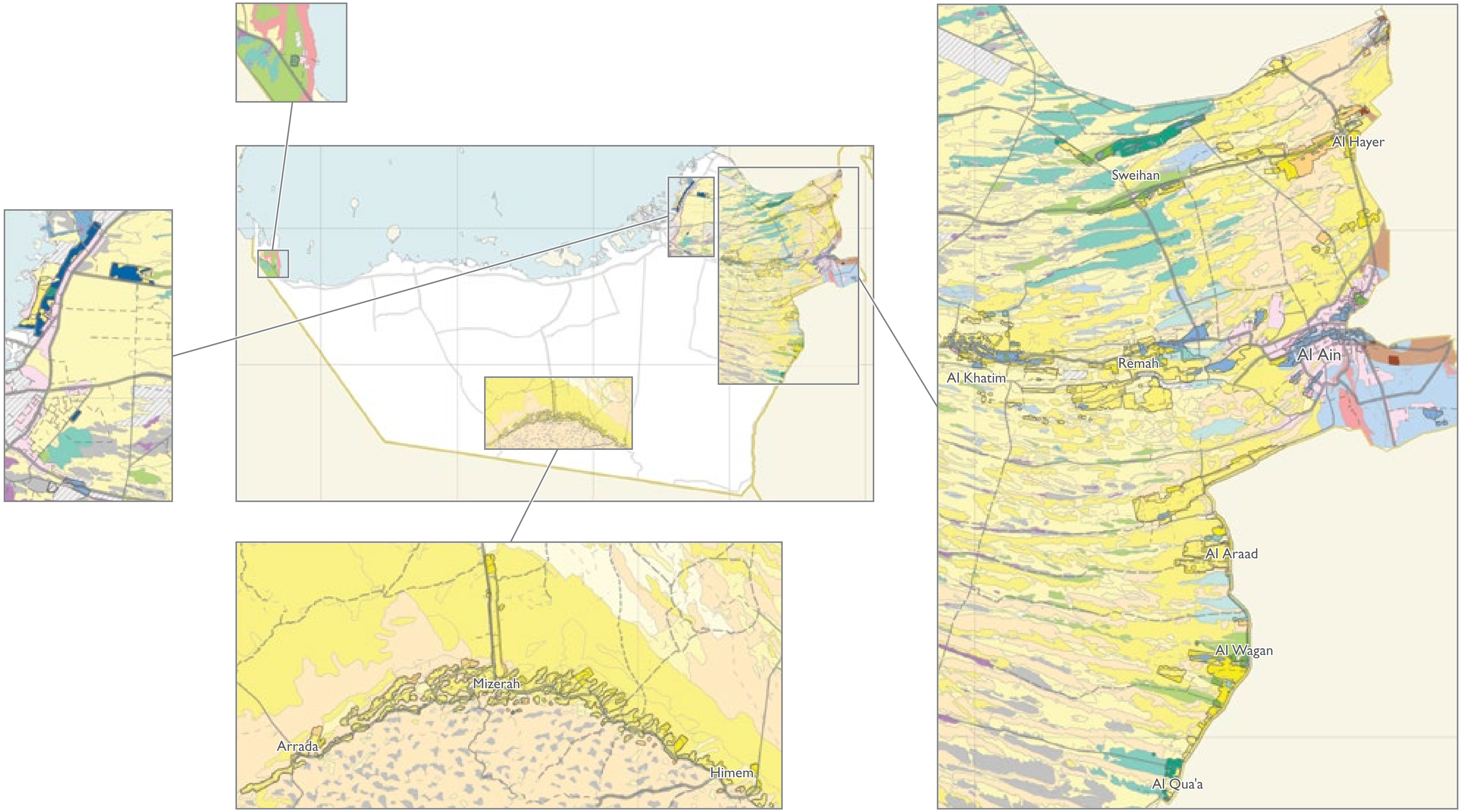
Farm soils have been altered by levelling or terracing, decapitating profiles or depositing material on them. Irrigation may have the largest impact on farm soils, as dissolved salts in the water precipitates and leads to salinization and hardened soil layers.

Abu Dhabi Region - Farm soils in the Al Khatim area are characterised by the widespread occurrence of Haplocalcids and –gypsids (27%). Present irrigation suitability is limited: although nutrient capacity is moderate, the region possesses the highest proportion of culturally induced highly saline soils (Haplosalids 20%) due to poor irrigation water quality. The balance is made up of Torripsamments, mostly of the salidic subgroup.

Al Ain Region - Around the city of Al Ain is the only place that hosts loamy soils with some profile differentiation (Haplocambids). They are formed on the alluvial deposits of the Hajjar mountains, and intermingle with Torriorthents. Together with Calcids and Gypsids they are found in 69% of the farms sampled. These are among the best soils of the Emirate with good nutrient capacity. In the Sweihan area, gypsic and calcic soils dominate (54%). They are characteristic for the former sabkhas in which these evaporites precipitated and have a low to limited irrigation suitability. In Remah and Al Araad, mainly Torripsamments occur.

Al Dhafra Region - The farm soils in Liwa, Madinat Zayed and Ghayati are mainly (90%) classified as Torripsamments. Torripsamments are sandy soils with no profile development. They are typical for the undulating dune landscape. Sandy soils have low nutrient retention capacity and can retain only very little water in the root zone, but due to their high permeability, salt is easily washed out and only a low proportion of the farm soils in these areas are very saline (Haplosalids). Irrigation suitability can still be considered as moderate.

