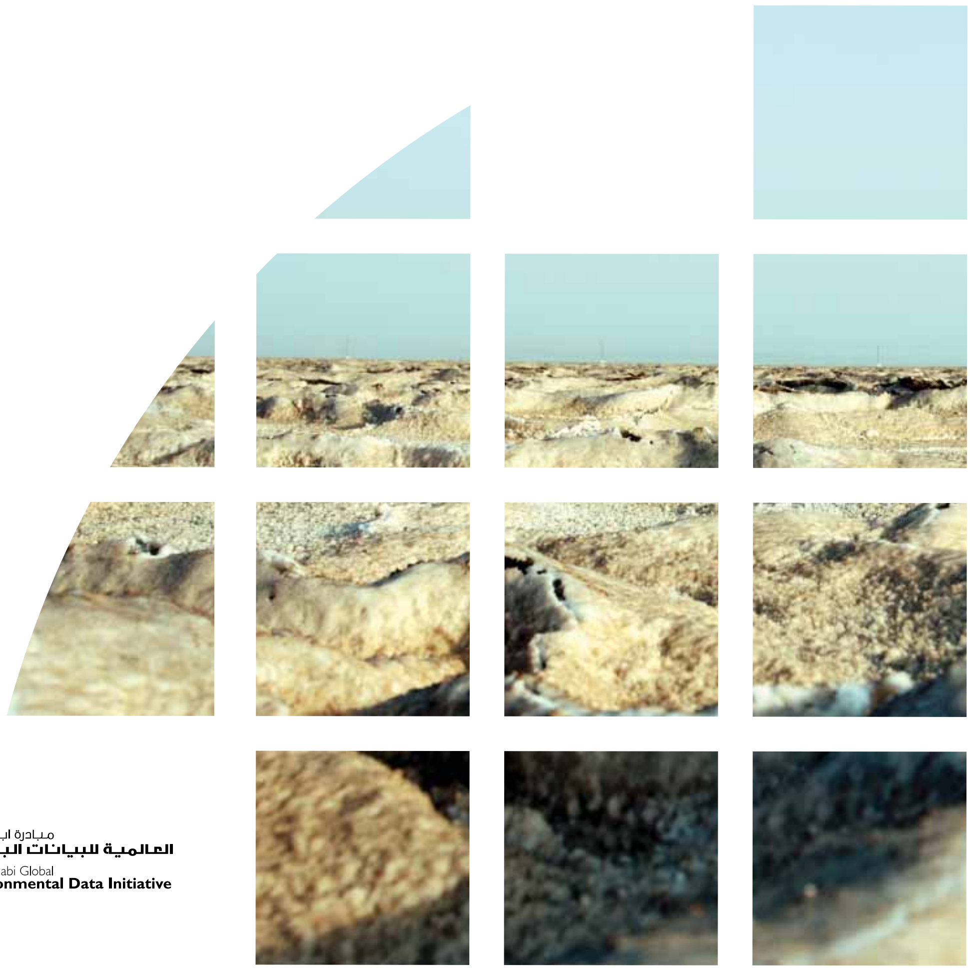
physical geography

of Abu Dhabi Emirate, United Arab Emirates



هيئة البيئة - أبوظبي
Environment Agency-ABU DHABI

مبادرة أبوظبي
العالمية للبيانات البيئية
Abu Dhabi Global
Environmental Data Initiative

physical geography

of Abu Dhabi Emirate, United Arab Emirates

H. H. Sheikh
Khalifa bin Zayed Al Nahyan
President of the United Arab Emirates

H. H. Sheikh

Mohammed bin Zayed Al Nahyan

Crown Prince of Abu Dhabi,
Deputy Supreme Commander
of the UAE Armed Forces

H. H. Sheikh
Hamdan bin Zayed Al Nahyan
Deputy Prime Minister

- البيانات
- الأدوات والأساليب
- التوعية
- بناء القدرات
- السياسة

الأوراق القطاعية

خلال السنوات الماضية قامت مختلف القطاعات المعنية بشؤون البيئة بتجميع كم من المعلومات المتنوعة بعدة صور تصف ما هو معروف عن البيئة في إمارة أبوظبي ودولة الإمارات العربية المتحدة والخليج العربي. خلال المرحلة الأولى لمبادرة أبوظبي العالمية للبيانات البيئية، تم تنظيم سلسلة من ورش العمل في عام ٢٠٠٥ لجمع المعنيين من هذه المنظمات ، لتحديد القطاعات ذات الصلة، ووضع إطار العمل لكل ورقة قطاعية، ومعالجة الاحتياجات الاجتماعية والاقتصادية والبيئية الرئيسية في إطار كل القضايا المتعلقة في القطاع . من خلال هذا الورش، تم إعداد ثماني ورقات لقطاعية ونشرها:

- التلوث وإدارة النفايات
- القوانين والسياسات البيئية
- الموارد المائية
- الجغرافيا الطبيعية لإمارة أبوظبي
- البيئة البحرية والساحلية
- التراث التاريخي والأثري والثقافي
- التطور الاقتصادي والسكاني
- التعليم والتوعية البيئية

وتم إعداد قطاع إضافي كجزء من البرنامج الأصلي، ومع ذلك، وسيتم نشرها للمرة الأولى كجزء من المرحلة الثانية:

- البيئات البرية وموارد الأرض

و لأن الأوراق القطاعية هي مجموعة من أفضل المعارف المتاحة المتعلقة بالقطاعات البيئية والاجتماعية-الاقتصادية الرئيسية وتمثل أساس كافة المخرجات التي سيتم إصدارها لاحقا كجزء من المرحلة الثانية للمبادرة، تم مراجعة الأوراق القطاعية الأصلية. وتم خلال ورشة العمل الدولية التي عقدت في عام ٢٠٠٧ تحديد ما يلي:

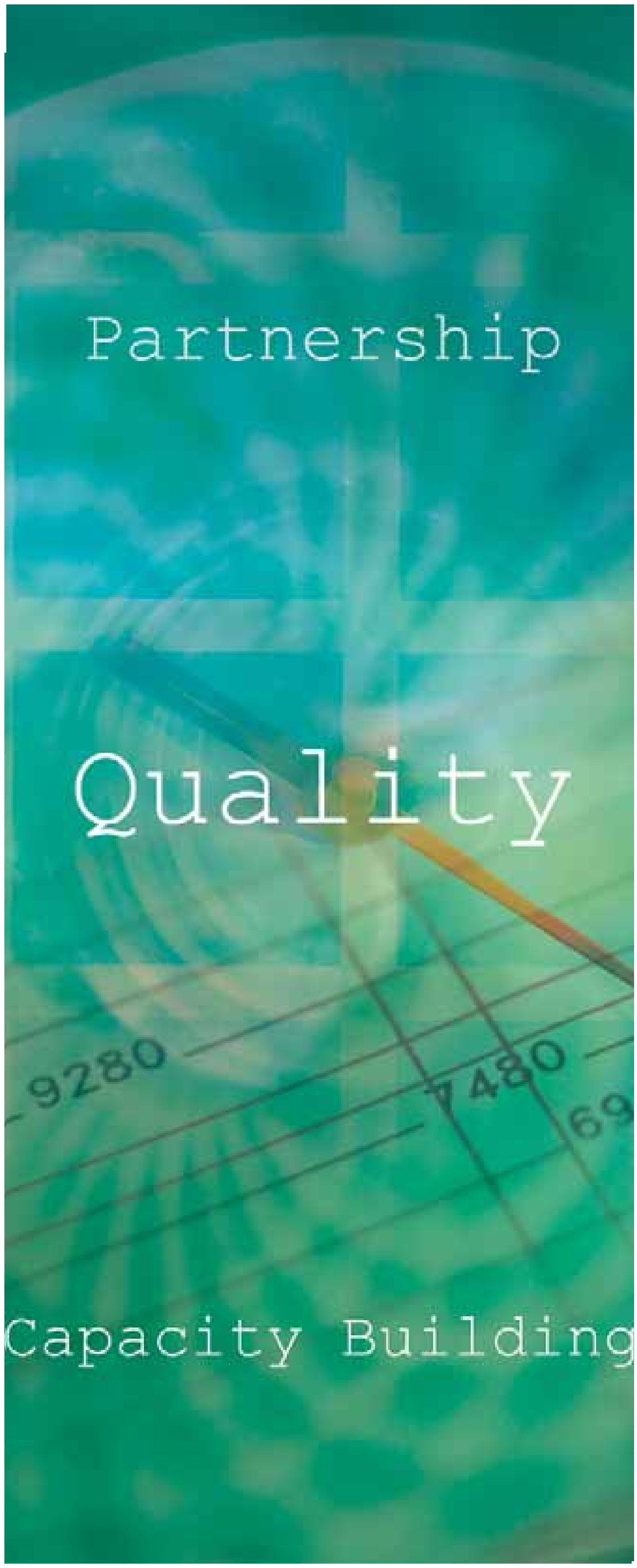
- بشكل عام، تم إعداد الأوراق القطاعية الأصلية بشكل جديد قدم فيها مجموعة قيمة من المعلومات
- لم تصل مشاركة الشركاء والجهات المعنيين إلى الحد المخطط له
- تم أعداد الأوراق القطاعية بدون دعم كافي من الهيئة أو الشركاء والجهات المعنيين، وبالتالي، كان على مؤلف الورقة القطاعية تحمل عبء إعداد ورقة هذا القطاع في وقت زمني محدود نوعا ما
- في بعض الحالات كانت البيانات المستخدمة قديمة نسبيا
- لم يتم إضفاء الطابع المؤسسي على عملية جمع البيانات وتبادلها

تهدف مراجعة المبادرة في إطار المرحلة الثانية إلى معالجة هذه الثغرات، فضلا عن غيرها من الثغرات التي تم تحديدها كجزء من الأوراق الأصلية. ولأن تنفيذ مهمة فرق العمل تم كجزء من المرحلة الثانية من البرنامج، فقد تم تقديم الدعم على جميع المستويات لمساعدة موظفي هيئة البيئة – أبوظبي والشركاء والجهات المعنية على معالجة وتحديد الثغرات، وجمع البيانات وإجراء التحليلات وتطوير مخرجات البيانات المكانية، وبناء العلاقات مع الشركاء والجهات المعنيين، وفي نهاية المطاف ، إعداد الورقة القطاعية وتنقيحها.

وتشكل الأوراق القطاعية مصدرا قيما للمعلومات البيئية والاجتماعية والاقتصادية لأبوظبي وتم استخدمها لمراجعة وتنقيح تقرير حالة البيئة لإمارة أبوظبي فضلا عن إعداد الأطلس البيئي لأبوظبي (النسختين المطبوعة والتفاعلية).

ولمزيد من المعلومات حول المبادرة أو للوصول لنسخة الكترونية من الأوراق القطاعية، يرجى زيارة الموقع الإلكتروني في www.agedi.ae.

ما هي مبادرة أبوظبي العالمية للبيانات البيئية ؟



تم إطلاق مبادرة أبوظبي العالمية للبيانات البيئية في الثاني من سبتمبر ٢٠٠٢ خلال مؤتمر القمة العالمي للتنمية المستدامة الذي عقد في مدينة جوهانسبرغ بجنوب إفريقيا من قِبل دولة الإمارات العربية المتحدة، كمبادرة شراكة من الصنف الثاني، لتكون أداة مبتكرة لِتنفيذ الأحكام المتعلقة بالبيئة والواردة في الفصل ٤٠ من جدول أعمال القرن ٢١ وفي الأهداف الإنمائية للألفية.

وفي أوائل عام ٢٠٠٧ ، نظمت بأبوظبي ورشة عمل دولية لاستعراض الانجازات التي حققها برنامج المبادرة ووضع خطة إستراتيجية لمدة خمس سنوات. وعلى هذا النحو، بدأت المرحلة الثانية من المبادرة في عام ٢٠٠٨ بناءا على ما تم انجازه في المرحلة الأولى، في حين تم معالجة الفجوات التي تم تحديها من خلال المعلومات التي وفرتها الجهات المعنية خلال ورشة العمل.

ولا تزال الرؤيا التي تعمل وفقها المبادرة في المرحلة الثانية هي "وضع وتنفيذ نماذج عملية يمكن تكرارها وتكييفها من أجل إنشاء هيكل أساسي للبيانات البيئية المكانية عالية الجودة، للمساهمة في توفير القاعدة العلمية لاتخاذ القرارات". وسيتم في المرحلة الثانية استخدم الدروس المستفادة لتحقيق نجاح أفضل في تنفيذ المبادرة في مرحلته الثانية.

وسيركز البرنامج الحالي على وضع سلسلة من المخرجات التي تتناول قضايا محددة في حين يتم تحقيق نتائج مؤسسية معينة، بما في ذلك:

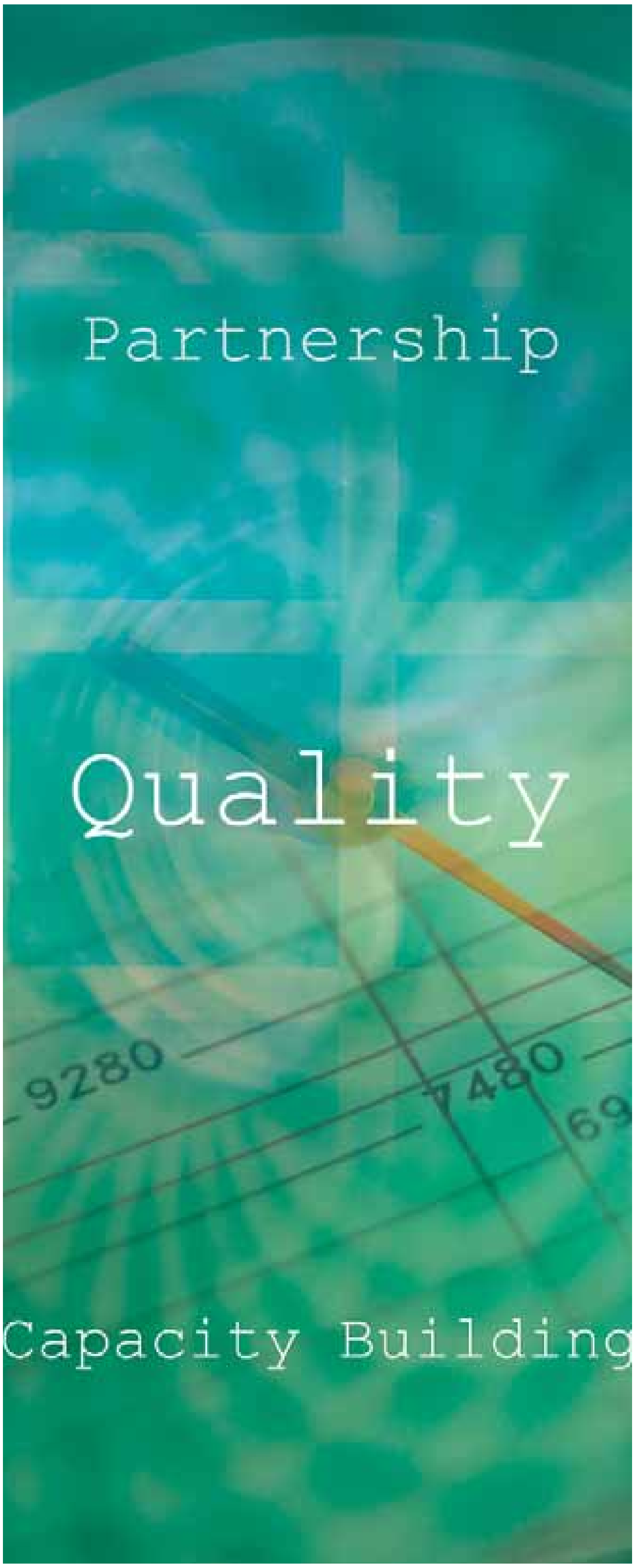
١. توفير بيانات بيئية أكثر جودة
٢. تحديد الثغرات في البيانات والأولويات
٣. تنسيق أقوي وشراكات لتبادل البيانات
٤. أساليب وأدوات أفضل للمعلومات
٥. ربط الإستراتيجية والتشغيل بشكل أفضل
٦. تحسين البنية التحتية البشرية والتقنية
٧. مؤسسة أقوي بشكل عام

والمخرجات التي تم تحديدها في إطار عملية التنمية هي أمور مترابطة ومتعاقبة مع المخرجات الأولية لدعم المعلومات والتفاهمات التي تصب في الأنشطة اللاحقة. وهي تشمل ما يلي :

- مراجعة الأوراق القطاعية وقاعدة المعرفة
- مراجعة وتنقيح تقرير حالة البيئة
- الأطلس البيئي التفاعلي
- تعزيز بوابة البيانات المكانية
- تحسين الموقع الالكتروني
- مؤشر الأداء الحكومي لابوظبي
- برامج وضع الإستراتيجية

ولضمان تحقيق نتائج ايجابية وتوفير الموارد التقنية الكافية للقيام بتطوير المخرجات، تم إنشاء مجموعة من فرق العمل بهدف تجميع الموارد لدعم فرق كل مخرج من المخرجات المبادرة. وتشمل هذه ما يلي :

What is AGEDI ?



The Abu Dhabi Global Environmental Data Initiative (AGEDI) program was fashioned around the United Nations World Summit for Sustainable Development (WSSD) Type II Partnership in 2002 as a tool to support the environmental provisions of Chapter 40 of Agenda 21 and the Millennium Development Goals.

In early 2007, an international workshop was conducted in Abu Dhabi to review the accomplishments of the AGEDI program and develop the next five year strategic plan. As such, AGEDI Phase II began in 2008 building off the accomplishments of the initial phase, while addressing gaps identified through stakeholder input during the workshop.

The vision of AGEDI Phase II remains to be a "replaceable, networked, adaptive and working model for the development and use of high quality spatial environmental data by all users within the Emirate of Abu Dhabi that will support sustainable decision and policy making." Phase II will use lessons learned to better guide the successful implementation of AGEDI in its second phase.

The focus of the current program is to develop a series of interrelated products that address specific issues while achieving certain institutional outcomes, including:

1. Better current and quality environmental data
2. Identification of data gaps and priorities
3. Stronger coordination and data sharing partnerships
4. Better information methods and tools
5. Better links between strategy and operation
6. Improved human and technical infrastructure
7. Stronger organization overall

The specific products under development are interdependent and sequential, with early products yielding information and understandings that feed into subsequent activities. These include the following:

- Sector Paper Review and Knowledgebase
- SoE Review and Refinement
- Environmental Atlas
- Interactive Environmental Atlas
- Geospatial Portal Enhancement
- Website Refinement
- EPI for Abu Dhabi
- Programs Alignment Strategy

To ensure positive outcomes and adequate technical resources for carrying out the product development, a series of task forces were established as pooled resources to support each product team. These include:

- Data
- Tools and Methods
- Outreach
- Capacity Building
- Policy

Sector Papers

Over the years, different organizations compiled a variety of information in many forms that describe what is known about Abu Dhabi, the UAE and the Arabian Gulf Region. Through the initial AGEDI phase, a series of workshops were developed in 2005 to bring together stakeholders from all these organizations, identify the sectors that were relevant, design a framework for each Sector Paper, and address the key environmental and socioeconomic issues relevant under each sector. Through this effort, eight Sector Papers were completed and published:

- Waste Management and Pollution
- Environmental Policy and Regulation
- Water Resources
- Physical Geography
- Marine and Coastal Environment
- Paleontological and Archaeological Resources
- Population, Development and Economy
- Environmental Education and Awareness

One additional sector was scoped as part of the original program, however, will be published for its first time as part of AGEDI Phase II:

- Terrestrial Environment

Because the Sector Papers are a collection of the best available knowledge pertaining to key environmental and socioeconomic sectors and serve as the basis for all subsequent products to be developed as part of AGEDI Phase II, a review of the original Sector Papers was conducted. Already known through the international workshop held in 2007 was:

- Overall, the original papers were done well and provided a wealth of information
- Stakeholder participation did not reach the level originally intended
- Sector Papers were developed without much agency or stakeholder support, and therefore, became the burden of the Sector Paper authors under a fairly limited timeframe
- Data used was outdated in some cases
- Data collection and sharing did not get institutionalized

The review under AGEDI Phase II sought to address these gaps, as well as the other gaps already identified as part of the original papers. Because the Task Forces were implemented as part of the Phase II program, support was provided at all levels to assist EAD staff and stakeholders in addressing and identifying gaps, collecting data, conducting analyses and developing spatial products, building stakeholder relationships, and ultimately, developing a refined Sector Paper.

The Sector Papers are a source of valuable environmental and socioeconomic information for Abu Dhabi and were used to review and refine the State of the Environment (SoE) report for Abu Dhabi as well as develop the Abu Dhabi Environmental Atlas (both hard-copy and interactive versions).

For more information and online versions

For more information about AGEDI or to access online versions of the Sector Papers, please visit the AGEDI website at www.agedi.ae

تقدر المخزونات الجوفية الكلية بحوالي ٦٤٠ كم مكعب، إلا أن ٩٧,٤٪ من مياهها مالحة وشبه مالحة وتبقى نسبة ضئيلة صالحة للشرب والزراعة (٢,٦٪ مياه عذبة، ١٨,١٪ مياه شبه مالحة، ٧٩,٤٪ مياه مالحة). هذا هو الواقع الطبيعي. وفيما لا تعتمد الإمارة على موارد المياه الجوفية لتوفير الجزء الأكبر من احتياجاتها من مياه الشرب، فإنها تعتمد بدرجة كبيرة على تحلية مياه البحر لتوفير مياه الشرب في صناعة باهظة التكلفة وكبيرة التأثير على البيئة. وعلاوة على ذلك ومع التوقعات باستمرار الزيادة الكبيرة في استخدام المياه وزيادة الطلب ، فسيزيد الاعتماد على معالجة مياه الصرف الصحي وتدويرها لاستخدام مختلف القطاعات.

تحدد الورقة القطاعية واحدة من القضايا العاجلة التي يتوقع أن تواجه الإمارة في العقود القادمة وهي التغير المناخي. ويبدو أن تأثيرات التغير المناخي ستمتد إلى دولة الإمارات العربية المتحدة على المدى المتوسط أو الطويل وخاصة في المناطق الساحلية التي تعاني من معدلات تلوث كبيرة.

لقد تم القيام بمحاولة من خلال هذه الورقة لتحليل المعلومات المتوفرة وإلقاء الضوء على القضايا الرئيسية للبيئة الطبيعية لإمارة أبوظبي بالإضافة إلى تحديد الثغرات الراهنة في المعلومات. ويتوقع أن تكون هذه الورقة موجهاً لأبحاث مستقبلية وتساعد في تطوير استراتيجيات لتقليل الآثار السلبية للأنشطة البشرية على البيئة الطبيعية لضمان التنمية المستدامة.

الورقة الخاصة بقطاع الجغرافيا الطبيعية

ملخص تنفيذي

تصف ورقة قطاع الجغرافيا الطبيعية الخصائص المكانية لمختلف الظواهر الطبيعية البرية والبحرية والجوية بإمارة أبوظبي ضمن فصوله الخاصة بالتربة والمياه والجيولوجيا والمناخ.

يتصف مناخ الإمارة بأنه مناخ قاحل شديد الجفاف بصيف حارٍ وجافٍ وشتاء معتدل إلى دافئ مع أمطار ضئيلة متفرقة. يلعب المناخ دوراً محورياً في التطور والتغيرات على سطح الأرض. وتغلب على طبوغرافية الإمارة الكثبان الرملية الكبيرة التي يزيد ارتفاعها في بعض المناطق على ٢٥٠ متر، الأمر الذي يجعلها من بين أعلى الكثبان الرملية في العالم. وتتخلل هذه الكثبان سهول منخفضة بغطاء نباتي ضئيل. جيولوجياً، تعتبر إمارة أبوظبي والمناطق المجاورة لها مستقرة نسبياً خلال الستمائة مليون سنة الماضية. وتوجد أقدم صخور متكشفة في الإمارة في جبل الظنة.

نتيجة للنمو السكاني السريع وما ترتب عليه من زيادة في استهلاك الموارد الطبيعية ، فإن الإمارة تعاني من التدهور البيئي. تعتبر التربة جزء حيوياً من البيئة وتلعب دوراً رئيسياً في التفاعل البيئي بما يربط بين الجو والموارد المائية واستخدام الأرض. وتعتبر حماية حالة التربة أمراً ضرورياً لدعم الزراعة والغابات والحياة الفطرية والاستخدامات الأخرى ، الأمر الذي يعد جزء هاماً من جهود المحافظة على البيئة وتعزيز الاقتصاد الوطني. إن لطريقة استخدام أنواع التربة المختلفة وتأثير أنشطتنا عليها تأثيرات هامة وعميقة على نوعية البيئة. وعليه، فإن من الضروري الإلمام بكيفية الاستخدام المستدام لأنواع التربة المختلفة. وفي هذا الصدد فإن الفصل الخاص بالتربة يقدم معالم إرشادية للمستخدمين حول الخصائص العامة لأنواع التربة في إمارة أبوظبي. ويتضمن هذا الفصل مقدمة عامة حول التربة والعوامل والعمليات الخاصة بتكونها وخصائصها الطبيعية والكيميائية والمعدنية وخصوبتها وتصنيفها والاعتبارات الخاصة باختيار الأراضي المناسبة للاستخدامات المختلفة. وقد تمت مناقشة مبادرات اتفاقية الأمم المتحدة لمكافحة التصحر والجهود المبذولة لتنفيذها من خلال مفهوم تخضير الصحراء فيما يتصل بدولة الإمارات العربية المتحدة. ويتضمن القسم الخاص بتدهور الأرض معلومات حول أنواع التدهور وأسبابه والجهود التي تبذلها دولة الإمارات العربية المتحدة لمعالجة هذه المشكلة. وقد بدأت هيئة البيئة – أبوظبي مؤخراً في تنفيذ مسح للتربة على مستوى الإمارة بتركيز على تقييم التربة ورسم خرائط الاستخدامات المناسبة. ويتوقع أن يقدم المسح مساعدة قيمة لأصحاب القرار في تخطيط الاستخدامات المستقبلية للتربة في الإمارة.

القضايا الرئيسية التي تم تحديدها فيما يتصل بالتربة هي التآكل بفعل حركة الرياح وزيادة ملوحة التربة. أما فيما يتصل بالمياه فتكمن المعضلة في ندرة موارد المياه العذبة وزيادة الطلب على المياه. ولا تكفي الكمية الضئيلة من مياه الأمطار التي تتلقاها الإمارة سنوياً للوفاء بالزيادة الكبيرة في الطلب الذي قدر حالياً بما يعادل (٢٦) ضعفاً من كمية المياه الجوفية التي يعاد شحنها بصورة طبيعية.

PHYSICAL GEOGRAPHY SECTOR PAPER

EXECUTIVE SUMMARY

The Physical Geography sector paper describes the spatial characteristics of the various natural phenomena that exist in the lithosphere, atmosphere and hydrosphere of the Emirate of Abu Dhabi through its chapters on soils, water, geology and climate.

The Emirate has hyper arid climatic conditions, with hot and dry summers, and mild to warm winters with meager, sporadic rains. The climate plays a central role in determining the evolution and changes of the land surface. The topography of the Emirate is dominated with large sand dunes that in certain places exceed 250 m and belong to the largest in the world, interspersed with sparsely vegetated interdunal plains. Geologically the Emirate of Abu Dhabi and adjacent areas have been relatively stable over the past 600 Ma, with oldest exposed rocks in the emirate occurring in Jebel Dhanna.

As a result of a rapidly expanding population and consequent increase in the consumption of natural resources, the Emirate is facing environmental degradation. Soil, a vital part of our environment has a key role in environmental interaction, linking the atmosphere, water resources and land use. Protecting the activity of the soil to support agriculture, forestry, wildlife and other uses are an important part of a wider effort to conserve the environment and to promote the national economy. The way we use our soils, and the influence of our activities on it, will have important and far-reaching effects on the quality of soil environment. It is, therefore, necessary to understand the soils for sustainable use. In this regards the Soils Chapter is a milestone in orienting the users on the general characteristics of Soils in Abu Dhabi Emirate. The chapter presents general soil introduction, factors and processes of soil formation, physical, chemical, mineralogical, fertility, soil classification and land suitability aspects. The initiatives of the United Nations Convention to Combat Desertification (UNCCD) and efforts to implement it through Greening the Deserts concept are discussed in the perspectives of UAE. The topic on Land Degradation provides information on types of land degradation, their causes, and efforts made in the UAE to address these issues. The Environment Agency Abu Dhabi has recently initiated a four year Emirate wide soil survey with emphasis on evaluating soil and soil mapping units for its potential uses. The survey is expected to aid decision makers in future land use planning in the Emirate.

The key issues identified in soil are wind erosion and salinisation and for water, the worsening situation of the Emirates' fresh water resources and increasing demand for water. The meager volume of rainfall the Emirate receives annually is not enough to meet the excessive and growing demands. Current demands are about 26 times greater than the volume of water which is naturally recharged within the hydrological system.

The total groundwater reserves are estimated at 640Km^3 (2.6% fresh, 18.1% brackish, 79.4% saline) 97.4 % are either brackish or saline reserves, with meager fresh water. This is the natural condition and, whilst the emirate does rely on these groundwater resources for the most part of its non - potable requirements, it relies heavily, and will continue to do so, on the expensive and environmentally sensitive process of the desalination of seawater for drinking water. Furthermore, with overall water use expected to increase, there will also be an increased requirement and reliance on the treatment and re-use of waste water from all sectors of water use.

The Sector Paper identifies that one of the potentially urgent issues facing the Emirate in the coming decades will be that of global climate change. The effects of global climate change will affect the Emirate in the medium to long term, especially in the heavily populated coastal regions. An attempt is made through this paper to provide a synthesis of the available knowledge and highlight key issues of the physical environment of the Emirate of Abu Dhabi, together with existing gaps in technical information. It is expected that the paper will serve as a guide for future research and help in developing strategies that reduce the negative impact of human activities in the natural environment, while ensuring sustainable development.

Table of contents

List of Tables and Figures

1 INTRODUCTION

The United Arab Emirates covers a land area of approximately 83,000 km^2, of which the Emirate of Abu Dhabi makes up some 85% (**Figure 1.1**). This sector paper is concerned with the main aspects of the physical environment of Abu Dhabi, *i.e.* to explain the spatial characteristics of the various natural phenomena that exist in the lithosphere, atmosphere, hydrosphere and biosphere of the Emirate. As such, it provides a descriptive account of its geology, climate, water and soils. A clear understanding of these topics is fundamental to assessing the economic potential of the Emirate and understanding the environmental framework for protecting its natural heritage, including biodiversity, and addressing a host of complex environmental issues.

The environmental conditions for life in Abu Dhabi are extremely harsh. Away from the Al Hajar Omani mountains, the surface is dominated by sand dunes and gravely plains. The sand dunes, which in the south of the Abu Dhabi Emirate exceed 250m in height and belong to the largest in the world, are interspersed by sparsely vegetated interdunal plains. Hypersaline, barren *'sabkha'* is a common landscape feature, especially in western coastal regions, but also locally inland. With extremely hot and dry summers, when temperatures regularly exceed 45°C, and mild to warm winters with meager, sporadic rainfall, the climate of most of the Emirate can be regarded as hyper-arid. Life in the desert has adapted to such inhospitable conditions in a number of ways. Some organisms escape the harshest period of the year, the summer, by either falling into a state of inactivity or migrating to more favourable areas. However, for those organisms that remain and persist, the absolute necessity to conserve water is fundamental to all survival strategies. This surely should be the guiding principle for human existence, given the paucity of natural freshwater resources.

At present, the Emirate is heavily reliant on oil as its main source of revenue, a natural product formed millions of years ago under a very different climate and under specific geological conditions. The development of alternative sources of income is in part dependent on the environmental setting of the Emirate. For instance, developing a sustainable agriculture with limited water resources, extreme climatic conditions and with poor soil resources will prove to be a major challenge. Similar, if not so severe, constraints apply to industrial development.

Figure 1.1: Reference Map of Abu Dhabi Emirate

It is well-established that around the world, the frequency and magnitude of human-mediated environmental problems have been, and are continuing to steadily increase. These increases are the result of an expanding human population and the consequent increase in the consumption of natural resources. Today, mankind has an enormous potential to modify the environment to his benefit, but also with serious negative impacts. As a consequence, environmental degradation is a serious global issue, and Abu Dhabi Emirate has more than its fair share of problems and challenges, confounded by the harsh climatic conditions.

In this context, the sector paper presented here provides a synthesis of our knowledge of the physical environment of Abu Dhabi. Apart from indicating what is known, the paper highlights the main technical information gaps which exist. It is hoped that this synthesis will therefore serve as a guide not only for future research, but also to help develop strategies that reduce the negative impact of human activities on the natural surroundings and ensure the wise and sustainable use of its natural resources.

2 SOILS

By Dr. Shabbir A. Shahid, Salinity Management Scientist, International Centre for Biosaline Agriculture (ICBA), Dubai

Soil is the unconsolidated mineral or organic material on the immediate surface of the earth that serves as a natural medium for the growth of land plants (Soil Science Society of America, 1987), therefore soil is indispensable for crop production. The most recent definition is by the USDA-NRCS (1999) which defines soil as a natural body comprised of solids (minerals and organic matter), liquid, and gases that occur on the land surface, occupies space, and is characterized by one or both of the following: horizons or layers, that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter or the ability to support rooted plants in a natural environment. The word “soil” has several definitions based on its uses; *e.g.*, from a Potter point of view soil is material for making pots, for a builder it is the base for construction of buildings, *etc*.

The upper limit of soil is the boundary between soil and air. The lower limit is the boundary that separates soil from the non-soil underneath and it is most difficult to define. The USDA-NRCS (1999) for the soil classification purpose sets the lower soil boundary at 200cm. In soils where soil forming processes extend to depths greater than 200cm, the lower limit of the soil for classification is still 200cm. This definition of soil is mainly concerned with soil classification in relation to plant growth, for other uses the depth for soil may extends below 200cm.

All terrestrial life ultimately depends on soil, energy and water. Soils have always been central to human civilization and life and are an integral part of the physical and cultural environment that we may take them for granted and even tend to treat them contemptuously. The Emirate landscape is covered mainly by low-lying sandy deserts, extensive coastal salts-flats, alluvial plains and gravely plains in both the far west and east of the Emirate. The study by Shahid *et al*. (2004) revealed that, a rather uniform looking coastal landscape in fact, presents a diversity of sub-surface features that help to categorize the soils into 13 different soil classes. The different landscape features suggest the occurrence of soil diversity in terms of classification, chemistry, physics, mineralogy, fertility, suitability for different uses and vulnerability to land degradation etc. Below are facts about soils.

Soils are:

- The essence of life
- A product of the environment
- Developed and not merely an accumulation of debris from rocks and organic matter
- Different from the material from which they are derived
- Continuously changing due to natural and human influences
- Different in inherent capability
- The sites for chemical reactions and organisms
- Medium to support plants
- Medium to filter water and recycles wastes
- Very fragile
- Very slowly renewable

Soils have been studied, investigated and interpreted for several uses by scientists from multi-disciplinary backgrounds. The soils have very widely been taught as a subject under the title "Soil Science", which is essentially an agricultural science. Soil Science deals with soils as a natural resource on the surface of the earth, including its formation, classification and mapping and the physical, chemical, biological and fertility properties in relation to their management for the growth of plants and to clean the environment. Soil science is a broad subject and is divided into a number of interlinked branches, such as soil survey and classification, soil chemistry, soil physics, soil fertility, soil conservation, soil mineralogy, soil genesis, soil morphology, soil microbiology, soil ecology and soil management.

In this *Soil Section* of the Sector Paper of *Physical Geography*, emphasis have been given to Abu Dhabi Emirate soils, although scarce information is available, the author, to his best judgment, knowledge and experience on Emirate and similar soils of other regions presents a general view on different aspects of soils. The information presented in this paper is a preliminary attempt and is not a substitute of a more detailed investigation in the Emirate or an on-site investigation prior to its use for specific purpose. It is hoped that the future soil survey project (EAD-ICBA, 2006) which the Environment Agency - Abu Dhabi (EAD) in cooperation with the International Centre for Biosaline Agriculture (ICBA) will be implementing during the next four years, will produce massive soil information to answer queries for broad land use planning in Abu Dhabi Emirate.

2.1 Soil Formation

Soil formation is the development of a particular soil in a particular place and it is a diverse and complex process that is affected by certain factors working in combination. Soil formation includes production of parent material by weathering processes and the soil profile development. In the real sense the weathering process and the changes within the soil mass occur simultaneously. Understanding of soil formation requires information on three important components; 1) *Soil genesis* - the evolution of soil from its parent material; 2) *Soil classification* - grouping of soils having common properties and 3) *Soil survey* - the description of geographic distribution of soils and their relationship to landscapes. This information on Emirate soils is scarce and far from complete; however, the future soil survey (EAD-ICBA, 2006) shall provide information on these aspects.

2.1.1 Factors of Soil Formation

Soil is a result of the complex interaction of soil formation factors i.e., climate, parent material, biological activities and topography interacting over a period of time to produce a product Soil. *Climate* is the dominant factor and plays an important role in desert soil formation where high temperature, low and infrequent rainfall restricts soil development. The hyper-arid conditions in combination with strong wind support soil erosion and, therefore, most of the Emirate soils are aeolian in origin. These aeolian soil *parent material*, also contain carbonates and gypsum that may be added to soil and leached to lower horizons. The coastline soils are formed from different kinds of parent material such as coastal shells, silts and clay, marine and aeolian sand, and evaporites of Na^+,K^+,Ca^{2+},Mg^{2+} with Cl^- ,SO_4^{2-} and HCO_3.

Living organisms (plants, animals, microorganisms) in the Emirate soils play a minor role in soil development due to low organic matter content and scarce vegetation cover, which results into less profile mixing, low nutrient cycling and low soil structure stability. *Topography* of land can delay or hasten the work of climatic factors, *e.g.* on flat surfaces water is removed less rapidly than steep slopes; the latter encourages water erosion and reduces the development of deep soils. Water erosion is common in the barrier islands. The Emirate desert soils comprise sand dunes of varying heights that are hummocky and prone to wind erosion. In desert plains, the presence of surface gravels indicate that productive soil has been removed through wind erosion leaving behind gravels of heavy mass called '*gravellag*'. The soil systems develop and change through *Time*. Soils tend to develop more rapidly under warm, humid and forested conditions, which do not prevail in the Emirate; therefore, soils develop very slowly under hyper-arid conditions. It is, therefore, very valid to state that the internal soil features (clay illuviation, carbonates deposition, *etc*.) of Emirate soils may take longer time to develop, whereas surface features may takes less time, *e.g*., removal and deposition of surface aeolian sandy sediment by wind erosion.

2.1.2 Processes of Soil Formation

From the above discussions it can be deduced that although soil development in the Emirate desert is slow the soils are not static but dynamic natural bodies changing over a period of time. Formation and degradation are occurring simultaneously and interacting with the desert environment resulting in soil through various soil forming processes such as erosion, aeolian, cumulization, salinization, desalinization, sodication or alkalization, gypsification, hydration, calcification, decalcification, gleization, homogenization, oxidation and reduction, *etc*.

Erosion refers to the removal of surface layers of soil by water (raindrop splash, run-off waters) and wind (creep, saltation and suspension). Wind has a major role in drifting soil from loose surfaces. Whereas, water to some extent, plays an important role in removing soil material during torrential rain. Both agents remove soil material from land surface, leaving behind the degraded land. *Aeolian* deposits (soil deposits formed through the wind transportation of soil material) are the most predominant in the Emirate desert environment (**Figure** 2.1). Deposition of wind born particles occurs when the gravitational force is greater than the forces holding the particles in the air. The soils formed through aeolian process are the least developed young soils without any horizon development (Entisols) and are very widely distributed in the Emirate in the form of loose sandy, hummocky and sand dune soils. *Cumulization* expresses the accumulation of soil material onto the surface by either wind (aeolian) or water. In fact, aeolian process may be considered as a geogenic process rather than a pedogenic process. *Salinization* is a process of soluble salts accumulation in the soils and it is common in coastal (**Figure** 2.2) as well as some of the agricultural farms of Abu Dhabi. In these areas, soils are enriched with salts faster than they are leached. In the coastal areas, the salinization process can be recognized by surface salt crust due to sea water intrusions. Whereas, in the agricultural farming areas it occurs through anthropogenic activities where saline/brackish water is used for irrigation and subsequent evaporation causes salts to appear at the surface and in soil matrix. *Desalinization* is a process when soluble salts are removed from the horizons or soil profile through leaching, this occurs during heavy rain or irrigation with fresh water. *Sodication or alkalization* is a process of the accumulation of sodium on the soil exchange complex. The sodicity is expressed as Sodium Adsorption Ratio (SAR) or Exchangeable Sodium Percentage (ESP). Which is high in the coastal soils due to sodium rich seawater intrusion, however, sodicity was recognized in the farming areas to a relatively lesser extent. *Gypsification* is the process of gypsum accumulation in soil profile (**Figure** 2.3). Such an accumulation was frequently recorded in the coastline soils and less frequently in the inland areas. *Hydration* refers to the association of water molecules with minerals. An excellent example can be quoted from the Emirate coastline where anhydrite and gypsum were recorded together (Shahid, et. al., 2004). Most probably anhydrite is converted to gypsum ($CaSO_4 + 2H_2O \rightarrow CaSO_4.2H_2O$), where $CaSO_4$ is anhydrite and $CaSO_4.2H_2O$ is gypsum. *Calcification* is a process by which calcium carbonate equivalents accumulate in soils, and most commonly in subsurface horizons ($CaCO_3 + H_2O + CO_2 \leftrightarrow Ca(HCO_3)_2$). Calcification occurs when H_2O or CO_2 is removed from the system and the reaction moves to the left. *Decalcification* occurs when $H_2O + CO_2$ are present and the reaction moves to the right. The direct source of calcium carbonate in soil is the calcareous parent material. Emirate soils in general contain carbonates to a varying extent. In the coastline soils, the most likely source is the coastal shells and the aeolian deposition of soil material. In these soils, carbonates were disseminated or finely dispersed throughout the soil matrix such that specific carbonate features were not visible. In some profiles, carbonates are precipitated or cemented to a hardpan which is called Petrocalcids. These soils are common in the eastern coast of Abu Dhabi Emirate. The calcium carbonate accumulation is coupled with its removal from overlying horizon (decalcification). The process where carbonates are dissolved is called decalcification and where they accumulate is called calcification. Living organisms' activities are common in moist and fertile soils particularly in urban landscape areas where organic fertilizers are used in sufficient quantities. These activities can be noticed by the presence of granular droppings of the living organisms on the soil surface. These activities churn the soil and destroy signs of soil formation through *homogenization*. Homogenizations through rodents and ants are called faunal *pedoturbation* **(Figure 2.4).** Living organism activity indicates that the soils are productive and rich in nutrients. The yellow and red mottling recorded in some coastline soils show *oxidation* process, and where grayish colour soil was observed indicates a *reduction* process. *Oxidation* is the chemical process by which an element loses an electron ($Fe^{++} \rightarrow Fe^{+++} + e^{-}$; where e^{-} = electron transfer), as in the very common and important oxidation of iron which gives red colour in soil (Error! Reference source not found.). Reduction occurs where the soil is saturated with water, oxygen supply is low and biological oxygen demand (BOD) is high, the effect is to reduce the iron to the highly mobile ferrous form. In this form it losses from the system leaving behind green and blue-green and grayish colour (**Figure** 2.6). This has been frequently observed in the subsurface of coastal soils in the Emirate. All above soil formation components can be grouped into four processes *i.e.*, additions, losses, transformation and translocation.

Figure 2.1: Typical aeolian deposits in the Emirate of Abu Dhabi.