SOIL CLASSIFICATION - FOCUS ON AGRICULTURAL AREAS



0 5 10 20 30 40

Kilometres

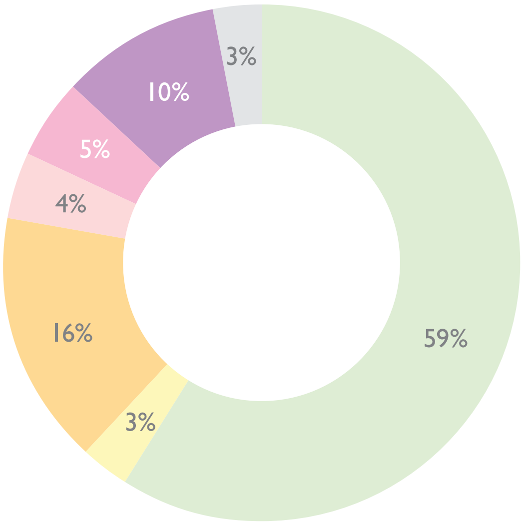
N

Data Sources: DMA 2015/16, EAD-SS 2008, EAD-WSI 2017

Great Groups

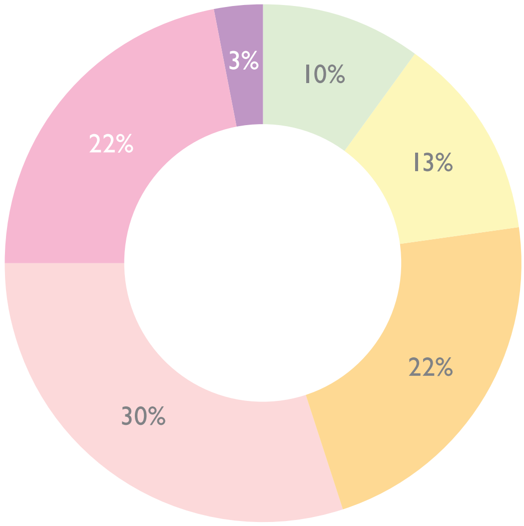
- Calcigypsids
- Haplogypsids
- Petrogypsids
- Haplocalcids
- Petrocalcids
- Aquisalids
- Haplosalids
- Torriorthents
- Rock Outcrop
- Torripsamments Low
- Torripsamments Low Medium
- Torripsamments Medium High
- Torripsamments High
- Urban
- Not Surveyed during 2008 Soil Survey
- Area Surveyed During the EAD Well Inventory Project

FARM SOIL SALINITY



Soil Salinity, Abu Dhabi Emirate, 0-25 cm Depth Layer

- Non Saline
- Very Slightly Saline
- Slightly Saline
- Moderately Saline
- Strongly Saline
- Very Strongly Saline
- Not Mapped



Soil Salinity, Farm Areas in Abu Dhabi Emirate, 0-25 cm Depth Layer

The water resources of Abu Dhabi Emirates face severe depletion and quality deterioration. Similarly, farms find themselves lacking in good irrigation water quality and consequently face salinisation of their soil resources. This has led to widespread temporary fallow (40%) of farmlands.

EAD compiled the *Soil Salinity Map of Abu Dhabi Emirate* in 2008, reflecting the natural soil conditions. During the *Groundwater Well Inventory and Soil Salinity Mapping* project 2015 -2018, additionally 16,000 samples were taken on more than 4,000 different farms. The soil salinity of farm soils is significantly higher than the salinity of neighbouring unaltered soils of same origin. About 80% of the irrigated land is affected by soil salinity to a varying degree.

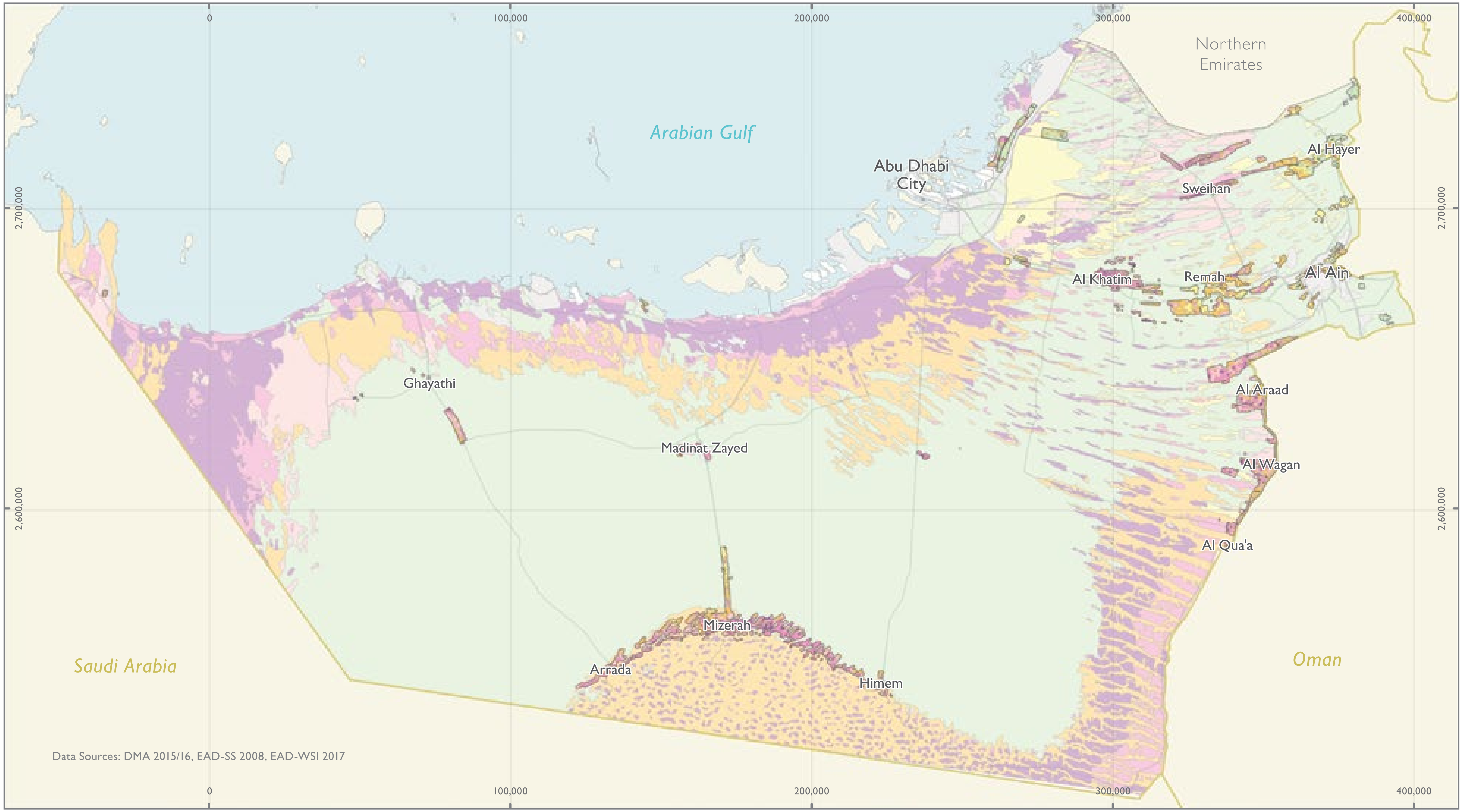
Soil salinisation is the result of:

- Low rainfall to wash out natural salts from the soil (arid climate)
- Use of brackish groundwater for irrigation
- Soils, which prevent free drainage of water and leaching of salts: loamy texture, hardpan layers, man-made soil compaction
- Poor on-farm water management (too low or excess irrigation)

Excess irrigation is applied to control soil salinity (leaching), but using the frequently brackish groundwater, limited effects can only be achieved. The excess irrigation water percolates down and returns to the aquifer (hence termed irrigation return flow). This flow contains saline water, and often fertilisers and pesticides. It leads to the degradation of groundwater quality in the aquifer.

Soil Salinity in the 0 - 25 cm Depth Layer	Non Saline	Very Slightly Saline	Slightly Saline	Moderately Saline	Strongly Saline	Very Strongly Saline	Not Mapped
Farm Areas [ha]	7,510	10,432	17,189	22,740	16,700	2,287	0
Abu Dhabi Emirate [ha]	3,479,297	182,377	952,152	236,983	299,735	586,622	134,232

SOIL SALINITY IN THE 0-25 CM SOIL LAYER



0 10 20 40 60 80 Kilometres

N

SALINITY CATEGORY	CONDUCTIVITY [µS/CM]	CROP RESTRICTIONS
I Non Saline	<2,000	No Restriction
II Very Slightly Saline	>2,000 - 4,000	Limited for Unrestricted Crops
III Slightly Saline	>4,000 - 8,000	Restrictions for Most Crops
IV Moderately Saline	>8,000 - 16,000	Salt Resistant Crops Only
V Strongly Saline	16,000 - 40,000	Only Extremely Salt Resistant Crops
VI Very Strongly Saline	>40,000	Unsuitable For Any Crops

Not Mapped

Agricultural Area

SOIL SALINITY - FOCUS ON AGRICULTURAL AREAS

The farm soil salinity reflects the quality of the groundwater, which is primarily used for irrigation. In the east of Abu Dhabi Emirate, groundwater resources with a low salinity (2,000 - 7,000 µS/cm*) cause only moderate soil salinity (2,000 - 8,000 µS/cm) (e.g. Al Ain, Remah, and Al Hayer).