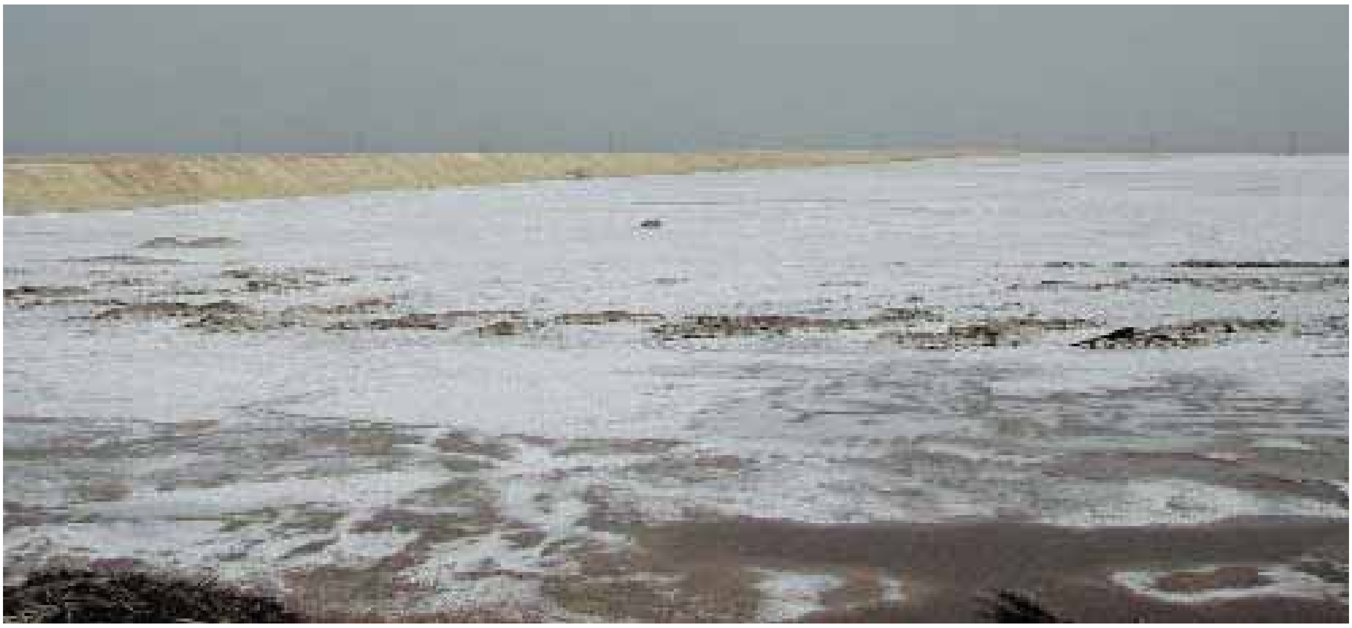


Figure 2.2: Salinization in Abu Dhabi Emirate coastline.

Figure 2.3: Accumulation of gypsum in the soil profile “gypsification”

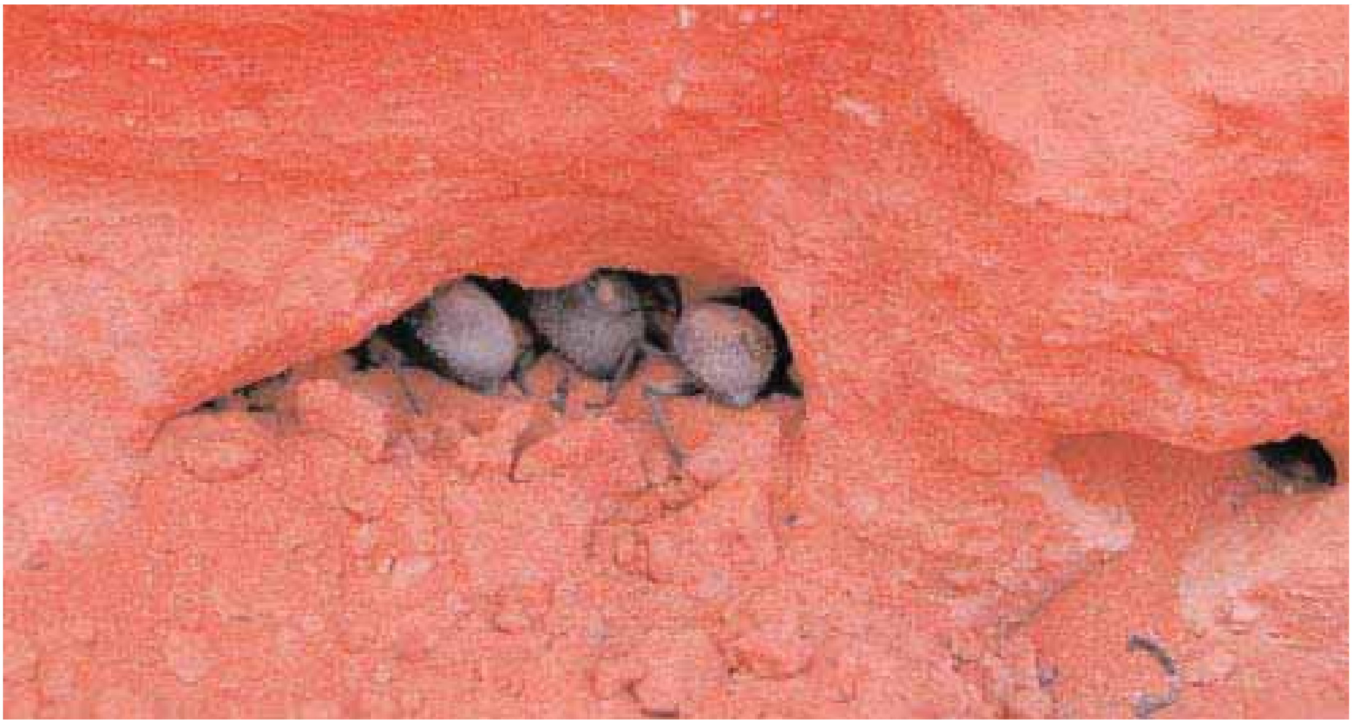


Figure 2.4: Insects activity in soil development “pedoturbation”.

Figure 2.5: Red zone in soil matrix showing oxidation process.
Lenticular gypsum crystals embedded in soil matrix are also evident..

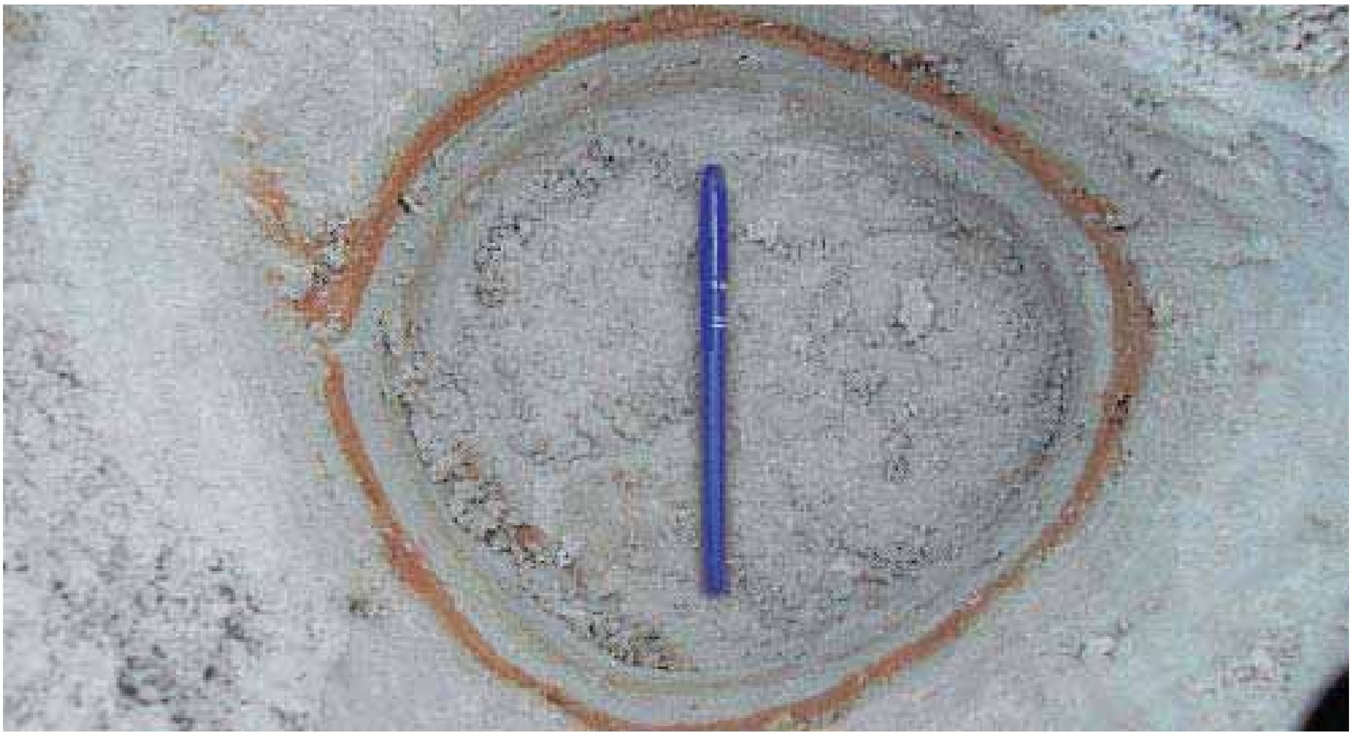


Figure 2.6: Grayish soil colour as an indication of reduction process.
Red colour shows oxidation process.

2.2 Physical Properties of Soils

Physical properties of soils are largely controlled by the sizes of soil particles (particle size distribution or soil texture) and the arrangements of soil particles (soil structure). The latter is developed through binding of soil particles in the presence of flocculating/ cementing agents such as organic matter, oxides of iron, carbonates, *etc*. The most important soil physical properties are texture, structure, bulk density, porosity, consistence, temperature and, to a certain extent, colour. The physical properties control root penetration, seedling emergence, water movement, drainage capacity, composition of soil air and air exchange, nutrient availability, *etc*. Soil tilth is the term used to present soil physical health for plant growth, which is the combined effect of texture, structure, and consistence.

Primary soil particles (sand, silt and clay) determine the soil texture, and the relative percentage distribution of sand, silt and clay finally result into a soil textural class. In soil texture mineral particles less than 2 mm in equivalent diameter (fine earth fraction) are considered. Mineral particles greater than 2 mm are not considered in soil texture but considered as gravel (USDA, 1993). The soluble salts, gypsum, and organic matter are flocculating agents and should be removed when determining soil texture. The coarse (> 2mm) fragments are also excluded from soil texture. The soils of the Emirate, in general, contain sufficient quantities of carbonate equivalents (calcite, dolomite, aragonite, etc), which have very low solubility to interfere with soil dispersion for textural analysis. Therefore, it is sensible to consider it as a part of texture and to determine in what size fraction it dominates. Soil texture performs a major role in water-holding capacity, permeability, infiltration rate, consistence and porosity.

The soils of Abu Dhabi Emirate, in general, are sandy in nature and the texture ranges between sand and sandy loam. A typical composition of soil texture of the upper 40 cm (Shahid *et al*., 2004) in the desert soil "*Typic Torripsamments*" is shown in **Table 2.1.**

Name of soil separate	Diameter range* (mm)	Percentage distribution
Very coarse sand	2.0 - 1.0	*1.0*
Coarse sand	1.0 - 0.5	*3.5*
Medium sand	0.5 - 0.25	*14.5*
Fine sand	0.25 - 0.10	*46.0*
Very fine sand	0.10 - 0.05	*30.0*
Coarse silt	0.05 - 0.02	*1.0*
Fine silt	0.02 - 0.002	*0.0*
Clay	< 0.002	*4.0*
Total sand	2.0 - 0.05	*95.0*
Total silt	0.05 - 0.002	*1.0*
Total clay	<0.002	*4.0*
Textural Class		*Fine sand*

* *(USDA-NRCS, 2004)*

Table 2.1: Particle size distribution of the upper 40 cm of a typical sandy desert soil in Abu Dhabi Emirate.

Table 2.1 illustrates that the primary soil particles in the desert environment soils in general are dominant with sand fraction, and more specifically in the fine sand fraction (0.25 - 0.05 mm). Silt and clay are the least occurring soil particles. Other coastal white sandy soils present different quantities *i.e*., sand (92.5%), silt (4.5%) and clay (3.0%) at upper 40 cm with slight differences (±1% in each fraction) to a depth of 110 cm, however the textural class remains "sand". The sand is dominant in the medium and fine fraction (~ 67%) which is different than sandy desert soils. Sandy soils have a high infiltration rate (more than 250 mm/hr), very high drainage capacity (well to somewhat excessively drained), moderate to rapid permeability, low runoff, and are highly prone to wind erosion.

Formation of *soil structure* (arrangement of soil particles) in the Emirate desert is inhibited due to hyper-arid conditions and continuous movement of soil material through wind action. Therefore, the dominant structure of the loose desert sand and sand-dune soils is mainly single grain *i.e*., non-cohesive (Figure 2.1) and massive without any lines of weakness (Figure 2.9). In places where clay and silt are present in relatively more quantities, other structure classes such as blocky structure may occur. *Bulk density* is the mass of a unit volume of bulk soil including solid and pore spaces. Coarse textured soils such as desert sandy soils compared with fine textured soils occupy less volume and therefore present relatively high bulk density and less total pore spaces. Bulk densities greater than 1.6 g/cm^3, may inhibit root penetration and cause low hydraulic conductivity. Bulk density values can be used to determine mass of soil to a certain depth to quantify the nutrients and the amendments required for soil reclamation such as gypsum, which is used to reclaim saline-sodic and sodic soils. The bulk density of the Emirate soils ranges between 1.74 to 1.371 g/cm^3 resulting in a porosity of 33 to 48% respectively, however, gypsum rich horizon or that contain salt crystals, present bulk density as low as 0.898 g/cm^3 (66% porosity). In general, the bulk density of the desert soil is high, however, due to the loose sandy nature and coarse size of pores, it does not inhibit root penetration or hydraulic conductivity of soil. Soils that are compacted may inhibit these properties.

Soil consistence refers to the action of a soil under an applied pressure. It includes resistance to compression and sheer, friability, plasticity and stickiness. The consistence of desert sandy and sand dune soils (*Typic Torripsamments*) is soft; whereas in coastal salt crusts it is very rigid. Combined effect of salts and sand is determined as friable when moist; gypsum rich horizons are either firm or friable when moist and moderately hard when dry; soils dominant with coastal shells are loose at surface and very friable at deeper depths.

Soil colour is the most easily measured soil physical property. It is an indicator of the presence of different quantities of organic matter, iron minerals and reduced and oxidized soil conditions. Standard soil colour is determined through Munsell colour notation, which is recorded in the form: hue, value/chroma. *Hue* is the measure of the chromatic composition of light that reaches the eye, *Value* is the degree of lightness or darkness of a colour in relation to a neutral gray scale, and *Chroma* is the relative purity or strength of the spectral colour. The typical soils of the Emirate deserts, in general, are light in colour when dry due to the low quantities of organic matter It presents a hue of 2.5Y, a value of 6 or 7 and chroma 3, and ranges between light yellowish brown (2.5Y 6/3) to pale brown (2.5Y 7/3). The colour of the coastal white sandy soils ranges from light gray (2.5Y 7/2) at surface to pale yellow (2.5Y 7/3) at depths more than 1 metre. Ferruginous sands (Figure 2.7) are either 2.5YR 5/6 (red) or 10YR 5/6 (yellowish red), coastal salt-crust and anhydrite layer (Figure 2.8) is 5Y 8/1 (white), gypsic layers are 10YR 7/3 (very pale brown), reduced conditions present light gray (2.5Y 7/2), and cemented carbonate hard pans are very pale brown (10YR 7/3). Moist soils, due to less reflection of light than dry soils, appear darker.

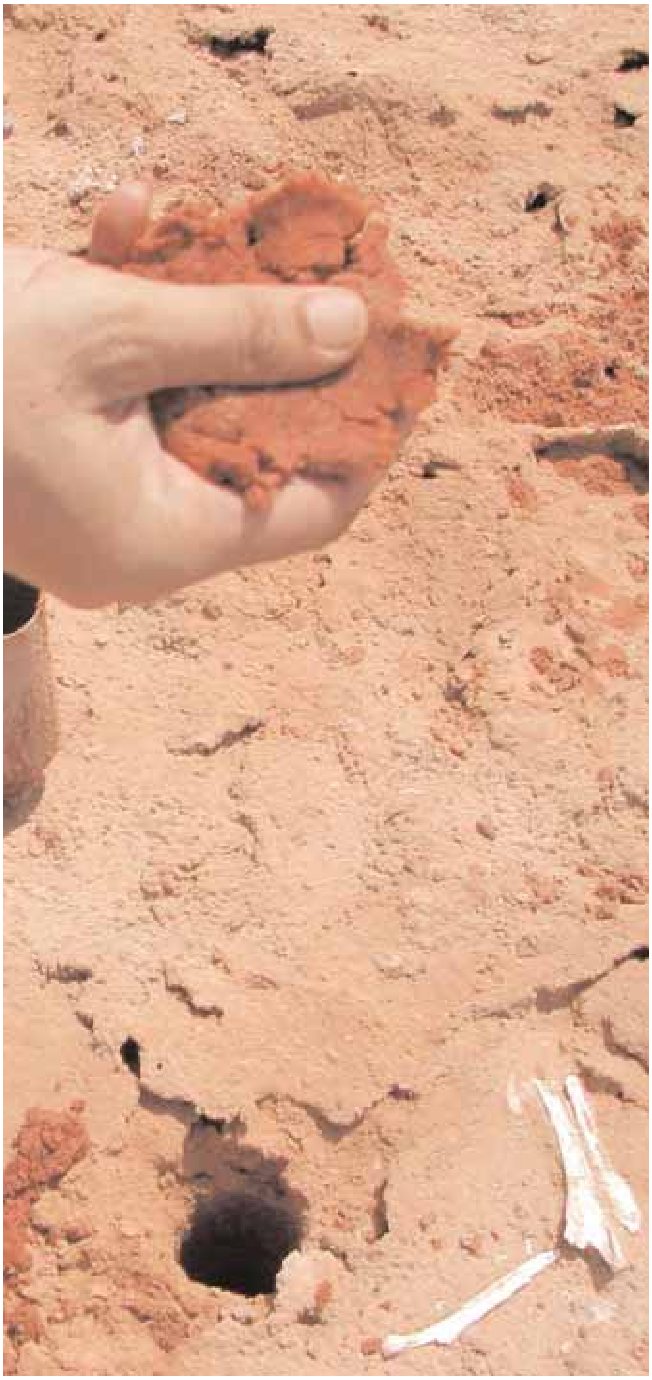


Figure 2.7: Red colour ferruginous sandy material.

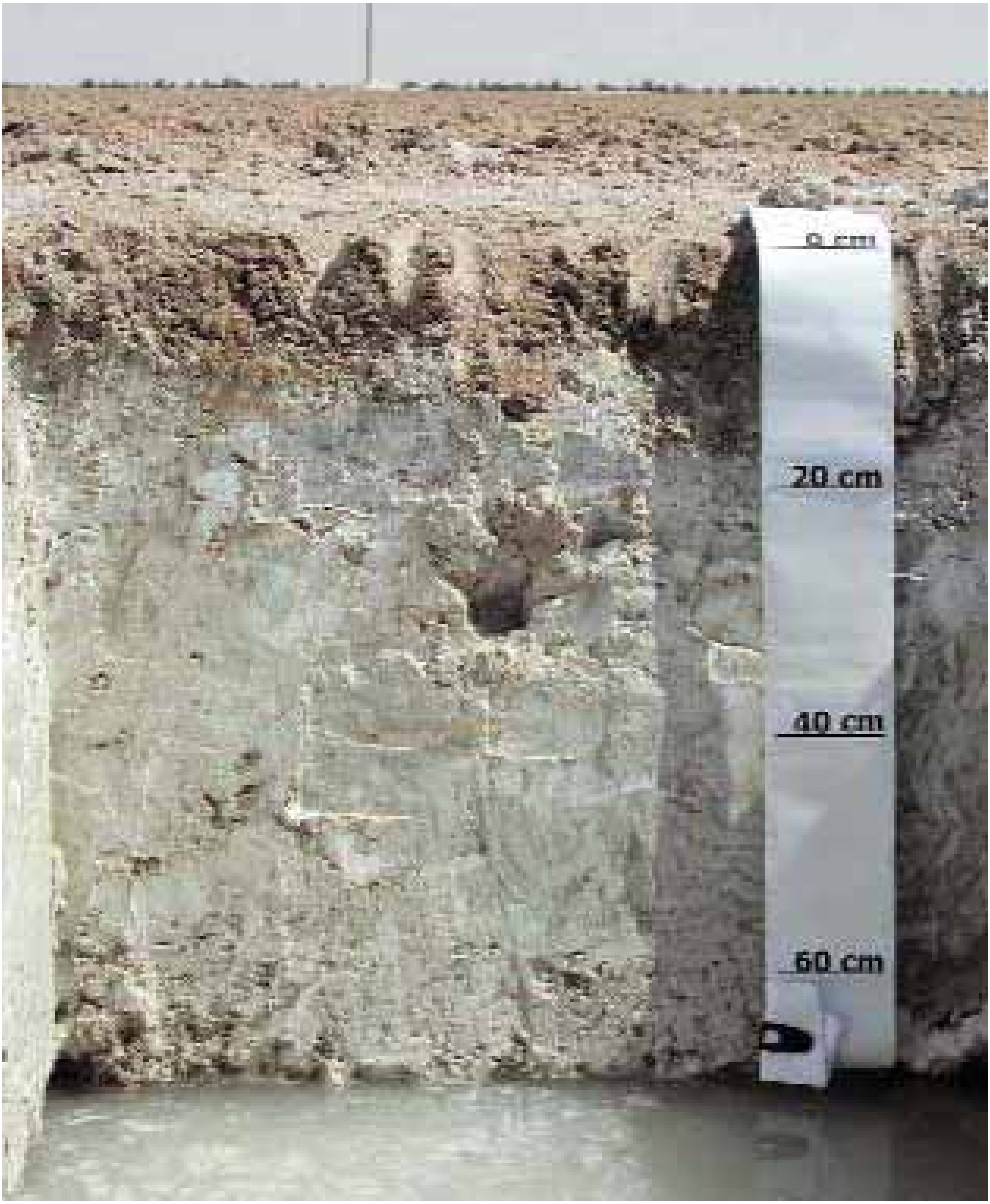


Figure 2.8: White colour of anhydritic material.

Soil temperature is important for chemical and biological reactions in soils, seed germination, plant growth, microorganisms' activities in decomposing organic matter and physical weathering of soils. Soil temperature in the Emirate is determined as "hyperthermic" (see details under soil classification section).

In general, every rise of 10°C of soil temperature doubles the soil chemical reactions, which is true in soils where sufficient moisture is available to appreciate chemical reactions. In the hyper-arid conditions, this may not apply as the soil reactions are very slow and limited to only the rainy season.

2.3 Soil Chemistry

From a mass standpoint, soil in general is an O-Si-Al-Fe (Oxygen-Silicon-Aluminum-Iron) matrix containing relatively small amounts of the essential elements. The background matrix itself is virtually inert as far as plant nutrition is concerned, but the ions held by the matrix are extremely important. The chemistry of soil is controlled by three phases; crystal chemistry (ions within the crystal lattices of clay, silt, sand, and gravel particles, which are unusable by plants); surface chemistry (ions adsorbed on the surfaces of soil particles due to negative charges, they are available to plants through ion exchange phenomenon); and solution chemistry (those soluble in water).

As stated above, the main soil mass (crystal composition) is an O-Si-Al-Fe matrix. Looking at the soil mineralogy of the control section of soils in Abu Dhabi Emirate, it is inferred that the main mass in the desert soils is O-Si-Al-Ca (Oxygen-Silicon-Aluminum-Calcium) matrix, which is indicated by the presence of quartz, plagioclase and calcite as major mineral species. Exceptions are in the coastline where halite (NaCl), gypsum ($CaSO_4.2H_2O$) and anhydrite ($CaSO_4$) minerals have been identified in the control section of soil families. These depths present O-Si-Ca-Na-S-Cl (Oxygen-Silicon-Calcium-Sodium-Sulphur-Chlorine) matrix.

The surface chemistry is controlled by the negative charges of soil colloids and retained cations in the water films on the colloidal surfaces. The retention of cations at the ion exchange sites reduces the loss of cations such as Ca^{2+},Mg^{2+},Na^{+},K^{+} and others by leaching and keeping them available for plants. These retentive cations can easily be exchanged with other cations, hence are called exchangeable cations. Exchangeable cations are defined as those released from the soil by solutions of neutral salts. They can also be manipulated by chemical fertilizers and irrigation etc. The distribution of major exchangeable cations in productive agricultural soils is generally $Ca^{2+} > Mg^{2+} > K^{+} > NH_4^{+} > Na^{+}$ (Bohn *et al*., 1985). The sum of exchangeable cations is expressed as milli equivalents per 100 gram of oven-dried soil (meq/100g), in the Standard International (SI) system; CEC is expressed as centimoles of charge per kilogram of oven-dry soil (cmolc/kg) and is termed Cation Exchange Capacity (CEC). The CEC determines the inherent fertility of the soil. The CEC of the typical desert soils of Abu Dhabi is less than 3 cmolc/kg which is, low due to dominance of sand fraction and hence native desert soils are infertile. In places where clay rich horizons may occur, the CEC may be higher, the future survey (EADICBA, 2005) may identify these soils in the Emirate. The CEC of the dominant Emirate desert soils, *i.e.*, Typic Torripsamments, in general is dominant with $Ca^{2+} > Mg^{2+} > K^{+} > Na^{+}$, in places $Na^{+} > K^{+}$. In the coastline of Abu Dhabi and due to sea water intrusions, the trend of exchangeable cations is $Na^{+} > Mg^{2+} > Ca^{2+} > K^{+}$, in places $Ca^{2+} > Mg^{2+}$. The presence of high quantities of Na^{+} on the soil exchange complex increases ESP and soils become sodic. This soil forming process is observed in Abu Dhabi coastline (Shahid *et al*., 2004), and may occur in agricultural farms due to the use of irrigation water with high SAR. Sodic soils present poor soil conditions for plant growth and require special attention for reclamation. The reclamation of sodic soils is an expensive and time consuming process.

Solution chemistry of the soil is controlled by the presence of soluble salts which can be removed by water alone. A typical desert sandy soil of Abu Dhabi Emirate, *i.e.*, Typic Torripsamments (Shahid *et al*., 2004; Shahid and Abdelfattah, 2005) is in general low in soluble salts, *i.e.*, Electrical Conductivity of the soil saturation extract (ECe) is less than 4 dS/m. However, within this low soluble salts contents the trend of cations occurrence is $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$ and anions $SO_4^{2-} > Cl^{-} > HCO_3^{-}$. The trend of cations and anions in the coastline soils (Shahid *et al*., 2004) due to sea water intrusion is different than inland sandy desert soils. In the coastline soils, the trend of the occurrence of cations is -

$$Na^{+} > Mg^{2+} > Ca^{2+} > K^{+} \text{ and anions } Cl^{-} > SO_4^{2-} > HCO_3$$

Salt-Affected Soils

Based on the electrical conductivity of the soil saturation extract (ECe) and Exchangeable Sodium Percentage (ESP) values, salt-affected soils are categorized into 3 classes; **1)** Saline; **2)** Saline-sodic and **3)** Sodic. Following are the ECe and ESP (**Table** 2.2) values of three categories (Richards, 1954). Based on the criteria in Table 2.2, the assessment results are shown in **Table** 2.3, which shows all soils to be saline-sodic, except petrocalcids (carbonatic hardpan) and inland desert sandy soils (Torripsamments).

Soil —›	Normal	Saline	Saline-sodic	Sodic
ECe	< 4 dS/m	> 4 dS/m	> 4 dS/m	< *4* dS/m
ESP	< *15*	< *15*	> 15	> 15

Table 2.2: Criteria for the classification of salt-affected soils (Richards, 1954).

Table 2.3 clearly illustrates that the native desert soils, to a large extent, are normal (non-saline and non-sodic) and do not present salinity and sodicity, whereas coastal soils are mostly saline-sodic.

Soil reaction (pH) and alkaline earth carbonates

Soil reaction is an expression of the degree of acidity and alkalinity of a soil and is expressed as pH. It influences plant nutrients availability: if the pH is too high, the availability of iron, manganese, copper, zinc and especially phosphorous and boron is low. A pH above 8.3 indicates a significant level of exchangeable sodium. It is also important in determining the risk of corrosion.

The pH_s (pH of saturated soil paste) of the soils of the Emirate of Abu Dhabi (**Table 2.3**) differs with respect to soil types and location. The desert calcareous sandy, sand-dune soils are dominantly moderately alkaline in reaction (pHs ranges between 7.9 to 8.4). In places, they are slightly alkaline in reaction (pHs ranges between 7.4 and 7.8). The coastline soils with sufficient quantities of gypsum, anhydrite and halite present pHs in the neutral range (pHs 6.6-7.3), however, those rich in carbonates content (hardpans, coastal white sandy and carbonates rich saline soils) are strongly alkaline (pHs ranges between 8.5 to 9.0). It is clear that the quantities of alkaline earth carbonate contents in different soils buffered the soil pH in ranges from neutral to strongly alkaline. Calcium carbonate increases the soil pH by the hydrolysis process as shown below:

$$CaCO_3 \text{ (solid)} + HOH \text{ (liquid)} = Ca^{2+} + HCO_3^- + OH^-$$

Soil name at family level using USDA Soil Taxonomy	Common soil properties	ECe (dS/m)	ESP	Salt-affected soil category	pHs	CaCO3 %
Sandy, carbonatic, hyperther-mic Typic Aquisalids	Saline calcareous with water table in the upper 1 metre	204	70	Saline-sodic	8.62	43
Sandy, mixed, hyperthermic Typic Aquisalids	Saline with water table in the upper 1 metre	212	81	Saline-sodic	7.06	20
Fine-clayey, anhydritic hyperthermic Gypsic Aquisalids	Saline-anhydritic with water table in the upper 1 metre	198	58	Saline-sodic	7.15	12
Sandy, gypsic, hyperthermic Gypsic Aquisalids	Saline-gypsiferous with water table in the upper 1 metre	184	74	Saline-sodic	7.29	26
Sandy, carbonatic, hyperthermic Typic Haplosalids	Saline calcareous with water table below 1 metre	203	72	Saline-sodic	6.86	43
Sandy, mixed, hyperthermic Typic Haplosalids	Saline with water table below 1 metre	133	73	Saline-sodic	7.78	6.4
Sandy, gypsic, hyperthermic Gypsic Haplosalids	Saline gypsiferous with water table below 1 metre	229	75	Saline-sodic	6.74	42
Sandy, gypsic, hyperthermic Leptic Haplogypsids	Gravelly gypsiferous with gypsum accumulation starting at less than 18 cm	17	27	Saline-sodic	8.08	15
Sandy skeletal, mixed hyper-thermic Leptic Haplogypsids	Gypsiferous with gypsum accumulation starting at less 18 cm from surface	12	16	Saline-sodic	7.97	3.3
Sandy, carbonatic, hyper-thermic Typic Petrocalcids	Carbonatic hardpan	1.3	1	Normal	8.53	53
Sandy, carbonatic, hyper-thermic Typic Torriorthents	Coastal rich in sea shells and carbonates	16	24	Saline-sodic	8.12	34
2Carbonatic, hyperthermic Typic Torripsamments-Inland	Typical desert sandy and sand-dune	2.8	1.2	Normal	8.25	45
Carbonatic, hyperthermic Typic Torripsamments-Coastal	Typical coastal white sandy, sandy beach	12.6	16	Saline-sodic	8.73	80

Table 2.3: Assessment of soil families1 at the upper 50 cm depth with regards to saline, saline-sodic and sodic criteria in the coastline of Abu Dhabi Emirate.

[1] Source: Shahid *et al.* (2004)

[2] Soil type cover large parts (>70%) of the Abu Dhabi Emirate desert

The above reaction produces hydroxyl (OH^-) ions which can increase pH to as high as 8.5. This reaction is common in the desert soils of the Emirate. The rise of soil pH due to hydrolysis depends upon the final base formed, *e.g*., in the presence of $CaCO_3$, a weak base $Ca(OH)_2$ is formed and the pH may rise up to 8.5; however, if a strong base is formed from Na_2CO_3 and $NaHCO_3$ to form NaOH, this may increase the pH to as high as 10. Such high pH has not so far been observed in Emirate soils. As per Foth (1984), the optimum pH for alfalfa, barley, beans, sugar beets and clover ranges between 6.0 to 8.0; rice, maize, tobacco, wheat, peas, peanuts do well in the range of 5.5 to 7.0, and a pH range 4.0 to 7.0 is the best for forestry plantations. Due to low solubility, it is not easy to leach carbonates, however, if the soil is treated with sulphur it can decrease carbonates in soil and lower soil pH. In agricultural soils where carbonates equivalents are of high quantities, deficiency of micronutrients commonly occurs. Therefore, the best way is to use foliar application of the fertilizers containing micronutrients, although foliar application has its own limitations due to leaf burn.

Almost all soils of the Emirate contain variable quantities of carbonates. Carbonates (carbonate equivalents) influence the availability of plant nutrients such as phosphorous, molybdenum, iron, boron, zinc, and manganese deficiencies, which are common in plants growing in soils that have significant levels of calcium carbonates equivalents. The carbonates are minimal in the coastline soils, which are rich in salts and where the water table starts below 1 metre deep, and in soils rich in gypsum and anhydrite contents. Sandy desert and sand dune soils are high in carbonate contents and generally present more than 30% and as high as 80% or even more in white sandy coastal soils such as Typic Torripsamments and coastal shells soils such as Typic Torriorthents. Carbonates occur in the form of calcite and dolomite in sufficient quantities and aragonite in relatively small quantities (Calcite > dolomite > aragonite). Future soil survey may identify other forms of carbonates in the Emirate soils.

2.4 Soil Mineralogy

The physical and chemical properties of the soil are controlled to a great extent by the soil minerals. Soil mineralogical information is useful in making predictions about soil behaviour and responses to management. Knowledge of soil mineralogy is of importance in determining mineral resources in an area and in determining soil potential for agricultural and other activities. Identification of soil mineral types and composition can be accomplished by using number of techniques, among all techniques x-ray diffraction (XRD) is by far the most powerful tool in soil mineral identification and this has been used in the coastline survey. As stated earlier, very scarce information is available on soil aspects which also apply to soil mineralogy of the Emirate of Abu Dhabi. An attempt has been made by Shahid *et al*. (2004) to explore the whole soil mineralogy and mineralogy classes of the control section (soil depth on which soil classification is based) to identify soil families in the Emirate soils. In other words, it is the depth where most of the constituents accumulate through soil forming processes. The soil material above the control section may be different in soil mineralogical contents, *e.g*., halite was dominant in the salt-crusts identified in the coastline. These semi-quantitative results (**Table** 2.4) are summarized from the x-ray diffraction pattern of soil samples (less than 2mm) from the control section of the identified soil families (Shahid *et al*., 2004).

Table 2.4 illustrates that the mineralogy of the control section is dominant by Quartz (SiO_2) mineral accompanied by varying quantities of plagioclase feldspar, dolomite, calcite, gypsum, anhydrite and halite. Quartz is the most abundant in all soils except in anhydrite rich soils. Quartz is universally present in soils and it is relatively resistant to chemical and physical weathering processes. It is one of the most abundant minerals and occurs as an essential constituent of many igneous, sedimentary and metamorphic rocks. The universal dominance of quartz is due to the fact that 99% of the Earth's elemental composition consists of 8 elements (O, Si, Al, Fe, Mg, Ca, Na, K), of which O and Si accounts for 46.6% and 27.72% respectively (Paton, 1983). From a mass standpoint, soil is an O-Si-Al-Fe matrix containing relatively small amounts of the essential elements. Quartz and plagioclase feldspar are important members of the tektosilicates group of silicate minerals. Calcite is the second mineral that widely occurs in the Emirates' soils. Both quartz and calcite constitute the main mass in Emirate soils. The presence of quartz and calcite together in the soil media restricts the uses of quartz for construction and calcite for cement factories. If somehow both can be separated at large scale, they can be a valuable source for these uses. The future soil survey will identify areas where these minerals may occur independent of each other. Anhydrite and gypsum are other minerals of commercial value, the latter is widely used and considered most suitable for the reclamation of saline-sodic and sodic soils. Halite was detected in salt rich soils (Salids) in the coastline. The coastline of Abu Dhabi Emirate is rich in halite sources. Halite as table salt or rock salt is used in many industries and it can be harvested through evaporation in evaporation ponds. Halite is used in soda manufacturing factories ($NaCl + H_2O \rightarrow NaOH$ (caustic soda) + HCl (Hydrochloric acid), which also produces hydrochloric acid as by-product, the HCl has many uses.

Soil name at family level using USDA Soil Taxonomy	Depth (cm)	Quartz SiO_2	Plagioclase $CaAl_2Si_2O_8$	Dolomite $CaMg(CO_3)_2$	Calcite $CaCO_3$	Gypsum $CaSO_4.2H_2O$	Anhydrite $CaSO_4$	Halite NaCl	MineralogyClass
Sandy, carbonatic, hyperthermic Typic Aquisalids	40	D	M	Mi	D	-	-	M	*Carbonatic*
Sandy, mixed, hyperthermic Typic Aquisalids	50-80	D	M	Mi	-	-	-	M	*Mixed*
Fine-clayey, anhydritic, hyperthermic Gypsic Aquisalids	40-70	Mi	-	-	-	M	D	Mi	*Anhydritic*
Sandy, gypsic, hyperthermic Gypsic Aquisalids	5-30	M	-	Mi	Mi	D	Mi	M	*Gypsic*
Sandy, carbonatic, hyperthermic Typic Haplosalids	80-140	D	Mi	Mi	D	-	-	D	*Carbonatic*
Sandy, mixed, hyperthermic Typic Haplosalids	15-50	D	Mi	Mi	Mi	-	-	M	*Mixed*
Sandy, gypsic, hyperthermic Gypsic Haplosalids	20-60	D	-	M	D	M	-	M	*Gypsic*
Sandy, gypsic, hyperthermic Leptic Haplogypsids	60-100	D	Mi	Mi	M	D	-	-	*Gypsic*
Sandy skeletal, mixed, hyperthermic Leptic Haplogypsids	10-40	D	M	Mi	Mi	M	-	-	*Mixed*
Sandy, carbonatic, hyperthermic Typic Petrocalcids	0-20	D	Mi	Mi	D	-	-	-	*Carbonatic*
Sandy, carbonatic, hyperthermic Typic Torriorthents	40-60	D	M	M	D	-	-	-	*Carbonatic*
1Carbonatic, hyperthermic Typic Torripsamments-Inland	40-75	D	Mi	Mi	D	-	-	-	*Mixed*
Carbonatic, hyperthermic Typic Torripsamments-Coastal	30-60	Mi	Mi	Mi	D	-	-	-	*Carbonatic*

Table 2.4: Semi-quantitative summary of the minerals in the soil control section of Abu Dhabi coastline.

Soil types cover large parts (>70%) of the Abu Dhabi Emirate Desert; D = Dominant; M = Major; Mi = Minor; - = undetectable.

Mineralogy Classes

Four mineralogy classes have been identified in the coastline of Abu Dhabi Emirate: namely, carbonatic, anhydritic, gypsic and mixed (Shahid *et al*., 2004). These have been used to name soil families. The soils which present more than 40% carbonates (expressed as $CaCO_3$) plus gypsum ($CaSO_4.2H_2O$) in the fine earth fraction (< 2mm) were designated with carbonatic mineralogy class. However, when more than 40% (by weight) carbonates (expressed as $CaCO_3$) plus gypsum was present, with gypsum constituting more than 35% of the total weight of carbonates plus gypsum, Gypsic mineralogy class was designated. Anhydritic mineralogy is a new mineralogy class that was introduced by Shahid *et al*., (2004) when anhydrite ($CaSO_4$) was identified instead of gypsum. Mixed mineralogy is only used when other mineralogy classes were not keyed out as specified in USDA-NRCS (1999) and the soil has no single mineral dominant but it is mixture of a number of minerals.

2.5 Soil Fertility

Soil fertility is the capacity of the soil to supply essential nutrients to plants. In the broader perspectives it is the capacity of soil to produce certain yields of crop with optimum management. Fertility is one component towards production of crop yields, therefore, it is considered as part of soil productivity. It should be very clear that fertile soils are not always productive, *e.g*., a soil may be very fertile due to nutrients but non-productive due to high salinity and sodicity, which may restrict nutrient availability to plants.

Plants contain almost 92 natural elements but need only sixteen for good growth. Thirteen of which, are essential and must be either available in soil or applied through fertilizers and manures. Six elements are considered as macronutrients, of which three elements, *i.e*., N, P and K are major and applied in the form of fertilizers to all crops on most soils; and three as secondary nutrients, *i.e.*, S, Ca and Mg and applied in the form of fertilizers to certain crops on some soils. The critical contents of macronutrients in plants are 2-30 g/kg of dry matter; seven micronutrients (heavy metal, *i.e*., Fe, Mn, Zn, Cu, Mo; non-metals *i.e.*, Cl, B) of which the critical contents in plants are 0.3 to 50 mg/kg of dry matter. The Na, Si, Co, Cl and Al are other nutrients that have a beneficial effect on some plants but are not essential.

Soils of the Emirate desert environment, in general, are sandy in nature consisting of dominant minerals such as quartz (SiO_2) and carbonates ($CaCO_3$), with low proportions of clay, silt and organic matter contents, and therefore, they are low in inherent or natural soil fertility. The fertility of the Emirate soils can be considerably improved by the addition of nutrients in the form of chemical and organic fertilizers. Following are the facts about soil fertility constraints of the Emirate soils.

Soil depth - arable crops require a soil depth of about 1 metre without any hardpan. The Emirate sandy desert soils, in general, are very deep. However, in places where there is hardpan sand may be deposited over the hard pan which may cause waterlogged conditions through irrigation. The deep sandy soils are very porous and there is a danger that most of the plant nutrients may be leached below the root zone and pollute the subsoil and perhaps ground water resources. Particular concern is with NO_3^- ions, which due to negative charge cannot be held up on soil exchange complex (which is already negatively charged) and move to deeper layers. In contrast NH_4^+ due to a positive charge can be held up on negative surfaces of the exchange sites on clays and organic matter and becomes available to plants through ion exchange phenomenon. Addition of organic matter, manures and synthetic polymers may enhance sandy soils stability to hold more water and nutrients for plant growth.

Soil Structure of most of the Emirate soils is single grain and massive, and the macro pores in such sandy soils do not hold water, therefore, water and nutrient storage capacity is very low. In low storage capacity soils, fertilizers should be split into different doses or added in the form of slow release fertilizers. Soil structure can be improved by increasing vegetation cover and by adding organic matter and synthetic polymers.

The alkaline *pH* and sufficient quantities of *carbonates* in the Emirate soils (**Table** 2.3) are inherent constraints for the availability of most of the nutrients to plants. Amongst other nutrients, phosphorous availability to plants is inhibited in the presence of carbonates. Use of acidifying N fertilizers can be advantageous through resulting in a better supply of micronutrients such as Mn or Zn which tend to be immobilized.

Hyper-arid condition, bare or low vegetation cover, and pressure of soil degradation on soils resulted into low organic matter content in most of the soils. Exceptions may be in the areas cultivated with forestry plantations in the Emirate. Low *organic matter* and soil moisture ultimately inhibits activity of soil microorganisms and therefore, even if there are small quantities of organic matter in soils, it may not be mineralized to release nutrients.

Coastal soils rich in soluble salts are infertile and non productive for any kind of vegetation. Most of Abu Dhabi Emirate coastline is bare, in places thick surface salt crust does exist, in other places halophytes were observed.

2.6 Soil Classification

A detailed practical soil map of the Emirate does not exist at present; however, previous studies (UAEU, 1993; Shahid *et al.*, 2004) strongly suggest the occurrence of soil diversity in the Emirate. The future Emirate wide soil survey (EAD-ICBA, 2005) will present detailed soil classification for which there are currently preliminary results soon to be published. Therefore, this gap has been addressed while an additional land use/land cover working group has been established by the Abu Dhabi Spatial Data Infrastructure (AD-SDI) program that the soil survey can contribute to. A soil classification in the Emirate will enhance the interchange of information on soils from one area to another. It also helps in predicting the suitability of different areas for agricultural and other uses.

The soils of Abu Dhabi Emirate (Shahid and Abdelfattah, 2005) can broadly be categorized as sandy, sand-dune, sandy calcareous, gypsiferous, saline, saline-gypsiferous, and hard pan soils *etc*.. These soils have been classified under three soil orders (Aridisols, Entisols and Inceptisols) of the Soil Taxonomy (USDA-NRCS, 1999). Entisols are the most occurring soils, followed by Aridisols to a relatively lesser extent, and the Inceptisols is the least occurring soils in the Emirate. In the above two publications, soil classification is described in which detailed descriptions of soil masses and their discontinuities are made through auger-holes, soil pits and complete soil profiles, and supported with laboratory soil data. These soils are described in the context of their formation, temperature and moisture regimes, properties and occurrence in the Emirate (see Shahid & Abdelfattah, 2005 for further details).

Soil moisture is an important property that determines the process of soil development and ultimate soil formation. In general, arid zone soils are considered dry, however, they may not be necessarily dry, they can be moist or saturated based on location of landscape, where water may have been accumulated through runoff or other sources. In the Emirate, Aridic (L. *aridus*, dry) or Torric (L. *torridus*, hot) and Aquic (aqua, water) soil moisture regimes have been identified. Hyperthermic is the soil temperature regime identified in the Emirate soils. This shows that Emirates' soils, in general, present mean annual soil temperature of 22 °C or higher and the difference between mean summer and mean winter soil temperature is more than 6 °C either at a depth of 50 cm from the soil surface or at a densic, lithic or paralithic contact, whichever is shallower. Mineralogy classes identified at the soil family level are discussed in the Soil Mineralogy Section.