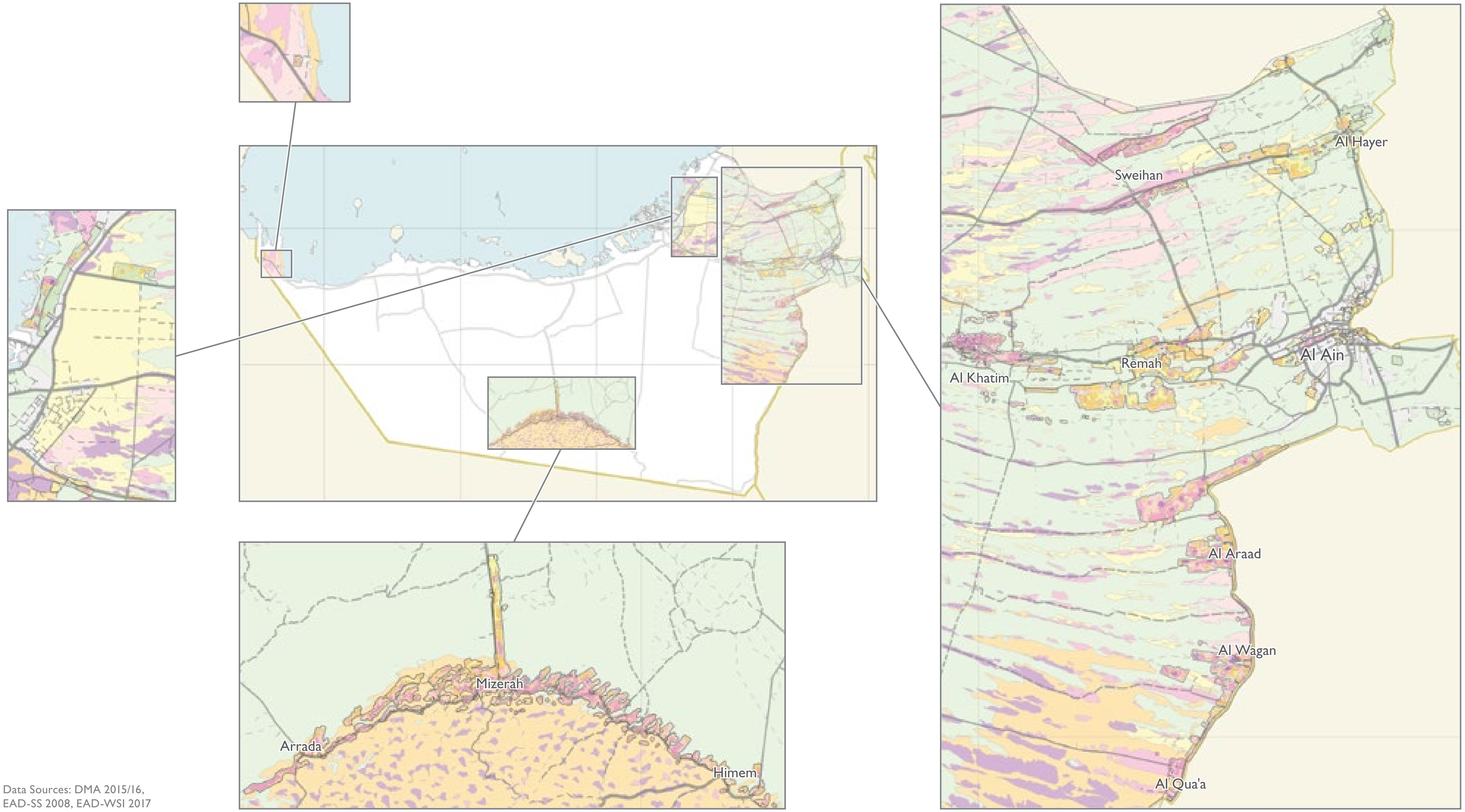
Higher farm soil salinities are measured further west in Al Khatim (16,000 - 40,000 µS/cm) and Sweihan (8,000 - 40,000 µS/cm). Corresponding water qualities reach 18,000 and 11,000 µS/cm, respectively. Groundwater along the Arabian Gulf coastline is too saline for irrigation. Farms in this area rely on desalinated seawater for irrigation, so their soils are less saline. In the Liwa area (Al Dhafra Region), soil salinity is also related to the salinity of the groundwater. On the southern fringe of the Liwa Crescent, soil salinity reaches 8,000 - 40,000 µS/cm, which reflects the average water quality of 22,000 µS/cm. The farms in the northern fringe and along the road to Madinat Zayed (4,000 - 8,000 µS/cm), are profiting from good water quality (average 7,000 µS/cm).

Up to 35 kg of salt are deposited per m^2 soil every year during palm tree irrigation.

*µS/cm: Micro Siemens per centimetre, is a unit for the electric conductivity e.g. of soil water or groundwater. It depends on the amount of dissolved minerals in the water. The more dissolved minerals, the higher the electric conductivity.


Salt Crust on Agricultural Soil

SOIL SALINITY IN THE 0-25 CM SOIL LAYER - FOCUS ON AGRICULTURAL AREAS



Data Sources: DMA 2015/16, EAD-SS 2008, EAD-WSI 2017

0 5 10 20 30 40
Kilometres

N

SALINITY CATEGORY		ECe [µS/cm]	CROP RESTRICTIONS
I	Non Saline	<2,000	No Restriction
II	Very Slightly Saline	>2,000 - 4,000	Limited for Unrestricted Crops
III	Slightly Saline	>4,000 - 8,000	Restrictions for Most Crops

SALINITY CATEGORY		CONDUCTIVITY [µS/cm]	CROP RESTRICTIONS
IV	Moderately Saline	>8,000 - 16,000	Salt Resistant Crops Only
V	Strongly Saline	16,000 - 40,000	Only Extremely Salt Resistant Crops
VI	Very Strongly Saline	>40,000	Unsuitable For Any Crops

Not Mapped

Agricultural Area

FARM SOIL SALINITY - CHANGES IN DEPTH

Soil salinity changes with depth. To understand the dynamics of soil salinity changes in the different soil layers, soil samples and soil salinity measurements were taken at four depth intervals down to 150 cm. Close to 16,000 farm samples and measurements were taken on 4,000 farms.

In spite of observed seasonal variations, soil salinity is always highest at the soil surface, and decreases with depth. Surface water evaporation and capillary rise of water from lower layers lead to the crystallisation and deposition of salt. As the irrigation water evaporates, formerly dissolved salts are retained in the soil matrix and salt crusts form at - or close to - the surface.

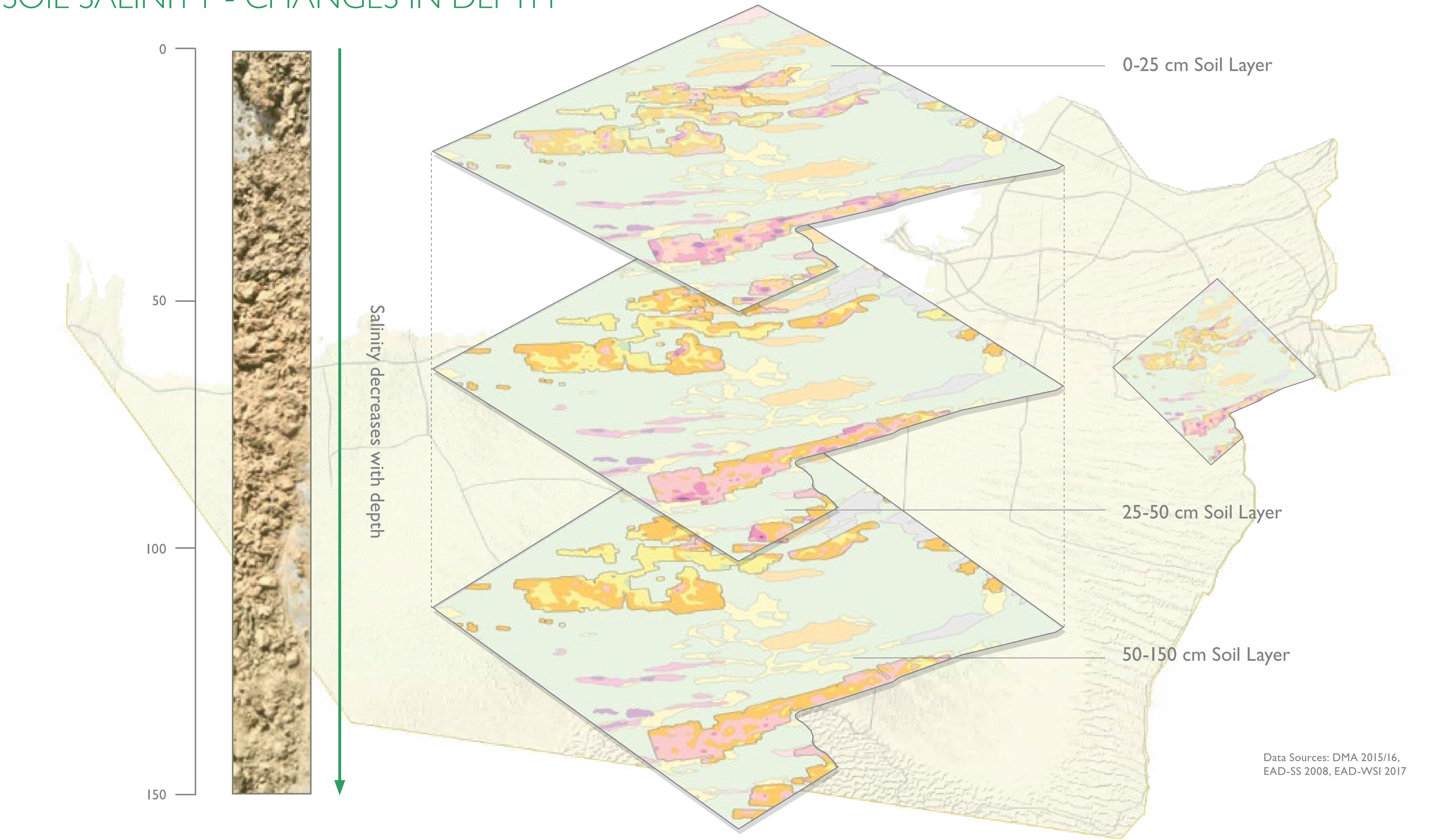
Soils with a saline groundwater table close to the surface may show an inverted salinity trend: Here, soil salinity is higher at depth than at surface. The maps on the right side show the soil salinity for three different investigated depth intervals. The general trend of decreasing soil salinities with depth is observed. But it is noteworthy that farming activities not only lead to salinisation of the uppermost (0 - 25 cm) soil layer: Enhanced soil salinity can be traced until the lowermost investigated soil layer (50 - 150 cm).

80% of agricultural land in Abu Dhabi Emirate are affected by salinisation

Farm Soil Salinities

	Farm Soils [ha]		
Soil Salinity Categories	0-25 cm Depth Layer	25-50 cm Depth Layer	50-150 cm Depth Layer
Non Saline	7,510	5,957	4,995
Very Slightly Saline	10,432	14,933	14,815
Slightly Saline	17,189	25,303	29,847
Moderately Saline	22,740	23,318	22,659
Strongly Saline	16,700	7,175	4,484
Very Strongly Saline	2,287	172	58
TOTAL	76,858		