2.6.1 Diagnostic horizon identified in the Emirate soils

The soils are classified on the basis of the occurrence of diagnostic horizons, their thickness and the quantities of the mineral contents. Three diagnostic horizons are identified in a previous study (Shahid *et al*., 2004) on Abu Dhabi Emirate soils. They are salic, gypsic and petrocalcic diagnostic horizons. Salic horizon is widely distributed in the coastal soils influenced by sea water intrusion and is rich in soluble salts. Gypsic horizon was identified in the coastal areas and is rich in gypsum and anhydrite contents. In the inland, gypsum rich horizon was also identified. Cemented carbonatic layer of petrocalcic horizon was identified in the eastern part of the Emirate. A future soil survey may identify more diagnostic horizons and subsequently more soil types.

A Entisols – Sandy Desert Soils

Entisols are the least developed sandy mineral soils, low in organic matter, and present no evidence of accumulation of specific features to form diagnostic horizons. Three suborders (psamments, orthents and fluvents), and three soil great groups (torripsamments, torriorthents and torrifluvents) have been recognized in the previous studies (UAEU, 1993; Shahid *et al*., 2004). Article on "*Sands of Time Heritage*" published in the Gulf News (2003), describes the background of seven colour sands in the United Arab Emirates.

Psamments are typical inland poorly graded desert sandy soils (**Figure** 2.9). The Psamments have low water holding and run-off capacity, high infiltration, well drained, low inherent fertility and occur as shifting or stabilized sand dunes of various heights ranging from nearly level to two and more than 50 metres height. The white sandy beaches scattered along the coast are also psamments with relatively more coastal carbonate contents (**Figure** 2.10). Psamments are generally deep soils but they may occur as thin sand cover over hardpan. Native sandy soils are calcareous, slightly to moderately alkaline, and non-saline and non-sodic. Surface very often-present well developed nabkha features (**Figure** 2.11).

Orthents are formed on recent erosional surfaces along the coastline where the diagnostic horizon from other orders does not occur. They occur as narrow and broader, level to nearly level ridges along the coastline (**Figure** 2.12). Orthents are recognized as rich in calcareous material dominated by seashells, and are strongly saline due to intrusions of the nearby saline sea water, in the inland they may be non-saline. Texture varies from sand, loamy sand, sandy loam, loam.

Fluvents are the least abundant soils, and are dominated in the mountain areas, where they are non-saline to moderately saline, texture is generally loamy, and some are sand and gravelly. They are not found along the coastline of Abu Dhabi Emirate.

Figure 2.9: Typical inland desert sandy soil “Psamments”.

Figure 2.10: Typical coastal white sandy soil “Psamments”.

Figure 2.11: Nabkha features on inland desert sandy soil “Psamments”.

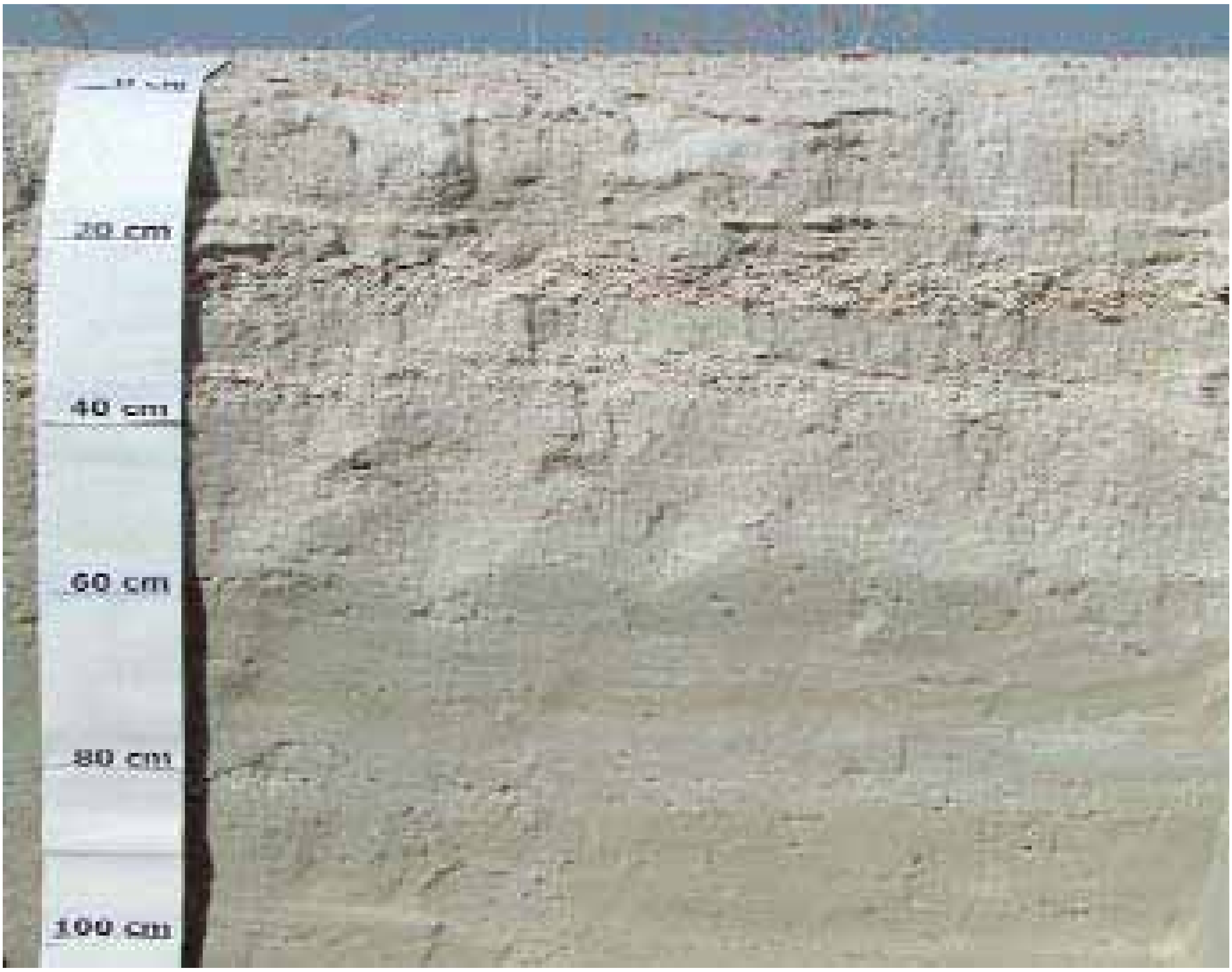


Figure 2.12: Typical soil developed on sea shells and sand “Orthents”.

B Aridisols

Aridisols are soils in which water is not available to mesophytic plants for long periods, *i.e.*, there is no period of 90 consecutive days when moisture is continuously available for plant growth. The soils are usually dry, soil water is held at potentials less than the permanent wilting point. Due to imbalance between the evapotranspiration and precipitation, many soils in the Aridisols contain soluble salts to a degree that affect plant growth. A striking feature is observed in Emirate soils, a cemented and compacted layers composed of carbonates (caliche), gypsum, silica (hardpan) and due to their resistance to weathering, they may be relics of older landform and not related to present profiles. These layers impede excavation in building and landscaping, restrict water movement, limit drainage, and impose problems for irrigation. In contrast to caliche or a duripan, the dissolution of subsurface gypsum may cause subsidence of soils through solution and removal of gypsum can crack building foundations, corrode concrete, *i.e.*, gypsum contents of 1.25% are high enough (Soil Conservation Service, 1971) to provide enough sulphate to place the soil in a high corrosion class - greater than 7,000 ppm sulfate, break irrigation canals, and make roads uneven.

In the Emirate of Abu Dhabi, Aridisols soils are second most occurring after Entisols. According to the USDA Soil Taxonomy (USDA-NRCS, 1999), three suborders have been identified in the coastline of Abu Dhabi Emirate, *i.e.*, Calcids, Gypsids, and Salids. The future soil survey will diagnose more soil types and their potential uses (EAD-ICBA, 2005). At the suborder level, in the old Soil Taxonomy (USDA, 1975) only Orthids has been recognized (UAEU, 1993), divided into three great groups (calciorthids, gypsiorthids and salorthids).

Salids - Soils with soluble salts

Salids are frequently recorded in the coastline of Abu Dhabi Emirate (Shahid *et al.*, 2004). The evaporation and continuous seawater intrusion, reaction between the sediment and the extremely saline groundwater (with EC > 200 dS/m) has produced these very strongly saline soils. The salids present picturesque features such as thick salt crust of polygonal pattern (**Figure** 2.13) and constitute one of the most common landforms along the coastal plains as well as some inland areas. When the water table is in the upper 1 metre, they are classified at the subgroup level as "Typic Aquisalids" (**Figure** 2.14) otherwise they are "Typic Haplosalids" (**Figure** 2.15). In the presence of gypsum and/or anhydrite horizon and the water table in the upper 1 metre, they are classified as "Gypsic Aquisalids" (**Figure** 2.16) otherwise as "Gypsic Haplosalids". Saline soils have also been recorded in agricultural areas; however, the salt contents are not high enough to qualify as Salids. Halite (NaCl), gypsum ($CaSO_4.2H_2O$), and anhydrite ($CaSO_4$) are common evaporite minerals identified in the Emirate coastline. The soils where gypsum is found closely correspond to the distribution of anhydrite.

Gypsids - Soils with gypsum

Gypsum occurs as rock outcrops, powdery and crystalline material, and large well-developed lenticular crystals. The rock outcrops are exposed in the northwestern part of the Emirate. In the coastal areas gypsum is found as flakes, acicular, lenticular and rosettes forms. Inland, gypsum is found mainly in the lower horizons of the soil profiles; however, in the coastal areas it frequently occurs within the upper 18cm depth. When the gypsum is present in the subsurface horizon as 15cm or more thickness, and has 5% or more gypsum than the upper horizon, and has product of thickness in cm multiplied by the % gypsum content of 150 or more it is termed *'gypsic horizon'*. Based on these criteria, soils are classified as Typic Haplogypsids (when the gypsic horizon is below 18cm of surface), and Leptic Haplog ypsids (when the gypsic horizon starts its upper boundary within the upper 18cm depth). Leptic Haplogypsids **(Figure** 2.17**)** is common in the coastal area, whereas Typic Haplogypsids may occur inland, in places gypsum is cemented and identified in the upper 1 metre (Petrogypsids). In the interior of the Emirate, they occur extensively in the southeastern part (UAEU, 1993).

Calcids - Soils with carbonates

The soils of Abu Dhabi Emirate, in general, are calcareous (containing carbonates equivalents) to varying degrees. In these soils, some of the carbonates are present through the weathering of the carbonatic parent material, while others are derived from the influx of carbonate-rich wind borne dust as a part of the desert environment. With limited and infrequent rainfall, carbonates are dissolved and precipitated at a depth based on depth of wetting through a complex of geochemical and physical processes. In places, the carbonatic soil material is well laminated and cemented to form aeolianites. Chemical analysis shows that, in the sand dune and loose sandy soils which cover most of the Emirate desert carbonate ranges between 6 and 47%, whereas, in the coastal soils it ranges between 30 and 83%, in the calcrete up to 53% carbonates were recorded (Shahid & Abdelfattah, 2005). The soils presenting sufficient calcium carbonate contents within the upper 100 cm depth are qualified as having calcic diagnostic horizon. These soils are classified as Calcids (suborder). When the water table is present below one metre, the soils are classified as '*Typic Haplocalcids'.* In case of a petrocalcic horizon, it is classified as "Typic Petrocalcids" **(Figure 2.18).** The petrocalcids are calcrete/hardpan soils and occur mostly in the northeastern part of the Emirate in the form of gently undulating landform type.

Figure 2.13: Polygonal salt features on the surface of Salids.

Figure 2.14: Typic aquisalid showing surface salt crust and water table within upper 1 metre.

Figure 2.15: Typic Haplosalids showing water table below 1 metre.

Figure 2.16: Gypsic Aquisalids showing gypsum accumulation and water table within upper 1 metre.

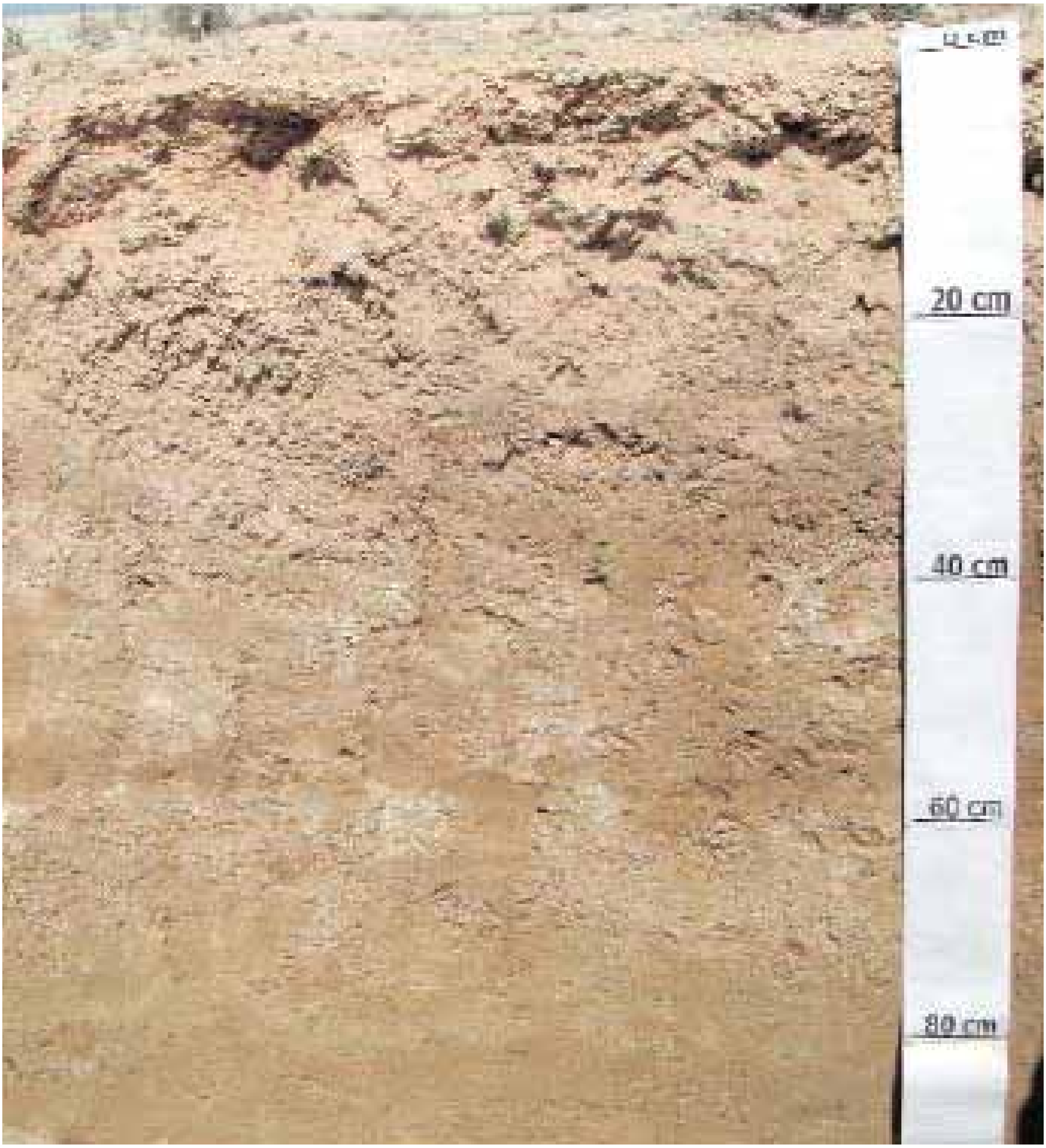


Figure 2.17: Leptic Haplogypsids showing presence of gypsum within upper 18cm.

Figure 2.18: Petrocalcids showing carbonate rich cemented hardpan.

C Inceptisols

Inceptisols (from the word inceptum, meaning beginning) is the third soil order identified in Abu Dhabi Emirate (UAEU, 1993). These soils are formed on slightly weathered parent material and are the least abundant in the Emirate. They occur in the low interdunal area and are associated with natural springs and are often cultivated. Only two great groups (Haplaquepts and Eutrochrepts) have been recognized in the Emirate (UAEU, 1993). Haplaquepts are formed on loamy deposits and are poorly drained, with near surface water table except where they are drained, and often saline to varying degrees. Eutrochrepts differs from Haplaquepts as they are better drained.

Soil classification hierarchy (2 order, 5 suborders, 6 great groups, 8 subgroups and 13 families) of the coastline of Abu Dhabi Emirate (Shahid *et al*., 2004) is shown as **Figure** 2.19. The Entisols adjoining to coastline extends inland to a larger extent, and represent more than 70 % of the Emirate desert. The future Emirate wide soil survey will identify more soil classes and demonstrate greater soil diversity in the Emirate.

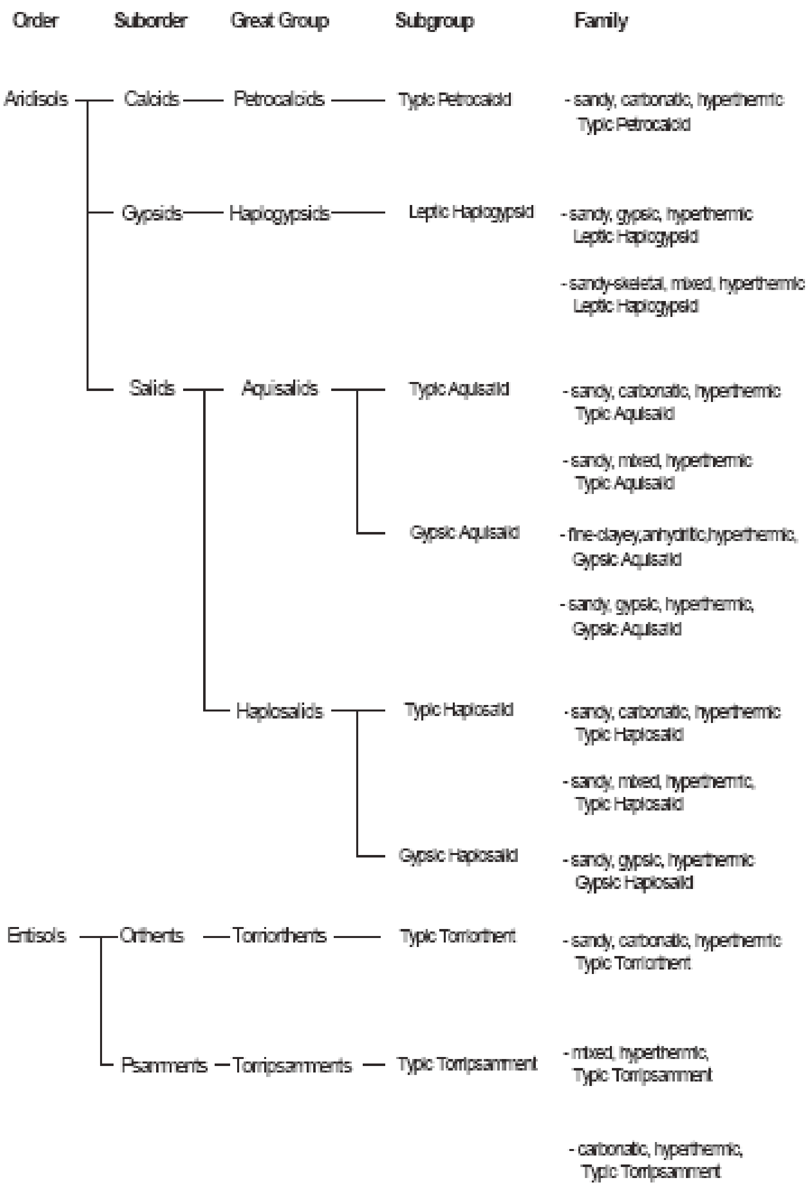


Figure 2.19: Classification hierarchy of soils identified in the Coastline of Abu Dhabi Emirate (Shahid et al., 2004).

2.7 Land Suitability Evaluation

The land suitability evaluation is a process of assessing the potential of soil types for one or more uses. In the past, soil survey information in many countries have been mainly assessed for agricultural activities, however, the soil survey discipline has now been broadened to include uses other than agriculture including environmental, industrial and urban concerns. Presently, such evaluation of the Emirate soils does not exist. In a previous soil study (UAEU, 1993), a general soil map was produced that lacked a detailed database needed to accomplish suitability evaluation. The recent soil study for the coastline of Abu Dhabi Emirate (Shahid e*t al*., 2004) presented detailed soil information that allows a suitability evaluation; however, this study focused only on the coastline of Abu Dhabi. In that study, thirteen soil families were identified at family level, of which one soil family "*carbonatic*, *hyperthermic*, *Typic Torripsamments-Inland*" represents large desert area (sand, sand sheets and sand dune soils) of Abu Dhabi Emirate and therefore, have high relevance to perhaps the large (> 70%) sandy desert soils of the entire Abu Dhabi Emirate.

To fill this gap on the soils of Abu Dhabi Emirate, the Executive Council of Abu Dhabi approved a soil survey action plan and allocated the necessary funds (EAD-ICBA, 2005) for its implementation over the next four years. In this action plan, emphasis have been made to evaluate soils and soil mapping units for a number of potential uses to aid the decision makers for future land use planning in the Emirate. A number of uses such as suitability for agriculture, rangelands, forestry, wildlife, sanitary landfills, and sources for anhydrite, gypsum, gravels, sand, clay, sweet soil, carbonates have been proposed. In addition, a Soil Information System (SIS) will also be established to present Emirate wide thematic maps, *i.e*., suitability, land degradation, soil salinity, water table, vegetation and hardpan, *etc.*

In the absence of a detailed Emirate wide soil inventory and soil database, it is not justified to present an overall soil suitability classes for potential uses. Therefore only a brief general description of the potential suitability of soils given and this is based on the limited information available and authors experience in similar soils. This highlights the need for detailed on-site investigations.

The future Emirate wide soil inventory (EAD-ICBA, 2006) will present a clear picture for potential uses of Emirate soil resources.

The suitability classes for irrigated agriculture are those described by FAO (1976), where S1 is highly suitable without significant limitation; S2 is moderately suitable with moderate limitations; S3 is marginally suitable with severe limitations; N1 is currently unsuitable with severe limitations which cannot be corrected with existing knowledge and technology at currently acceptable costs; N2 is permanently unsuitable with severe limitations which cannot be corrected at all. Other potential uses are described in terms of limitations for specified uses *e.g*., soils with *Slight* limitations require no additional measures other than normal procedure for site uses; *Moderate* limitations require changes to the original design or the application of corresponding conservation practices, or both, to overcome the limitations; *Severe* limitations are found where soil properties are unfavorable and the limitations can be offset only by costly soil reclamation. Possibility of some resources is described as *Probable* where the material is likely to be in or below the soil, and *Improbable* where the material is unlikely to be in or below the soil.

The Psamments are the most abundant soils in Emirate of Abu Dhabi desert environment. The soils under the *Psamments* category present severe limitations for their uses as camp areas (too sandy), shallow excavations (cutbanks cave), septic tank absorption fields (poor filter), sewage lagoons (seepage), and sanitary landfill sites-trench (too sandy). The soils, however, have potential as desert plant habitat and as a probable source for sand and carbonates mining. Leveled Psamments can be designated as S2, whereas the high sand dunes although presenting similar soil material require intensive intervention and high investments for leveling, therefore they are designated as S3. The soils under Psamments are non-saline, however, sandy soil have other limitations, such as, they are vulnerable to wind erosion, high infiltration rate, poor inherent soil fertility *etc.*

The soils in the *Orthents* (soils developed on sea shells, marine clays and silts and aeolian sand) category present similar limitations to uses as the *Psamments*, but are poorly suited as desert plant habitat (excess salinity and carbonates) and are improbable for sand sources. Orthents are designated as N2 (permanently unsuitable for irrigated agriculture) due to high salt and coastal shells and their distribution near the sea. Inland Orthents may be designated as S2 or S3.

The soils in the *Salids* (coastal soils rich in soluble salts and water table within the upper 1.25m) category present severe limitations for their uses as camp areas (water ponding, wetness, excess salts), shallow excavation (wetness, high water table), septic tank absorption field (ponding, wetness, high water table), sewage lagoons (seepage, ponding, wetness, high water table), sanitary landfill area (ponding, wetness, high water table). Salids are poorly suited as desert plant habitat (excess salts) and improbable for sand sources (excess salts, wetness), probable source for minerals such as rock salt-halite (NaCl), gypsum ($CaSO_4.2H_2O$) and anhydrite ($CaSO_4$) (see Shahid *et al*., 2004). Salids are designated as N2 (permanently unsuitable for irrigated agriculture) due to a very high salt content and high water table. Coastal Salids are influenced by continuous sea water intrusion.

The soils in the *Gypsids* (rich in gypsum) category present severe limitations for their uses as camp areas (too sandy), septic tank absorption field (subsides, percs slowly), sewage lagoons (seepage) and sanitary landfill trench (too sandy). Gypsids are suited as desert plant habitat, and improbable for sand sources, and probable for gypsum source. In places, Gypsids (sandy-skeletal) have probable source for gravels. Gypsids are designated as N1 (when gypsic layer identified below 18 cm), and N2 when gypsic layer was identified within the upper 18 cm depth. The limitations to agriculture are high gypsum content, subsidence behaviour, and sometimes high salt contents.

The soils in the *Petrocalcids* (carbonate rich hardpan) category present severe limitations for their uses as camp areas (thin surface sand followed by cemented pan), shallow excavations (cemented pan), septic tank absorption fields (cemented pan), sewage lagoons (cemented pan) and sanitary landfill sites-trench (cemented pan). The soils have potential as desert plant habitat where there is more than 50cm loose sand above the hardpan, and no potential where there is exposed hardpan. Petrocalcids are an improbable source for sand and gravels, but probable source for construction material (limestone) used for road beds, *etc*. Petrocalcids, which have some soil material over the hard pan, are designated as N1 (currently unsuitable for irrigated agriculture), whereas, those where the hard pan is exposed due to truncation of soil material and through human activity are designated as N2 (permanently unsuitable for irrigated agriculture).

2.8 Land Degradation and Desertification

Land and soil are the important components of the Emirate's desert ecosystem and of the wider environment in which all plants and animals live. Over many years human used the environment to gain different benefits, however, many of the methods used to gain those benefits are now being seen as unsustainable because in many cases they lead to degraded land and "desertification". Degradation is the result of a number of interrelated factors ending in land that is chemically or physically too degraded for productive use or environmental services, and often also results in degraded visual amenity. The degradation driving forces produce pressures that result in the current state of land resources with a negative impact on society and the environment. Abu Dhabi land resources are of high environmental value, clearly there is a lot riding on our capacity to understand, conserve and manage the land resources of the Emirate efficiently and as much as possible close to sustainable, that ultimately leads to combat desertification. Theoretically, a natural environment is one that is relatively unchanged or undisturbed by humans. In reality this is not possible due to the complexity of the natural and human influences that reduce biodiversity and change habitats for different species.

Desertification is a world-wide phenomenon and is much discussed as an environmental and social problem. The UN General Assembly in 1994 approved the Convention to Combat Desertification (CCD), however, the UNCCD entered into force on 26 December, 1996. As of 10 March 2004, a total of 191 countries had ratified and accepted the convention; the UAE has joined the UNCCD on 21 October 1998 and became a member on 19 January 1999. The UNCCD defines desertification as land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors, including climatic variations and human activities (UN, 1994). However, it is intensified in the hyper-arid climate as is the case in Abu Dhabi Emirate. In this definition, land includes soil, vegetation and groundwater resources. This definition is in fact modified from an earlier UN version (UN, 1992) that stated only the human actions as the causal mechanisms. Gray (1999) stated land degradation as an attribute of human causes, and many relate it to a reduction in productivity. Johnson and Lewis (1995) defined land degradation as the substantial decrease in either or both of an area's biological productivity and usefulness due to human inferences. Lindskog and Tengberg (1994) defined it as a reduction of the physical, chemical or biological status of land which may restrict its productive capacity. Johnson *et al*. (1997) defined it as any disturbance to the land perceived to be deleterious or undesirable. In the author's opinion land degradation (desertification) is the reverse of soil development or formation, and desertification can best be reversed by early action and prevention rather than costly rehabilitation of degraded lands.

Land degradation has been a major global issue during the 20th century and will remain high on the international agenda in the 21st century. The importance of land degradation among global issues is enhanced because of its impact on world food security and quality of the environment. Land degradation (desertification) affects about one sixth of the world's population, 70 % of all drylands, amounting to 3.6

billion hectares, and one quarter of the total land area of the world. The most obvious impact of desertification is the degradation of 3.3 billion hectares of the total area of rangeland, constituting 73 % of the rangeland with a low potential for human and animal carrying capacity; decline in soil fertility and soil structure on about 47 % of the dryland areas constituting marginal rainfed cropland; and the degradation of irrigated cropland, amounting to 30 % of the dryland areas with a high population density and agricultural potential.

Soil and land are defined from different point of views, following are the key definitions used in desertification. *Soil* is the unconsolidated mineral or organic material at the surface of the earth, capable of supporting plant life (Bridges, 1977), where as *Land* is a delineable area of the earth's terrestrial surface, encompassing all attributes of the biosphere immediately above or below this surface, including those near the surface, the climate, the soil and terrain forms, the surface hydrology (including shallow lakes, rivers, marshes and swamps), the surface sedimentary layers and associate groundwater reserve, the animal population, the human settlement patterns and physical results of past and present human activity (terracing, water storage or drainage structure, roads and buildings, *etc.* (FAO, 1995). Soil and land degradation are commonly used terms in desertification. Soil degradation is a process that lowers the current and/or the potential capability of soil to produce goods or services (FAO-UNEP-UNESCO, 1979), or loss or a reduction of soil functions or soil uses (Blum, 1997). Land degradation encompasses soil degradation and the deterioration of natural landscapes and vegetation. Human-induced degradation includes the adverse effects of overgrazing, excessive tillage, over clearing, erosion and sediment deposition, extractive industries, urbanization, disposal of industrial wastes, road construction, decline of plant communities, the effects of animals and noxious plants, and pollution of the air with its effect on land (Houghton & Charman, 1986). It is clear from the above definitions that land degradation covers a wider concept of desertification and also includes soil degradation.

2.8.1 Combating Desertification-UNCCD in the UAE Perspectives

The United Arab Emirates is located within the arid west continent desert belt, its environment similar to the other semi-arid and arid environments of the world is very fragile, sensitive and very slowly renewable. The desert environment of Abu Dhabi is a very fragile ecosystem with unique features, *e.g.*, vast loose sandy deserts, oasis, long coastline, islands and few mountains, *etc*.

Combating desertification is the most spoken about and frequently used term in many countries of the world, the UAE looks to it from different angle and perspectives based on its environmental conditions and the vision of HH Sheikh Zayed Bin Sultan Al Nahyan in improving UAE desert conditions. Therefore, the term "combating desertification" as a compromise is used for '*Greening The Desert*" (FEA-UAE, 2002). Greening The Desert is concerned with converting the natural desert environment into productive agricultural land, conserving its biodiversity and increasing its economic outcome. On the other hand, Combating Desertification is the sum of activities leading to integrated development of land (not soil) in arid, semi-arid and sub-humid areas for sustainable development aiming at prevention and/or reduction of land degradation; rehabilitation of partly degraded land; and reclamation of desertified land.

2.8.2 Efforts of UAE for Greening the Desert

The UAE efforts in Greening the Desert increased the agricultural area from only 2.4% of the land area in the UAE to 6.5% of cultivated land by the year 2000. As of 2005, 330,000 ha area has been planted through afforestation project in Abu Dhabi Emirate to reduce sand movement and to enhance the environmental quality **(Figure 2.20).** Additionally, the government allocated funds to monitor the shortage and imbalance of the underground water that will help in future planning of agricultural activities. The achievements and success stories of the Greening the Desert concept would not have been possible without the wise policies and urgency that HH Sheikh Zayed Bin Sultan Al Nahyan had placed on dealing with the environmental issues. HH highlighted this interest in His message to the Earth Summit in 1992. Following are the major achievements and activities towards "Greening The Desert of UAE" (FEA-UAE, 2002 and others):

- Authorization of the Federal Environmental Agency (FEA) as the functional national coordination body in the UAE for the UNCCD.
- National Environmental Strategy and the National Action Plan - The FEA prepared the strategy and action plan and were adopted in 2002 in the context of the national policies for conservation and sustainable use of natural resources, combating desertification and fulfilling the commitments of Agenda 21.
- Completion of detailed Strategies and National Action Plan to Combat Desertification in the UAE (FEA-UAE, 2003).
- Scientific and technological activities resulting

in greening deserts i.e., afforestation, planning nutritious productions for human being and animal feed, as well as opening of scientific centres.

- Approval and funding for the implementation of Soil Survey for the Emirate of Abu Dhabi project over the next four years (2005-2009) (ICBA-EAD, 2005) by the Executive Council of Abu Dhabi Emirate.
- Preparation of a national project on the reclamation of degraded agricultural lands in the UAE (Shahid, 2004) and approval by the National Committee on the Environmental Strategies - UAE.
- Completion of the state-of-the-art Soil Survey for the Coastline of Abu Dhabi Emirate (Shahid et al., 2004).
- Completion of Abu Dhabi Coastline - Oil Spill Protection Priorities (ERWDA, 2000).
- Establishment of Abu Dhabi Global Environment Data Initiative (AGEDI) by Environmental Agency-Abu Dhabi.
- Formation of a National Committee for the Follow up of UNCCD.
- The legal and legislative framework for protection of the environment - Law number 24. The law is concerned with developing natural resources and sustaining biodiversity in the UAE through the utilization in the most efficient and sustainable manner.
- Integration of combating desertification programmes into the national development plan.
- Sub-regional, regional and international cooperation in combating desertification.
- Participation in the preparation and implementation of the national action plan.
- The Consultative process and partnership agreements with developed countries.
- Identification of key projects and national allocations to different sectors e.g. Agriculture, soil and water management and conservation, animals etc.
- Establishment of International Centre for Biosaline Agriculture (ICBA) Dubai with partial support from the Government of the UAE and Ministry of Agriculture and Fisheries.
- Implementation of “Desert Greening Projects”.
- Afforestation of 330,000 ha area in Abu Dhabi Emirate.
- Increase in Agricultural areas etc.

Please note that more detailed descriptions of the items listed above can also be found in the Policies and Regulations sector paper.

2.8.3 Land Degradation - Desertification in the Abu Dhabi Emirate

Figures and facts about different components of land degradation (causes and mechanisms) in the Abu Dhabi Emirate are not available, however, scattered information are available in the literature. From this information, one can conclude that land degradation is an existing phenomenon in the desert environment of Abu Dhabi Emirate. There is a great need of an integrated and coordinated information system (database) among different agencies to share the information and for a better understanding of the problem. This can be achieved by linking information from different agencies and government departments. Recently Shahid & Omar (2001), have described causes and impacts of land degradation in the arid environment of Kuwait, similar information in the Abu Dhabi Emirate is lacking.

The terrestrial environment of Abu Dhabi Emirate is being subjected to various stresses. These stresses are outlined below in the form of causes and indicators of land degradation.

Figure 2.20: Greening the Desert - Plantations in the Abu Dhabi Emirate.

Figure 2.21: Uncontrolled grazing in the desert environment - loss of vegetation.

Figure 2.22: Wind erosion causing dust storm.

Figure 2.23: Effect of run-off and water erosion on highland soil; surface gravel lag is evidence indicating the loss of soil surface.

Figure 2.24: Combined effect of wind and water erosion on desert land.

Figure 2.25: Excavation for construction materials and exposure of hard pan.

Figure 2.26: Sea water intrusion causing salinization in depression areas.

Figure 2.27: Halophytes growing in degraded area.

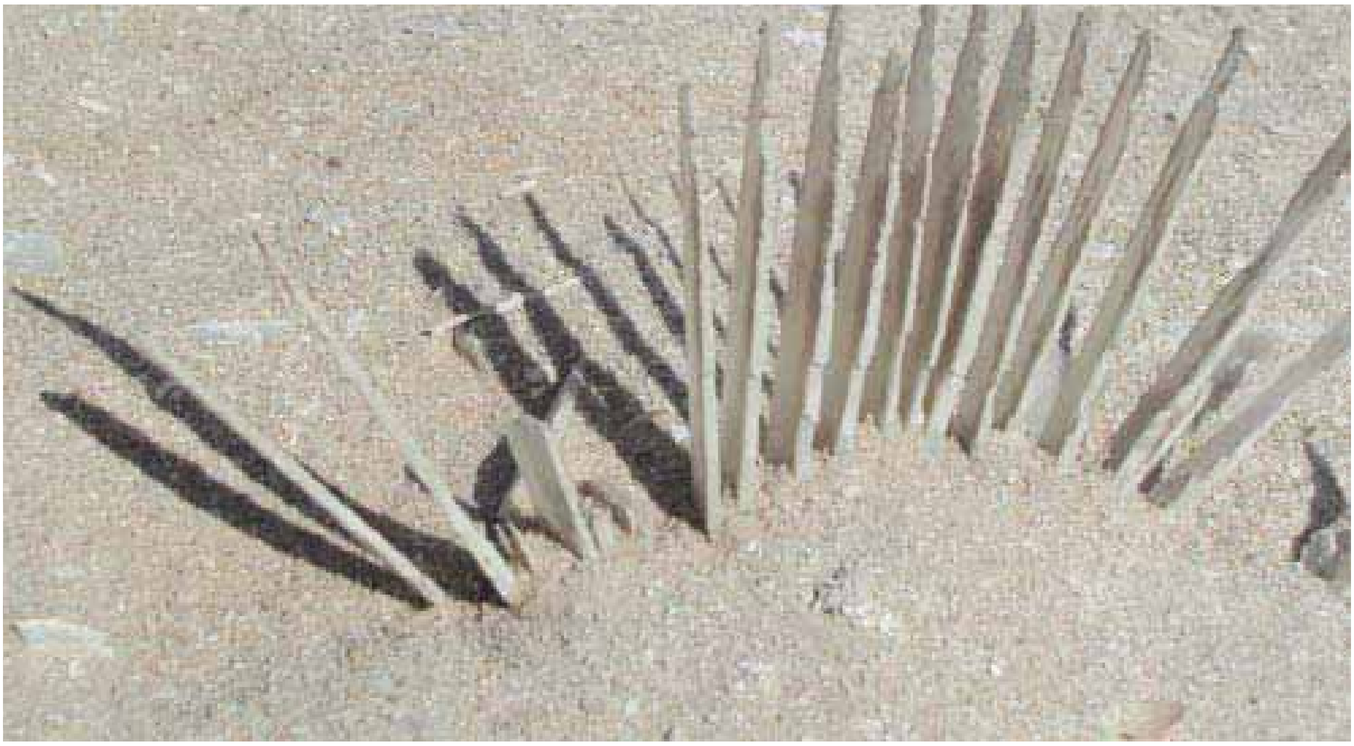


Figure 2.28: Exposure of subsurface gypsum crystals showing the loss of productive soil through erosion.

Figure 2.29: Salt marsh on the coastline of Abu Dhabi Emirate.

2.8.4 Causes of Land degradation

- Hyper-arid conditions (drought), evaporation exceeds rainfall.
- Lack of a detailed scientific soil inventory and subsequent use of soil resources.
- Subsidy to farmers increased the number of animals and pressure on rangelands.
- Uncontrolled overgrazing on native vegetation (Figure 2.21).
- Lack of trained labour dealing with herd management.
- Clearing of vegetation and shrubs.
- Irrigation with saline/brackish water.
- Intensive use of ground water, recycling increased water salinity.
- Wind erosion and sand encroachment (Figure 2.22).
- Run-off and combined effect of wind and water erosion (Figure 2.23-Figure 2.24).
- Excavation for construction material, sand, gravels etc. (Figure 2.25).
- Off-road vehicular maneuvering.
- Sea water intrusion in the coastal areas (Figure 2.6h).
- Urbanization.

2.8.5 Indicators of Land Degradation

- Loss of biodiversity - vegetation clearing and overgrazing (Figure 2.21).
- Sand encroachment on roads, agricultural and other areas.
- Salinization in agricultural and coastal areas (Figure 2.26).
- Only salt tolerant species or halophytes are present (Figure 2.27).
- Small to large bare areas - clearing of vegetation or through salinization.
- Waterlogging - due to poor drainage conditions or a near surface hardpan.
- Loss of productive top soil - nutrients and organic matter is removed (Figure 2.28).
- Exposure of hard pan - top soil is lost through erosion, excavation for construction material, hardpan has low potential for many uses (Figure 2.25).
- Surface gravel lag - due to heavy weight retained on the surface, good quality soil is lost (Figure 2.23).
- Reduced plant growth or stunting in crops - due to soil and water salinity.
- Surface compaction and hardsetting - uncontrolled heavy vehicle maneuvering and rain drop splash action.
- Rills and gullies formed on slopes of highland - run-off during water erosion.
- Dust storms - caused through wind erosion (Figure 2.22).
- Salt-marshes developed on the coastline of Abu Dhabi Emirate (Figure 2.29).

2.8.6 Efforts of Abu Dhabi Emirate in Combating Desertification “Greening The Desert”

A Afforestation

The record of the Emirate in caring for the environment, particularly wildlife, has been excellent (*see* Terrestrial Environment Sector Paper), however, the lack of an Emirate wide soil inventory sometimes threaten long term care of the environment. The recent approval and funding by the Executive Council of Abu Dhabi for the implementation of an Emirate-wide Soil Survey Project (EAD-ICBA, 2005), for which there are now preliminary results, over the period of 2005-2009 will provide state-of-the-art soil information for the decision makers for master planning in the Emirate. In the last few years, to clean and enhance the environmental quality in the UAE, the wisdom of HH Sheikh Zayed Bin Sultan Al Nahyan undertook activities for soil fixation, and to date 330,000 hectares have been planted (forestry plantation) to stop the creeping of sand, and to catch suspended particles. In addition, many green belts in the urban and along road sides have been established. The implementation of afforestation was considered as preventive measures for some of the desert lands that are not yet degraded, or which are only slightly degraded or prone to be degraded in the Emirate.

Forestry plantations are providing multiple benefits; *e.g.*, halting degradation, promoting sand stabilization and hydrological balance, controlling creeping sand, enhancing environmental quality, improving habitat restoration and increasing the aesthetic value of the area. The benefits of the above forestation have been felt but never fully quantified. It is, therefore, suggested that, the government should support integrated data collection and research work related to desertification assessment and associated problems, in general, and quantification of benefits associated to the present afforestation in particular. The implementation of the UAE action plan to combat desertification (FEA-UAE, 2003) will allow scientists to develop integrated information systems, environmental monitoring, and environmental impact assessment and to quantify the benefits of actions taken in the Emirate. To achieve this objective, a capacity building programme should be launched for the Emirati Nationals. ICBA at its Headquarters conducts trainings to enhance capacity of UAE nationals in soil salinity and ecosystem management.

Recent figures (ERWDA, 2002; Atkins, 2005) show that a total of 3,239 million cubic metres (Mm^3) of water were consumed in Abu Dhabi Emirate in 2002, this comprised of 1% (fresh water), 80% (brackish water), 15% (desalinated water) and 4% (treated wastewater). Forestry plantations in Abu Dhabi Emirate used 16% (512 Mm^3) of the total water; the majority of this was brackish groundwater. Future estimates show that each year 131 Mm^3 total fresh and brackish water will be available in Abu Dhabi Emirate, and total abstraction made in 2002 was 512 Mm^3, this shows that forestry irrigation results in a net deficit of groundwater of 318 Mm^3. Estimates shown by NDC-USGS in 1996 reveal that, at the rate of abstraction in 1996, brackish groundwater may last for about 250 years. However, with abstraction rate in 2002, they will last for only 50 years. It is clear from the above figures that in future abstraction of groundwater will be difficult and uneconomical. While the afforestation programme was well intentioned, its benefits are in need of a reassessment as there are a number of serious problems associated with the use of the plantations. With insufficient rainfall to support them naturally, they are entirely dependent on irrigated water. A substantial proportion of this water is provided from precious groundwater reserves, and at present, the abstraction rates far exceed that of natural recharge. The excessive use of groundwater will have serious consequences for years to come.