SOIL SALINITY - CHANGES IN DEPTH



Data Sources: DMA 2015/16, EAD-SS 2008, EAD-WSI 2017

0 10 20 40 60 80
Kilometres

N

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Not Mapped

Agricultural Area

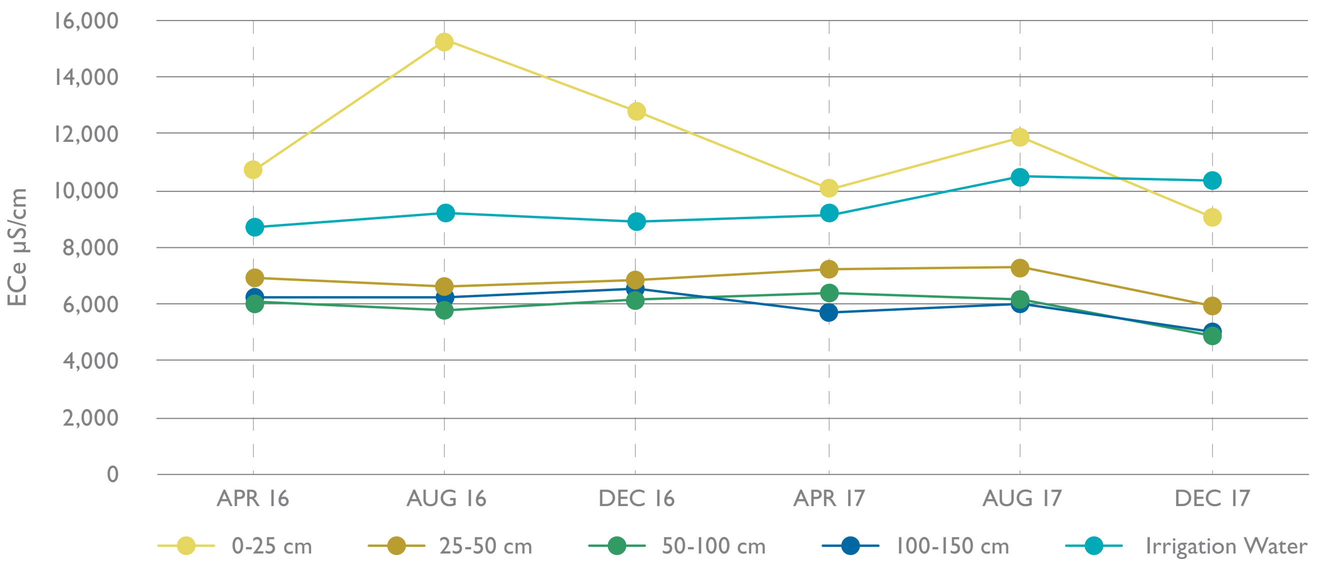
LONG-TERM FARM SOIL SALINITY MONITORING

The Long-Term Monitoring of Farm Soil Salinity programme of the EAD commenced in 2016. One hundred representative farms were chosen to be sampled three times a year. The monitoring programme is still ongoing and set to continue for the coming years. The aim is to investigate the impact of irrigation water quality on farm soil salinity, and to establish a reference for the seasonal changes of farm soil salinity. The monitoring programme will further assess the long-term changes and trends in soil salinity of agricultural land. These key performance indicators are necessary for the development of a nationwide concept for the optimal use of available water and soil resources. Decision makers will be able to build policies and regulations based on a scientific basis.

Seasonal changes of soil salinity are most pronounced in the upper 25 cm depth layer, where the salinity follows a seasonal pattern. It shows an increase in salinity in summer and a corresponding decrease during the winter. Seasonal changes have various causes:

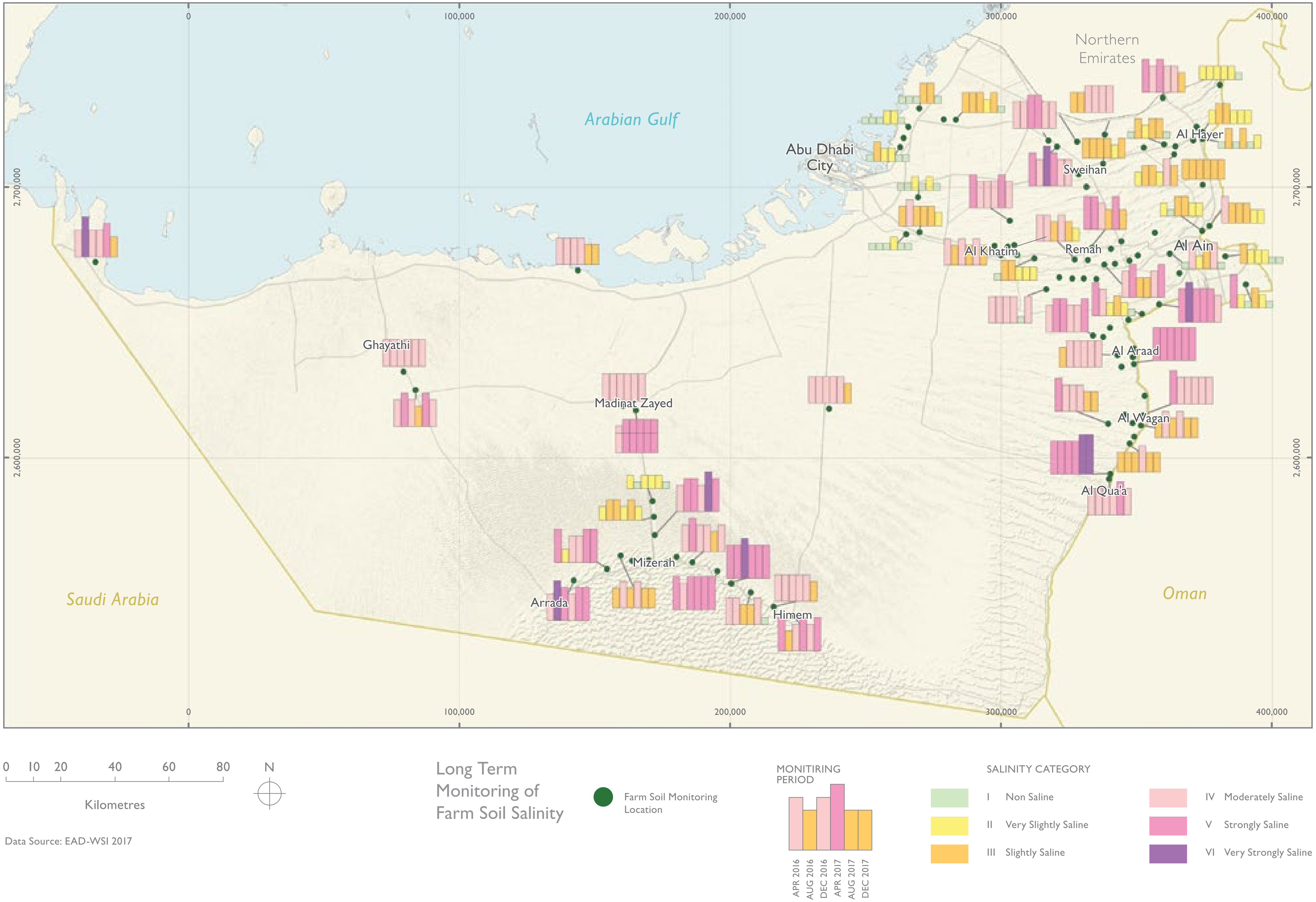
- **Precipitation:** In April, rainwater leaches salt down, reducing soil surface salinity.
- **Leaching fraction:** The proportion of irrigation water, which is able to infiltrate into the soil and to wash out salts depends on the season: In December and April, more irrigation water is able to infiltrate into the soil and to contribute to leaching, because of less evaporation and plant use.
- **Ascending capillary action of dissolved salts:** Higher evaporation in hot summer leads to rising capillary transports of dissolved salts from depth to surface.
- **Irrigation management:** High irrigation and evaporation rates in August bring in more salt to the soil. Salt accumulation occurs at the surface. Conversely in December and April irrigation required is less (depositing less salt), and lower evaporation allows better leaching.
- **Over-irrigation and impermeable layers:** A perched groundwater table can form either through an impermeable subsoil layer. Salinisation is induced by capillary rise and the lack of leaching possibility.