In addition, aside from the groundwater use implications, it has been observed that the development of the plantations also pose adverse habitat and cultural effects. Extensive earth-moving works are required to prepare the land for tree plantation, which destroys important natural heritage including archaeological artifacts. Habitat fragmentation has also occurred due to the kilometers of walls and fences that enclose the plantations, thus seriously restricting the movement of larger animals. In addition, an increase in soil salination has also occurred due to the use of improper irrigation techniques, and therefore, certain plant species are becoming less tolerant to saline conditions and are being replaced by halophytic ones, thus inevitably leading to simplified ecosystem conditions (less biodiversity).

The pressures of today greatly concern the sustainability of land resources for future generation. It has become apparent that there is a need to adopt a new philosophy concerning land, one that regards land in an ecological sense, and that considers both human and the natural world as parts of the same ecosystem. We should promote and coordinate effective planning and management of the equitable, efficient and sustainable use of water, land and other environmental resources in the Emirate. In this regard, community education is a must to enhance awareness of the land degradation problem and to protect natural livelihood “the land”.

Identification and conservation of protected areas in Abu Dhabi Emirate will promote protection of biodiversity and reduce risks of species extinction. An inventory of natural resources (soil, water and vegetation) will help assessment of present status, and comparison with previous information will identify the extent of degradation of these resources.

B Land Degradation in the Desert of Abu Dhabi Emirate

To date a land degradation map of Abu Dhabi Emirate does not exist, however, the need for this important information at the Emirate level has been highlighted in the soil survey action plan (ICBA-EAD, 2005) and a land degradation map of the Emirate at a working scale of 1:100,000 has been proposed, however, the map will be published at scale of 1:500,000. The information presented here is either gathered from different scattered sources or from author’s experience on local and similar conditions. Therefore, it may not present the complete picture of land degradation in the Emirate, which calls for a separate land degradation assessment study in the Emirate.

Among the five major land degradation processes (wind erosion, vegetation degradation, salinization, water erosion and compaction), wind erosion is the major cause of irreversible land degradation in the Emirate (**Figure 2.22**), where loose, dry non-cohesive sandy soils, poor vegetation cover protection of the soil, periods of strong winds and hyper-arid condition prevail. Other important processes are salinization and vegetation degradation. Water erosion and compaction are the least significant in the Emirate environment.

1. Wind Erosion and Aeolian Deposits

The desert of Abu Dhabi Emirate is dominated by sandy soils and sand dunes of varying heights that are moving continuously at different rates, therefore, it is sensible to state that in general aeolian deposits are the most predominant. It is, therefore, pertinent to understand the soil texture (particle sizes) of desert soils and to determine the mechanisms of particles movement to aid in formulating necessary measures to reduce aeolian movement.

Mechanisms of Soil Particle Movement in the Emirate Deserts

Shahid *et al*. (1999; 2001 & 2003) based on their experience on desert sandy soils described the chain reaction of soil particles into three different modes of transport as creep, saltation and suspension. During surface *creep* particles > 500μm (> 0.5mm) are set in motion by the impact of saltating particles. They are large and generally cannot be lifted up by the wind and tend to roll or slide and creep along the surface. During the rolling process they lose their sharp edges and become rounded. In *saltation* movement, the particles (63-500μm) are rolled on the surface, a vacuum is created at the rear of the moving particles, whereas, in the front the air is compressed below the particles and they are lifted up in the air. The lifted particles follow distinct trajectories under the influence of air resistance and gravity. On hitting the soil surface, they may rebound or become embedded when impacting the surface, or induce creep and suspension (the raising of fine particles). The saltation particles on hitting the surface can dislodge soil particles (< 63 μm diameter) and lift them into the air. They remain in the atmosphere for a longer period and this process is called *Suspension* movement. They cause dust storms and reach the soil surface with rain and clog the soil surface to form a surface crust. During this process, plants can be buried, blasted by air-borne sand, have their roots exposed through scouring of soil, highways are blocked, dust storm created, air polluted, waterways filled, fertile soil removed, and crops dislodged.

To evaluate the particle movement mechanisms in surface deposits of Emirate desert soils, the soil samples were analyzed for particle size distribution. It is deduced that, the particles range from 5 to 24% in the creep, 70-92% in saltation and 2-8% in suspension (Shahid & Abdelfattah, 2005). This illustrates that the soil particles in the Emirate desert are in the size range, which is susceptible dominantly for saltation movement, and therefore, saltation moves the main mass of wind-blown particles. Fewer particles are moved by creep and the least by suspension. To reduce saltation movement that ultimately causes dust storms and "*toze*" the practices which maintain soil structure, increase aggregate size and conserve moisture should be followed. This can be achieved by the addition of organic matter, green manures, mulching material, synthetic polymers, introduction of shelter belts and sand dunes stabilization through afforestation (**Figure** 2.20). The latter has been practiced on an area of 330,000 ha in Abu Dhabi Emirate.

2. Soil Salinization in Abu Dhabi Emirate

Soil Salinization is a process whereby soluble salts are accumulated in the soil. Due to the prevailing hyper-arid conditions, Abu Dhabi Emirate receives inadequate and irregular precipitation to effectively leach the salts from the soil profile; therefore, salts accumulate in the soil and ultimately become saline. Saline soils are the most common feature that can be recorded along the coastline (**Figure** 2.26) of Abu Dhabi Emirate (Shahid *et al*., 2004), with picturesque features. Locally these saline soils are known as *Sabkha* which could be found in coastal or inland areas. Coastal *Sabkha* are developed through sea water intrusion, reaction between the sediment and the highly saline groundwater and evaporation. The coastal '*sabkha*' stretches over a distance of more than 400km by 4-7km in width from the sea. The largest area covered by '*sabkha*' occurs in the western part and is known as Sabkhat Mati (*see* Error! Reference source not found.). Sabkhat Mati extends inland from the coast for about 120km and within Saudi Arabia it reaches a height of 40 m above sea level at its southern tip. Inland '*sabkha*' occur in the deserts where water is accumulated in the low lying landscape through seepage, hydrological flow from surrounding areas and evaporated leaving surface salt crust. Detailed soil types and salinity status in the coastline of Abu Dhabi Emirate are available on Soil Survey for the Coastline of Abu Dhabi Emirate (Shahid *et al*., 2004). The soil types are discussed in an earlier section on soil and soil formation.

Insufficient and infrequent rainfall and shortage of fresh water necessitates the use of ground water of different salinity and sodicity levels for irrigation of agricultural farms in Abu Dhabi Emirate. In irrigated agriculture, irrigation water is the primary source of salts, and poor-quality irrigation water is generally of more concern in arid conditions. Irrigation leads to phenomenal enhancement of land productivity, however, if this important resource is mismanaged it will cause soil degradation and increase salinization risk. A soil salinity survey of agricultural farms in Al Ain (El Bershamghy & Al Tamimi, 2003) shows that 43% farms have salinity of more than 9.4dS/m, 26% (6.25 to 9.4 dS/m), 19.8% (3.12 to 6.25dS/m) and 11% (less than 3.1dS/m). These statistics revealed that about 90%

soils surveyed are saline according to Richards (1954) classification. About 70% surveyed farms are in the range of salinity where either yields of many crops are restricted (4-6dS/m) or only tolerant crops yield satisfactory (8-16dS/m). Only 11% surveyed farms presented salinity below 4dS/m and, hence are classified as non-saline or normal. In response to farm salinization a national project on the assessment of affected agricultural lands for sustainable use (Shahid, 2003) has been prepared on a request from Committee on Soil and Water Resources, and approved by the National Committee on Environmental Strategies in the United Arab Emirates. Farm salinity in other areas of Emirate has also been reported by UAE Ministry of Agriculture and Fisheries. Water Resources and Quality is discussed by Shahid (2003), which shows that most of the groundwater resources are saline to varying degrees.

3. Water Erosion

Most of the desert environment of Abu Dhabi Emirate consists of sandy, sand dune soils which absorb the rainwater due to its very high drainage capacity and therefore, no water erosion occurs in these areas. However, the soils that are more stable (such as aeolianite and highlands) and cohesive have shown signs of combined effect of wind and water erosion (**Figure** 2.23 **and Figure** 2.24). Water erosion in Abu Dhabi Emirate is active only during the intensive rainy season, it causes severe runoff flows in the sloppy landscapes in the form of rills and gullies, in flat areas signs of sheet erosion are also noticed. The Ministry of Agriculture and Fisheries have taken necessary steps to collect the run-off water from highlands in the dams. These dams collect run-off water from highlands and become a source for irrigation to agricultural farms.

4. Vegetation Degradation

The Abu Dhabi Emirate vegetation is dominated by four major ecosystems: sandy desert plains, desert plateau and sand dunes, salt marshes, and coastal. The pressure of overgrazing on the rangelands of Abu Dhabi (**Figure** 2.21) may have resulted into a loss or reduction in vegetation cover. El-Keblawy (2003) while comparing the number of species, species richness, total density and plant cover reported significant differences in species diversity and frequency between inside and outside the recently protected site in the Al Ain-Dubai road region. The dominant species inside the enclosure were more palatable and important range legumes. These species were either absent from outside the enclosure or attained greater densities and more cover inside than outside the enclosure indicating that they are selectively eaten by grazing behaviour and not able to tolerate the current grazing intensity in the study area. The vegetation communities of Abu Dhabi Emirate are discussed in the Terrestrial Environment sector paper.

5. Compaction, Sealing and Crusting

Surface sealing, crusting and compaction are indicators of land degradation in the Emirate desert where soils are vulnerable to such changes. These soils are heavy, cohesive, rich in silt and dispersible clay contents, and are leveled. Dispersible clay in crusted soil with mechanical energy, e.g. rain drop impact, breaks free of its attachment within aggregates and goes into suspension (Southerland et al., 1996). This clay ultimately accumulates at the surface to form crust or translocates into the soil as an internal sealing of pores (clogging). In addition, these processes interact with other soil degradation processes such as water erosion, decrease soil infiltration, and increase runoff. Soil compaction due to off-road maneuvering of heavy vehicles, soil preparation machines have also been observed in places; these are smaller in extent compared with other land degradation types. Compaction can be noticed with signs of heavy vehicles tyres, chains marks, reduced void sizes, and water ponding after rain due to compaction. The difference between non-compacted and compacted soils can be assessed by measuring penetration resistance, bulk density and porosity, and infiltration rate. However, such assessments have not been reported on local soils in large scales.

6. Other land degradation types

Other land degradation processes observed in Abu Dhabi Emirate are; mining and quarrying, excavation for construction material, land filling *etc*.

3 HYDROLOGY

By Mike Brook -Water Resources Programme, Environment Agency Abu Dhabi

The climate of Abu Dhabi is arid and rainfall is erratic and unreliable and is largely deficient throughout the year. Evaporation rates are also in excess of 3000 mm/yr. The amount of rainfall available for runoff and contribution to recharge of the Emirates aquifers is very variable both in time and space, but overall amounts are small in this generally arid environment. Some years, there is no rain at all, and in others, rain occurring on only a few days in the year can total more than three times the long term annual average and has a very significant impact on restoring groundwater levels. There are no perennial stream courses which supply reliable water sources; rather, groundwater is the main bastion of water supplies, contributing almost 80 % of the Emirate's total annual requirements (ERWDA, 2004). However, it has been estimated that at least 100 mm/yr of rainfall is required in order to achieve groundwater recharge (Dincer *et al*., 1974; Faloci & Notarnicola, 1993). The only natural, perennial surface water resource is found at Ain Al Fayda spring and it is therefore important to understand the various hydrologic processes and hydrogeologic settings which control the extremely valuable groundwater resources present.

The hydrological cycle for the Emirate commences with rainfall over the Al Hajar Oman Mountains in the eastern region, producing rapid runoff to surface hydrological processes and recharge to underlying aquifers. The recharge zone in the eastern region provides the pressures to drive groundwater; there are three types of groundwater flow systems, local, intermediate and regional (Alsharhan, A.S. *et al*. 2001). The end points of the hydrological processes are the '*Sabkha*' and other groundwater discharge zones which are found at the Gulf coast or inland on the borders with the Sultanate of Oman and Saudi Arabia.

The purpose of this chapter is to describe the hydrology components in the Emirate and provide a regional hydrogeological framework with respect to hydrological processes. The chapter is based on more comprehensive material presented in the Water Resources sector paper.

3.1 Surface Water Hydrology

Historically, villages originated in areas where fresh water occurred either at or very close to the surface. Means of groundwater development were either Aflaj (Rizk, 1998), shallow hand dug wells or wadi diversion/rainfall harvesting structures. Due to declining water tables, there are now no totally natural flowing aflaj systems (traditional irrigation canals used for agriculture in oasis areas of Al Ain - see **Figure** 3.1) left in the Emirate; all nine operating are either fully or partially supplemented from groundwater which is abstracted from nearby wells drilled within the oasis areas (ERWDA, 2003; Brook, 2006). Today, the only perennial, natural surface water system in the Emirate is found at Ain Al Fayda, Al Ain. Wadi flows and surface sabkha ponding are ephemeral but there are also numerous lakes and ponds; *e.g.* Al Wathba Wetland Reserve and Mubbazarah lake, which serve as areas of recreation, conservation and environmental education, but these are all artificial.

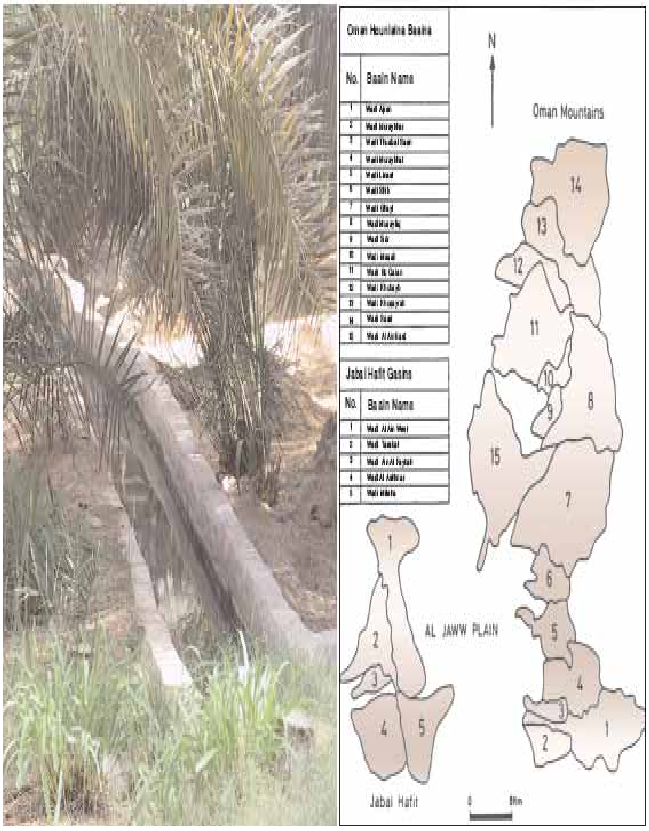


Figure 3.1: Al Jimi Falaj System, Al Ain

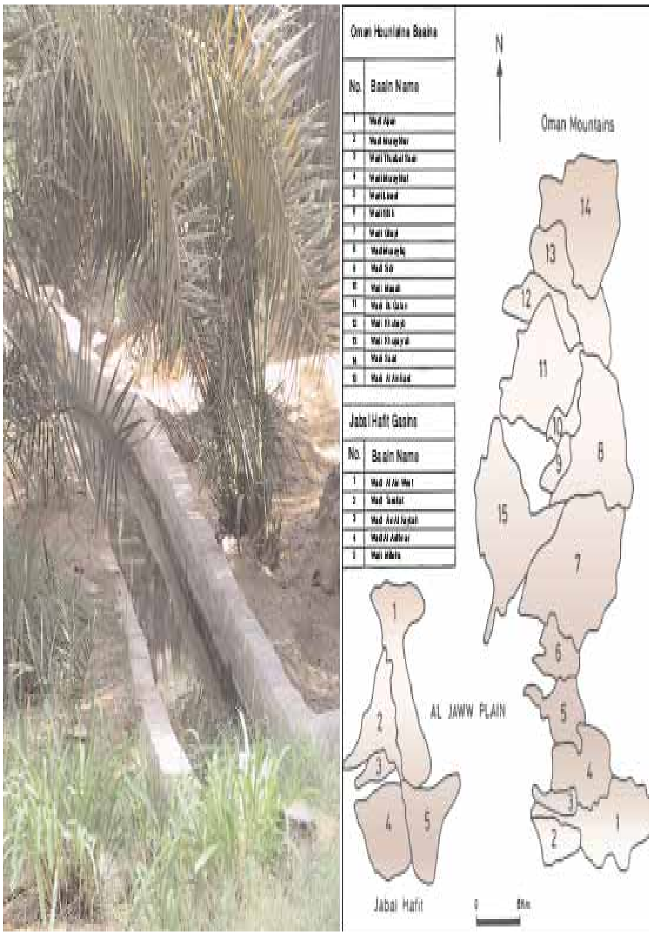


Figure 3.2: Eastern Region Catchments (Rizk et al., 1998)

3.1.1 Springs

The strict definition of a spring is a point where groundwater flows out of the ground and is thus where the aquifer surface meets the ground surface. Depending on how constant the source of the water is, springs can be ephemeral (intermittent), perennial (continuous) or artesian. Whilst numerous springs are found in the Northern Emirates, Abu Dhabi has only one perennial spring, that of Ain bu Sukhanah spring at Ain Al Fayda (Elschami, 1990). Located 15 km south of Al Ain city, the spring produces clear, brackish water at a constant temperature of 39.3 C with a flow of around 160 l/s (Terratest, 1974, 1975). The karstic sink out of which the spring emerges has been developed in the 1980's as part of Ain Al Faydah Tourist Resort. The rise of water to surface is brought about by development of true artesian conditions since the water is circulated at depth, hence attaining the required pressure for emergence at surface. The water is of Calcium -Sodium Chloride type with a salinity of around 5500 mg/l total dissolved solids (TDS) (low brackish), higher salinity than expected due to the springs passage through a Miocene gypsum sequence.

3.1.2 Wadis

A wadi is a dry river bed that only contains water during times of heavy rain and subsequent run-off. The gravel and boulder filled channels, in the case of Abu Dhabi Emirate, all emanate in neighbouring Sultanate of Oman where they cut through and flow out from the Al Hajar Mountain group onto piedmont plains and alluvial fans before crossing the International border into U.A.E. **Figure** 3.2 shows the location of the main wadi catchments in the eastern region.

Wadis cross the Oman - Abu Dhabi boarder from twelve main catchments and the total mean annual surface wadi flow entering the Emirate is estimated at 7.6 Mm^3/yr (MWR, 1998). Sometimes, cross boarder flows are significant and have caused flood damage. In March, 1997, a 55 Mm^3/week wadi flow occurred in the Al Fatah / Dank catchments and caused significant flood damage to the town of Al Quaa, south of Al Ain. Rizk et al. (1998) have studied the surface runoff and flood potential of the major drainage basins within the Emirate. Rainfall occurs mainly in the months of February and March and there are 4-5 year cycles of above average rainfall. The wadi basins, located both adjoining the Oman Mountains and also surrounding Jebel Hafit, have relief varying from 300-800 m and 100-800 m respectively. The basins have high to very low risks of flooding and the study showed that the minimum rainfall required to produce runoff for the Oman and Jebel Hafit basins is 75 mm and 90 mm respectively. The highest risks of flash flooding occur in wadis Shik, Sidr and Ayn Al Faydah, and the lowest risk in wadis Khuqayrah and Muraykhat. The average annual runoff depth for the study period 1981-1990 ranges from 5 mm to 20 mm and the percentage of rainfall generating runoff averages about 7 %, with a range from 3 % (Jebel Hafit basins) to 18 % (Oman mountain basins). The predicted long term annual average runoff for the former basins is 1.96 Mm^3/yr and for the latter, 13.78 Mm^3/yr.

3.1.3 Sabkha

These surface deposits occur in Abu Dhabi Emirate as extensive inter-tidal and inland saline flats, known locally as *Sabkha*; taken as a general term in the area to describe saline and hyper-saline desert flats devoid of all vegetation (Barth & Böer,2002). *Sabkha* occurs in groundwater discharge zones, either along the coastal plain and the inland sabkha matti (Evans & Kirkham, 2002) or within interdunal areas in the south of the Emirate, close to the boarders with Oman and Saudi Arabia. The coastal and inland *Sabkha* occupy an area of about 13,500 km^2, or around 20 % of the total landmass of the Emirate (**Figure** 3.5). The *sabkha* plains are dry for the most part of the year, but contain surface water when strong onshore winds drive seawater inland, after periods of heavy rainfall and also in winter when groundwater levels rise within the coastal belt. The hydrogeology of the 'sabkha' has been described in detail by Sanford and Wood (2001) and *Sabkha* as aquifers will be described in section 3.2.2. *Sabkha* are classified as coastal, supralittoral or inland. There are also three subclasses, namely permanently wet, periodically flooded and permanently dry. The first contains lakes and ponds where the groundwater table is always within a few cm of the ground surface and the *sabkha*' is permanently wet. The second subclass refers to ephemeral surface water brought about by heavy rains or windblown tides. The latter is permanently dry.

3.1.4 Artificial Lakes and Ponds

These have been created in the Emirate mostly for recreational and conservation purposes. Occupying an area of about 132 hectares (3.5 x 1.5 km) and located about 40 km south-east of Abu Dhabi City, the largest artificial lake is found at Al Wathba Wetland Reserve (ERWDA, 2001) and is the first protected area declared by Royal Decree in the Emirate of Abu Dhabi. Managed by the Environment Agency Abu Dhabi (EAD) since 1998, the site shows great biodiversity despite a typical lake salinity of 180,000 mg/l TDS (reaching max 230,000 mg/l TDS). Other significant lakes and ponds occur at Shahama (Javed, 2003), Khazna, Mubazzarah (Resources en Eaux Minerales, 2004), Ain Al Fayda and Ajban (Javed, 2002). The Shahama saline body (52,000 to 119,000 mg/l TDS) is 37 ha in size and is dredged *sabkha* with water contribution from runoff and groundwater. The Khazna and Al Ajban (1ha - located 24.62983'N, 54.79265'E) surface water bodies are also formed by runoff from excess drainage from irrigation of nearby farms and forestry. At Al Mubazzara, Jebel Hafit, a brackish, artificial lake has been constructed as a recreation feature to collect pumped water from a series of groundwater wells which tap geo-thermal waters of potential therapeutic value. The lakes at Ain Al Faydah are artificially excavated and are supplied brackish water from the nearby Ain bu Sukhanah spring.

3.1.5 Surface Water Developments

Development of surface water is achieved through constructing dams and other diversion / retention structures. Abu Dhabi topography is not generally suitable for the construction of recharge dams. In fact, only one recharge structure, a diversion bund with several downstream recharge basins, exists in the Emirate at Al Shwaib and succeeds in diverting Wadi Sumeni into a series of recharge basins as it enters Abu Dhabi territory and has a combined storage capacity of 31.5 Mm³. The main beneficiary of the enhanced recharge is agriculture: numerous farms exist immediately south of the diversion structure. Details of the wadi diversion structure are given in Error! Reference source not found..

Project Item	Dimensions	Capacity (Mm3)
Shwaib Dam	Length 3000 m, height 11m	5
Approach Channel	Length 3600 m, width 150m	5.5
Shwaib Reservoirs	Seven reservoirs	21
Total Shwaib Dam and Reservoirs project7		**31.5**

Table 3.1: Details of Shwaib Diversion Structure
Source: Al Ain Municipality, Road & Dams Department

The more mountainous terrain of the Northern Emirates is far more suitable for their construction; 114 dams have been constructed with a combined capacity of greater than 114 Mm³. Other surface water management methods practiced include wadi diversion and bunding, *sabkha* pond bunding and control, development of artificial wetlands, *e.g.*, Al Wathba, excavation of artificial lakes for beautification, *e.g.,* Mubazzarah, Ruwais Town centre lakes development associated with recreational activities, *e.g.*, Abu Dhabi Golf Club, Ain Al Fayda.

3.2 Groundwater Hydrology

Groundwater occurs in the Emirate as either consolidated or unconsolidated surficial deposit aquifers and as bedrock / structural aquifers, and contributes 79 % to the total water demand. The other water source contributions, desalination and treated wastewater, are shown in **Figure** 3.3.

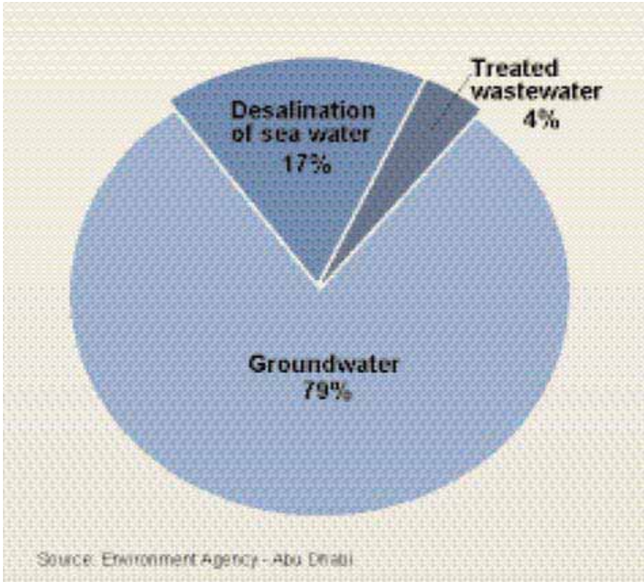


Figure 3.3: Water Sources in the Emirate of Abu Dhabi (ERWDA, 2004)

3.2.1 Groundwater Flow Systems

The groundwater systems present are controlled by recharge processes, geology of the host rocks, residence time of groundwater and discharge processes. The resultant groundwater quality is largely influenced by groundwater residence time, type of recharge process, and in more recent times, by anthropogenic activity. **Figure** 3.4 shows an understanding of the three types of flow systems that occur within the Emirate, based on hydrological, hydrochemical and isotopic characteristics of groundwater studied, and their main characteristics are given in **Table** 3.2**.**

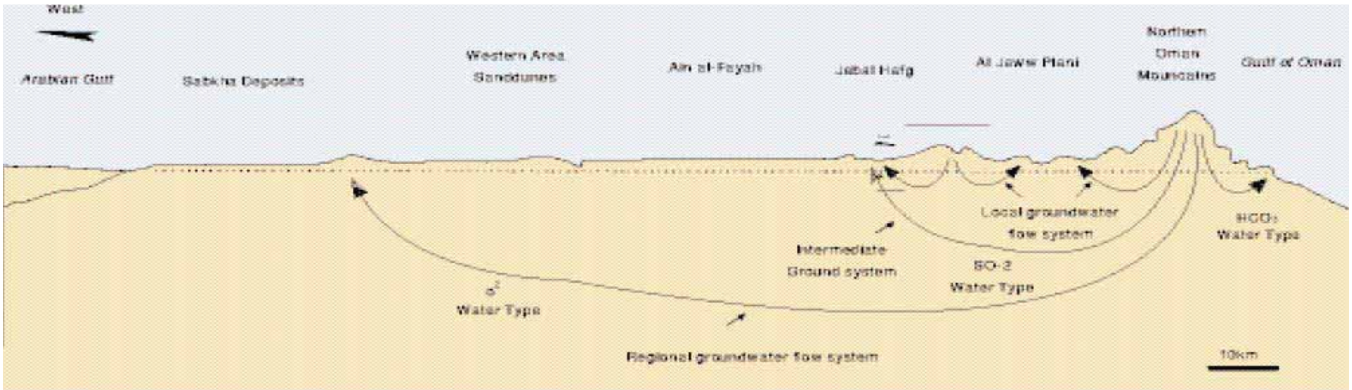


Figure 3.4: Regional Groundwater Flow Systems in Abu Dhabi Emirate (Alsharhan, A.S et al, 2001)

System Type	Main Physical & Development Characteristics	Main Hydrochemical Characteristics
Local	Occurs as springs, shallow hand dug wells, aflaj and shallow boreholes within surficial gravel and alluvium aquifers. Short groundwater residence time in active recharge areas, rapid hydrological cycle. Limited to eastern region, close to Oman boarder	*Low salinity and temperature and close to ambient air temperature. Groundwater of Bicarbonate (HCO3-) type, indicative of active recharge e.g Al Jaww plain, Gashaba, Shuwaib areas*
Intermediate	Inland *Sabkha* are main discharge areas. Groundwater contained in relatively thin sand aquifers, low groundwater velocities with moderate residence times	*Generally brackish to saline and of Sulphate (SO4-) type. Hypersaline at discharge areas i.e. Sabkha. No or little active recharge, most of western region has this system, although Ain bu Sukhanah spring at Ayn Al Fayda also belongs to this system*
Regional	This slow moving, long residence groundwater system moves towards the North West and the Gulf and also to the South West into Saudi Arabia where discharge areas are low lying *Sabkha*	*Discharge areas have waters of high temperature and are highly mineralized. Sabkha are hyper-saline. Residence times of up to 15,000 years produce Chloride water types*

Table 3.2: Groundwater Flow systems within Abu Dhabi Emirate

Figure 3.5 shows a hydrogeologic overview of the Emirate. Overall groundwater movement is generally from east to west for all three flow types, although north of the Liwa crescent a groundwater high allows flows to the south and across the border with Saudi Arabia. Flow times from recharge zones in the east to the s*abkha*' discharge zones along the Gulf coastline can take up to 15,000 years. This slow groundwater movement allows for considerable dissolution of salts in the groundwater and the longer the residence time, the higher the salt content; hyper-saline waters in excess of 200,000 mg/l TDS are found along the Abu Dhabi coastline.

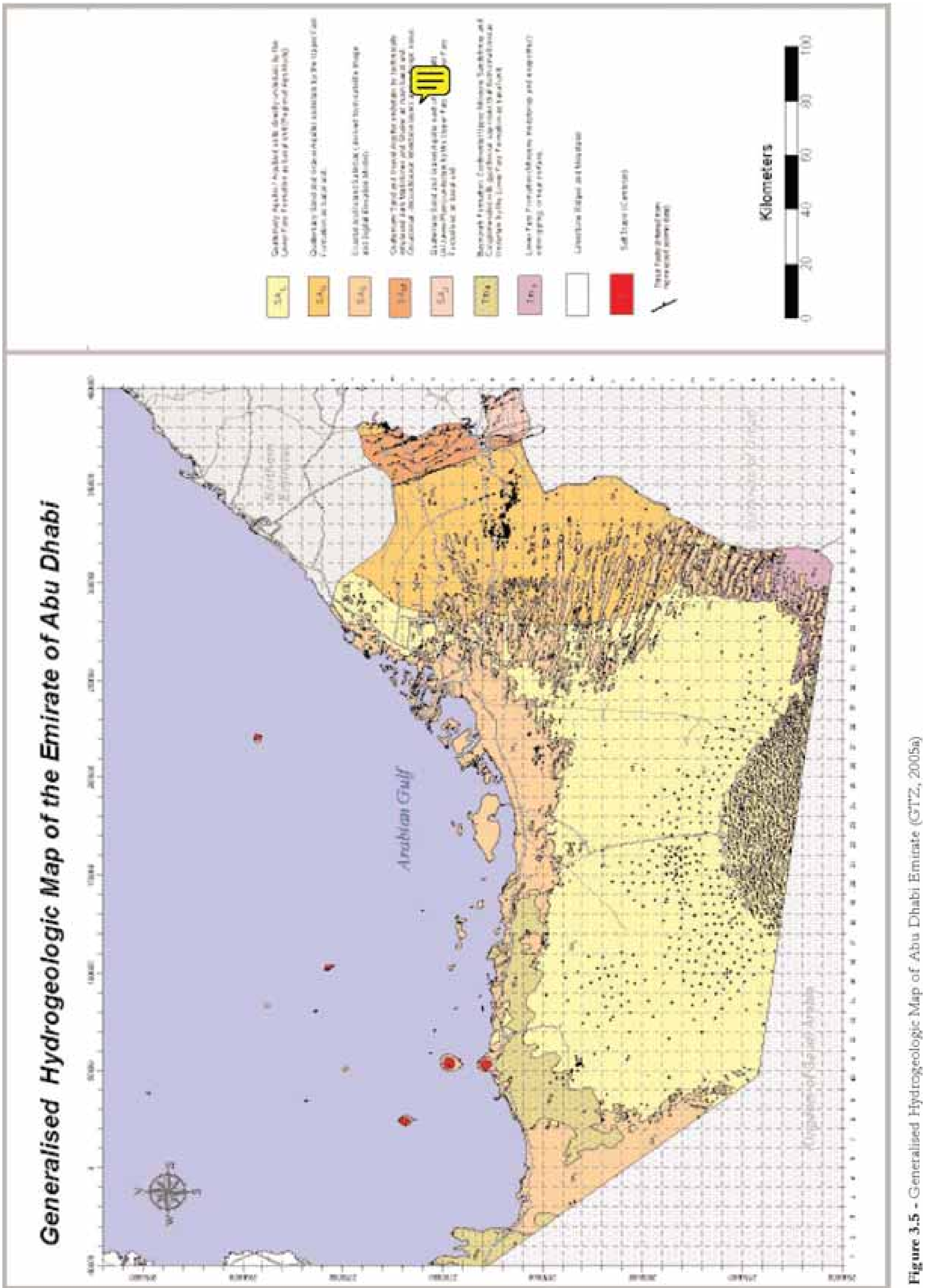


Figure 3.5: Generalised Hydrogeologic Map Of Abu Dhabi Emirate (GTZ, 2005a)

3.2.2 Aquifer Types

Figure 3.5 shows the main aquifers present in Abu Dhabi Emirate; 80% of the territory comprises Quaternary sand and sand and gravel aquifers. The eastern region main aquifers are Quaternary sands and gravels underlain by the Upper Fars Formation, which continues eastwards into neighbouring Oman, the Lower Fars Formation in the south eastern, Umm Az Zamoul area, limestone bedrock units (Dammam and Simsima) and discontinuous carbonates as part of the tectonically effected hydrogeology north of Al Ain. The western region largely comprises the Quaternary sand aquifer directly underlain by the Lower Fars Formation as a basal unit, but unlike its occurrence in the eastern region, the Fars here represents a regional aquiclude. Also present are thin coastal *sabkha*' aquifers and the Baynunah Formation, comprising continental Upper Miocene sandstones and conglomerates with gypsiferous cap rocks that form numerous, low lying mesas in the area. Both Formations are poor aquifers and are largely undeveloped. They are both underlain by the regional Lower Fars basal unit aquiclude.

A Unconsolidated Aquifers

These are the most common and productive aquifers and comprise both recent sand dunes and alluvial deposits of varying age. Collectively, the deposits comprise the surficial aquifers of Abu Dhabi Emirate or alternatively, the shallow (water table) aquifer, the top of which is defined by the water table. The thickness (see **Figure** 3.6) varies from 0m to greater than 50m. The following units of the shallow aquifer have been mapped (see **Figure** 3.5**)**:

- SAL Quaternary aquifer/ aquitard units directly underlain by the Lower Fars Formation as a basal unit (regional aquiclude).
- SAU Quaternary sand and gravel aquifer underlain by the Upper Fars Formation as a basal unit.
- SAS Coastal and inland Sabkha.
- SAM Quaternary sand and gravel aquifer underlain by tectonically emplaced dark Marlstones and shales as main basal unit.
- SAJ Quaternary sand and gravel aquifer east of Jebel Hafit (Al Jaww Plain) underlain by Upper Fars and Lower Fars Formations as basal unit.

Figure 3.7 shows the salinity distribution within the surficial aquifers. The depth to the brackish-saline interface within the upper aquifer in the western region ranges from 5m to more than 80m below the recorded static water level in individual wells.

Sabkha deposits

Sabkha are uneconomic aquifers and contain groundwater of hyper-salinity and brine quality in some places. Their distribution in the Emirate is shown in **Figure** 3.5. Their hydrogeology and hydrochemistry is described in detail by Wood and Sanford (2002) who concluded that rainfall is the dominant source of water whilst ascending terrestrial brine is the dominant source of contained solutes for the coastal *Sabkha* which comprise a 300 km long by 15 km (range 2-20km) wide strip. The area is flat with topographic and groundwater gradients of 1:5000 and a depth of groundwater of between only 0.5m - 1.0m. The 10m deep sabkha, which comprises uniform fine sand composed of detrital carbonates and quartz with minor amounts of feldspars, anhydrite and heavy minerals, is of Holocene age (Abu Dhabi Formation) and is superimposed over Tertiary and Pleistocene sediments. The sediments have a consistent porosity of about 38% and field tests show a hydraulic conductivity of 1-2 m/d. The sabkha aquifer was formed 7,000 and 8,000 yBP and contained seawater in the interstitial pores, after which brines from the underlying Tertiary formations started to discharge into the newly formed aquifer, which serves as a regional groundwater discharge area for the deeper Paleozoic to Cenozoic aquifers. The major water input is rainfall rather than lateral groundwater flow which, by comparison, is negligible.

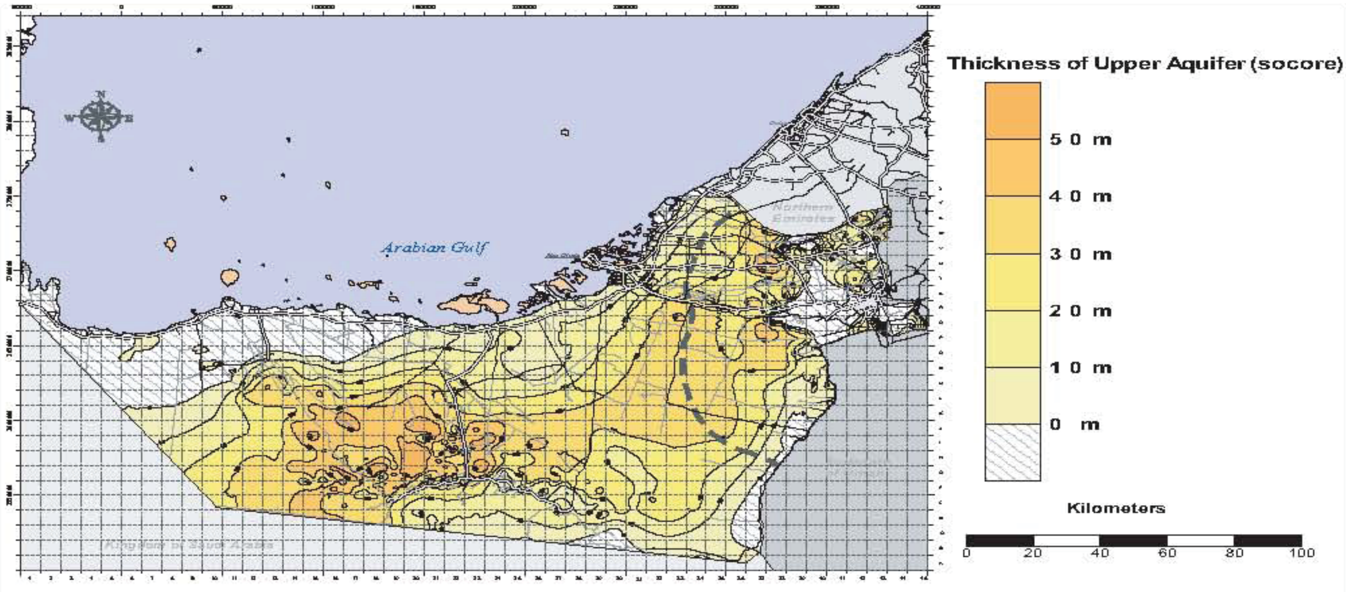


Figure 3.6: Thickness of the upper aquifer (GTZ, 2005a)

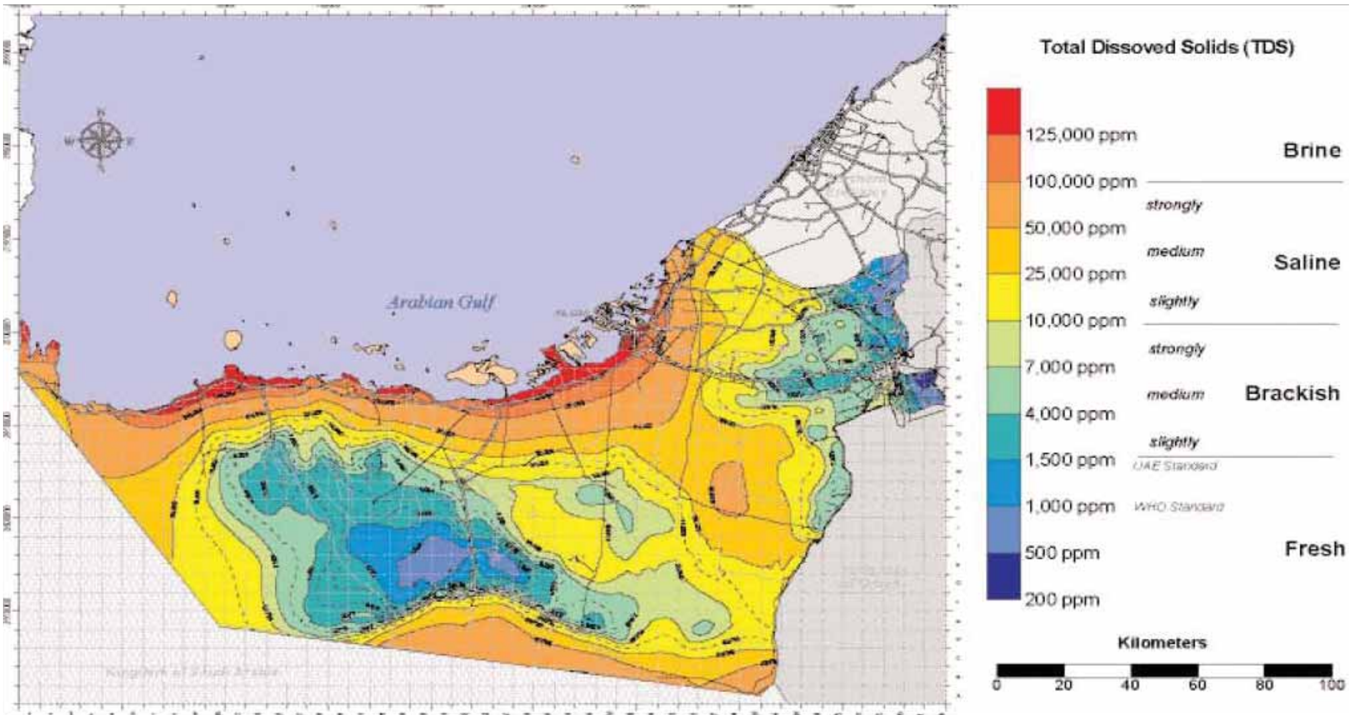


Figure 3.7: Salinity of the upper aquifer (GTZ, 2005a)

Sand Dunes

Much of the Emirate is covered with quaternary age (Holocene) Aeolian sand deposits that comprise many different types of dunes. Dunes range in size from mega barchans found in the dune field directly south of the Liwa crescent where the average relative dune heights are 103m, to small barchans south east of Baynunah which have an average relative height of less than 10m (UAE University, 1993). The dunes are a common north - eastern extension of the well known sand sea “Ar Rub Al Khali” which lies mainly within Saudi Arabia. Topographic elevations range from 0m (offshore Islands) to 259m above mean sea level (mega barchan dune field south of Liwa). Inland *sabkha* is found within the depressions of the mega barchan dune field. The dune sands aquifer, which is dominant in the western region, comprises mostly medium to very fine grained Aeolian sands, sub-rounded to well rounded, which become progressively argillaceous with increasing depth. Individual sand grains are frosted, white to reddish-orange and composed of quartz, carbonate, and dark heavy and evaporate minerals. The upper parts of the aquifer are relatively clay and silt free and thus have moderate permeability and high porosity (NDC/USGS, 1993, 1996) and this permeable and productive zone is termed the upper shallow aquifer which is underlain unconformably by the gravels and conglomerates in the eastern region and by a zone of lower permeability and productivity in the western region, termed the western aquitard (GTZ, 2005a).

This aquifer contains the fresh water basin north of Liwa Crescent (USGS, 1994) and is the beneficiary of the artificially recharged desalinated water introduced as a pilot ASR scheme (GTZ, 2005b). Another fresh water mound is also found in the sand dunes of the Bu Hasa oil field (Rizk & Alsharhan, 2003). In the Liwa area, where 2,400km² are underlain by fresh groundwater (Moreland, 1998), the sand dunes comprise medium to very fine grained sand with silt composed of carbonates, quartz and heavy minerals. The unconfined Liwa aquifer has an average transmissivity and specific yield of 300 m²/d and 22% respectively. In the Liwa crescent area, the average thickness of fresh water is 30m and a total storage of 16,000Mm³ and 101,000Mm³ of fresh and brackish groundwater has been estimated (USGS, 1994). Whilst some, small degree of modern day groundwater recharge still occurs in the Liwa area, as proven by groundwater tritium content values, the majority of the water recharged some 6,000 to 9,000 (Wood & Imes, 1995) years before present and so therefore the fresh groundwater water lense is largely fossil in nature.

Paleodune deposits

These are ancient consolidated sand dunes of pre-Quaternary age and occur mostly as erosional remnants within interdune *sabkha* areas. The deposits crop out as either minor exposures mantled by Holocene sand dunes or as relatively thick exposures that cap or flank the leeward sides of buttes formed of Miocene sedimentary rocks (Hadley, 1995). The quartz component of the dunes increases progressively from north to south so that in the Liwa area it can comprise up to 90% of the overall paleodune deposit. The dunes unconformably overlie the Baynunah Formation and are themselves unconformably overlain by the Holocene age sand dunes, comprise mostly fine to medium grained, rounded to well rounded quartz sand, and consist of well rounded grains with miliolid foraminifera, coral, red algae, ooids, shell fragments, evaporite minerals, heavy minerals and micritic carbonate cement. Whilst most of the dunes are found in the coastal belt described above, they are also found as far south as the Saudi Arabian border, south west of Liwa, where they crop out in interdunal *Sabkha*. They have similar hydrogeologic properties to the dune sands, although a higher degree of cementation causes a reduction in permeability and effective porosity.

Baynunah Formation

The Baynunah deposit comprises poorly consolidated fluvial sand of late Miocene age and outcrops over an area of about 3000km² (**Figure** 3.5). Sediments are horizontally bedded and form relatively high topography up to 60m above mean sea level (m.a.m.s.l). The formation can contain thin sandstone, conglomerate, clayey silt and gypsiferous sandstone beds. Sediment source is from the west in Saudi Arabia. Groundwater quality is high brackish to hypersaline and there is little development potential.

Alluvial deposits

These comprise Quaternary sands and gravels and depending on the underlying formation, have been classified into three mapped units, SA_U SA_S and SA_J (see **Figure** 3.5). In the eastern region, alluvial fans coalesce into piedmont plains which occur on the edge of the Oman Al Hajar mountains and Jebel Hafit. The sands and gravels are largely an erosional product from the Oman Ophiolite complex, whereas the smaller fans at the foot of Jebel Hafit comprise almost exclusively limestone clasts. The deposits contain clasts and boulders of gabbro, serpentinite, limestone and chert within either a fine grained cement or clay matrix. Highly productive parts of the alluvium are found in coarser grained deposits which were laid down in paleochannels and are now buried at depth (Fitterman *et al.*, 1991; Woodward & Menges, 1991; Rizk, 1998b).

The alluvium also extends beneath a large area of aeolian sand along the border with Oman, north of Al Ain. The mapped unit SA_U is the most extensive Quaternary gravel sequence which is unconformably underlain by the Upper Fars Formation as the basal unit. This unit is tapped by most of the farm wells in the Al Khazna / Remah region where individual wells have been tested at rates of above 150 m^3/hr. Here the formation is 40-50m thick and the groundwater salinity ranges from 1,500 - 10,000 mg/l TDS. The alluvial deposits, along with the sand dune aquifers, are the most productive of the unconsolidated units in the Emirate. **Figure** 3.8 shows the distribution of the specific capacity of wells drilled in the surficial aquifer throughout the Emirate, with some of those in the western dune sands and the eastern sands and gravels above 12 m^2/hr. The most productive well fields are found north of the Liwa crescent and in the Al Khazna and Al Khader areas. Transmissivities range from <1 - 8,000 m^2/d with an average of 594 m^2/d.

Upper Fars Formation

The Upper Fars Formation is present throughout the Eastern Arabian shield and can be a productive aquifer in places. The Fars Formation has its type locality in Southern Iran where it outcrops. In neighbouring Sultanate of Oman, a $100 million groundwater fed drinking water supply scheme to 100,000 people has been developed in the locally named Al Masarrat Fars Aquifer, to serve the Al Dhahirah region (Brook, 2001). The Upper Fars UAE equivalent underlies about 80% of the eastern region of the Emirate, specifically occurring under mapped units SA_U and SA_J, as shown in **Figure** 3.5. The Upper Fars comprises primarily conglomerates (moderate to highly productive) with inter bedded dolomitic marls, clay and siltstones. The dolomite can occur as metre thick, impervious beds which tend to compartmentalize the aquifers, resulting in multi aquifer layers with varying hydrochemistry. This phenomena is seen within the units which occur in the Al Wigan / Al Quaa area south of Al Ain (Brook, 1994 and Khalifa, 2004). The upper zone is in hydraulic connection with the Quaternary shallow aquifer and permeability and porosity of the aquifer decreases with increasing depth. Deeper, thin conglomeritic lenses can also be productive down to depths of around 120m below sea level. The formation is found at its thickest in the Al Khazna area (400m) and also west of Bida Bint Saud (300m). In the eastern region, the Miocene Upper Fars Formation is differentiated from the Quaternary gravels that unconformably overlie it by the occurrence of more cemented conglomeritic layers which are intercalated with dolomitic marlstones and siltstones with mostly dolomitic matrices. In the western region, the Upper Fars Formation consists mainly of marl and mudstone with inter-bedded thin sandy layers. These altered Tertiary deposits range in Transmissivity from 1 to 270 m^2/d (average 58 m^2/d) and have average well yields of 535 m^3/d (Bright & De Silva, 1998

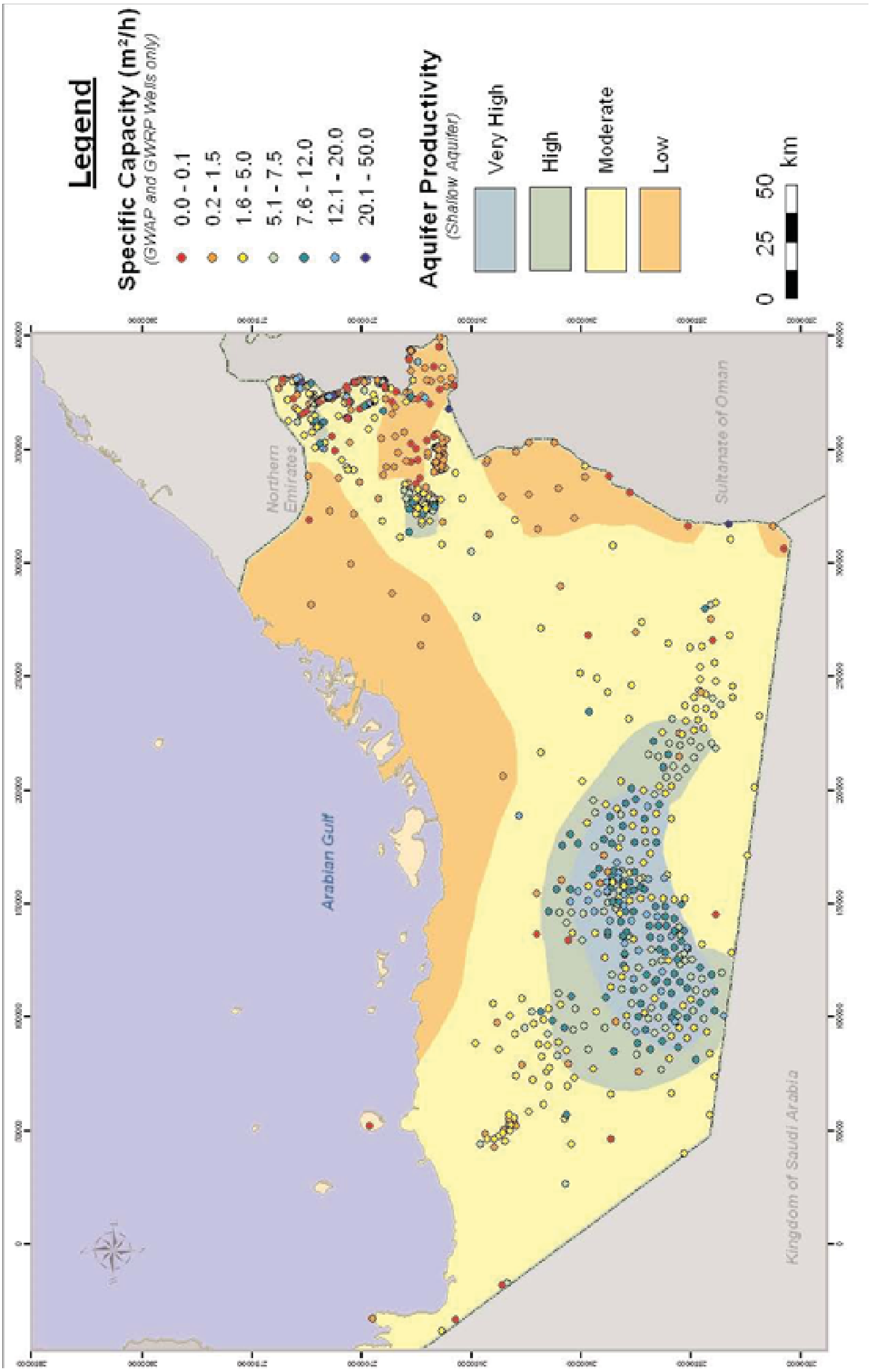


Figure 3.8: Specific capacity of wells drilled throughout the Emirate (GTZ, 2005a)

Lower Fars Formation

This formation occurs as thick (up to 650m) early Miocene age mudstones and marly dolomites, intercalated with evaporites (gypsum and anhydrite) deposited in a shallow marine environment. It is present throughout the Emirate largely as an aquiclude and is unconformably overlain by Upper Fars and also the western region aquitard which comprises Quaternary aeolian sands with frequent intercalations of inter-dunal sediments. In the eastern region, the Lower Fars formed a sedimentary basin or trough that was filled with sediments of the Upper Fars Formation. Few wells have penetrated the Lower Fars and the top of the Formation has largely been mapped by use of vertical electrical soundings. The deepest contact occurs in a geological trough west of Jebel Hafit. At Seh Al Gharabah, the trough bottoms at 280m below sea level. The evaporitic section of the formation consists mostly of anhydrite and represents a lagoonal type depositional environment, with the anhydritic section being generally confined to the base of the Lower Fars Formation.

B Bedrock and Structural Aquifer Formations

Bedrock aquifers occur throughout the Emirate and are largely carbonate deposits laid down in shallow marine seas. Their potential as aquifers has not yet been fully proven; the aquifers occur generally at significant depth and have not been explored or exploited anywhere near to the same extent as the unconsolidated aquifers described above. Hydrogeological cross sections have been prepared by the Groundwater Research Program (GWRP, 1996) based on wells which have fully penetrated the Asmari Limestone, partial penetration of the Dammam Formation and also seismic surveys. The Emirate can be divided into two structural regions as follows:

- Eastern - includes Eastern Region of the Emirate, underlain by the eastern edge of the Arabian Shelf and the Oman Mountain Foredeep (Foreland Mobile Belt).

- Western - occupies 57,000km^2 and occurs in the western and central part of the Emirate and includes the relatively stable Arabian shelf Province and Rub Al Khali basin. Main structural feature is gentle, simple folding of Tertiary strata.

The karstified and fractured nature of the strata produces multi-aquifer systems (Al Mardi, Al Aidrous. 1985).

Asmari Formation

This Oligocene, carbonate formation occurs in both the eastern and western regions and has been relatively unexplored to date. In the western region, its equivalent occurs as an Oligo-Miocene clastic continental unit, comprising siliceous sand, sandstone, and minor interbedded shale layers, whose upper contact is recognized by an overlying anhydrite bed at the base of the Lower Fars Formation (Imes *et al*., 1994). The continental character of the deposits is expected to grade into marine facies of shales and carbonates of the Asmari Formation along the basinal slope and further into the eastern region. Here the Formation has been mapped largely from seismic profiles and has an average thickness of about 200m. In the region of Jebel Hafit, it is significantly folded and affected by thrust faulting. The ridges are dominated by coralliferous limestones with subordinate marls rich in fossils (Kirkham, 2004).

Karstic Limestone Formations

These formations occur throughout the Emirate but are only exposed in the Eastern Region where they occur as fractured and solution channeled limestones of late Cretaceous to Tertiary age within a north south trending structural zone measuring about 25km by 80km that represents a transition between the buried, flat lying to slightly folded strata in the western region and the highly deformed, uplifted rocks of the Al Hajar Oman Mountains. Rock outcrops are scarce but crystalline limestones can be found at Jebel Hafit, Muthaymimah, Malaqat, Oha, Masakin, Mohayer and at Qarn Tarab, Saba, Bida bint Saud and Mutarid in the northern structural domain. The various limestones occur along the axes of regional anticlines which have been mapped using data obtained from seismic surveys (Woodward, 1990; Woodward & Jeelani, 1993). Because the outcrops are associated with steeply plunging anticlines, the aerial extent of the productive aquifers is limited to shallow horizons near the exposures (Bright & De Silva, 1998) and the aquifers were found not to be productive below depths of about 150m below ground level. The transmissivity and therefore the individual well yields within the limestones are highly variable, ranging from 5 m^2/d to 8,700 m^2/d and 200 m^3/d to 6,000 m^3/d respectively.

Dammam & Rus Formations

These carbonate sequences have been relatively unexplored to date, largely because of their occurrence at significant depth (>500m below ground) although the double plunging anticline at Jebel Hafit and other anticlines has brought the formations to surface and has allowed wells to penetrate the aquifer. Exposures of Dammam limestone can be seen at Jebels Oha and Hafit and also at smaller qarns and jebels along the eastern side of Al Jaww plain.

The Dammam, of Eocene age (54.8 to 33.7 Mya) has largely been mapped from petroleum exploration maps and dominates the crest of the Hafit structure. The marine carbonate has an average thickness of 270m, but thins to 180m. It attains a maximum thickness of 320m in the Liwa region in a localized trough area. The top of the formation marks a regional unconformity and ranges in altitude from 150m to 1200m below sea level.

The Rus Formation is also of Eocene age and occurs directly beneath the Dammam and a 184m section is found within the core of the Hafit anticline. In the western region, it is largely evaporitic in nature and does not constitute an aquifer. At Jebel Hafit, it comprises limestones and marls that are dominated by calcite nodules which are well cemented and therefore reduce permeability significantly.

The southern structural domain includes Jebel Hafit, the distal fold of the same area and also outcrops in the Al Jaww plain. Jebel Hafit comprises interbedded carbonate (Dammam) and evaporite (Rus) formations and is largely limestones and marls interbedded with gypsum and dolomite. The Jebel is a doubly plunging, asymmetrical anticline and the rocks are cut by numerous normal and near vertical faults and fractures providing significant secondary permeability and sometimes very high well yields. The fractures and joints provide for significant infiltration from rainfall events with relatively little run-off, despite bunded structures being constructed at the foot of the Jebel to collect and store runoff waters for enhanced recharge.

The 15-well Mubazzarah well field has been developed at Jebel Hafit by Al Ain Municipality with a combined daily yield of about 4,600 m^3/d. Water supplied by the well field has been used for recreational purposes and for “greening” of the location. Because well fractures at depths between 100-200 m below ground intersect much deeper fractures that have their origin of up to 2,000m below ground level, groundwater in some wells attain temperatures of greater than 50°C (Khalifa, 1997) and, because of the mineral salts content, have potential for therapeutic spa treatment (REM, 2004).

Umm er Radhuma Formation

This Paleocene age carbonate aquifer, widespread throughout the Arabian Peninsula, forms prolific aquifers in Saudi Arabia and Oman, but does not have the same potential in Abu Dhabi Emirate. Very few water wells have penetrated this aquifer in the Emirate and our knowledge of it is restricted mostly to the southern structural domain, south of Al Ain. Attempts at deep exploration in the western region have been fraught with difficulty and campaigns have been few and largely unsuccessful to date with very high groundwater salinities and low well yields. Only one GWAP well intersected Umm er Radhuma limestone; thickness of 200 m between depths of 600-800 m below ground with a TDS content of 185,000 mg/l and a small yield of 12 m^3/hr. Further investigation into this aquifer system, however, is warranted.

Simsima Formation

This Cretaceous limestone formation occurs in the eastern structural domain region and crops out as outliers near the Al Ain - Dubai highway. Exposures of crystalline, fossiliferous limestone of the Simsima Formation can be found at Jebel Mohayer, Qarn Saba, Jebel Masakin, Qarn Tarab and Qarn Bida bint Saud. Over 40 exploration wells have been drilled into this formation by the Groundwater Research Project (GWRP) with very variable results dependent on intersection of permeable fractures and joints which provide all the yields from the wells. Where fractures are encountered, transmissivities of greater than 3,000 m^2/d and yields in excess of 5,800 m^3/d have been recorded.

3.3 Groundwater Quality Classification

Table 3.2 provided a summary of the three different kinds of groundwater flow system found in the Emirate. Generally, the longer the residence time, the higher the salinity (Total Dissolved Solids-TDS) content of the indigenous groundwater. TDS is widely taken as an indication of groundwater quality and also proximity to either a recharge source or discharge area. There are other factors, besides those mentioned above, which may also have an over-bearing effect on salinity, *e.g.,* occurrence of gypsum or anhydrite layers within a succession, which although may be very thin, will have a tremendous effect on increasing the TDS of water sampled from a well.

Various classifications of groundwater type have been used internationally and different classifications are also found associated with different projects and government agencies within Abu Dhabi Emirate. **Table** 3.3 shows a summary of the main classifications used in the Emirate; all generally use TDS for classification of groundwater type. The classifications of groundwater quality shown in Table 3.3 are all more detailed than the World Health Organization simplistic classification for drinking water which has fresh defined up to 1600 mg/l and brackish above this value. In Abu Dhabi Emirate, the term “Fresh” is generally a local standard for potable water.

The Agriculture Extension Department of Abu Dhabi Municipality & Agriculture classification uses electrical conductivity and differentiates according to suitability of irrigation of selected crops under pre-selected groundwater salinity classes. The distribution of groundwater salinity in the main, upper aquifer is shown in **Figure** 3.7, based on the classification system used by Deutsche Gesellschaft for Technische Zusammenarbeit (GTZ) Groundwater Assessment Project (GWAP).

Although pollution of groundwater from anthropogenic activities, especially agriculture, does exist within the Emirate, it has not had a significant impact on regional groundwater salinity. Rather, local pollution (*e.g*. nitrate) of some parts of the surficial aquifers has occurred, and is invariably associated with the use of inorganic fertilizers on numerous farms.

Source	TDS Range (mg/l)	Classification
EAD (formerly ERWDA, ERWDA, 2004)	0-1500 1500-8000 8000-15000 15000-35000 >35000	Fresh Low Brackish High Brackish Saline Hypersaline
GTZ/Dornier/ADNOC (2005a)	0-1500 1500-4000 4000-7000 7000-10000 10000-25000 25000-50000 50000-100000 >100000	Fresh Slightly Brackish Medium Brackish Strongly Brackish Slightly saline Medium Saline Strongly Saline Brine
USGS/NDC (1996)	0-1500 1500-6000 6000-15000 >15000	Fresh Low Brackish High Brackish Saline
Forestry Dept Abu Dhabi Municipality & Agriculture	0-1500 1500-10000 10000-20000 >20000	Fresh Brackish Saline Very Saline
Abu Dhabi Municipality & Agriculture -Agriculture Extension Service	0-4000µS/cm 4000-8000µS/cm 8000-12000µS/cm >12000µS/cm	Class I Fresh Class II low brackish Class III high brackish Class IV saline
Al Ain Municipality & Agriculture -Agriculture Extension Service (2001)	0-1000 1000-2000 2000-4000 4000-6000 6000-8000 >8000	Class 1 very Fresh Class 2 Fresh Class 3 low brackish Class4.medium brackish Class 5 high brackish Class 6 saline

Table 3.3: Summary of Groundwater Classification Schemes used in Abu Dhabi Emirate.

3.4 Groundwater Resources Evaluation

The methods used to calculate the groundwater in storage differ between the GWAP and GWRP projects, but both have ultimately calculated average saturated aquifer thickness and specific yield to estimate stored volumes. The volume of fresh groundwater calculated differs by only 8%. It is not possible to compare the saline and brackish groundwater calculations, since different thresholds have been used to define this water quality. The GWRP calculated a total groundwater reserve of 253 Km^3 (7% fresh, 93% brackish) and the GWAP total estimate of 640Km^3 (2.6% fresh, 18.1% brackish, 79.4% saline) is much larger since groundwater of salinity of up to 100,000 mg/l TDS was included, whereas the GWRP included groundwater with less than 15,000 mg/l TDS. The most striking feature of both estimates is that the amount of fresh groundwater remaining in storage is very small, ranging from 2.6% to 7% of the total. According to the GWAP assessment (GTZ, 2005a), more than three-quarters (12.5 km^3) of the fresh water in storage occurs in the Liwa lens and only about 4km^3 in the Eastern region. According to the GWRP (USGS, 1996) assessment, at current groundwater abstraction rates, it is projected that the fresh and brackish groundwater resources will be depleted in 50 years from now.

3.5 Abbreviations

ASR	Aquifer Storage and Recovery
Bm^3	Billion Cubic metres
EAD	Environment Agency Abu Dhabi
ERWDA	Environmental Research and Wildlife Development Agency
GTZ	Deutsche Gesellschaft für Technische Zusammenarbeit
GWAP	Groundwater Assessment Project Abu Dhabi
GWRP	Groundwater Research Program
ha	Hectare
m^3	Cubic metre
Mm^3	Million Cubic metre
NDC	National Drilling Company
Mya	Million years ago
SWL	Static Water Level
TDS	Total Dissolved Solids
UAE	United Arab Emirates
USGS	United States Geological Survey
yBP	years before present

3.6 Conversion Measures

1 m3 = 220 Imperial Gallons (IG)

1 IG = 0.045 m3
1 m3 = 264 Gallons (G)
1 G = 0.0038 m3
1 IG = 1.2 G
1 Ha = 2.47 Acres
1 Acre = 0.405 Ha
1 Liter = 0.264 Gallons
1 G = 3.785 Liters
1 IG = 4.54 Liters

3.7 Glossary of Terms

ABSTRACTION: The removal of water from a groundwater reservoir, usually by pumping. [L^3/T] m^3/d, m^3/a.

ALLUVIAL DEPOSITS: The general name for all sediments, including clay, (**ALLUVIUM**) silt, sand, gravel or similar unconsolidated material deposited in a sorted or semi-sorted condition by a stream or other body of running water, in a stream bed, floodplain, delta or at the base of a mountain slope as a fan.

AQUICLUDE: A geological stratum or formation that may be capable of storing water but is unable to transmit it in significant amounts.

AQUIFER: An aquifer is a formation, group of formations or part of a formation containing enough saturated permeable material to produce significant amounts of water to wells and springs.

AQUITARD: A geological stratum or formation that is able to contain water but can only transmit it at very slow rates, enough to be significant in regional groundwater movement, but

BEDROCK: Rock underlying soil and other unconsolidated material.

BRACKISH: Water quality in between Fresh and Saline.

CATCHMENT: A surface from which runoff is collected. Examples include roofs, paved surfaces, or constructed surfaces covered with plastic.

CONFINED AQUIFER: Confined is synonymous with artesian. A confined aquifer or an artesian aquifer is an aquifer bounded both below and above by beds of considerably lower permeability than that existing in the aquifer itself. The ground water in a confined aquifer is under pressure that is significantly greater than that existing in the atmosphere.

DESALINATION: Process of removal of salts from either sea-water or saline / brackish groundwater / surface water.

DISCHARGE AREA: An area where ground water and water in the unsaturated zone is released to the ground surface, to surface water or to the atmosphere.

DRAINAGE: The removal of excess water from the land surface and/or from the soil profile.

> *Surface Drainage:* The diversion or orderly removal of excess water from the surface of the land by means of improved natural or constructed channels, supplemented when necessary by the sloping and grading of land surfaces to these channels.
>
> *Subsurface Drainage:* The removal of excess water from the soil profile by means of drain tiles, perforated pipes, or other devices.

DRILLED WELL: A well that is constructed with a drilling rig, such as an air rotary or cable tool drilling rig.

DUG WELL: A well that is dug by hand or excavated by backhoe. Dug wells are usually shallow.

EFFECTIVE AQUIFER THICKNESS: The saturated thickness of an aquifer over which groundwater flow is significant. [L] m.

EFFECTIVE POROSITY: For both confined and unconfined aquifers, the proportion of interconnected pore space which will yield water under gravity (drainable pore space or **Specific Yield**). [D].

ELECTRICAL CONDUCTIVITY (EC): EC is a measure of how well a material accommodates the transport of electric charge. For groundwater, it is directly measured and usually reported in μS/cm.

EVAPORATION: The process by which water is converted from a liquid to a vapour by the application of energy. Evaporation can take place from a wet soil surface, from snow, ice and open water bodies and from vegetation wetted by rain. In addition, vegetation conveys water from the soil to the atmosphere by evaporation mainly through the stomata in the leaves - a process known as **Transpiration.** [L] mm.

FALAJ: An ancient means of transporting water in channels, both surface and sub-surface, used in the Middle East for until today for irrigation of agriculture and town and village water supply.

FAULT: A fracture in the earth's crust along which dislocation has taken place so that the rocks on one side of the fault have been displaced in relation to those on the other side.

FLUVIAL DEPOSITS: Deposits related to a river or stream.

FOSSIL GROUNDWATER: Old groundwater which currently receives no recharge.

FORMATION (GEOLOGIC): The two basic types of geologic formations are defined below:

> *Consolidated:* A homogeneous layer composed of solid rock or cemented earthen material.
>
> *Unconsolidated:* A formation composed of loose, unsorted earthen materials, or particles such as clay, silt, sand, gravel, or stones.

FRACTURE: A break or crack in the bedrock.

FRESH WATER: Water which generally has a TDS content of less than 1500 mg/l

GROUND WATER: Water in the zone of saturation that is under a pressure equal to or greater than atmospheric pressure.

GROUND WATER TABLE: That surface below which rock, gravel, sand or other material is saturated. It is the surface of a body of unconfined ground water at which the pressure is atmospheric.

HYDRAULIC CONDUCTIVITY: Hydraulic conductivity is a measure of the ability of a fluid to flow through a porous medium determined by the size and shape of the pore spaces in the medium and their degree of interconnection and also by the viscosity of the fluid. Hydraulic conductivity can be expressed as the volume of fluid that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

HYDROGEOLOGY: Study of ground water in its geological context.

HYDROLOGIC CYCLE: The continued circulation of water between the ocean, atmosphere and land is called the hydrologic cycle.

HYDROLOGY: The science dealing with the waters of the Earth, their distribution and movement on the surface and underground, and the cycle involving evaporation and precipitation (Hydrologic Cycle).

HYPERSALINE: With salinity of greater than sea water

JEBEL: Arabic expression for mountain or hill

LITHOLOGY: All the physical properties, the visible characteristics of mineral composition, structure, grain size *etc.* which give individuality to a rock.

MULTI AQUIFER: A hydrogeological situation where several aquifers exist within a formation which are largely independent of each other because they are separated by an **Aquiclude** or **Aquitard**.

OASIS: An area of traditional palm trees and agriculture irrigated by means of aflaj and wells.

PERENNIAL: A stream or spring flowing throughout the year.

PERMEABILITY: The capacity of a rock, sediment, or soil to transmit a fluid; it is a measure of the relative ease of fluid flow under a **Hydraulic Gradient.** Commonly taken to be synonymous with the term Hydraulic Conductivity which implies the fluid is water. **SPECIFIC** or **INTRINSIC Permeability** is a function only of the porous medium. [L2] millidarcys.

POROSITY: The volume of openings in a rock, sediment or soil. Porosity can be expressed as the ratio of the volume of openings in the medium to the total volume.

POTABLE WATER: Water that is safe and palatable for human consumption.

QUATERNARY: The period of geologic time (1.8 million years ago to present day) that follows the Tertiary. The Quaternary includes the Pleistocene and Recent Periods and is part of the Cenozoic Era.

RECHARGE: The quantity of water that is added to a groundwater reservoir from areally distributed sources such as the direct infiltration of rainfall or leakage from an adjacent formation. [L] mm.

RUNOFF: The portion of precipitation or irrigation water that moves across land as surface flow and enters streams or other surface receiving waters. Runoff occurs when the precipitation rate exceeds the infiltration rate.

SABKHA: Sabkha is an Arabic name for a salt-flat ordinarily found nearby sand dunes. These relatively flat and very saline areas of sand or silt form just above the water-table where the sand is cemented together by evaporite salts from seasonal ponds.

SALINE GROUND WATER: Ground water consisting of or containing salt.

SPRING: A surface water body created by the natural emergence of ground water to the Earth's surface.

Contact Spring: A spring that usually occurs where a mass of permeable rock or unconsolidated materials overlie a mass of impermeable material.

Depression Spring: A spring that occurs where the topography of the Earth's surface dips below the water table, thus forming marshes or small ponds.

Fault Spring: A spring that originates where there is a fault in the rock layer.

STATIC WATER LEVEL: The level of water in a well that is not being influenced by ground water withdrawals. The distance to water in a well is measured with respect to some datum, usually the top of the well casing or ground level.

STORAGE COEFFICIENT: Volume of water stored or released from a column of aquifer with unit cross section under unit change in head.

THROUGHFLOW: The lateral movement of a significant amount of water through the soil above the regional water table.

TOTAL DISSOLVED SOLIDS (TDS): Concentration of total dissolved solids (TDS) in ground water expressed in milligrams per litre (mg/L), is found by evaporating a measured volume of filtered sample to dryness and weighing this dry solid residue.

TRANSMISSIVITY: Rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity values can be expressed as square metres per day (m^2/day), or as square metres per second (m^2).

UNCONFINED AQUIFER: An aquifer in which the water table is free to fluctuate under atmospheric pressure.

UNCONSOLIDATED DEPOSITS: Deposits overlying bedrock and consisting of soil, silt, sand, gravel and other material which have either been formed in place or have been transported in from elsewhere.

WADI: A channel, ravine or valley, dry, except in the rainy season.

WASTEWATER: Water which is of no further immediate value to the purpose for which it was used or in the pursuit of which it was produced because of its quality, quantity or time of occurrence. However, waste water from one user can be a potential supply to a user elsewhere.

WETLAND: A land area that is inundated or saturated by surface and/or ground water with a frequency and duration sufficient to support an abundance of hydrophytic (water-loving) plants or other aquatic life that require permanently saturated or seasonally saturated soil conditions for growth and reproduction. Examples include swamps, marshes, bogs, sloughs, potholes, wet meadows, river overflow areas, mud flats, and natural ponds.

4 GEOLOGY AND GEOMORPHOLOGY

The present desert land surface of Abu Dhabi overlies rocks that were deposited over a time span of more than perhaps 950 million years. Much of this deposition took place below the sea but there were lengthy periods when the land surface was uplifted and underwent subaerial erosion, thereby removing any trace of its geological history over that period. Most of the evidence of that ancient history is now buried beneath the land surface and adjacent Arabian Gulf and is studied by geologists and geophysicists mostly in the search for oil and gas. Today, apart from rare localities where these ancient rocks are uplifted and exposed at the surface, the remainder of Abu Dhabi is a country whose geomorphology and sedimentary cover tells us much about its sub-recent development as a desert marginal to an Arabian Gulf that fluctuated greatly in size over the past few million years or even less.

4.1 Geology

4.1.1 Subsurface Geological Framework

The oldest exposed rocks in Abu Dhabi occur at Jebel Dhanna in the western part of the Emirate and also on several offshore islands including, for example, Sir Bani Yas (**Figure** 4.1). These jebels and islands are dome-shaped at the surface and are covered by Hormuz Salt, named after similar salt on Hormuz Island in the Strait of Hormuz. The salt, possibly over 1,000 metres thick, was deposited around the Cambrian-Precambrian time boundary about 540 million years ago (Sharland et al., 2001; Al-Husseini et al., 2003) on the floor of an almost enclosed sea, when evaporation resulted in its water becoming super-saturated with respect to *halite* (common salt).

Figure 4.1: Landforms and Simplified Geology of Abu Dhabi

About 20 million years before the present (20 Ma BP), much of the Red Sea was also floored with salt in a similar way. Salt can flow and, unlike the sedimentary rocks that overlie it, cannot be compacted with increased depth of burial. For this reason, salt at depths greater than about 1,000 metres is less dense than its immediate overburden and, using any vertical weakness, can penetrate upward *(diapirism)* lifting or breaking through the overlying rock sequence eventually to form *salt domes* at the surface. In the south-eastern Arabian Gulf, the source of the diapiric Hormuz salt now lies at a depth of up to 7 to 10 kilometres (Beydoun 1991; Sharland et al., 2001), and underlies much of the Zagros Mountains of Iran (**Figure** 4.2). Within the southern Gulf there is a line of salt domes between Zakum in the southwest and Larak Island in the northeast that are almost parallel to the coastline between Abu Dhabi city and northern Musandam. Here the Emirates coastline steepens, especially northeast of Umm al Qawain. The reasons are not known but may well be related to the southern limit of the Hormuz salt.

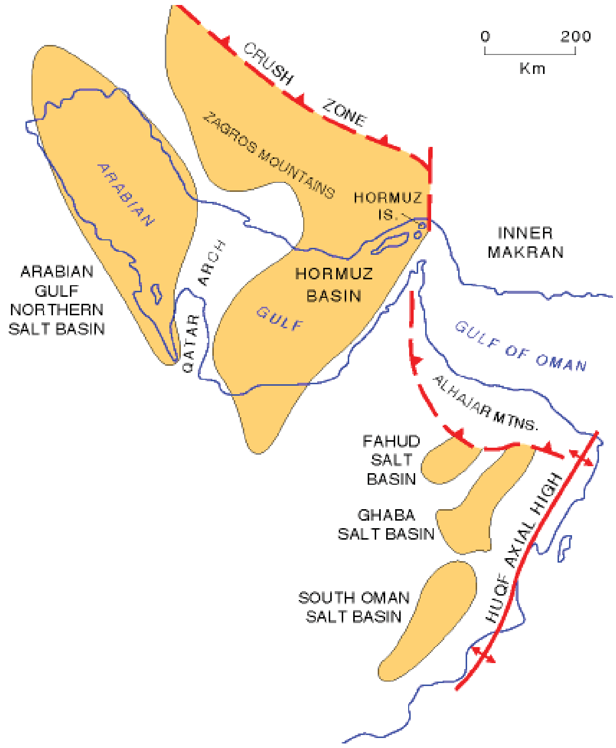
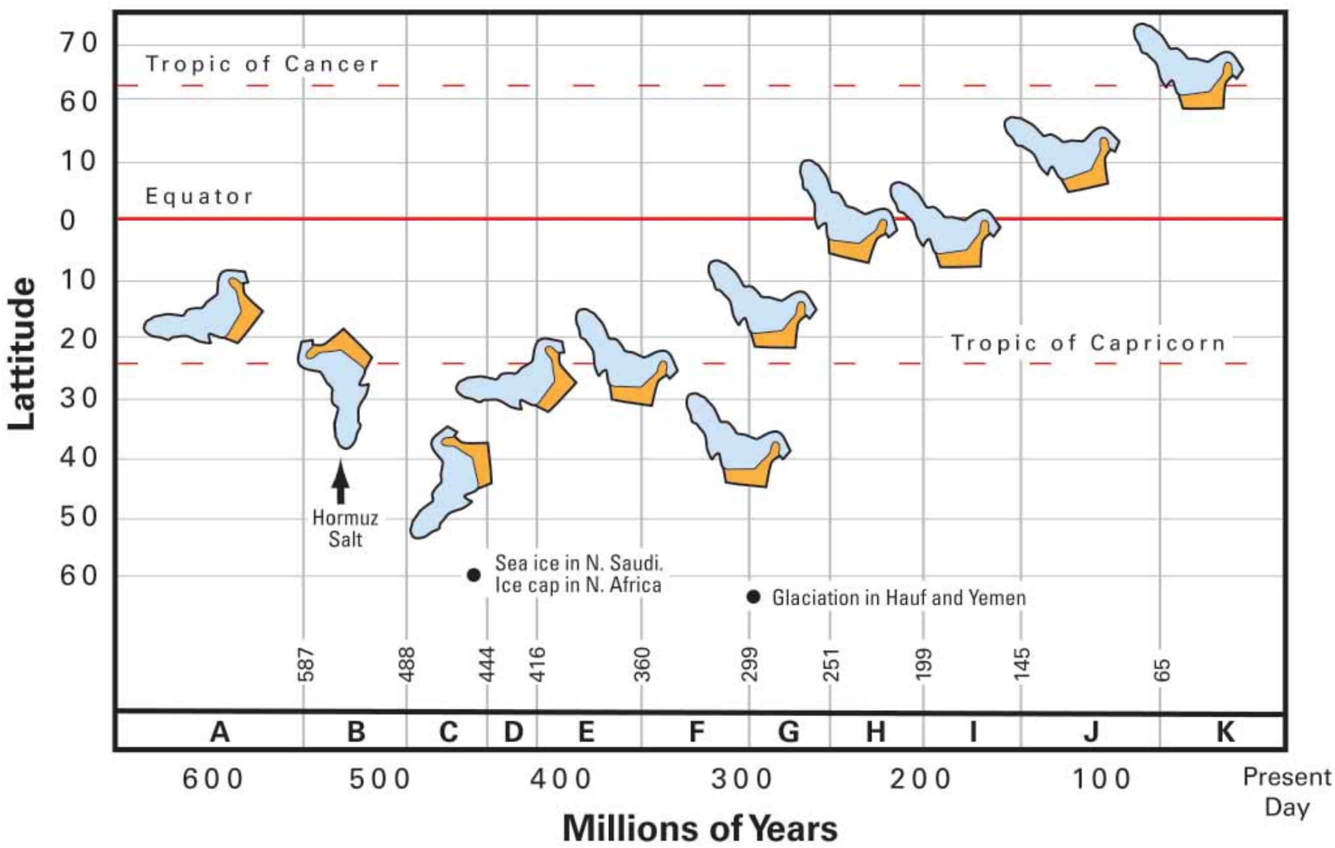


Figure 4.2: Hormuz/Eo-Cambrian Ara Salt Basins

Arabia, as part of the megacontinent *Gondwana,* was located south of the Equator virtually throughout the Palaeozoic era (**Figure 4.3**). Under the influence of *plate-tectonic* processes, initially it was geometrically 'up-side-down' relative to the poles as Gondwana moved south across the South Pole and came up the other side the 'right-way up'. Because Arabia's southern traverse was undertaken largely in temperate latitudes, most of the Palaeozoic rocks comprise sandstones and shales, a small exposure of which occurs in Jebel Rann, south-west of Dibba within the Al-Hajar (Oman) Mountains.

In complete contrast, from the Late Permian (about 260 Ma BP) to Late Miocene (part of Neogene in **Table** 4.1; about 5–10 Ma BP), Arabia slowly drifted northwards across the Tropics, where warm, shallow, tropical seas were ideal for the growth of corals and other shallow-marine creatures with calcareous shells. Their accumulation, after death, led to the formation of varieties of *limestone*, some of which later became important reservoirs for oil and gas.

Abu Dhabi's Plate-Tectonic Migration Relative to the Equator Plotted Against Time



A. Pre-Cambrian
B. Cambrian
C. Ordovician
D. Silurian
E. Devonian
F. Carboniferous
G. Permian
H. Triassic
I. Jurassic
K. Cenozoic

Older glaciations were widespread throughout Oman within the Abu Mahara group (~>605 Ma and ~713 Ma) whether these occurred near the north or south poles is not known to Glennie but the possibilities can be seen from this diagram.

Modified from Hughes-Clarke (1999) Oman's Geological Heritage (PDO, Muscat).

Hydrocarbon source rocks**:** Depending partly on a water depth that varied with time, the sea floor was intermittently covered by a variety of rocks that included organic-rich muds which later became the sources of hydrocarbons (oil and gas) now stored in porous reservoir rocks. **Table** 4.1 shows a simplified outline of the subsurface geology of the desert plains. Source rocks of late Precambrian age occur in Oman and may be present beneath Abu Dhabi's offshore area but if so will be so deeply buried that they will long since have given up their oil and gas. Rocks of Silurian age underlie and source many of the major oil fields of Saudi Arabia, and possibly also provide oil and gas to some of Abu Dhabi's offshore fields structured by Hormuz salt (Bordenave, 2008). Most fields, however, both onshore and offshore, derive their oil and gas from Jurassic or Lower Cretaceous source rocks and are produced from overlying Cretaceous limestone reservoirs.

Reservoir rocks range in age from the Late Permian (Khuff Formation) to the Jurassic, where the Arab reservoirs are important, and from Cretaceous (Shuaiba, Mauddud and Mishrif) to the Lower Tertiary (Pabdeh Formation). Seals, which prevent the relatively buoyant hydrocarbons from escaping to the land surface or sea floor, cap the reservoirs. The best of these are evaporites such as gypsum and anhydrite, which are inter-bedded with the different Arab reservoir horizons or the overlying latest Jurassic Hith Formation (Al Silwadi et al. 1996). These seals were probably deposited in almost enclosed coastal lagoons or on extensive coastal sabkha similar to those now found along the shore and on the offshore islands of Abu Dhabi (Alsharhan & Whittle 1995).

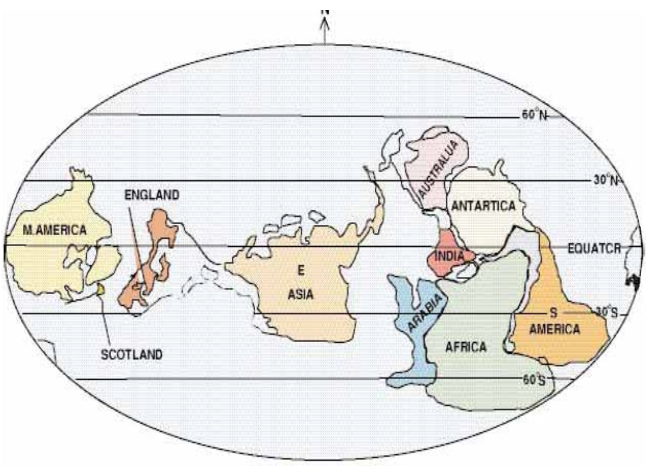


Figure 4.3: Distribution of continental plates during the early

Arabia then formed part of the megacontinent called Gondwana, which included Australia, Antarctica, India, Africa and South America. Gondwana was separated from eastern Asia by an ancient ocean called Palaeotethys.

For source rocks to become *mature* and give up their oil, they need to be buried to a depth where the temperature approaches that of boiling water (about 3 km, depending on the local *temperature gradient* through the underlying rock sequence). At a depth of around 4 km, it starts to become mature for gas production but post-mature for the generation of oil, and by 6 km, the temperature is so high (around 180°C) that the source rock is 'burnt out' and even gas generation ceases (post-mature for gas). Newly generated oil is squeezed out of its source bed and migrates (usually upward) into a porous reservoir rock (e.g. sandstone, dolomite). The oil or gas can be retained in the reservoir rock only if it is kept in by an impervious *cap rock* or *seal,* and the reservoir/seal couplet forms a trap. Structural deformation of the reservoir/seal couplets to form traps can occur in a variety of ways; these can include fault movement at basement level, which affects all overlying rocks at the time of faulting, differential compaction of underlying sands and shales and, most prominently in the southern Gulf area, by diapiric uplift of the Eo-Cambrian Hormuz salt and its sideways withdrawal from the deep salt horizon to feed that diapirism (**Figure** 4.3). For a general discussion of Arabian petroleum geology, see Beydoun (1991) and more specifically for Abu Dhabi and the rest of the Emirates, Alsharhan (1989).

Some traps form anticlines. A clearly visible anticline that unfortunately has no proven oil is Jabal Hafit. The surface of Jabel Hafit, just south of Al Ain, consists of Lower Cenozoic limestones and marls that have now been deformed into a sharp, steeply flanked anticline whose axis plunges to both north and south. The time of its deformation possibly coincided with uplift of the Oman (Al Hajar) Mountains sometime within the past 4-5 million years.

Plate-tectonic movements associated with the origin of the Al-Hajar Mountains may have induced local warping of the continental crust within the emirate of Abu Dhabi and surrounding countries (e.g. Glennie, 2005a). Hypothetically, such warping, whose locations cannot be predicted, may have affected the local development of Mesozoic hydrocarbon source rocks within structural lows or of carbonate reservoir rocks surrounding shallow structural highs.