The impact of the rare rainfalls is significant: On abandoned farms, the soil salinity reverts to originally low levels after some years. This is caused by the natural 'soil washing' through rainfall.



Number of Samples					
APR - AUG 2016	AUG - DEC 2016	DEC - APR 2017	APR - AUG 2017	AUG - DEC 2017	Change in Salinity Class 0-25 cm
45	23	24	26	12	Increase by one class or more
34	38	50	47	46	No change
21	39	50	47	46	Decrease by one class or more

LONG TERM MONITORING OF FARM SOIL SALINITY



Data Source: EAD-WSI 2017

FARM SOIL MANAGEMENT

Farm soil salinity is largely determined by the quality and quantity of irrigation water and the permeability of the soil. Quality of the irrigation water and permeability of the soil are usually specific to the farm location, and cannot be altered. However, the quantity and timing of irrigation water application is under control of the farm manager.

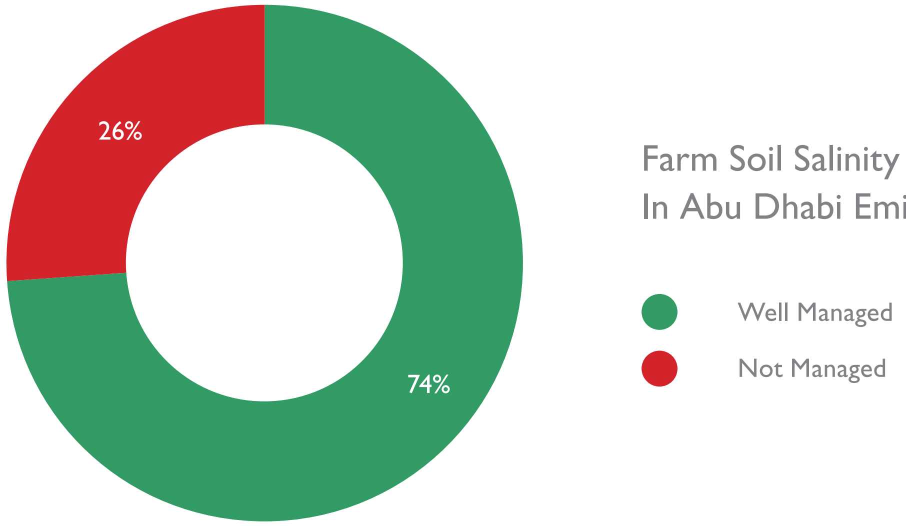
To determine whether a farm is "well managed" or "not managed", the International Center for Biosaline Agriculture (ICBA) established a simple factor that compares the farm soil salinity (ECe) with the salinity of the applied irrigation water (ECw). If the farm soil salinity is less than 1.5 times as high as the salinity of the irrigation water, the farm can be considered well managed. If the farm soil salinity is relatively higher, it is considered to be not managed.

In Abu Dhabi Region, only 66% of farms are well managed. With desalinated water (ECw 200 µS/cm) applied, soil salinity frequently exceeds an ECe 2,000 µS/cm. The absolute level of salinity remains low, which is good. In the Al Ain Region, 74% of all farms are "well managed". This is because of often good quality water resources, but also because of well drained soils. The Al Dhafra Region has moderately high saline soils (class IV), but irrigation management can be considered satisfactory: 85% of all farms are "well managed", indicating good farm management of the saline water (ECw 15,000 µS/cm).

'Soil washing' can reduce soil salinity. However, it washes the salt into the aquifer and leads to deterioration of groundwater quality! First and foremost, the deposition of salt should be reduced by limiting the amount of applied irrigation water.