AGE Ma		PERIOD	① PLATFORM AREA: GROUP		① PLATFORM AREA: FORMATION	② MUSANDAM PENINSULA (PARAUTOCHTHONOUS)	③ OMAN MOUNTAINS (ALLOCHTHONOUS)
2	CENO-ZOIC	QUATERNARY NEOGENE PALEOGENE		FARS PABDEH	PABDEH (G)	ERODED/ NOT DEPOSITED	
65	MESOZOIC	CRETACEOUS	H S G	ARUMA WASIA THAMAMA	LAFFAN (S) MISHRIF (O) MAUDDUD (O) SHUAIBA (S/O)	MUSANDAM	SEMAIL NAPPE HAWASINA SUMEINI, HAMRAT DURU, AL ARIDH, KAWR, UMAR
145	MESOZOIC	JURASSIC	H S G	SAHTAN	ARAB (O) DIYAB (S) ARAEJ (O) MARRAT (O)	MUSANDAM	
199	MESOZOIC	TRIASSIC	H S G	AKHDAR	JILH (S) KHUFF (G)	ELPHINSTONE RUUS AL JIBAL	
251	PALAEOZOIC	PERMIAN	H S G	AKHDAR	JILH (S) KHUFF (G)	THRUST OVER ARUMA & HAWASINA	
299	PALAEOZOIC	CARBONIFEROUS	MAJOR HIATUS				
360	PALAEOZOIC	DEVONIAN					
416	PALAEOZOIC	SILURIAN					
443	PALAEOZOIC	ORDOVICIAN	?				
488	PALAEOZOIC	CAMBRIAN					
542	PRECAMBRIAN		HORMUZ SALT				
	PRECAMBRIAN		?				
700	PRECAMBRIAN		CRYSTALLINE BASEMENT FIRST FORMED AROUND 950 Ma B.P.				
800	PRECAMBRIAN						

NOTES:

1. Autochthonous rock units - Geological groups in L.H. column. R.H. column lists some important source rocks (S) and oil- (O) & gas- (G) bearing formations. Note Basal Cambrian Hormuz Salt.
2. Parautochthonous rocks of Musandam Peninsula are similar to those of the platform area but have been thrust short distance over Aruma and Hawasina covering deeper platform rocks, probably at end of Paleogene.
3. South of the Musandam Peninsula, the Hawasina comprises an imbricate sequence of continental slope (Sumeini) and ocean floor sediments (Hamrat Duru to Umar groups). They are overlain by the Semail Nappe comprising former oceanic crust. Obduction of both Hawasina & Semail took place during time span of deposition of the Aruma Group on the Arabian Platform.

←—— indicates sense of thrusting

HSG = Hajar Supergroup

Table 4.1: Rock Units of the United Arab Emirates. (Based Gradstein et. al., 2004).

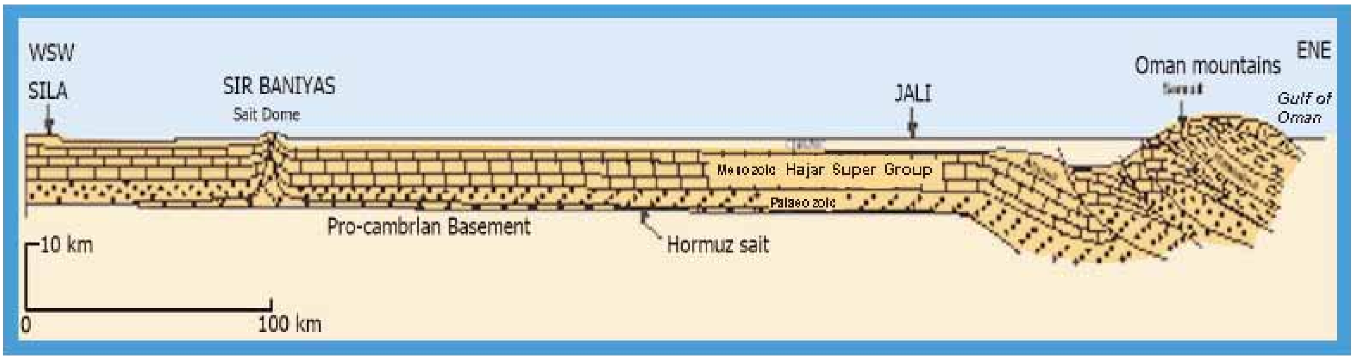


Figure 4.4: Geological Cross-Section through the United Arab Emirates.

The deformation leading to the creation of hydrocarbon traps within the Hajar Super Group resulted from movements associated with basement faults and the Hormuz salt. Most diapirs are too small to show at scale of section. The nappes of the Oman Mountains were obducted when the eastern margin of Arabia and adjacent ocean floor attempted to underthrust oceanic crust now represented by the Semail Nappe.

4.1.2 Terrestrial Sediments of Western Abu Dhabi

Global sea level has been falling erratically for the past 60 Ma. Younger falls occurred in the mid-Miocene some 15 Ma ago with the start of glaciation over Antarctica and around 3-4 Ma during the Plio-Pleistocene glaciation of Greenland (Boulton, 1993; Glennie 2005b). At the time of continental collision between Arabia and Asia in the early Miocene, perhaps 19-16 Ma ago or even slightly earlier (Hill & Whybrow, 1999), shallow-marine sedimentation was replaced by terrestrial conditions over much of the Gulf region. In western Abu Dhabi, and apparently overlying dolomites with marine bivalves of the Dam Formation in the Sila area (Ditchfield, 1999) the unfossiliferous Shuwaihat Formation (Bristow, 1999) comprises continental sabkha evaporites (base seen only south of Sila) that are replaced upwards by dune sands which, like those of today, were deposited under the influence of a northern (*shamal*) wind; the sands are riddled with the moulds of plant roots (Glennie and Evamy 1968), which indicate the former proximity of the water table at fairly shallow depth. Among other places, aeolian sediments of this age (about mid Miocene) are exposed on Shuwaihat Island, at Jebel Dhanna and south of Sila (**Figure** 4.1). The Shuwaihat Formation contains minor eastward-flowing fluvial sands.

After an erosional interval representing several million years, these dune sands were overlain by fluvial gravels and sands of the Baynunah Formation (**Figure** 4.1), which contain a wide variety of vertebrate fossils of both terrestrial and aquatic types: crocodile, turtle, hippopotamus, an early type of elephant, buffalo and ostrich, as well as smaller mammals (Whybrow and Hill 1999; Friend, 1999). Friend (1999) interprets a late Miocene Bunaynah river system flowing to the southeast that may have been tributary to an early south-flowing Tigris-Euphrates system; if so, that river will probably have reached the sea north of the Umm as Samim in Oman, whose northern edge is rimmed by cliffs bearing Miocene marine fossils. The change from arid dune and *sabkha* to the more humid non-saline conditions needed for the hippopotamus and crocodile to thrive requires a considerable change in climate, a change that, perhaps on a shorter time scale, seems to have taken place repeatedly during the Pleistocene. The erosional time gap between the Shuwaihat and Baynunah formations is possibly the result of climatic changes associated with the earliest development of the north polar ice caps during the mid Miocene (Boulton, 1993). Using palaeomagnetic techniques, Hailwood and Whybrow date deposition of the Shuwaihat Formation at around 15 Ma and the Baynunah Formations at around 6 Ma. These rocks are now exposed in occasional jebels and along the flanks of widespread tablelands, mesas and buttes just inland from the coast mostly in western Abu Dhabi.

4.1.3 The Influence of High Latitude Glaciations on Arabian Deserts

During the past approximately 800,000 years, one process has repeatedly affected global climate, including that of tropical deserts. With a cyclicity of around 100 ka (100,000 years), Greenland, the whole of Scandinavia and the northeastern half of North America, suffered repeated slow build-ups of an ice cover up to two or three kilometres thick, which then melted very rapidly within 10 ka or less (Shackleton 1987; Boulton 1993; Lambeck et al, 2002); because global temperatures were lower during glaciations, many highland areas became the sites of mountain glaciers, whereas the ice cap over Antarctica, which had been a permanent feature of the southern hemisphere from at least the early Miocene onward, only expanded and contracted in size.

Apart from lowering global temperatures, these glaciations affected climate in two other ways (Glennie, 2005):

- Because the ice caps became the centres of very large areas of high atmospheric pressure, all other air-pressure belts around the globe were squeezed towards the low-pressure equatorial area. With isobars much closer together than is the case today, global winds will have been much stronger and more persistent than any we now experience.

- So much water went into building the ice caps that global sea level at the last glacial maximum, about 18 ka BP, was some 130 metres lower than today's. Since the floor of the Arabian Gulf is everywhere less than 120 metres deep, during glacial maxima the exposed floor of the Gulf would have been the site of sand dunes (e.g. Sarnthein, 1972) migrating southward under the influence of the northern (*shamal)* wind and across Abu Dhabi into the Rub' al-Khali. The only sign of water in the Gulf area would have been in the combined Tigris-Euphrates River, which derived its water from the wetter Anatolian highlands and reached the open sea southeast of the Strait of Hormuz.

The high-latitude glaciations took some 80 to 100 ka to reach their maximum extent; the last then melted within about 10 ka to produce a global sea level similar to that of today's by about 6 ka BP; thus sea level rose at an average rate of about 1.3 cm per year but possibly exceeded 4 cm/year for short periods (Boulton 1993; Lambeck et al., 2002). This rapid rise in sea level within the Gulf is considered to have been the origin of the biblical story of 'Noah's Flood', perhaps between 6 and 9 ka BP (Glennie, 1997; 2001; Teller et al. 2000). Noah is thought to have lived in an area now covered by the Arabian Gulf. Over the almost flat floor of the Gulf, any continuous rise in sea level would have been noticed by the people living there as the water advanced towards Mesopotamia at an average of about 150m/year. Noah's family possibly lived in the drier environment of a gentle rise, perhaps a stabilised tree-covered former sand dune, to escape the effects of a rainfall that was probably considerably higher than any experienced today. As sea level rose in the Gulf, Noah's slightly elevated pasturage would have become isolated from the mainland and then be seen to shrink in area, leading to the need for a barge or raft if he and his family and flocks were to survive the encroaching sea; necessity is the mother of invention.

Many desert areas, including much of the Sahara, had a higher rainfall between about 9 and 6 ka BP. This induced the growth of much more vegetation, which fed abundant game, leading to the term 'Climatic Optimum' (Petit-Maire 1994); since then, most tropical deserts have become more arid again.

Flooding of the Gulf had a profound effect on the Emirates. Instead of sand dunes migrating southward into the area from the dry Gulf floor, the supply of wind-driven sand was progressively cut off by the increasing extent of sea water. The wind continued to blow, however, so that in land areas close to the expanding sea, sand was deflated (removed by wind action) down to the level of the water table, which was rising in concert with the rising sea level in the Gulf. Evaporation caused the resulting moist surface to develop into *sabkha*, which are described later. The deflation of sand from coastal areas and its deposition inland to the southwest resulted in the asymmetry in elevation of the basin between the Hajaz Asir and the Oman Mountains (**Figure** 4.5).

4.2 Geomorphology

4.2.1 Mountains

Abu Dhabi Emirate is a low-lying country, most of which is less than 200 metres above sea level. Within the Emirate a maximum altitude of just over 1,100 metres is reached in Jabal Hafit on the western flank of the Oman Mountains.

The relatively high altitude of adjacent mountain-edge sediments extends northward of Jabal Hafit for several kilometers while decreasing in height to the west (Al Ain University, 1993).

The Oman Mountains are the product of:

a) The Hawasina turbidite sequences, which were deposited in two adjacent and consecutively formed NW-SE trending marine troughs (Neo-Tethys 1 & 2) that developed to the northeast of the country between the Late Permian and the mid to Late Cretaceous (*e.g*., Glennie, 1995/2005; Glennie 2000).

b) The sedimentary sequences of these troughs were obducted (emplaced over) the NE margin of SE Arabia during the Late Cretaceous, together with their cover of Cretaceous-age Samail ophiolites (a thick sequence of oceanic crust and underlying mantle rocks) that developed during 'back-arc spreading' behind a NE-dipping *subduction* trench. Obduction had ceased before the close of the Cretaceous to leave what was probably little more than an island archipelago for much of the Cenozoic era.

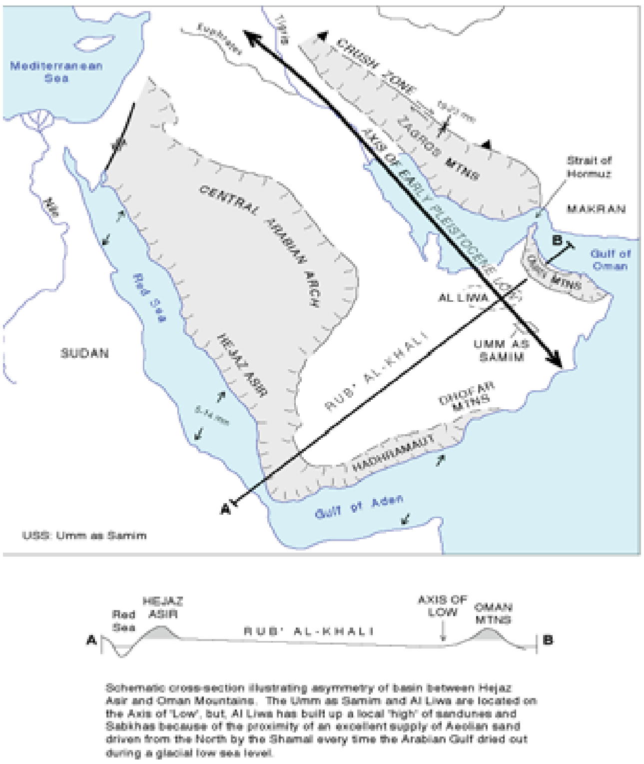


Figure 4.5: Asymmetry of the Rub' Al-Khali Basin

c) The Oman Mountains probably began to rise into a mountain range late in the Miocene, around 4-6 million years ago, following the 'opening' (creation) of the Red Sea and especially the Gulf of Aden. This 'push' to the NE was resisted first by the Neo-Tethys oceanic crust that lay beyond the site of the future mountains and eventually by collision with continental Eurasia. The Arabian crust was warped into a gentle, asymmetric, syncline that trended from south of the Huqf on the Arabian Sea coast of Oman, through the salt-covered Umm as Samim, across Abu Dhabi and through the Arabian Gulf to Mesopotamia. (Figure 4.4). Compression between NE Arabia and the Iranian microcontinent of the Sirjan-Sanandaj Zone of SW Asia led to uplift of the Zagros Mountains, and these are still moving to the NE at a rate of about 5-14 millimetres/year relative to Africa and 'closing' across the Zagros Crush Zone at 19-23 millimetres/year relative to Eurasia (McClusky et al., 2000, McClusky et al., 2003; **Figure** 4.4). No wonder the latter is a zone of constant earthquakes.

d) The Oman Mountains have been rising at a rate of some 2 millimetres/year (200 metres/Ma) in the recent past, but it is not known whether this rate of uplift was slower or more rapid in earlier years. The most important impact that this uplift had/has on Abu Dhabi resulted from erosion of the rising mountains, first the ophiolites followed by the Hawasina, and the resulting deposition of alluvial fans that in Oman extend over 200 km SW from the mountain edge and in SE Abu Dhabi begin to underlie younger sand dunes within a few kilometers of the mountains.

During the later Miocene, a marine Arabian Gulf did not exist (Ziegler, 2001; see also the fluvial Baynunah Formation mentioned above). The Gulf of Oman is now being subducted beneath the Makran coast of Iran at a rate of about 18? millimetres/year. This rapid rate of closure may be caused by right-lateral movement of the Naiband Fault in Iran (**Figure** 4.6; see also Figure 4 in Glennie et al., 1990). These movements seem to be confined to east of the Musandam Peninsula, which itself may also be in the process of subduction to the NNE between the Dibba splay fault and the eastern thrust/depositional boundary of the Zagros Range. Relative to the flooding of the Gulf, however, note the location of the 60 fathom channel that curves to the SE from near the drowned northern tip of Musandam; this probably represents fluvial erosion caused by a combined Tigris-Euphrates River that cut a channel down to about 71 fathoms (130m) during an extensive late glacial maximum of some 10 ka duration (~30-20 Ka BP).

The northern extension of the Musandam Peninsula passes to the east of the salt domes exposed on Larak and Hormuz islands, so subduction beneath the Zagros Mountains can almost certainly be ruled out.

Once a route through the Strait of Hormuz had formed, however, it must have been utilized preferentially to drain the Tigris-Euphrates river system during glacial periods of low sea level extending back beyond the penultimate glacial maximum (~150 ka BP). This interpretation is based on the knowledge that dune sands, well above current global sea level, have existed over Al Liwa for at least the past 160 ka (p. 281 in Pugh, 1997) thereby blocking any older fluvial route southward via the Umm as Samim; rising post-glacial waters from the Gulf of Oman would have flooded through the Strait of Hormuz into the relatively low axial depression now occupied by the Arabian Gulf.

4.2.2 Sand Seas and Dunes

Away from the Oman Mountains and the Abu Dhabi coastline, the surface of the Emirates is dominated by the presence of sand dunes. *Dunes* migrate in the direction of the sand transporting wind (**Figure** 4.6). With a *linear dune,* this is achieved by the movement of sand along the dune flanks and deposition (causing elongation) at its down-wind end; if the up-wind supply of sand ceases for any reason (*e.g*., flooding of the Gulf), that end of the dune 'shrivels' and the dune shortens as sand is removed downwind and not replaced. The same principle applies to *transverse dunes,* but because their long axes are at right angles to the wind, sand is transported preferentially over the top of the dune to its leeward side (where it forms an *avalanche slope* with a maximum inclination of 34°) rather than around its flanks. Where the supply of sand is limited, crescent-shaped *barchans* are formed; here, in addition to the movement of sand over its crest to the avalanche slope, sand is also readily transported along the dune flanks, which are drawn out into the long 'horns' that point down wind. On a much smaller scale, the axes of *ripples* are always at right angles to the wind that formed them, so their distribution gives an indication of the short-term pattern of wind flow over and around the dune.

Most of the big dunes of especially the NE Emirates are of the linear type. From their currently well preserved distribution they must have formed during the last glacial maximum when glacially strengthened Shamal winds deflated the sands then exposed on the floor of the Gulf. In the eastern Emirates their western ends look as if they originated beneath the sea. Because their sands had a content of fragmented carbonate shells, they tend to be fairly well cemented and more resistant to erosion at their seaward ends. Their down-wind extensions seem to have curled towards the NE as they approached the wind-block of the northern Oman Mountains.

Across central Abu Dhabi, a broad belt of large, partly eroded (deflated) north-west to southeast trending linear dunes skirt the north-east margin of the Liwa. Changing climatic conditions caused partial erosion of these dunes and the creation of smaller N-S oriented linear dunes extending southward as the Oman border is approached; these dunes overlie the alluvial fans that flank the Oman Mountains (**Figure** 4.1). These variable trends are thought to outline the fairly constant direction of dune-forming winds at, or shortly after, the peak of the last glaciation; and since that time the outlines of the dunes have been modified although the basic plan is still recognizable. Fitting into the same wind pattern are the giant *barchanoid* dunes (up to 150 metres above the interdune *sabkha*) of the Liwa. The axes of these dunes are transverse to the dune-forming wind, which there blew towards the SSE. An unusual feature of the Liwa is that most of its interdune areas are the sites of inland sabkha up to 90 metres above present sea level. The occurrence of older sabkha can be recorded from the ages of intervening dune sands back to at least the penultimate glacial maximum Travelling further to the west, the modern (and perhaps also the ancient) winds blow increasingly towards the south, eventually to veer south-westward in Saudi Arabia across the central Rub al-Khali towards the mountains of Yemen. This semi-circular pattern is typical of what are known as *trade wind deserts* (following the same sort of path as the trade winds sought by sailing ships heading westward from Europe and North Africa to the Americas) such as the Sahara or, in the southern hemisphere, the Australian desert.

Figure 4.6: The Influence of Prevailing Winds on Dune Formation in the Rub Al-Khali and Wahaybah Dune Systems.

The broad pattern of large dunes outlined above has been modified by the effects of changing sea level in the Gulf. When sea level rose at the end of the last glaciation, the supply of aeolian sand from the north was stopped. Although the wind still blew, its direction was out of equilibrium with the geometry of the existing dunes so their shape became modified; these modifying winds apparently were not as strong as formerly, so the new resulting dune forms were smaller than the pre-existing large dunes. This can be seen by the belt of small transverse dunes that drape the northern and north-western margins of the Liwa.

Over the course of recent history, the trade winds have not been as constant in direction as one might imagine. Today's strongest sand-transporting wind (the northern *shamal*) at Abu Dhabi airport has shifted about 30° to the north relative to its Glacial equivalent, and the winds are more variable than they used to be. This variability is illustrated by small west-east trending linear dunes that cross the interdune areas of the Awir oasis in southern Dubai, for instance, and other similar areas further north; it is also indicated south-west of Jebel Hafit by star-shaped peaks on some of the large linear dunes which occur when dune-forming winds blow in more than one direction. Today's more variable dune pattern could be the product of a wind system that is much weaker than it was in glacial time.

Every time the Arabian Gulf was flooded by the sea, shallow-marine organisms flourished and eventually died, many leaving the evidence of their former existence on the sea floor in the form of calcareous shells. When the Gulf floor was exposed to the wind during sub-polar glaciations, the smaller of these shells were transported southward to the Emirates where they formed carbonate-rich dunes. Similar dunes near the coast of north-western India are known as 'miliolite' after their content of miliolid foraminifera, and the same name has been applied in south-eastern Arabia. Inland from the coast, miliolite is widely exposed, in many cases within the core of, or adjacent to, modern dunes (e.g. draping exposures of the Baynunah Formation in western Abu Dhabi, from Silmiya south to Hameem, at the eastern end of the Liwa, or the Abu Dhabi – Al Ain road south-east of Bani Yas). Along the Hameem road, two sequences of miliolite are separated by evidence of a wetter climate (dikaka); the lower sequence has a depositional age of 99 ka BP and the upper of 64 ka BP, times when the ocean's surface was about 25 and 80 metres, respectively, below the present level of the Arabian Gulf. A study of the bedding attitudes of the miliolite indicates variations in wind direction similar to those deduced for the modern dunes (Glennie 1994).

It is clear that the dune systems of the Emirates have been controlled not only by global shifts in wind strength and direction, but also by glacially controlled changes in exposure of the Gulf floor, which in turn have controlled the distribution of both coastal and inland *sabkha*. Those dunes and *sabkha* are still reacting to today's climate and associated wind directions.

Colour: after burial beneath the water table, aeolian sand grains acquire a thin coat of dust that has percolated down from the surface; and in an arid environment the same can happen to the less common fluvial sands. Groundwater generally has a content of ferrous iron in solution. Climatic instability causes the water table to fluctuate, and when the thin but wet coats of dust are exposed to oxygen above the water table the ferrous ions change to the insoluble red ferric variety (like rust), which colours the sand to a reddish hue. Thus dune sands can vary in colour from almost white, usually an indication of a high content of shell fragments of marine origin, through yellow to reddish brown, as seen in the fluvial and aeolian sands of the Baynunah and Shuweihat formations respectively.

4.2.3 Fluvial sediments & wadis

When there is sufficient rainfall, gravels and sands are transported down the mountain sides and across the valley floors within the mountains by fluvial processes. In recent years such rainwater reached the sea about once in every ten years in the northern emirates, but south of Jebel Faiyah it always dissipates within the sand dunes that block the lower reaches of the fluvial channel and never reaches the sea. Such channels are better called 'wadis': 'desert watercourses that are dry except after rain' (*see* Glossary).

True continuously flowing rivers were active at various times from the late Miocene onwards. The crocodile-bearing meandering rivers of the Baynunah Formation have already been described (Friend, 1999). Since the uplift of the Oman Mountains, however, fluvial erosion resulted in the creation of broad alluvial fans that stretched far to the west of the mountains and, in the east, to the shores of the Gulf of Oman. To achieve that sort of sediment distribution, some of it of cobble and even boulder size, implies much more frequent and heavier rain than is experienced today. Both east and west of the mountains, these older fluvial sediments are now covered by extensive wind-blown sands so there must have been a very marked change in climate for this succession to take place.

West of the Al Hajar mountains is a broad sheet of fluvial sands and gravels that spread for a considerable distance beneath the present cover of dune sands. In south-east Oman, the same spread of *alluvial fans* extends as much as 200 km south of the mountains; in the north, they stretch some unknown distance beneath the floor of the Arabian Gulf and westward beneath the dunes and sabkha of Al Liwa. The time of deposition of some of the younger gravels now exposed in incised wadi banks have been dated at around 30,000 and 70,000 thousand years before present (30 and 70 ka BP), while others, in Wadi Dhaid for instance, coincided with the Climatic Optimum (Sanlaville 1992) of only 6-9 ka BP. The fans have been subjected to repeated deflation, however, and near-surface sediment has been dated in Oman at over 300 ka, while the degree of diagenetic alteration of some ophiolite-rich fluvial sediment to a white dolomite (Barzamanite; Maizels, 1987) suggests deposition possibly a million or more years ago. White barzamanite is known from along the western edge of the northern Oman Mountains and in the 1970s was discovered near the Dubai coast while excavating beneath the Port Ali sabkha (Glennie, 2005b); to judge from the presence of diagenetically altered boulders, the 'barzamanite' river must have extended some considerable distance into what is now the Arabian Gulf, and may well have been a tributary of an older Tigris-Euphrates river. In parts of eastern Oman south of the mountains, large white areas of barzamanite are overlain by undated fluvial channels whose surfaces have been blackened by desert varnish and now show clearly on Landsat images. The channels are of two types; a) sinuous (meandering) channels that indicate a continuous annual flow of river water typical of a relatively humid climate; and b) straight channels, which indicate the occurrence of seasonal flash floods more typical of a arid or semi-arid climate (Glennie, 2005b, fig. 7.23). Climatic changes similar to those that have been taking place over the past few hundred thousand years are inferred.

The extent of the fluvial sediments in the alluvial fans, and the size of the pebbles and boulders found in them, indicate that at the time of their deposition there was much more rainfall over SE Arabia than is experienced today. The surfaces of such alluvial fans are exposed between some of the large linear dunes of the eastern emirates (**Figure** 4.1). Quaternary fluvial sediments are rarely exposed between the dune cover of most of Abu Dhabi. Along the western side of Sabkhat Matti, however, at the western limit of Abu Dhabi, another sequence of fluvial gravels is exposed at the surface. This extensive area of sabkha is probably controlled by an underlying fault, which created a zone of weakness utilized by past fluvial activity. The attitude of the fluvial bedding indicates that there, an ancient river flowed towards the north or north-east. The types of rock (e.g. limestone, volcanic lava) represented by the pebble content of the gravels point, in this case, to a source in the south-western highlands of Saudi Arabia. The time of their deposition has been dated at over 200 ka BP (Goodall 1995), which obviously was another period of higher rainfall than now, probably coinciding with an earlier interglacial (see Boulton, 1993; Fig. 4.2 in Glennie, 2005b); with the same sort of source area, these gravels are similar to those of the Baynunah Formation found nearer to Sila.

4.2.4 Islands

The islands of Abu Dhabi are of three main types:

1. Those created by the diapiric rise of ancient Hormuz salt, which pushed up the overlying strata into domes, or which broke through the overlying strata, which now flank the rising pillars of salt (section 4.1.1); they will not be discussed further;

2. Those formed under shallow-marine conditions (e.g. Great Pearl Bank) mostly within the past few thousand years but which may have had their origins in earlier glacial-age sabkha activity, and

3. A series of near-shore islands that are relics of an earlier sabkha history, plus very modern artificial islands, mostly close to areas of high population density or industrial activity in the vicinity of Abu Dhabi island.

Most of the shallow marine sediments found along the world's coastlines are either siliclastic (i.e. rich in quartz sand and mud) or bioclastic sands (broken carbonate rock material such as fragments of sea-floor shells, corals from reefs or floating micro-organisms such as foraminiferids) and lime mud. The islands off the Abu Dhabi coast are no different and contain elements of both types. The carbonate-rich material reflects current environments of a shallow sea in a tropical climate, whereas the siliclastics are relics of an earlier fluvial and especially sabkha environment. Wilson and Jordan (1983) produced a sketch-map of modern carbonate facies of the Arabian Gulf (see simplified version in Glennie, 2005b, fig. 8.10). In addition to the presence of salt-dome islands, the map shows the distribution of a long broad belt of bioclastic sand about 75 km offshore Abu Dhabi Emirate as well as the Qatar peninsula. The northern edge of these and other sands, including the Great Pearl Bank, and islands closer to the coast, are partly flanked by coral reefs. Most of these features are found in water depths of 10 fathoms (18 metres) or less.

A major feature of Abu Dhabi's shallow coastline is a network of inshore barrier islands. The barrier complex of islands and submerged reefs result in a breakwater effect that provides quiet backwaters consisting of shallow flats and lagoons with fine sediments. The importance of these barriers for the development of coastal plant communities is evident northeast of Abu Dhabi Emirate, within Dubai Emirate, where the exposed coast is characterized by high-energy beaches and a distinct lack of inshore coastal plant communities. Inshore barrier islands have grown landwards mainly by the creation of winged spits under the influence of predominantly northwest wind-dominated leeward accretion; Dabb'iya has actually been connected to the mainland by this process (Purser and Evans, 1973; Kirkham, 1998). The northwestern coastal barriers of Abu Dhabi and adjacent islands are backed on their landward sides by extensive coastal sabkha (see 4.2.5), whereas their eastern and western shorelines are liable to be flanked by mangroves, which themselves trap landward-moving shallow-water sands.

Artificial islands have been developed in Abu Dhabi Emirate and usually consist of the dredged spoils from marine works undertaken to cut navigation channels in shallow marine areas or to deepen harbours or existing channels. The artificial islands are often then developed for agricultural production or as private facilities. The past development of artificial islands in the Emirate has not been for investment purposes, and most of the islands so far developed have been utilized by the government for public amenity, *e.g.* Al Sammaliah Island, Masnoa Island and Lulu Island. The growth in popularity of the development of artificial islands for real estate investment, as is occurring in other areas of the region, is a looming threat to the coastal resources of the Emirate and planning for the adoption of coastal management principles in Abu Dhabi is urgently required.

4.2.5 Coastal Sabkha and Lagoons

Sabkha are flat areas of sand, silt or clay that are covered by a crust of salt (halite) for at least a part of the year. *Coastal sabkha* may be flooded by the sea during storm and spring high tides, whereas the inland variety has no direct marine influence but derives its moisture from rare rainfall and especially the proximity of the water table at shallow depth within *capillary* reach of the surface.

As already mentioned above, coastal *sabkha* formed when the supply of wind-driven sand from the north was cut off during the post-glacial flooding of the Gulf, and deflation removed dry sand down to the level of the water table. Water evaporates from the damp surface, especially during the hot summer months, and becomes saturated with halite (common salt) which crystallizes to form a hard crust. Beneath the surface, calcium sulphate also becomes concentrated and forms a mush of gypsum crystals about 50 cm below the surface. At ground temperatures greater than about 42°C, the water of crystallization is driven from the gypsum crystal lattice to create anhydrite. Shinn (1983) has many illustrations of *sabkha* in the Emirates and other areas of the Gulf; for Abu Dhabi, *see* Evans et al, 1964a and 1964b; Evans and Kirkham, 2002; Evans et al., 2002; Kirkham 1998 for much detailed explanation of the origins of these coastal sabkha.

Perhaps the most characteristic feature of an active coastal *sabkha* is a widespread mat of thin, black, algae. Most of the time, this *algal mat* is dry, and commonly cracked and curled up at the edges like flakes of mud in a dried-out pond. During high spring tides, however, or when storm winds drive sea water over the almost horizontal *sabkha* surface, the algae spring to life and regenerate into a slimy, wrinkly, rubbery layer. The slimy surface traps fine calcareous particles carried over the surface by the waves, and when it cracks and curls, wind-blown sand and silt can be trapped beneath its edges; with time, the *sabkha* again acquires a crust of halite. When halite crystallizes, it does so by growing horizontally rather than by increasing its thickness vertically. A space problem ensues, which is resolved by the salt sheets over-thrusting each other if thin, or by forming polygons (ideally hexagons) as it grows thicker especially where the polygon edges are forced to grow vertically.

Coastal *sabkha* cover the surfaces of much of the extensive system of low islands southwest and just to the north-east of Abu Dhabi Island. The *Shamal* blows almost at right angles to the Abu Dhabi coast. The resulting build-up of water is driven along the coast to the northeast, especially to Umm al-Qaiwain and Ra's al-Khaimah, where the development of longshore bars has resulted in the creation of a series of shallow lagoons, which have tidally formed deltas at their mouths (Glennie 1970: Figs 98–100; Glennie 2005b, Figs 8.9a-c). Wave action builds the longshore bars into beaches, from which sands (mostly the wave-broken remains of shells and carbonate skeletons of sea grasses) are blown into the lagoon behind. In addition, as small carbonate-shelled creatures die, they leave their shells on the lagoon floor, which becomes shallower and eventually builds up to, or even above, normal high-tide level; it then acquires its own cover of coastal *sabkha* comprising a mat of black algae that is underlain by a mush of gypsum crystals.

And, as mentioned earlier, the flooding of the Gulf following the last Glacial Maximum led to deflation and landward transport of the pre-existing cover of sabkha sands down to the water table. The prevailing low tidal range, arid conditions and high tropical temperatures provide the ideal environment for the development of the very extensive coastal sabkha for which the emirate is justly famous (*e.g.*, Evans et al, 1969). For a more recent description of the origin of Abu Dhabi's coastal sabkha, see Kirkham (1997).

4.2.6 Inland Sabkha

Inland *sabkha* differ from the coastal variety in having no direct marine influence on their development, although wind-blown carbonate dust of marine origin may occur within them. Their supply of water comes from rare rainfall and the presence of a water table within capillary reach of the surface; a balance is achieved between evaporation and deflation at the surface and the supply of water from below which can trap wind-blown sediment, both being affected seasonally. Algae may be present, but extensive algal mats are not generally well developed; like coastal *sabkha*, gypsum crystals form a layer below the surface. In near coastal areas the almost flat coastal sabkha may pass almost imperceptibly into inland sabkha where they cease to have a direct marine influence (i.e. not even the occasional presence of water of direct marine origin); in such areas it is almost impossible to define a boundary between the two types.

Within the Emirates, extensive inland *sabkha* are found in three areas:

1. At the landward margins of the coastal sabkha beyond the reach of storm tides and extending into some adjacent interdune areas; this type of inland sabkha has been described in the previous paragraph.

4. Sabkhat Matti, a special case of (1) above, is a low lying area in the far west of Abu Dhabi, about 60 km across and extending south from the coast for almost 150 km, much of the southern half being within Saudi Arabia (see figures 7.52 to 7.59 in Glennie 2005b). Its western boundary is probably controlled by an underlying fault, which created a zone of weakness utilized by older fluvial activity. The surface of Sabkhat Matti is still no more than 40 metres above sea level some 100 km south of the coast (UAE University, 1993). Unlike the extensive interconnected coastal sabkha near to Abu Dhabi Island, Sabkhat Matti is covered with the relics of small sand dunes that were stabilized by the rising water table following the last (and perhaps also earlier) Glacials (e.g. ~2008±20 ka and 130±115 ka (See Glennie 2005a, p. 24)). Indeed, this large area really seems to comprise a multitude of small sabkha that developed within the interdune areas of southward-migrating sand dunes following the post-glacial rise in water table (see figures 7.53a,b in Glennie 2005b). The coastal sabkha to its north is mostly no more than about 3-4 km wide, and locally much less.

5. The large, rather unique, broad interdune sabkha at a height above sea level of up to 90 metres or more between the huge dunes of Al Liwa, and present along both sides of the E-W border between the emirate and Saudi Arabia (see Glennie, 2005b, figures 1.2 & 7.44).

The Liwa is an area of high dunes and interdune sabkha near the southern border of the emirate. At the time of every high-latitude glaciation, sands were deflated by Shamal winds from the exposed floor of the Gulf and transported south to the Liwa. During the next interglacial, not only was there a marked increase in rainfall but sea level rose again and induced a rise in the water table beneath the Liwa dunes; these two events led to the creation of inland sabkha within the interdune areas. Repetitions of this process with each rise and fall of global sea level resulted in the current Liwa water table reaching around 80 or 90 metres above sea level and the adjacent barchanoid dunes up to 150 metres above the sabkha surfaces. These processes transformed the Al Liwa area into an anomalously high build-up of dunes and interdune sabkha within what regionally is the axis of a regional structural 'low' (**Figure** 4.4). Because the Gulf hosted carbonate-shelled marine creatures at times of high sea level, their glacial-age products of deflation were also rich in fragmented carbonate grains and dust that aided cementation of the dunes between the present coastline and Al Liwa; but because the carbonate grains are fragile and their dust may even be blown south into the Arabian Sea, their influence as a cementing agent reduces with distance from the Gulf's coast. Another cementing mineral, however, is gypsum, which forms a mush of crystals beneath the sabkha surface. Where the damp sabkha becomes covered with little more than 2-4 metres of sabkha sand, lensoid crystals of gypsum intergrow to form 'desert roses' (Fig. 7.51 in Glennie, 2005b). Inland sabkha have been dated by interbedded and overlying dune sand extending back some 140 ka.

In the Liwa area, small flat-topped hills (*mesas)* are capped by a gypsum-cemented layer indicative of former *sabkha* conditions at a higher level than at present. Lightly cemented dune sand, whose bedding attitudes indicate sand transport towards the SSE (the same as today) is exposed in the flanks of these mesas; similar dune sands can be seen in pits dug below the gypsum-cemented surface of the interdune *sabkha*. The time of deposition of associated dune sands has been dated to 12 ka (in pits) and 40 and 141 ka BP in the mesas, thereby indicating that both dune and *sabkha*-producing conditions have been repeated in the area; the younger dune sands were preserved by the rise in level of the water table during the melting of the last high-latitude ice caps. During glaciations, *sabkha* occurred in neither inland nor, probably, modern coastal areas.

The *sabkha* is a dangerous place and chances should never be taken with one, its salt-encrusted surface often looking deceptively firm. Beneath the thin crust of the coastal *sabkha* the algal mat and underlying mush of gypsum crystals and clay-size carbonate has little bearing strength. Unwary humans are likely to break through the surface and sink to their knees, especially if the crust is new, while narrow-tyred vehicles can become a total loss. Inland *sabkha* are little safer. A sabkha tribesman in search of fresh pastures following rain, is likely to test the feasibility of crossing a suspect surface by sending first sheep and goats in the care of young light-weight children, followed in turn by himself with the heavier camels, and then his wife driving a laden Toyota Landcruiser pickup truck.

4.2.7 Buttes and Mesas

Buttes and mesas are relatively low plateaus, the former having considerably less surface area than the latter. The Bunaynah Formation forms many of these features, the almost flat surface being a product of low-angle bedding and a surface that probably was better cemented at some period in the past. Their current exposure probably results from a combination of perhaps early Pleistocene shallow-marine erosion coupled with deflation during glacial periods; their horizontal surfaces are almost certainly tied to former sea level or water table.

4.3 Seismicity

No detailed seismic studies have been conducted for Abu Dhabi, so there is no empirical evidence from which an assessment of risks associated with earthquakes can be made. The National Centre for Meteorology and Seismology has plans to install 5 seismic monitoring stations and deploy 3 mobile stations in Abu Dhabi during 2008. The stations will each house 8 sensors which will record a range of parameters including the direction of vertical and horizontal movements, motion strength, rate of acceleration, etc. (source: interview with Mohammad Al Jaradat, NCMS). This will mark the beginning of a systematic seismological data-collection and monitoring programme for the emirate.

The likelihood of Abu Dhabi being subjected to an earthquake is summed up in **Figure** 4.7. This figure shows the location of the epicentre and the varying strength of every earthquake within the whole of the Middle East from 1964 to 1994. Of direct concern, about 250 km across the Arabian Gulf from Abu Dhabi, is the broad (approx 250 km wide) seismic belt that coincides with the Zagros Mountains, whose own farther limit is known as the Zagros Crush Zone. The Crush Zone marks the line along which the NE edge of the Zagros Mountains is being thrust obliquely below the Sanandaj-Sirjan range of Central Iran because of the northern movement of Arabia away from the actively widening Red Sea and Gulf of Aden.

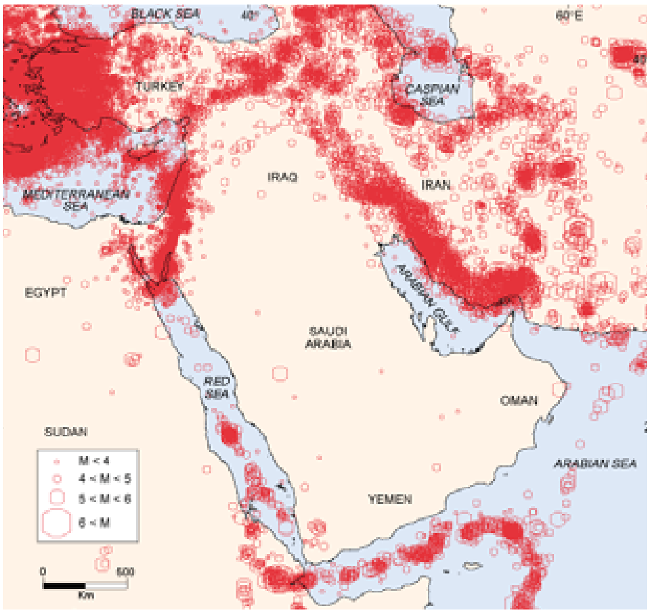


Figure 4.7: Seismicity of the Middle East Region (based on the International Seismological Centre catalog, 1964 – 1994)

This figure was originally published in Seber, D, et al., 2000. It is reproduced in this paper with permission of the publishers, GeoArabia.

In contrast, Abu Dhabi has no major faults within its territory, just one of minor strength being recorded on an offshore salt dome-structured oil or gas field. The only faults that may be associated with future seismicity are: 1) the deep faults considered to be responsible for uplift of Jebel Hafit on the western flank of the Oman Mountains (Noweir, 2000) and, 2) the SW extension of the Dibba Fault, south of the Musandam Peninsula (Al-Husseini, 2000). The major ancient Maradi Fault trends from the Huqf on the Arabian Sea coast of SE Oman, west of the Oman Mountains until it intersects and probably truncates the SW end of the Dibba Fault. It may once have continued along the western edge of the Musandam Peninsula. The Maradi Fault has a visible vertical expression (1-2 metres) east and southeast of the Natih oilfield in Oman, so it is still active.

The largest earthquakes recorded in Iran in recent years were at Ferdows in August, 1968 (magnitude 7.3 on the Richter scale; 12,000 – 20,000 deaths), at Tabas in September, 1978 (magnitude 7.8; more than 1,500 deaths), and at Bam in December 2003 (magnitude 6.6, more than 30,000 deaths); (Ramezani, 2004). These three towns lie adjacent to the important north-south trending strike-slip Naiband Fault of Iran (*see* Fig. 4.5 and Fig. 4 in Seber et al., 2000), a southwest splay of which is the Dibba Fault at the southern end of the Musandam Peninsula.(Ruus al Jibal). The difference in size of the Zagros and Naiband-related earthquakes suggests that the more vertical the fault, the more likely it is that any earthquake associated with movement across it is likely to be strong.

Apart from the 'Crush Zone', the Zagros Range itself seems not to have many strong earthquakes; just many smaller ones. This is possibly because the Hormuz Salt forms a plastic zone separating the relatively rigid basement rocks beneath from the overlying sedimentary sequences, which are deformed and faulted mainly by active salt diapirism. Within Abu Dhabi emirate, many diapirs reach the surface in salt domes such as Jebel Dhanna in western Abu Dhabi and small islands such as Sir Bani Yas in the Gulf, of which one, probably Umm Shaif has a single seismic record (Seber, 2000). These salt domes lack proximity to a major active geological boundary such as the Crush Zone or Naiband Fault and thus are likely to be relatively inactive until local stresses change; either the Arabian Gulf dries out, thereby reducing its load of water over the salt or, if global warming becomes a serious reality, the load of water increases considerably (10-30 cm?) over a time span of a century or more. Even then, seismic activity is likely to be slight.

Earth movements have been recorded in the northern Emirates and in Oman, but to-date, none of them in recent years have been strong enough to cause major damage on the Arabian Peninsula. In Oman, the most recent disastrous earthquake was at the end of the fourteenth century when the coastal city of Qalhat, southeast of Muscat, was destroyed when the whole harbour area was uplifted, resulting in the demise of a once famous and wealthy city. The strongest earthquake recorded in Abu Dhabi was at Masafi in 1993, on the western flank of the Mountains, and was possibly associated with slight uplift in the area. This earthquake measured 5.1 on the Richter scale; there were no casualties and minimal structural damage (source: meeting with Ministry of Energy, Geological and Mineral Resources Department). Small earthquakes can occur almost anywhere flanking the Oman Mountains, and even the odd big one as seen at Qalhat.

The reason for the Crush Zone earthquakes is the convergence of Arabia and Eurasia, and specifically:

- The Red Sea and Gulf of Aden have been 'opening' slowly since the early Miocene, some 20 million years ago, causing Arabia to move to the north relative to Africa at a rate of some 5-14 millimetres per year (McClusky et al., 2000).

The movement of Arabia relative to Eurasia (which is more static than Africa) is about 19-23 millimetres per year (McClusky et al., 2003; *see also* **Figure** 4.4).

Over a short geological time span of a thousand years this latter rate amounts only to about 20 metres of compression, but with geologically longer periods of tens, thousands or even millions of years, compressive stresses can be much greater and the crust will crack under the strain. The northern edge of the Zagros Range is currently being pushed obliquely beneath the Sirjan-Sanandaj Range of Iran.

At the eastern extremity of the Zagros, the three major earthquakes mentioned in the previous paragraph (Ferdows and Tabas in the north and Bam further south) were all associated with splays of the north-south trending right-lateral strike-slip (relative horizontal movement with an apparent clockwise sense across it) Naiband fault. This fault delimits the western margin of the Makran coast of Iran and Pakistan, beneath which the oceanic crust of the Gulf of Oman is sliding while its sedimentary cover is scraped off to form the Makran coastal ranges. To its west, at the northern end of the Oman Mountains, the Musandam Peninsula is subsiding into the Strait of Hormuz at 6 millimetres/year (Vita Finzi, 1979); its relative movement northward is not known but could easily be three times that figure. A presumed splay of the Naiband Fault (its northeast connections have not been mapped) crosses the southern margin of Musandam, southwest through the town of Dibba.

To the southeast in the Muscat area, the Oman Mountains are currently rising at some 2 millimetres/year, with marine terraces formed during periods of no uplift now 150-500m above sea level depending on locality. The small earthquake at Masafi on the west flank of the Mountains was probably associated with continued uplift of the mountains relative to the lower land to its west. It may have been associated with minor adjustments to the deep thrust faulting similar to that ascribed to the origin of Jebel Hafit (see, *e.g.*, Noweir, 2000).

Opinions from several geologists and seismologists familiar with the gulf region suggest that the risk of a catastrophic earthquake occurring in Abu Dhabi is low. Saleh Ahmed Al Mahmoudi, Director, Geology and Mineral Resources Department, UAE Ministry of Energy; Mohammad Al Jaradat, Seismology Department at the NCMS, and Professor Ken Glennie, Aberdeen University, are the specialists who offered that opinion. The reasons they cite are that Abu Dhabi is not in the Zagros Thrust Zone, but some distance from it; that the geology of the emirate is quite different to that in the Zone and in other earthquake-prone regions of the world; and that there is no historical evidence of major seismic events in this part of the Arabian Peninsula. Similarly, the risk of a tsunami causing significant damage to the Abu Dhabi coast appears to be low. The reasons for this are that the Arabian Gulf is too narrow and too shallow a body of water for an earthquake associated with the Zagros Thrust Zone to generate a large tsunami.

If a significant earthquake were to occur in the region, clearly the greatest risk of severe damage would be to infrastructure and people in the capital, Abu Dhabi city. This is where residential, commercial, transportation and utility infrastructure is concentrated, and where population density is highest. However, eminent geologist and seismologist, Dr Farouk El Baz, considers modern engineering standards in the capital to be adequate to cope with even fairly severe quakes. The Gulf News reports him as saying “every building in the UAE built in the last 15 years will be able to withstand any earthquake measuring more than seven on the Richter scale” (EAD, 2005). This does not address the issue of how infrastructures older than 15 years would hold up, nor does it indicate what the impacts of a more severe earth movement might be but, taken together with the consensus of opinion that suggests earthquakes of magnitude 7 are most unlikely to occur in Abu Dhabi, it does support the view that Abu Dhabi is a low risk area for significant damage from seismic events. *Note*: Where high mortalities occurred because of recent earthquakes in Iran and NW India (Bhuj), they were because most of the buildings were of mud-brick and using poor mortar with no steel reinforcing; this should prove of low-risk in those few parts of Abu Dhabi where earthquakes could occur.

Dr. El Baz goes on to say that, even if we accept that risks are low, Abu Dhabi should not be complacent in its efforts to measure and monitor seismic activity. He recommends that a seismic monitoring centre be established in the region, and as mentioned above, the NCMS has already made moves to fill this role by establishing a network of seismic monitoring stations. Several other initiatives are currently in the pipeline for conducting surveys and monitoring earth movements. These include a study DMA is considering conducting to assess general seismic risk in the emirate (based on a proposal from Erdal Safak, who is currently conducting a similar assessment for Dubai emirate), and another study to assess the risk and potential impact of liquefaction on infrastructure in major cities in UAE. One issue that the liquefaction study would pay particular attention to would be the degree to which structures built on reclaimed land are at greater risk from liquefaction than are structures built on more solid ground. This study was originally a component of Phase II of the Ministry of Energy’s National Geologic Mapping project, but was taken out of the project scope when seismology was moved from the Ministry of Energy to the NCMS under the Ministry for Presidential Affairs.

4.4 Brief History of the Quaternary in the Emirates

The early Quaternary history of the Emirates is very poorly known. The limited evidence from sparsely dated alluvial fans suggests that it was probably a time of much higher rainfall than now. By about 800 ka BP near-polar glaciations led, in the Gulf area, to cyclic repetitions of lower sea level and stronger winds that caused sand dunes to migrate southward, with the warmer interglacials giving higher rainfall and less active dunes. For the past 5 ka, we seemed to have been heading slowly in the direction of increased aridity associated in the long term (80,000 years later?) with another glacial maximum in high-latitude areas – provided that man-induced global warming does not reverse that historical trend.

4.5 Conclusion

By extrapolation from elsewhere, the geological history of Abu Dhabi and adjacent areas of Arabia over the past 600 Ma or so seems to have been mostly one of relative stability. Following tropical shallow-marine conditions of sedimentation in the late Precambrian, the area was largely terrestrial during much of the succeeding Palaeozoic time span. Deep erosion preceded the Permian separation of a microcontinent from the eastern margin of Arabia. Throughout most of the Mesozoic era, Abu Dhabi was the site of shallow-marine sedimentation. Shallow-marine limestone deposition during the earlier Tertiary was terminated in the east when the Oman Mountains began to be uplifted. It was not until the late Miocene that they began to rise significantly into a high mountain range, but stable conditions of sedimentation continued over the bulk of the Emirates until major glaciations began to induce lower global sea levels perhaps some 2-5 Ma BP and created the present continental land surface. Near-polar glaciations have controlled sea level in the Arabian Gulf for at least the last 150 ka, thereby also controlling the supply of dune sand from the north or the cutting off of that supply, with the resulting widespread deflation and creation of both coastal and inland *sabkha*.

4.6 Glossary of Geological Terms

aeolianite: a consolidated sedimentary rock formed of wind-deposited sand; commonly, but not necessarily, rich in carbonate grains.

algal mat: a sheet of rubbery algae that covers the coastal *sabkha* surface after flooding.

alluvial fan: a fan-like spread of fluvial distributary channels, commonly at the junction of mountain and plain; fans coalesce along the length of the Oman Mountains.

anhydrite: an evaporite mineral composed of calcium sulphate, $CaSO_4$, found in some sedimentary rocks. It is often derived from *gypsum* by losing its *water of crystallization.*

avalanche slope: also known as **slip-face.** The slope that forms when wind-blown sand from the windward side of a dune passes into the calm air of the leeward side. The sand will start to slip if further deposition would result in the maximum angle of repose for dry sand of 34o being exceeded.

back-arc spreading: the process of creating new oceanic crust in the back-arc area behind a subduction trench.

barchan: see **dune.**

barchanoid dunes: see **dune.**

BP: abbreviation of Before Present, often given in Ka, thousands (K) of years (a).

capillary: resembling a hair; of very small bore. If a tube of very small bore is immersed in water, the water will rise up within the tube as a result of capillary attraction.

cap rock/seal: an impervious rock (seal) overlying a fluid-bearing reservoir.

carbonate: general term for calcium and magnesium carbonates (limestones and dolomites).

climatic optimum: the state of an ideal climate; inferred for existing desert regions to have had sufficient annual rainfall to render the area an ideal place for man to live. Such conditions are thought to have prevailed over much of the Saharan and Arabian deserts between about 9000 and 6500 years ago.

convection current: the transfer of heat from one part of a fluid or gas to another by flow of the fluid or gas from the hotter parts to the colder. A fluid will rise if heated from below because, through expansion, it becomes less dense than the cold.

deflation: the blowing away of dry fine-grained rock material (sand and dust), by the wind. A form of aeolian erosion at work chiefly in deserts.

diapir, diapirism: salt (halite) is less dense than most other rocks and is easily deformed. Salt can flow. When buried at depth, salt becomes more buoyant than overlying rocks; it may then withdraw sideways to create a vertical bulge (salt pillow) that deforms overlying strata into anticlines and, by breaking through them, create salt domes and even salt walls. This process is known as diapirism; the product of diapirism is a diapir.

dikaka: the moulds of plant roots in dune sands; rhizoconcretions

dolomite: a calcium-magnesium limestone, commonly formed by alteration of shallow-marine limestone.

dune: accumulation of wind-blown sand that possesses one or more slipfaces. Its size is dependent on the availability of sand and the ability of the wind to carry sand to the top without removing it again. The finest sand grains are usually found at the crest. There are several types of dune but only those common in eastern Arabia are described here.

barchan: crescent-shaped sand dune, which migrates downwind in the direction of its horns. It has a gentle windward slope and a slipface on its lee slope. Barchans sometimes unite laterally to form rather irregular *barchanoid dunes.*

barchanoid dunes: cross between a *barchan* and a *transverse dune.*

linear dune: dune whose long axis is parallel to the prevailing dune-forming wind; it grows by extending downwind. Avalanche slopes, where present, are almost parallel to the axis of the dune and can face towards either flank. May occur as a swarm of parallel dunes as in the Rub al Khali or the Wahiba.

megadune: any large dune whose height exceeds about 60 metres and has a crestal spacing of about 500 metres or more. Most are thought to have formed during the last major glaciation.

star dune: a roughly star-shaped pyramidal dune with three or more radiating arms with slip faces. Thought to form where seasonal winds are strongly oblique to each other. May result also by modification of older transverse or longitudinal dunes.

transverse dune: a dune whose long axis is at right angles to the prevailing dune-forming wind. Likely to break up into barchanoid and then barchan dunes if the supply of sand is not maintained.

evaporites: minerals, mostly anhydrite, gypsum or halite (common salt), that are typically formed in areas where the rate of evaporation exceeds that of rainfall or fluvial influx (i.e. in wadis or desert sabkha).

geomorphology: the study of present-day landscapes and the interpretation of their histories.

Gondwana: an ancient mega-continent named after the Gond tribe of northern India. Comprised of Antarctica, Australia, India, Afro-Arabia and South America. It began to split up into its modern components in the later Mesozoic.

gypsum: an *evaporite* mineral, Calcium Sulphate ($CaSO_4$.- $2(H_2O)$), typically found just below the surface of coastal and inland *sabkha.* With increasing depth and temperature, gypsum loses its *water of crystallization and* alters to the seal *anhydrite.*

Hawasina: an imbricate wedge of sediments of mid Permian to mid Cretaceous age that were deposited over the floor of Neo-Tethys and later obducted over the NE margin of Arabia.

hydrocarbons: any organic compound comprising carbon and hydrogen, usually refers to oil and gas.

Ka: abbreviation for thousands (**K**) of years (**a).**

limestone: calcium carbonate (CaCO3), mostly of biogenic origin, and largely formed in shallow seas.

linear dune: see **dune.**

Ma: abbreviation for millions (**M**) of years (**a**).

maturation, maturity: the process of 'ripening' a source rock to the state where it generates oil or gas; the state of a source rock with respect to its ability to generate oil or gas. Considered to range from immature, before any oil or gas has been generated, through mature to post-mature, when no additional oil or gas can be generated from it.

megadune: see **dune.**

mesa: a mesa is a flat-topped plateau bounded on at least three sides by steep, commonly cliffed slopes. The bedding is normally horizontal. A**butte** is a very small mesa. Both are found in the Miocene strata of western Abu Dhabi.

migration: the passage of a newly generated oil or gas out of a source rock (primary migration), and its movement via rock conduits to other locations, including hydrocarbon traps (secondary migration).

obduction: the process by which former oceanic crust or a wedge of oceanic sediments comes to lie upon crust of continental type.

porosity: the pore spaces within a rock; in oil fields, these pores are filled with oil or gas.

reservoir, reservoir rock: any rock that can contain moveable fluids in its pore spaces.

ripple: a surface undulation, generally of unconsolidated sand, whose wavelength depends on wind strength and is constant with time. The ripple axis is always transverse to the wind. The coarsest grains are found at the crest. The ripple height depends on the range of grain sizes present and the wind strength.

sabkha: a flat area of clay, silt or sand, commonly with crusts of salt. Subdivided into:

- **coastal *sabkha*:** a coastal flat at or just above the level of normal high tide. Its sediments consist of sand, silt or clay and its surface is often covered with a salt crust formed by the evaporation of water drawn to the surface by capillary action or from occasional marine inundations. The coastal *sabkha* is characterized by the presence of algal mats and the occurrence of gypsum and anhydrite within its sediment. It is subject to *deflation* down to the water table.

- **inland *sabkha*:** a flat area of clay, silt or sand, commonly with saline encrustations, that is typical of desert areas of inland drainage and some interdune areas. Their salts may be formed by evaporation of surface water, or of water drawn to the surface from the water table by capillary action.

salt dome: a dome-shaped structure caused by the upward penetration of a circular plug of salt, commonly 1-2 km in diameter, through overlying strata; the plug may also give strata through which it fails to penetrate a domal shape.

seismicity: the study of earthquakes; extended by oil companies who make controlled mini-earthquakes at the surface whose shock waves can be recorded and used to map the structure of rocks and faults in the subsurface.

Semail Nappe: the name given to the huge ophiolite nappe of the Oman Mountains.

shamal: Arabic word for north: applied to north or northwest wind that blows down the Arabian Gulf and clockwise across the Rub al-Khali.

star dune: see **dune.**

source rock: a rock rich in organic matter which, if heated sufficiently, will generate oil or gas.

strike-slip fault: fracture in rock with an apparent clockwise or anticlockwise sense of movement across it; sometimes called a 'transcurrent fault'.

subduction: the process at a plate margin of crustal consumption down a subduction trench.

trade wind desert: a term sometimes applied to those deserts in subtropical land areas that are crossed by the *trade winds*.

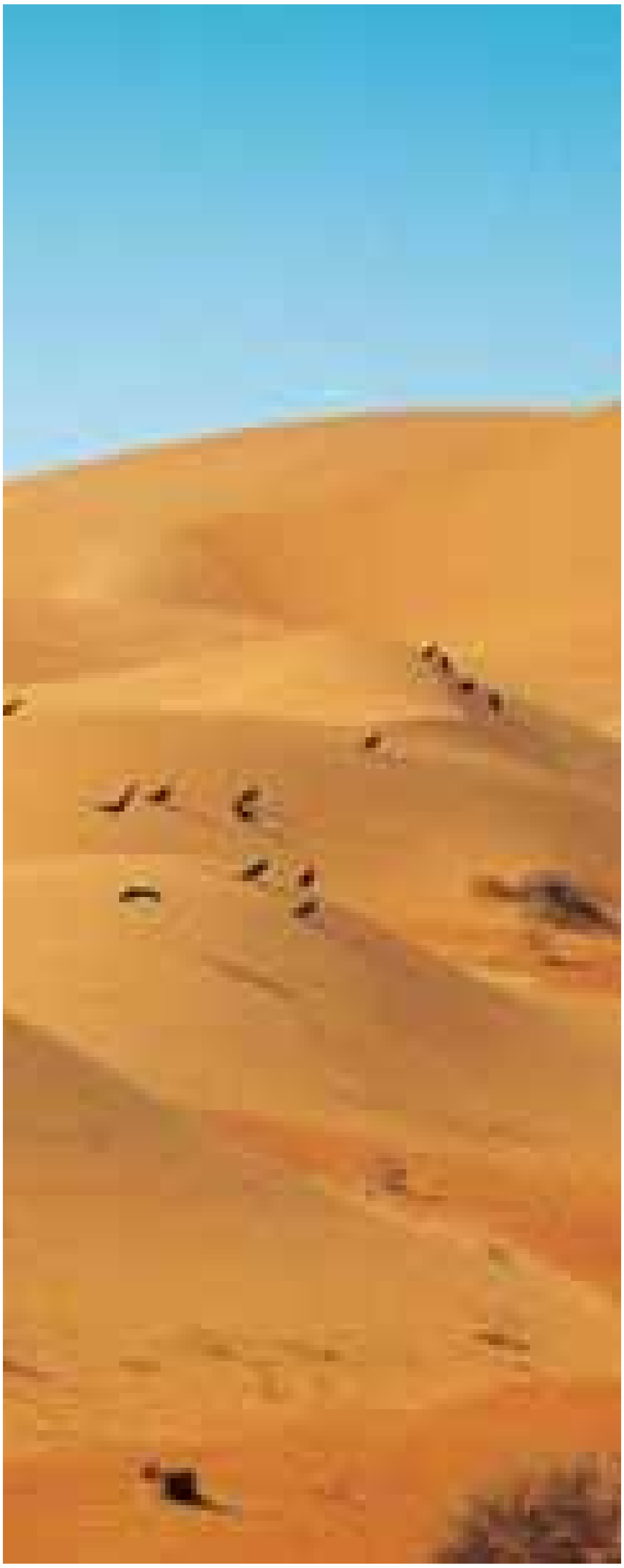
transverse dune: see **dune**.

trap: any deformation (fold, fault, wedge-out) of a reservoir rock/seal couplet that can cause hydrocarbons to be trapped as they migrate from their source rocks.

wadi: desert watercourse, dry except after rain, or a valley where water may continue to flow intermittently.

water of crystallisation: the water present in hydrated compounds such as gypsum ($CaSO_4.2H_2O$). If the temperature of the gypsum crystal is raised above about 50°C, either by deep burial or by near-surface heating in a desert, it loses its water of crystallisation ($2H_20$) and becomes the anhydrous mineral *anhydrite* ($CaSO_4$).

5 CLIMATE



By Hussein Raafat, Department of Meteorology, Ministry of Communications.

Abu Dhabi Emirate belongs to the tropical desert zone (WMO-No 327-pp66), as per Koppen classification (1982), and can be classified as semiarid to arid as per Thornthwaite's schemes (1931, 1948). In general, the Emirate lies in a climatic zone where high temperature and less rainfall are the main climatic features. There is a wide variation in weather systems during the course of the year, and from year to year and henceforth in climate.

An attempt is made through this chapter on climate in the Physical Geography sector paper to give a brief description of the climate of the Emirate of Abu Dhabi. The chapter is divided into two sections, while the first provides some information about the history of the climate processing and the availability and quality of the climatic data in the Emirate, the second section describes the weather and climate systems dominating the area. A brief discussion on the behaviour of some climatic elements of interest is also included in this section.

5.1 Climate recording and processing in Abu Dhabi

5.1.1 Historical Background

The earliest information about the climate of the United Arab Emirates dates back to the late 1800's. This is evident from the references about "Heavy Storms" that caused losses of fishermen and boats in the local Pearl Trading community during that time, as reported in the Administration Reports published by the Government of India in Calcutta. This documentation only included "climatic events" and no statistical records of climate were recorded. Few observations were recorded in the immediate years after 1855 following Admiral Fitzroy's commission to develop the marine activities in the Arabian Gulf (Jackson, CCE 1988 'Sea temperature in the Arabian Gulf' Weather 113, 429- 439).

It was not until 1934 when the British Royal Air Force and Imperial Airways founded an airstrip in Sharjah with a small weather observing and recording station that recording of climate started. Even then these stations were not recording regular observations but recorded only when needed for operational uses. The quality and amounts of these data were slightly improved by late 1949. The log books of these historical data were stored in the United Kingdom Meteorological Office until 1995, when the UAE National Meteorological Service of the Ministry of Communications succeeded in restoring the data and processing it through the National Bank of Meteorological Data (NBMD).

By the late 1950's there were only 6 state coastal weather stations along the whole Gulf region, but the exploration of offshore oilfields necessitated, for the safeguard of the offshore drilling rigs and platforms, the need for more weather observing stations, either inland or offshore. These stations were confined to daylight hours and in a manner often highly individual ("Hand book of the weather in the Gulf" IM 104 by IMCOS Marine Ltd 1976).

5.1.2 More Recent Activities

The situation remained as such until January 1971 when the Government of Abu Dhabi opened Abu Dhabi International Airport at Bateen with a continuous 24 hours weather observing station. This station was fully equipped, in terms of the standards at that time, to provide hourly and daily data. Climatic stations, recording mainly rainfall and temperature, were setup and managed by Abu Dhabi Municipality and Agriculture Department.

Following the declaration of UAE as a Federal State in 1971, and to meet the exceeding growth in trade, economic activities and travel, the process of weather and climate recording was expanded. The Military setup another 8 weather stations in their airbases to serve operational purposes. On January 1, 1982, the new Abu Dhabi International Airport (ADIA) was opened with a well equipped and fully operating surface weather station.

By March 1983, an Upper Air Radiosonde became available to provide information twice a day at 00:00 and 12:00 GMT. In addition to these, recordings from pilot balloons at 06:00 and 18:00 GMT daily were also available. Oil companies, such as ADMA, ADCO, ZADCO and TOTAL, setup several marine and land based stations on their respective sites. Although many stations were established by many organizations in the country, climatic data processing were done individually by the meteorological staff at each airports/department meteorological offices.

The Ministry of Communications set up the Central Forecasting Office (CFO) in Al Dhafra Air Base on January 1, 1992, with the collaboration of the UAE Military. The CFO was intended as a nucleus for the UAE National Meteorological Service (**UAE NMC**) that takes the responsibilities of all Weather and Climate Services in the UAE at the local, regional, and international levels.

In April 1994 the National Bank of Meteorological Data (**NBMD**), a well equipped and highly standardized climatic database, was set up by the UAE Meteorological Department (**UAE MD**) (or the formerly known National Meteorological Service). Since then the NBMD, the sub-division of the climatic section in the UAE MD is responsible for gathering, validating, quality control, storing and processing, all weather and climate data available within the UAE. The NBMD issues monthly and annual climate reports for UAE, besides providing all climatic services to end users and decision makers. The "*Climate of UAE*" book published by the Abu Dhabi Cultural Foundation in 1996 was one of the NBMD products.

The opening of the new international airport at Al Ain in May 1994 and subsequent setting up of the weather observation station aided in providing very useful information about the weather and climate in the eastern inland area of Abu Dhabi Emirate. Since early 2000 efforts have focused on implementing more advanced weather observing stations; mostly automatic stations for surface observations.

The already implemented stations are geographically well distributed and cover most parts of the UAE. However, these stations are too recent, from the climatic point of view, to provide any climatic data series. The metadata about these stations are also incomplete. The maintenance, quality control criteria, standards and even their raw data are hardly or not at all available, with the exception of the newly implemented 10 Automatic Weather Observing Stations managed by the UAE MD in the Ministry of Communications.

The Al Ain International Airport has a fixed weather radar, the only one in the whole of Abu Dhabi Emirate, and two or three mobile ones. The information obtained by these radars is very useful, particularly for cloudiness and precipitation.

There are also a few workstations that can receive and process cloud cover images from the meteorological satellite, the oldest of these is in the Abu Dhabi International Airport Met Office. The acquisition of such images was not on a regular basis, but only for hard weather conditions. By late 2000, the UAE MD set up a facility to archive these images directly to the climatic data base.

5.1.1 Data availability and reliability

Figure 5.1: The distribution of meteorological stations (over 50 stations).

Data provided by NCMS.

These stations are owned and managed individually by different authorities and departments. The ownership of these stations by different entities could give rise to certain difficulties when processing their data, including:

- The lack of homogeneity due to
  - o the use of different equipments from different suppliers;
  - o the different quality control criteria applied;
  - o the many data formats used.
- The lack of standards: there is no guarantee that all stations follow the same levels of standardization adopted by World Meteorological Organization (WMO).
- Some of the stations serve the owner's specific operational objectives: recording two or three elements only, operating from sunrise to sunset, making observations at only one or two hours or providing data with fewer details; *e.g.*, METARs (with measurement rounded to a whole figure), not suit able for climate operations.
- The regular and professional maintenance of the weather recording station is a matter of concern.

However, these new stations provide more or less useful information that definitely will improve the climatic studies of the UAE in the near future.

5.2 Climatic features of Abu Dhabi Emirate

It is well recognized that the Climatic systems can, in terms of different scale lengths, be classified into: Planetary (~5000km), Synoptic (~1000km), and meso-scale (~100km or less). The planetary and the synoptic weather systems in combinations with the meso-scale orographic features excite the meso-scale weather systems that provide the local peculiarities of the climate in any area. In other words, the topography of the land is one of the main factors directly responsible for the local peculiarities of the climate.

Therefore, for a better description of the climate in Abu Dhabi Emirate, the next two subsections describe the topographic features of the surrounding area as well as Abu Dhabi Emirate. Then a brief description of the different weather/climate systems that dominate the area concerned is given.

5.2.1 Geographical and Topographic Features of Abu Dhabi Emirate

Abu Dhabi Emirate is one of the seven Emirates comprising the UAE Federal State. The UAE lies in the south-eastern part of the Arabian Peninsula Gulf Region (APGR), between latitudes 21.5° and 25.5° N and Longitude 51.5° and 56.5°E.

The UAE is part of the Arabian Peninsula (AP), which, in turn occupies the main area of a wider region, the South West Asia (**SWA**). The Arabian Peninsula and the adjacent area looks like a basin surrounded by massive ranges of mountains: the Taurus family of mountains in southern Turkey, the Pontic mountain in northeast Turkey, the Caucasus mountains of Georgia at the north and northwest side, the Zagros mountains and the Iranian Plateau at the northeast side, the Hejaz mountain at the west/southwest side, and the Hajar mountains at the east/southeast side. (**Figure** 5.2**).**

These mountain barriers act as a blocking mechanism that influences the crossing of the extra tropical lows through the Arabia and prevents the invasion of the colder air masses from the middle latitudes, as shown later.

South West Asia can be delineated on the map by five bordering seas: the Mediterranean and the Red Sea to the west, the Caspian and the Black Sea to the north, and the Arabian Sea to the south. The influence of such water surfaces, however, is restricted by the prevailing pressure patterns and the restraining influences of the surrounding mountains so that the aridity and continentality characterize most of the area (Ali, A.H., 1997).

The **UAE** has two distinct land elevation zones; the larger sandy desert zone, to which Abu Dhabi Emirate belongs, covers over 90% of the country's surface area extending from Almayann region in the NW across to the eastern parts of **UAE**, where it is truncated by the mountain zone. The mountain zone has North-South extent of about 150km above mean sea level and East-West extent of 50km, and peaks up to 1500 metres above mean sea level. With exception of Al Ain Area, located very close to the eastern mountain region, most of Abu Dhabi Emirate is characterized by sand dunes which rise gradually from the coastal plain, up to 250 metres above mean sea level in Liwa, Al Bateen basin.

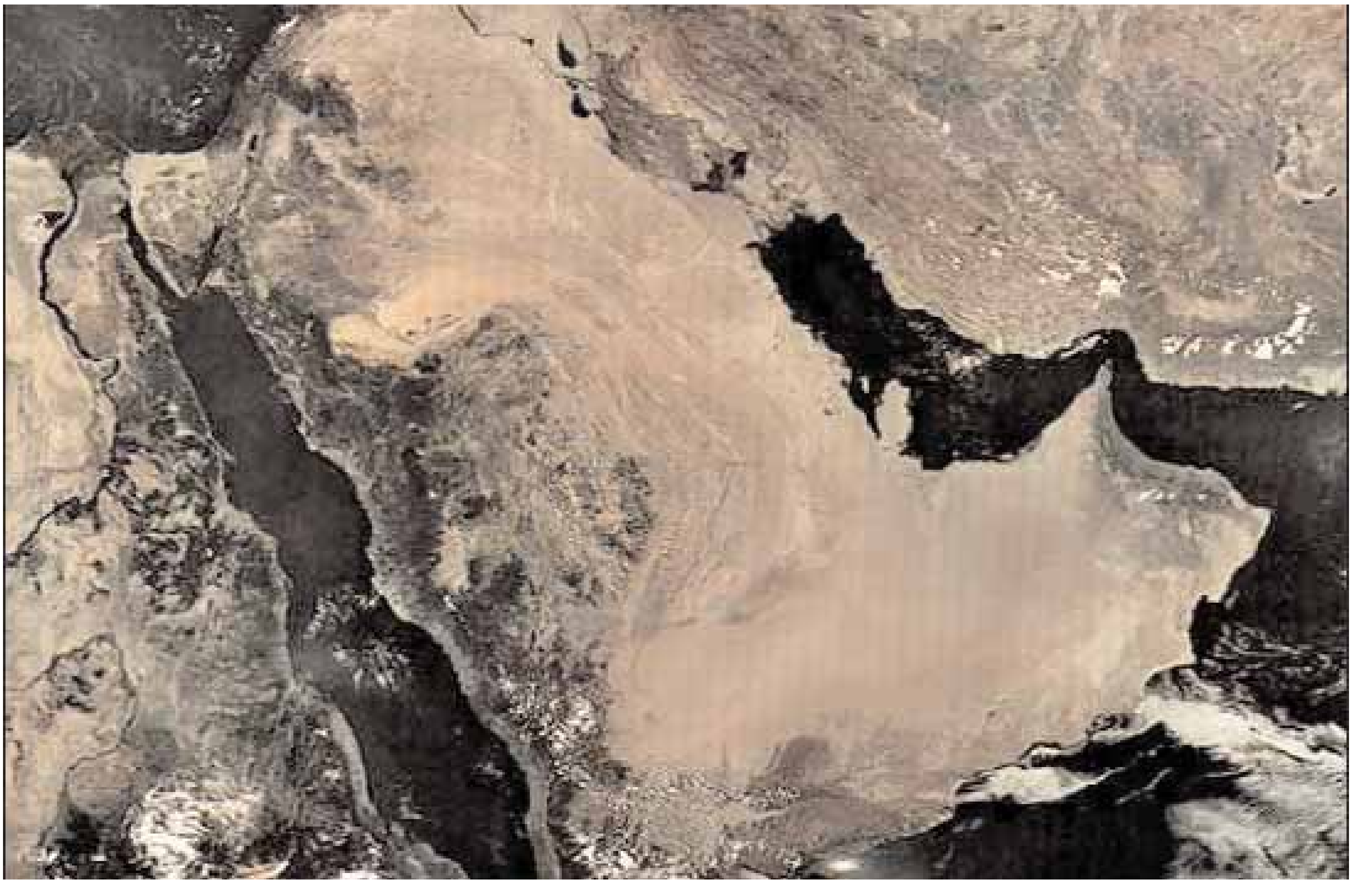


Figure 5.2: South West Asia (SWA) topographic features and location of UAE

The Abu Dhabi Emirate has a long coastal strip along the Arabian Gulf, with a large number of offshore islands and coral reefs, which makes the impact of the Gulf Sea on the weather and the climate very noticeable.

5.2.2 General Climate of Abu Dhabi Emirate

A brief description of the common climatic features is outlined here, followed by detailed description of some climatic elements based upon observation, statistical analysis of climate data, and analysis of weather charts. The climate of Abu Dhabi Emirate is a complex combination, including the mutual interaction of common climatic features of the bigger region, the Arabian Peninsula, or more specifically most of the SW Asia region, with its specific local, Mesoscale or microscale climatic features.

The unique location of United Arab Emirates with the tropic of cancer passing through it and characteristic land-sea distribution provides this region with a tropical desert climate with several typical climatic features. There are two main air circulation patterns; the winter circulation and the summer one. These two circulations are separated by two transitional periods,which do not have sharp cut features, as the weather situations during these two periods are not stable. The first transitional period (spring) starts at the end of March and ends towards the end of May. During the spring the winter circulation weakens and the summer circulation starts by the beginning of June. The second transitional period (autumn) starts at the end of September and ends by the end of November. During this period the summer circulation weakens and the winter circulation starts to get established as December approaches.

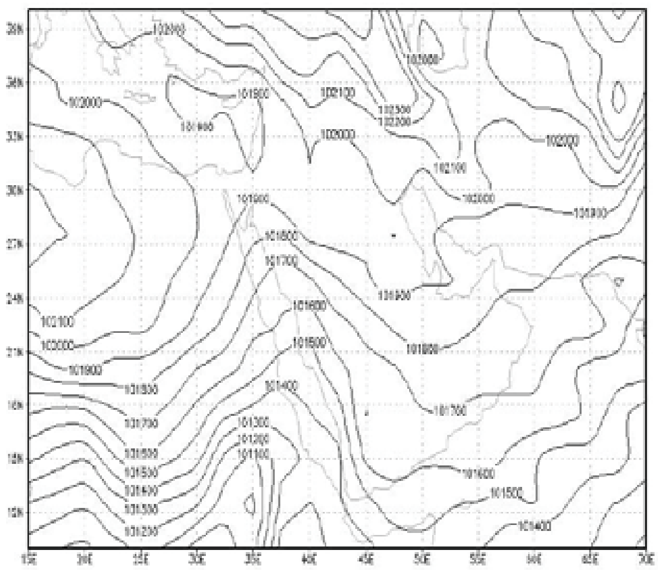


Figure 5.3: Shows the mean sea level pressure distribution for January (winter month).

* Note: all long-term Grads Charts used here are obtained from NOAA/NCEP/CDAS web sites.

A Winter Circulation

In winter, the **S**iberian **H**igh **P**ressure **(SHP)** intensifies and extends over Pakistan and Iran. As a result of this, the surface air over the surrounding land mass, north of the Arabian Gulf becomes colder than that over the Arabian Sea. This establishes a low-level pressure gradient that causes the air to flow from land to sea, resulting in the northeast NE monsoon **Figure** 5.3**.**

The mountain ranges existing to the north and west of the South West Asia region prevent most of the cold air from invading the Arabian Gulf. The sea-land temperature contrast is weaker in winter than is summer, and consequently the northeast monsoon winds are generally weaker.

The upper level flow is, in general, westerly **Figure** 5.4, and relatively warmer than the low level flow. This temperature inversion, and hence the stable weather conditions, inhibit cloud growth and leave the skies mostly clear.

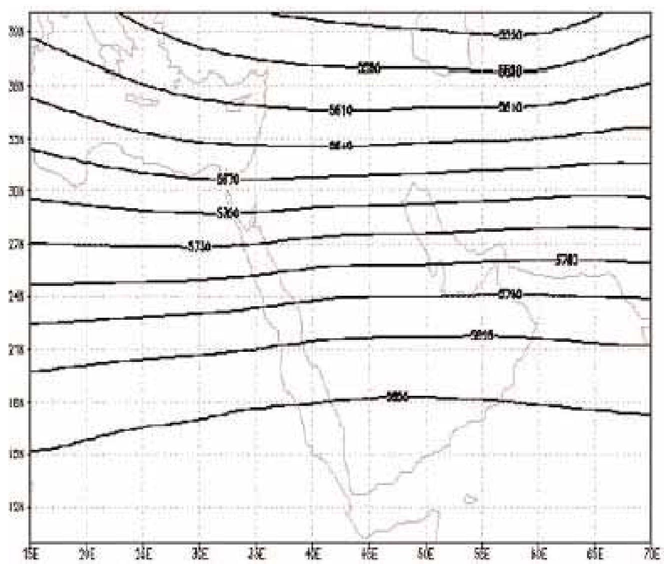


Figure 5.4: The 500 hPa geopotential heights for January (winter month).

The above mentioned represents the steady-state conditions; however, fluctuations in either or both the Siberian high or the upper air zonal flow cause the changes in the weather conditions over the area. In some occasions, the extension of the Siberian High Pressure (SHP) over Pakistan and Iran intensifies, inducing the North East flow to reach the strong force (9-11m/s), that is 4-6 m/s above the usual wind speed. The strong, cold and dry North East surges, locally known as "ELNASHI", reduce the temperatures and raise the sea level over the western offshore area of the UAE. The very complex topographic features of the vast South West Asia region, to which UAE belongs, has a major impact in the weather/climate conditions of the area. The large mountain ranges to the north and the west of this region, divert the extra tropical lows that reach the eastern Mediterranean, often into tracks away from Arabia. This is particularly true when the Subtropical High Pressure (SHP) is extending over the area. If the upper air flow exerts a force there is a possibility that this may drive these extra tropical lows towards the

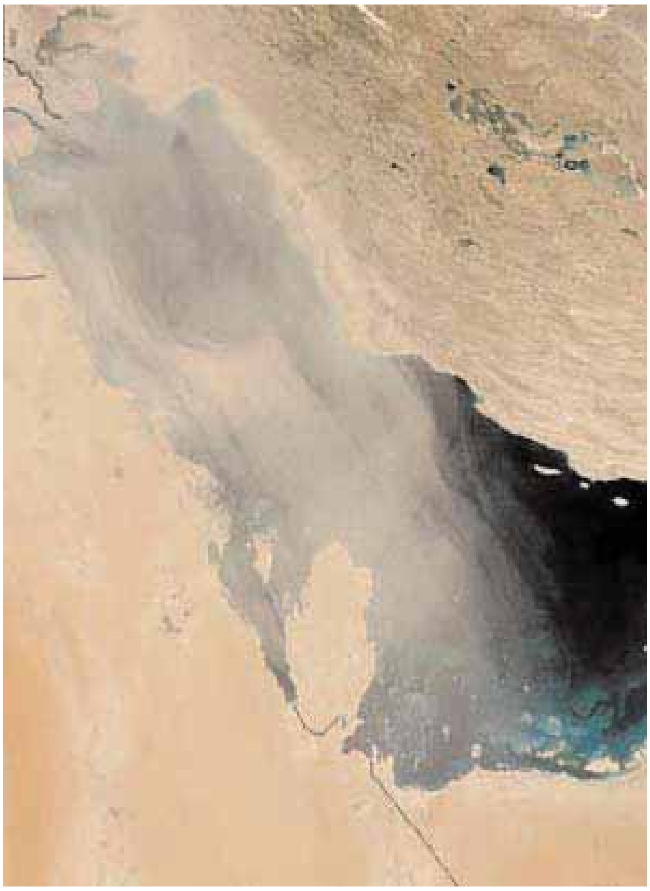


Figure 5.5: Dust advected after extra tropical low passage across Iraq in May 14, 2004.

area. This force exists when the zonal (westerly) upper air flow experiences some sinusoidal perturbations. Such perturbations in the zonal (westerly) upper level flow, which appear on weather charts as troughs and ridges, move steadily eastwards at average of 4 to 5 a month during winter. Some of these troughs may extend southwards over the Arabian Peninsula. In some of these cases, the upper air troughs induce extra tropical lows to move eastwards across the north of the Arabia. The north-westerly flow that follows such lows, occasionally, advects thick dust from over Iraq, southwards to the Gulf region as shown in Figure 5.5**.**

In some other rare cases, the upper trough may deepen further to the south. As a result, the **SHP** weakens and shrinks northeastwards, giving way to some of these extra tropical lows to follow a southeast track towards the Arabian Gulf. The vertical contrast between the cold air above and the warm water below acts as a source of energy, enough to keep such lows alive and continuing their tracks across to the southern part of the Arabian Gulf and even to the south west coasts of India (WMO PSMP Report, series No. 24). Occasionally, fluctuations in the surface wind flow over the Arabian Gulf are usually associated with the passage of these low pressure areas such as:

- A low level, hot and dry south-easterly flow develops ahead of, and increases in intensity with the approach of such low pressure waves. The southeasterly flow, or '*Alkaus*' as locally known, favours the conditions for squall-line thunderstorms. Widespread blowing sand / sandstorms usually accompany such flow patterns.

- Outbreaks of strong cold air mass from the north follow in the wake of the passage of these extra tropical waves cause northwesterly ('*Shamal*') winds, which chiefly occur from November through March. This winter '*Shamal'* invades the Arabian Gulf on 1-4 occasions per month. It usually lasts for 1-2 days, and occasionally 3-4 days. The wind speed may exceed 10 m/s, especially over sea. Gusts of 20 m/s or more are not unusual with the *'Shamal'* flow during winter and pre-monsoon months (Perrone, 1979 and Membury, 1982).

During winter months (December to March) cloudiness above 4/8 oktas (8/8 oktas means overcast sky, that is, the sky is fully covered with clouds) occurs in 4-8 days per month. It is important to note that 80% of the total rainfall amounts occur during winter seasons, and occur in 3 to 5 days per month, on the average, compared with 0 to 1.0 day for other months. The average mean monthly rainfall amounts, during winter, range between about 5 mm to about 25 mm per month.

Some of the rainfall results from the frontal depression traveling across the area, while most of the rainfall accompanies the frequent passage of the cloud bands, migrating from over Ethiopia and Sudan, across the area. Depending on the intensity of the low level convergence, these cloud bands can give intermittent or continuous rain for more than 24 hours, and heavy showers and thunderstorms at times (Note: all values used in this description, are for Abu Dhabi Emirate).

B Summer Circulation

During summer season, the Euro-Asian surface anticyclone (**SHP**) disappears due to heat and becomes established over the Azores Island (**Figure** 5.6**)** A series of seasonal and thermal low pressure systems appear over the South West Asia region as a result of the intense surface heating. These thermal lows, in association with the Asian monsoon system, contribute to the South Easterly flow

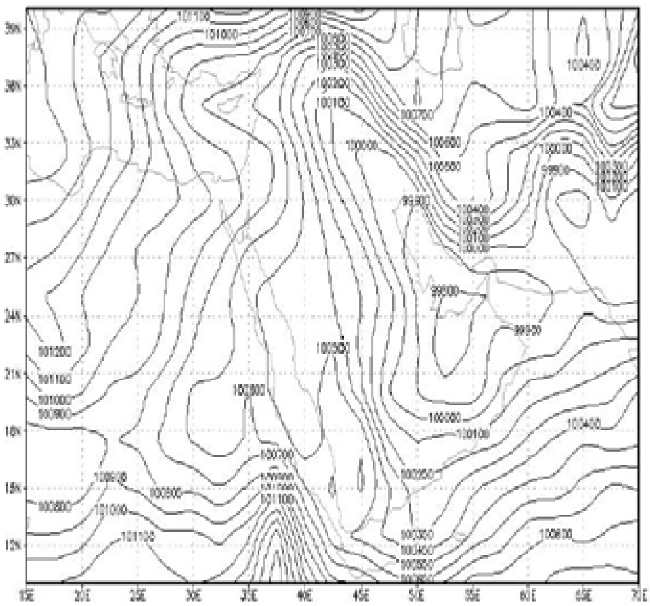


Figure 5.6: Shows the mean sea level pressure distribution for August (summer month)

over the Arabian sea and the South East Arabian Gulf area, and consequently to the occasional excessive heating and the occasional summer rainfall that may result there In the upper level, when the Subtropical High shifts north of UAE (**Figure** 5.7), the air in the upper level tends to subside downwards, decreasing any chance for cloud formation/ development. These static weather systems characterize the summer period with clear skies and high temperatures, accompanied by very humid weather.

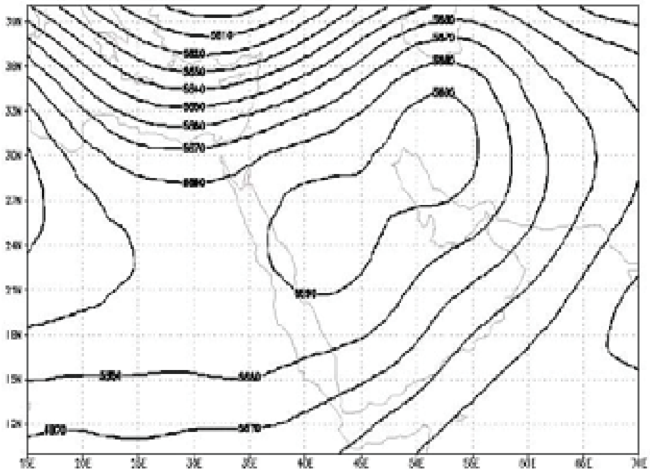


Figure 5.7: The 500 hPa geopotential heights for August (summer month).

During early summer, a deep monsoon low pressure area may be centred over Pakistan, forming what's known as Pakistani heat low that oscillates in an east-west direction. As this low strengthens, its western fringe may extend just west of the Arabian Peninsula. This can develop a fresh northwesterly flow over the southern parts of the Arabian Gulf, from late May till early June. This northwesterly flow is called "The summer 40 days Shamal" (Perrone, 1979). The summer '*Shamal*' brings rather cold air from sea to land, so it causes a relief from the very hot weather conditions. It is often strong during daytime and typically decreases by night. Occasionally, this summer Shamal brings thick dust haze into the south western of the UAE.