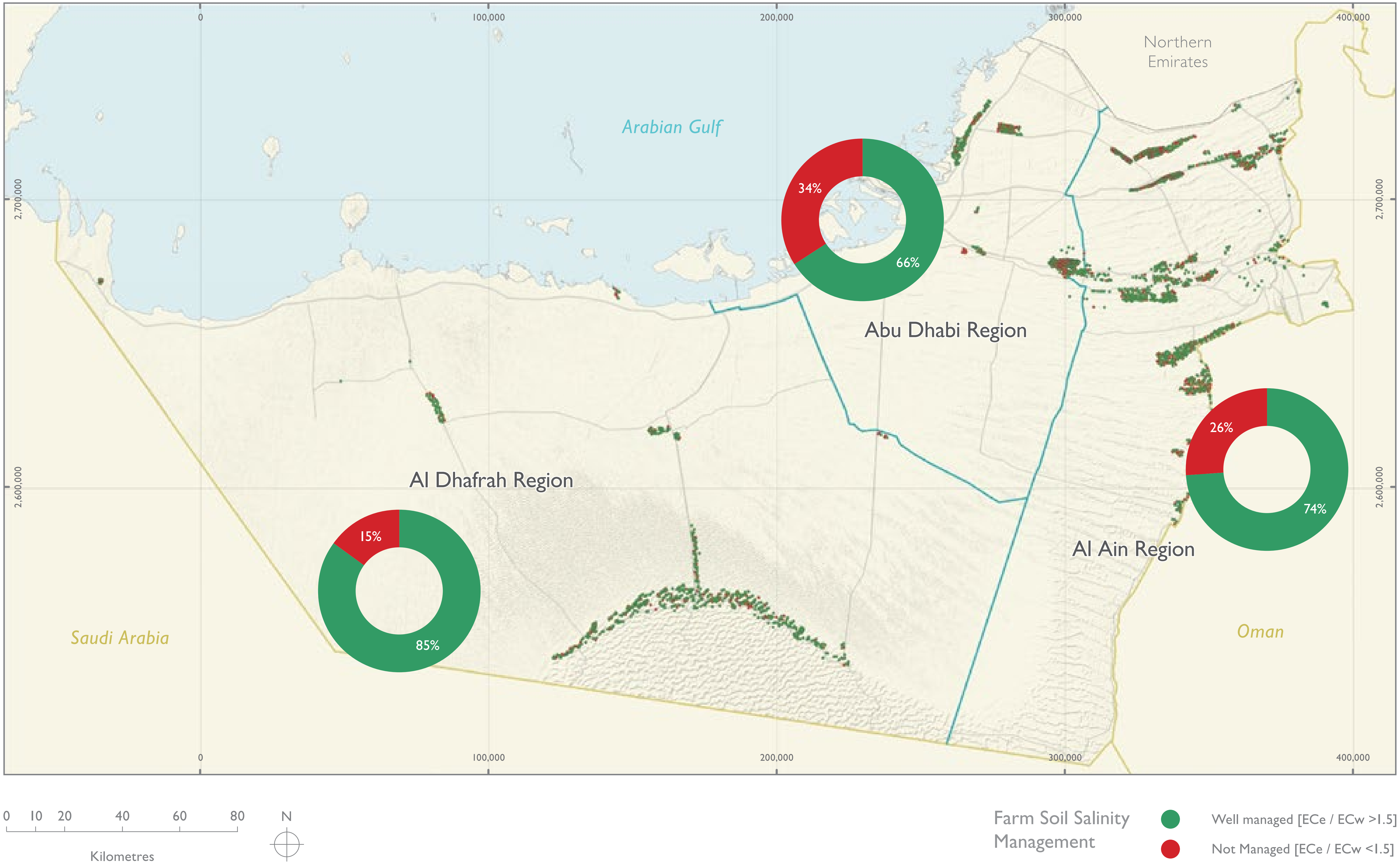
Rules for good farm management:

- Leach out accumulated salts, during the cooler and wetter season of the year when evaporation is low.
- Break crusts on the soil surface and cover the surface with mulch to prevent capillary action that leads to evaporation and salt deposition at the surface.
- Avoid over irrigation in summer to avoid salt deposition.
- Select crops according to available quality of irrigation water and soil.
- Use available good groundwater resources and desalinated seawater for high-value crops. Saline groundwater should be used for more salt tolerant crops. TSE use should be used whenever possible. However, it should not come in contact with products designated for direct human consumption, but can be used for landscapes and fruit tree irrigation without concern.



Farm Soil Salinity Management In Abu Dhabi Emirate

FARM SOIL SALINITY MANAGEMENT



Data Sources: EAD-WSI 2017, EAD 2017

Abbreviations:

ADNOC	Abu Dhabi National Oil Company
ADSSC	Abu Dhabi Sewerage Services Company
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
DEM	Digital Elevation Model
EAD	Environment Agency - Abu Dhabi
EC	Electrical Conductivity
ECe	Electrical Conductivity of a Saturated Soil Extract
ECw	Electrical Conductivity of the Applied Irrigation Water
GIS	Geographic Information System
GPS	Global Positioning System
ICBA	International Center of Biosaline Agriculture
LRM	Limestone Ridges and Mountains
m AMSL	metre above mean sea level
mio	million
MOE	Ministry of Energy
MOPA	Ministry of Presidential Affairs
µS	micro siemens
NGOs	Non-Governmental Organisations
Q	well discharge
SAR	Sodium Adsorption Ratio
SC	specific capacity
V-SMOW	Vienna Standard Mean Ocean Water
SOP	Standard Operation Procedure
SWSR	Strategic Water Storage and Recovery project
TDS	Total Dissolved Solids
TSE	Treated Sewage Effluent
UNESCO	United Nations Educational, Scientific, and Cultural Organization
UTM	Universal Transverse Mercator
WGS	World Geodetic System
yr	year
2H	Deuterium
18O	Oxygen-18

References & Sources:

ADSSC-MP 2008: ADSSC Masterplan

ASTER 2011: Global DEM - Digital Elevation Model v2 - ASTER GDEM is a product of NASA and METI.

ADM/ADNOC/AACM/DRM 2015/16/17: Stakeholder data from Abu Dhabi Municipality, ADNOC, Al Ain City Municipality, Al Dhafrah Region Municipality

DGMR 2012: MOE Department of Geology and Mineral Resources - Geological Map

DMA 2015/16: Cadastre data from Department of Municipal Affairs

EAD-SS 2008: EAD Soil Survey

EAD-MN 2015/18: EAD Groundwater Monitoring Network

EAD-HM 2016: EAD Habitat Mapping Project

EAD-WSI 2017: EAD Groundwater Wells Inventory and Soil Salinity Mapping Project

GWAP 2005: ADNOC Groundwater Assessment Project

MOE-HA 2014: MOE Hydroatlas United Arab Emirates 2014

NCMS 2003-2016: Climate data from National Center of Meteorology & Seismology

NDC 2007: National Distribution Company

OSM 2015: OpenStreetMap contributors

SYAB 2017: Statistical Yearbook of Abu Dhabi

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