The Arabian Sea and the Indian Ocean are the primary sources of moisture into the Arabian Peninsula Gulf Region. However, as can be seen from **Figure** 5.6, the atmospheric pressure over the Indian Ocean during summer is weak, but relatively high compared to that over the Arabian Peninsula; it reaches 1000-1008 mb over the Indian Ocean and 997-1000mb over the Arabian Peninsula**.** This yields a very slack pressure gradient (or the pressure difference from place to place that acts as a force driving the wind flow) to push maritime humid air mass from the Indian Ocean only into very limited extent across the Omani coast and not further inland into the Arabian Peninsula. This moisture is confined to a shallow layer with some drizzle rain. In very rare cases, incursion of South West monsoon flow takes place into UAE, generating occasionally heavy rainfall, especially during month of July. During summer season, the ITCZ (Inter Tropical Convergence Zone) usually lies between latitudes 22-24 north, occasionally moves further north bringing extensive unstable medium level clouds and rain to the UAE. Such a case occurred in July 1995 and gave rainfall of 41.4mm to Al Ain and 18.2mm to Abu Dhabi.

The land-sea breeze circulation is the most commonly diurnal wind circulation over the whole year, especially in the absence of fronts and strong depressions in winters, and as is often the case, for most days on the non-winter periods. The overnight south/southeasterly land breeze is 2-4m/s, while by afternoons, the north/northwesterly sea breeze sets in (usually at 9 GMT, 1 pm Local Time) to reach 4-7m/s speed. In some occasions, especially in summer when the sea- land temperature contrast is greater, the afternoon sea breeze can enhance to about 10 m/s, creating the sea breeze front. Some scattered clouds can appear by noon, accompanying such situations.

The horizontal extent of the sea breeze is typically 10-20km in higher latitudes, but in the tropics, it can extend up to 200km inland (Hastenrath, 1995). The hourly observations of Al Ain airport reveal the diurnal reversal of wind direction as an indicator to the land-sea breeze circulation.

Yet another important phenomenon is the afternoon thunderstorms which occur over the Hajar mountains. Heavy rain occasionally occurs during July and August over Al-Ain area due to these orographic clouds. Dry dust squall resulting from these thunderstorms can cause minor sandstorms. Gusty winds of 25 m/s is not unusual with these thunderstorms, in a few cases wind speed exceeding 35 m/s had been reported. The dust haze incidence frequency in summer is twice that in winter. The visibility is generally at its worst. The sea breeze that reaches Al Ain area during July and August may be one of the thermodynamic factors that cause afternoon thunderstorms there.

C The Transitional Periods

Spring Circulation

The winter disturbances decrease and as a result skies are mainly clear with mean daily sunshine of 10-11 hours. Starting mid April, the surface becomes hot enough to generate an upward current that when it meets the cold air in the upper level, local thunder activity cells occur and produce sudden heavy rainfall. The extreme maximum 24 hours rainfall of April exceeds that of winter months for some places; however, the mean monthly total rainfall is less. Wind direction is not steady as in winter, as the sea breeze tends to be stronger due to the higher land-sea temperature contrast. On rare cases the land south-easterly breeze can overcome or delay the sea breeze onset. In such cases the weather becomes hotter but with low humidity.

Autumn Circulation

The autumn months experience the most stable weather conditions. Rainfall is very rare, especially in September and October, but the chances of rain increase by late November. Winds are generally light. The least mean hourly wind speed is for autumn months. The land-sea breeze is generally weak as the land-sea temperature difference becomes smaller.

The impact of the Tropical storms and Cyclones in the Arabian Sea

Of the tropical storms that reach the Arabian Sea, one or two cyclones may hit the east coast of Oman every 3 years. This usually happens during the periods May to June (pre-monsoon period) and end of August until the first half of October (post monsoon period). Fortunately these cyclones often decay before reaching the UAE. Occasionally, some of these cyclones may curve northwards and become extra tropical depressions (Watt, 1977). The expansion of the clouds associated with these depressions may affect the Arabian Peninsula Gulf Region (Ali Hamid, 1997) as was the case on 18 May 2002 in UAE.

5.2.3 Specific Characteristics of Abu Dhabi's Climate

In light of the above mentioned general description, the behaviour of some individual climatic elements based on the statistical analysis of data is discussed below. Due to the limitations of data availability and reliability, this analysis is confined to data from the three international airports, *i.e.*, Abu Dhabi Intl. Airport (**ADIA**), Al Bateen Airport (**Bateen**) and Al Ain Intl. Airport (**Al Ain**).

A Dry Bulb Temperature

The temperature of Abu Dhabi Emirate noticeably fluctuates during the year. **Figure** 5.8 displays the monthly mean of the Dry Bulb Temperature for four stations; Abu Dhabi Intl. Airport (**ADIA**), Al Bateen Airport (**Bateen**), Al Ain Intl. Airport (**Al Ain**) and **Radoum**. The four stations show much symmetrical distributions, but with different values. This difference in values is related to the distance of the corresponding station from the coast, the longer the distance and the higher the temperature. The monthly mean Db temperatures have lowest values of 18-19°C in January and February and then rapidly rise during the period March to May. The rise in temperature continues during May and June, but at slower rate, to reach the peaks of 34-38°C in July and August. The temperature then declines 20.5-21.6°C in December. This distribution in temperature roughly exhibits the seasonal changes; it presents December until mid March as the cold period (winter season) and the second half of June through September as the hot period (summer season). It also presents the two periods in between the winter and summer, as the transitional periods of spring and autumn respectively.

The monthly average of the daily diurnal (difference between the maximum and minimum temperature for a day) range of temperature is shown in **Figure** 5.9. The diurnal range is smaller during the winter (9.6 to 12.5) and summer (11.0 to 14.9) while it reaches its peaks of 13 to 17.6 and 12.2 to 15.0 during the transitional periods of spring and autumn respectively. The highest peak occurs in May as a result of the occasional outbreak of the "*The summer 40 days Shamal*" cool flow.

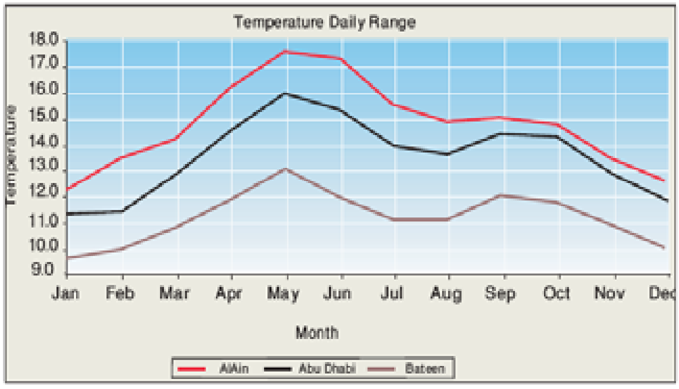


Figure 5.9: The monthly average of the Daily Temperature range.

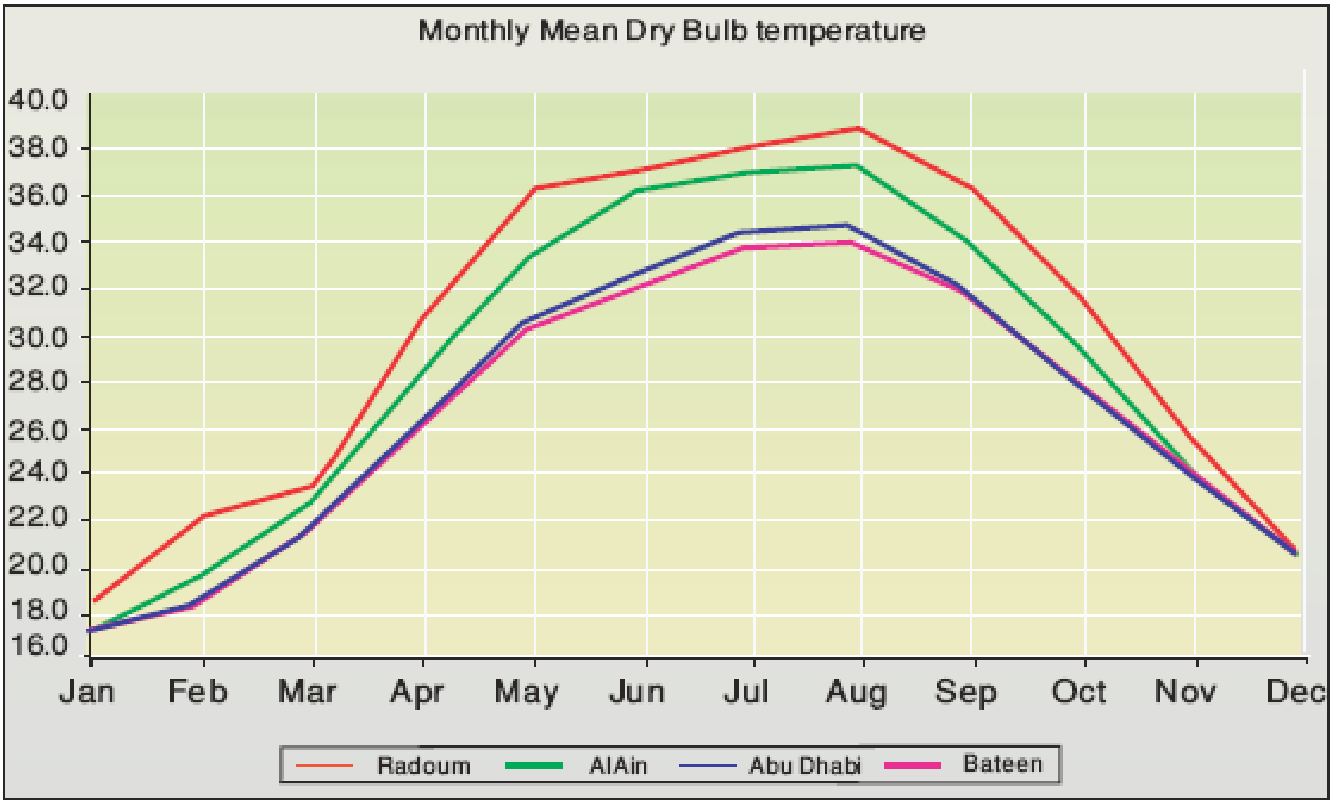


Figure 5.8: The monthly mean of Dry bulb temperature (˚C)

Comparing these values of the diurnal range with the annual range of the daily mean temperature of 0.2-7.4°C leads to one of the hallmarks of the temperature regime in the tropics: in the tropics, the diurnal range is great and the seasonality is reduced with no well identified four seasons. The noticeable fluctuations in temperatures can be attributed to the outbreaks of the cool northwesterly (‘*Shamal*’) wind that is often interspersed with warmer southeasterly (‘*Alkaus*’) wind, especially in winter. But in the non-winter months, the contribution is mainly confined to the local land-sea circulation and to the nature of the surface land.

The land-sea breeze strongly impacts the temperature regime of the area. The afternoon northwesterly sea breeze, being cooler, ceases the rapid rise of temperature, generally for places along the coastal fringe. Days with the maximum record of temperature along the coastal fringe are those when the sea breeze delays leaving the very hot land breeze from the Empty Quarter, 1-2 hours after 9 GMT. This very short delay is enough for the southeasterly land breeze to cause temperature jump abruptly.

In the interior area, out of the sea breeze horizontal extent, the static weather systems and the intense surface heating of the sandy desert keep summer times maximum temperatures, most often, above 45°C.as can be noted in **Table** 5.1 below .This table presents the monthly statistics of the extreme temperature. In this table, the maximum temperature exceeds 45°C between April and September, and reaches near 50°C in June, July and August in the southwest area (Radoum in **Table** 5.1). The extreme minimum temperatures occur during winter nights after the weakening of the cold Shamal wind. Values of extreme minimum temperatures below 0°C are not strange, especially in the interior of the south-west area, within the Empty Quarter as the clear skies, combined with higher reflectivity of the sandy surface increases the nocturnal cooling.

Station	Element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Adia	*Ext Max Db Temp*	34.3	35.9	43	44.7	46.9	48.5	48.7	49.2	47.7	43.1	37.9	33.8
	Mean Max Db Temp	24.3	25.6	29.1	34.1	39.1	40.8	42.2	42.6	40.4	36.3	31.0	26.4
	Mean Db Temp	18.6	19.8	22.6	26.6	30.9	32.8	34.7	35.0	32.6	28.9	24.5	20.5
	Mean min Db Temp	12.8	14.1	16.4	19.5	23.1	25.4	28.2	29.0	26.1	22.3	18.2	14.7
	Ext Min Db Temp	5.6	5.4	8.4	11.2	16.6	19.8	22.2	23.8	19.9	14.6	12	7.5
Bateen	Ext Max Db Temp	33.7	34.4	39.8	44.5	46.2	47.3	48	47.3	44.6	41.6	36.7	32.6
	Mean Max Db Temp	23.7	24.8	28.2	32.8	37.6	39.0	40.3	40.6	39.0	35.0	30.1	25.7
	Mean Db Temp	18.9	19.6	22.5	26.3	30.5	32.4	33.9	34.2	32.2	28.8	24.6	20.8
	Mean min Db Temp	14.0	14.7	17.3	20.7	24.6	26.9	29.0	29.5	26.8	23.2	19.1	15.9
	Ext Min Db Temp	7.9	7.5	9.8	13.3	16	21.7	22.7	25.6	20.4	15.4	12.3	9.6
AlAin	Ext Max Db Temp	31.8	35.5	42.9	44.4	47.9	49	49.1	48.7	47.8	42.9	37.5	35
	Mean Max Db Temp	25.1	27.8	31.1	37.1	42.5	45.0	44.9	44.9	42.1	38.0	31.7	27.5
	Mean Db Temp	18.5	20.6	23.6	28.7	33.4	35.9	36.7	36.9	34.1	30.2	24.5	20.7
	Mean min Db Temp	12.8	14.3	17.0	20.9	24.9	27.6	29.6	30.0	27.1	23.3	18.4	14.9
	Ext Min Db Temp	7.3	7.5	9.9	13.2	18.2	20.9	22.9	21.9	22.3	16.2	13.2	8.9
Radoum	Ext Max Db Temp	35.5	36.6	41.2	45	47.1	49.5	48.5	49.7	47.1	42.9	40.1	34.1
	Mean Max Db Temp	30.4	32.7	36.8	41.7	46.0	47.7	47.3	47.5	44.7	40.9	35.9	31.3
	Mean Db Temp	19.2	22.9	24.1	30.8	35.8	37.4	38.2	38.8	35.9	31.5	26.0	21.6
	Mean min Db Temp	5.9	7.4	11.1	12.5	18.0	18.6	20.2	19.3	16.3	13.9	9.0	6.7
	Ext Min Db Temp	-5	-0.6	-0.6	6.5	10.7	14.8	15	14	10.1	6.1	-1.1	2.1

Table 5.1: Monthly Extreme and average of daily maximum and minimum Temperatures.

B Relative Humidity

The daily mean of the relative humidity behaves similarly during most days of the year. Humidity starts a gradual increase a few hours after midday to reach values of 70-80%. It then declines to 35-50% by midday hours. The values during winter are 10% higher than those during summer. Along the coastal strip the values are higher than the inland area by values of 10-20% depending on the intensity and depth of the afternoon sea breeze. Increase in humidity increases the feeling of the temperature (called Effective Temperature). Generally, the most intolerable weather condition periods are those when the humidity is above 70% and temperature above 35°C.

C Sunshine and Solar Radiation

In UAE, the longest day is the 21st of June and the shortest is 21st of December. On the 21st of April and 22nd of September, the day and nights are equal. The monthly mean of the daily sunshine hours slightly differs from the astronomical day length (the time between sunrise and sunset), because the sky is mostly cloud free and its effect on sunshine is very slight. The monthly mean of the daily sunshine hours is similar all over the Emirate, and ranges between 8.4 hrs in winter, to 11.6 hrs in summer. These values accumulate total sunshine hours of about 3,600 hours per year, which is among the highest, around the world. Referring to the climatic atlases published by the WMO, the Arabian Peninsula and the African desert are the two areas that receive the highest amount of the incoming solar radiation. The following table shows the monthly distribution of the solar radiation in ADIA as coastal area and Al Ain as an inland one.

D Wind speed and direction

The several wind regimes that dominate the area are briefly discussed below. The statistical description of the wind direction and speed is given in **Figure** 5.10.

The selected stations were ADIA to represent a coastal area, Al Ain as inland area, and Abubukhoush (ABK) offshore oil-field in the west, for comparison. From these three wind roses, it is clear that NNW flow is the most prevailing direcion. The NNW represents about 47% for ABK, 36% for ADIA and 30% for Al Ain. Also Wind from the quadrant two around the South is remarkably noted in Al Ain as a direct effect of both the Alkaus and the Southwest monsoons. The contribution from South-Southeast breeze is, of course, very small in Abulbukhoush, whilst fairly contributing in ADIA. In general, the most prevailing wind direction is from the northwest.

Station	Element	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ADIA	Extreme maximum	549	700	853	938	973	958	973	777	750	728	693	516
	Daily Average	392.4	459.9	547.2	649.9	730.6	736.8	661.9	631.5	610.9	542.2	451.0	380.4
	Extreme minimum	43	52	60	126	172	184	229	229	205	209	128	32
Al Ain	Extreme maximum	560	656	767.9	837.7	862.4	882.1	829.1	794.3	752	670	566	554
	Daily Average	433.3	540.8	606.3	738.8	794.8	790.9	733.9	723.3	677.2	589.4	482.4	428.3
	Extreme minimum	43	235	85	224.7	358.5	557	407	515.2	446.6	230	256	78.9

Table 5.2: The monthly Global Solar Radiation

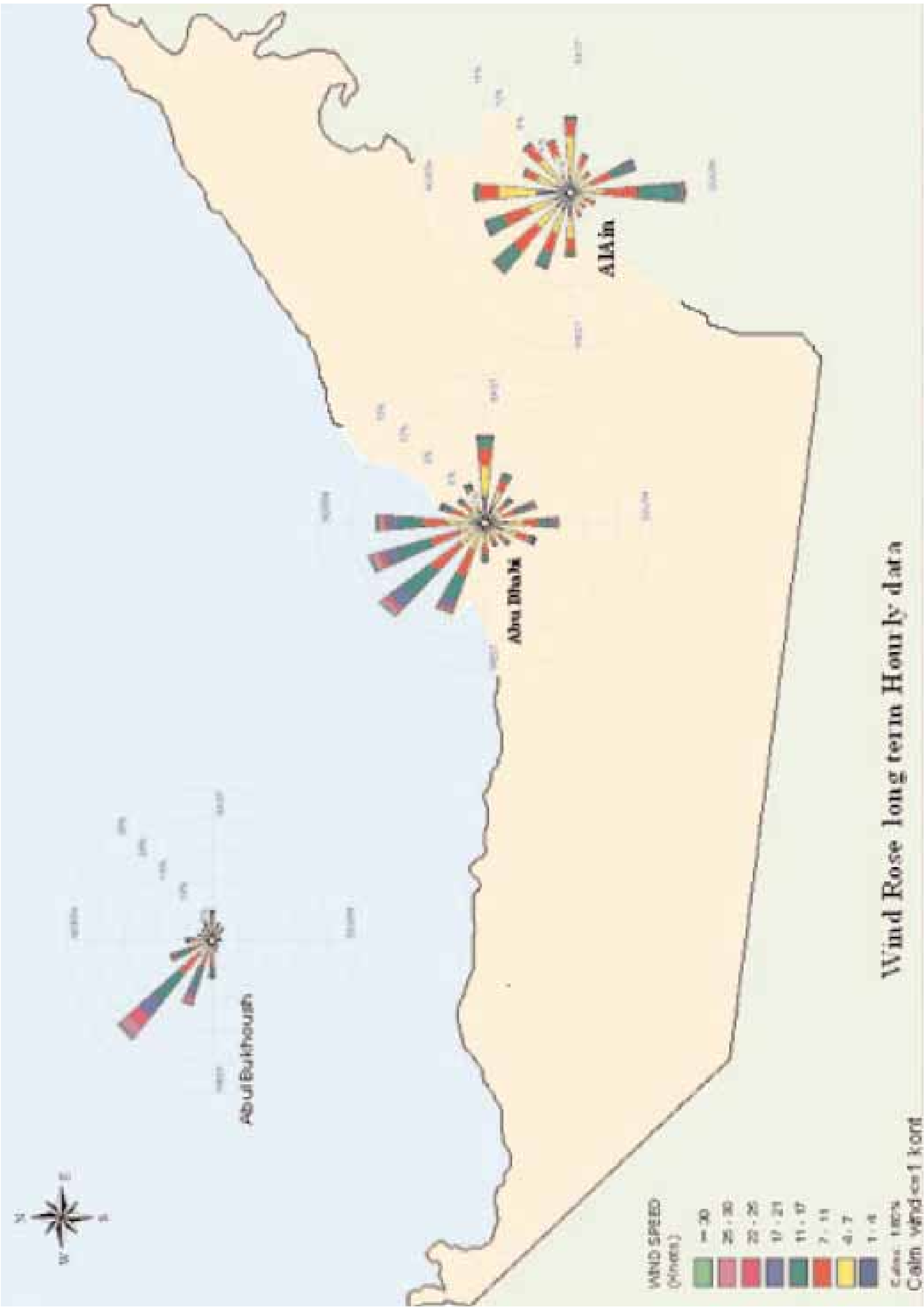


Figure 5.10: The wind rose graph

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Extreme maximum Gust												
Adia	54	54	99	68	41	40	41	39	32	38	41	41
Btn	41	57	46	60	69	39	37	54	33	37	37	39
Ain	44	44	43	74	47	63	77	37	58	37	44	39
Extreme maximum hourly wind Speed												
Adia	27	30	35	34	29	28	30	34	24	26	28	27
Btn	32	36	38	32	32	30	28	30	24	25	28	30
Ain	32	31	32	26	26	35	47	32	31	26	22	28
Mean Maximum Wind Speed												
Adia	12.2	13.9	14.9	14.8	14.9	14.5	14.5	14.8	13.9	12.9	11.9	11.9
Btn	13.3	14.9	16.1	15.5	15.4	15.3	14.9	15.2	14.1	13.1	12.2	12.5
Ain	12.8	13.9	15.6	15.7	16.4	16.4	15.8	15.7	15.4	13.7	12.2	11.9
Mean hourly Wind Speed												
Adia	6.5	7.8	8.0	7.5	7.5	7.5	7.5	7.7	7.0	6.3	6.0	6.1
Btn	7.1	8.3	8.7	7.6	7.6	7.9	7.4	7.6	6.9	6.2	6.0	6.5
Btn	6.9	7.7	8.5	8.0	7.9	7.6	7.9	8.0	7.7	7.2	6.5	6.5

Table 5.3: Different wind speed strengths in Knots (~0.5411 m/s)

E Rainfall

The different weather conditions that can give rain to the Emirate were discussed above. It is generally found that the westerly travelling upper air troughs are the main mechanism for rainfall production. The next 3 graphs, **Figure** 5.11, **Figure** 5.12 and **Figure** 5.13 show the annual total amounts of rainfall, the maximum amount of rainfall in 24 hours, and the annual average for Bateen (from 1971-1996), ADIA (from 1982-2004), and Al Ain (from 1995-2004).

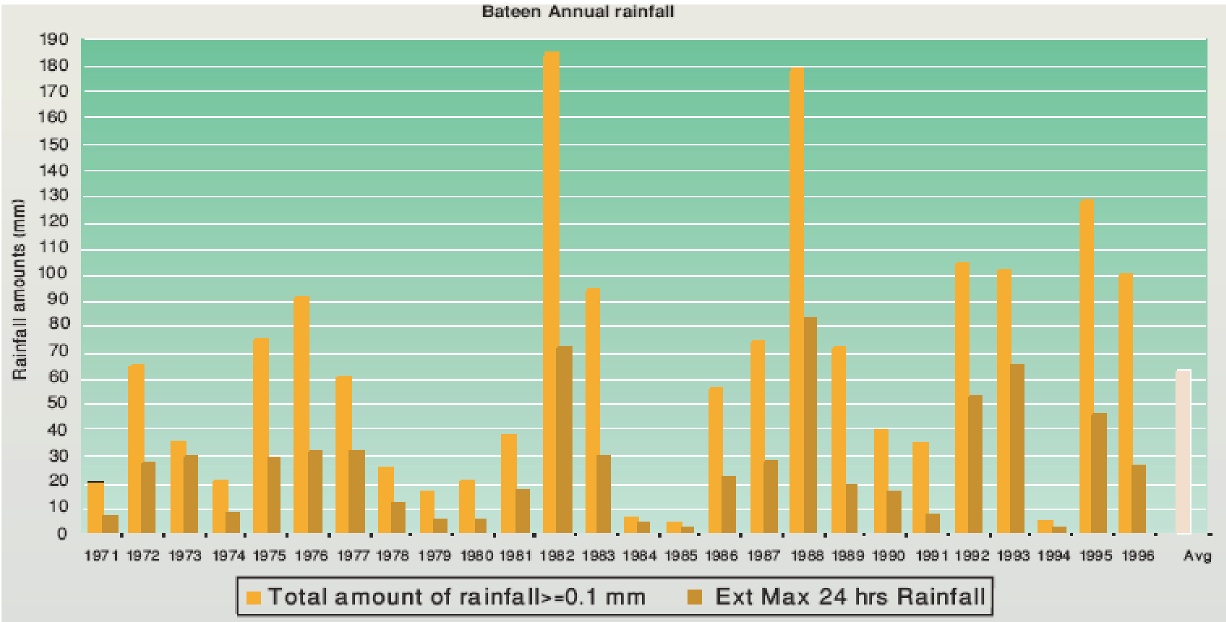


Figure 5.11: Annual Rainfall amount for BATEEN (1971-1996)

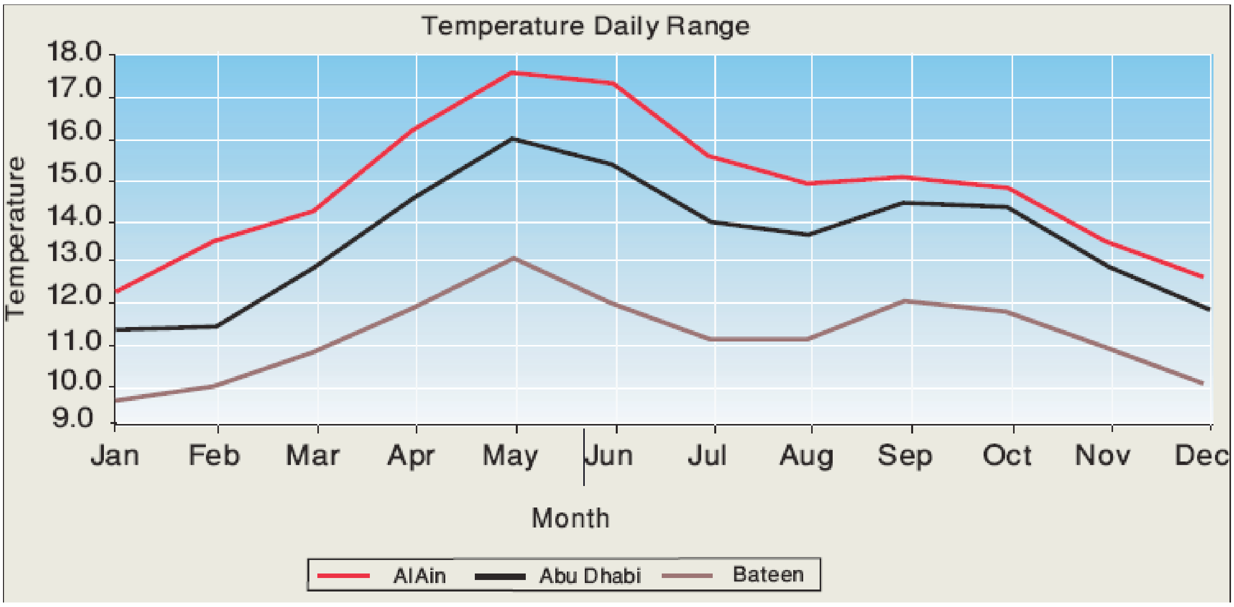


Figure 5.12: Annual Rainfall amount for ADIA (1982-2004)

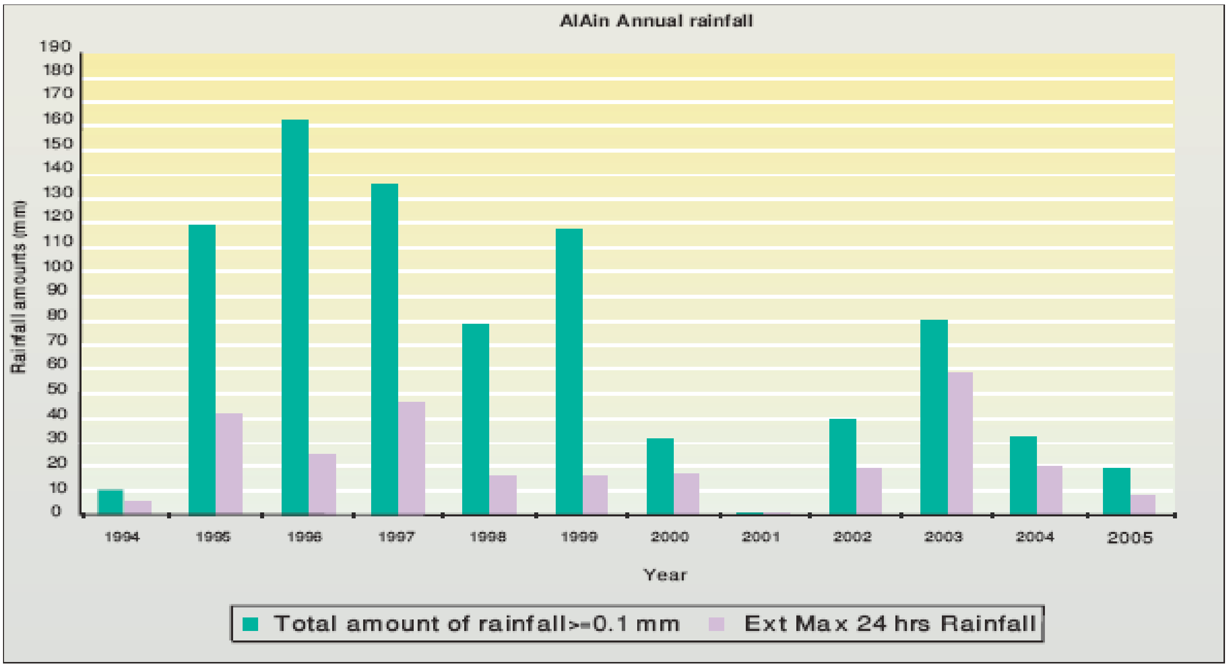


Figure 5.13: Annual Rainfall amount for Al Ain (1994-2004).

- The annual rainfall shows a great (above 70%) from year to year. One or two successive years with appreciable rainfall amounts then followed with years with less or no rain.
- One day precipitation may exceed the total precipitation of 2 or 3 years. This one day with such huge amount of precipitation significantly increases the calculated averages and in turn provides misleading information.
- The 24 hours rainfall in two nearby stations may significantly differ (120mm on Feb 19th 1988 in ADIA compared with 81.5mm in Bateen on the same day).

Table 5.4 displays the monthly statistical summary for rainfall. Bu before reading the information implied, please note the following:

- The calculation and the results are for data series of different periods and different lengths: (**Bateen** (1971-1997), **ADIA** (1982-2004), and **Al Ain** (1995-2004);
- One day with rain in one month over the whole period makes this month statistically rainy;
- Days with trace rainfall *i.e*. rain <0.1mm is not considered.

Station	Elem /Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ADIA	*Monthly Total amount*	267.3	585.3	430.1	184.9	4.8		20.2	4.1		5.4	32.5	192.6
	Monthly extreme rainfall	68.1	202.4	109.2	56.2	4.8	0	18.2	3.6	0	5.4	18.4	54.9
	Monthly Mean rainfall	11.1	24.4	17.9	7.7	0.2	0	0.9	0.2	0	0.2	1.4	8.4
	Ext Max 24Hrs Rainfall (mm)	37.8	120	50.2	56.2	4.8		18.2	3.6		5.4	11.3	18.6
Bateen	**Monthly Total amount**	263.1	569	443.2	184	26.3		10.2	31.2			5.2	165.4
	Monthly extreme rainfall	48.8	156.5	86.5	52.5	26.3	0	10.2	29.7	0	0	3.2	59.8
	Monthly Mean rainfall	9.8	21.1	16.5	6.8	1	0	0.4	1.2	0	0	0.3	6.7
	Ext Max 24Hrs Rainfall (mm)	30.2	81.5	45.4	52.2	16.1		9.6	28.7			2.4	26
Al Ain	**Monthly Total amount**	175.3	52.7	219.7	89	5.9	11	81.4	15.4	8	6.8	6.3	60.3
	Monthly extreme rainfall	77.3	30.5	63.3	62.9	3.6	10.6	**48.8**	7	7.8	3.4	4.4	26.8
	Monthly Mean rainfall	14.6	4.4	18.3	7.4	0.5	0.9	6.8	1.3	0.7	0.6	0.5	5
	Ext Max 24Hrs Rainfall (mm)	46.2	16.3	30.8	58.8	3.4	9.6	41.4	6.8	6.2	3.4	3.2	20

Table 5.4: The Monthly climatic summary for Abu Dhabi Emirate.

The next table shows that:

- Most of the rainfall occurs during the winter months for the 3 stations.
- Rainfall is also possible during July and August, particularly for AlAin area, which represents the southeastern area of Abu Dhabi. The heavy and flood-prone summer rain is a peculiarity for this area.

February and March have the highest rainfall amounts recorded. The 120mm rainfall recorded in ADIA on Feb 19, 1988 makes February as the month of highest rainfall record whereas March is the month with maximum number of days with rain, as can be seen from Table 5.5

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ADIA	46	61	77	29	1		2	2		1	12	39
Bateen	51	81	89	35	2		2	3			3	34
Al Ain	27	13	38	12	5	3	10	10	3	2	5	13

Table 5.5: Number of days with rain >0.1 mm.

F Evaporation

The rate of evaporation depends on the length of the sunshine hours, and the ability of air to take up more water. The less humidity air can receive more the vapor. In **Figure** 5.14 below, the mean maximum and the daily mean evaporation fairly coincides with the monthly sunshine distribution, with less values during winter and high values during summer.

G Mist and Fog statistics

Radiation fog is the most common type of fog experienced in Abu Dhabi Emirates. It occurs after the weakening of the '*Shamal*' wind in winter and spring or after a strong sea breeze. In both cases the air can carry moisture from the sea deeper inland, where the overnight cooling and the clear skies favor the condition for fog formation, usually 2-4 hours after midnight. Fog occurs on 31 days or an average of 106 hours per year near the coast, and 18 days or 45 hours at average per year in the interior areas. Fog is more frequent in winter (76 days) than in summer to (48 days). The reciprocal values in inland area are 36 days in winter and 5 days in summer. Fog incidence can last from half an hour to 10 hours, depending on the time of formation and the weather conditions.

5.3 Climate Change

Climate change is an issue that has been identified globally, and as the conclusion of this document will state, a gap in the current knowledge for the Emirate of Abu Dhabi. However, EAD has initiated a climate change study that will study the impacts of climate change in the UAE. A 9 month study has begun for which the results are under preparation at the time of this update. The study will analyze the potential magnitude of the physical impacts of climate change on three vulnerable sectors in the UAE: 1) coastal zones; 2) water resources; and 3) dryland ecosystems. The issue of climate change is discussed further in the Conclusion section of this document which provides better context within the UAE environment, and once the study has been completed, the knowledge needed in order to prepare for and mitigate against potential impacts of climate change will be better understood.

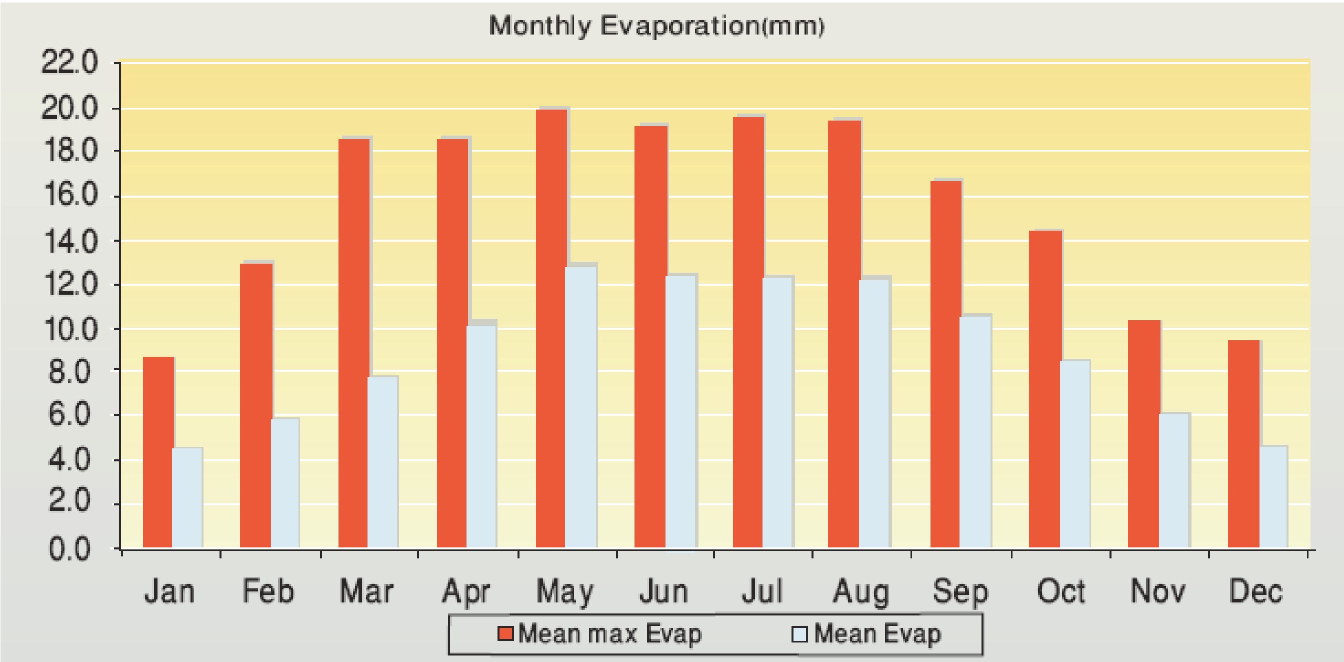


Figure 5.14: Monthly maximum and mean evaporation in the Emirate of Abu Dhabi.

6 CONCLUSION

Photo by HABITAT

The aim of this section is to evaluate the information presented in the sector paper and to highlight the major issues facing the Emirate in terms of its physical environment. It is evident that a number of the arising issues are closely interrelated, also with those of other sector papers.

Overall, we have a good understanding of the geology of the Emirate, which, given the overriding economic importance of oil in the region, is hardly surprising. It has remained fairly stable since the Cambrian Period, *i.e.* over the past 500 million years. However, this should not be interpreted as meaning that there have been no changes in the geological setting, and of particular relevance to this sector paper is the influence of climate in determining recent surface geological processes. For example, the dune systems of the Emirate are controlled to a significant degree by the global wind patterns. Although shifts in climatic patterns have generally taken place over long periods of time, the information will be invaluable in interpreting recent, more abrupt changes in climatic conditions ("global climate change" or "global warming"). This is already a major issue facing many parts of the world, and one which is destined to become more acute in the coming decades.

In general, we have only patchy information on the climatic situation in the Emirate, which, depending on the classification used can be described as arid or hyper-arid. The United Nations Environment Programme (UNEP) classifies the whole of Abu Dhabi Emirate and most of the surrounding area as hyper-arid, belonging to one of the most inhospitable regions on earth (Middleton & Thomas, 1997). Not only does climate play a central role in determining the evolution and changes in the land surface, as mentioned above, but it also strongly influences other key attributes of the environment, including soil development, flora, vegetation, fauna and water resources. This influence is discussed in more detail in other sector papers including those covering the terrestrial environment and water resources sectors. Even subtle changes in climatic conditions will have pronounced consequences for these attributes, and given the variability of climatic conditions throughout the Emirate, there is a strong case for developing a network of weather stations to cover the Emirate, integrated into an international system of monitoring stations.

As described in the Geology section, away from the Oman mountains and the Abu Dhabi coastline, the surface of the desert interior is dominated by the presence of rolling sand dunes, which, in the south around Liwa, reach impressive heights, often well in excess of 100 m. Dune soils are extremely poorly developed due to the extreme climate, which means that the largely unaltered parent material is present on the surface. In fact, because much of the desert surface is formed of aeolian or fluvial sediments which have been so little modified, the soils can hardly be called as such by any common definition. This would include the entisol order (US system of soil taxonomy), which dominates Abu Dhabi Emirate. In coastal areas, where the climate is slightly less extreme, the effects of pedogenesis become marginally more apparent, as indicated in the coastal soil survey (Shahid *et al*., 2004).

As in other parts of the world, true desert soils are not widely documented. This is probably due to the very nature of the environment, and the fact that classification schemes are not easily applied to relatively barren areas, which, from an agricultural point of view, are of little or no relevance. A striking feature of desert soils is that they are often characterised by the accumulation of windblown materials (salts, dust), rather than the modification and development of existing material *in situ*. It is therefore clear that in desert environments such as the Abu Dhabi, surface geological and soil development processes are for all intents and purpose identical.

Key issues from a soil perspective are wind erosion and soil salinisation. On the one hand, this is a natural phenomenon, and, as already underlined, much of the desert surface was created by the deposition of windblown materials. This is a continuing process and given the prevailing climatic conditions will not cease. However, with the rapid economic expansion in the Emirate, the problem of anthropogenic soil erosion has become quite acute in some areas. Intensive construction activities over large tracts of land have resulted in frequent, sometimes continual dust storms locally. On a much smaller scale, the same applies to mining and recreational activities such as off-road driving.

Soil salinisation is a widespread natural feature of semi-arid to hyper-arid climates. For instance, hypersaline soils are typical of sabkha, a characteristic landscape feature particularly in coastal areas of Abu Dhabi Emirate, but also far inland on interdunal plains. However, human-induced soil salinisation in areas where it did not previously occur is a major problem in agricultural and forestry areas, due to inappropriate irrigation techniques or simply due to the unsuitability of the land itself. In view of the fact that crop yield is apparently restricted on most farms due to enhanced salinity, the entire agricultural policy needs to be re-assessed. Rather than promoting crops which are dependent on large amounts of irrigation water (*e.g.* alfalfa, Rhodes grass), more emphasis needs to be placed on the production of “less-thirsty”, native fodder plants, as outlined in Peacock *et al*. (2003) and Brown *et al*. (2006). The production of halophytic crops may be feasible in naturally saline areas, but using brackish water to grow them in non-saline conditions will only exacerbate the problem of soil salinity.

Soil contamination does not appear to be a key issue in the Emirate at present, but against the background of rising populations and expanding economic development, it is an aspect which requires close monitoring. Given the free-draining, sandy soils which cover large tracts of the Emirate, high concentrations of pollutants could easily percolate down to the groundwater where this is close to the surface, if adequate precautions are not in place.

A pressing issue in the Emirate which requires urgent attention is the dire situation of water resources. With rainfall a meagre natural commodity, which can nowhere near meet the current excessive demand, and faced with alarming groundwater declines and severe deterioration of water quality due to over-abstraction in many areas, the Emirate is becoming increasingly dependent on non-traditional supplies such as desalinated water or treated wastewater. As such supplies are also subject to various constraints, the development and rigorous implementation of an effective Integrated Water Resources Management policy is a vital step to re-mediating the situation, and it appears as if decisive action has recently been taken on this front. But it is clear that, as with many regions of the world, the availability of freshwater will remain a major issue in the future that will require innovative solutions and responses, and not least, the willingness to conserve more effectively this valuable resource.

The Emirate is frequently perceived as being under severe threat from “desertification”. This term itself has suffered severe abuse over the past decades and is subject to much controversy (Verstraete, 1986). UNEP describes desertification as “land degradation in the arid, semiarid and dry sub-humid areas of the globe”, and the precise definition adopted by the United Nations Conference on Environment and Development (UNCED) and embodied in the Convention to Combat Desertification (CCD) is “land degradation in arid, semi-arid and dry sub-humid areas resulting from various factors including climatic variations and human activities" (Middleton & Thomas, 1997). Whereas some of the issues listed in this and other sector papers do indeed relate to this menace, the World Atlas of Desertification generally regards desertification as a non-issue in the UAE and other hyper-arid parts of the Arabian Peninsula. The reason for this exclusion is that these hyper-arid areas already, by their inherent nature, have "very strong desert characteristics and nutrient-deficient soils, giving limited potential for degradation by many processes; and they offer only limited opportunities for degradation-inducing human land-uses" (Middleton & Thomas, 1997). In general, land degradation (in the more arid regions of the world, often used synonymously with desertification) consists of two distinct components, namely vegetation degradation and soil degradation. In most cases, the latter is a consequence of the former, but given the extremely sparse natural vegetation cover in the desert interior and the lack of agriculture of other ground cover, the effectiveness in the vegetation in protecting the movement of sand is minimal, and so the two components are largely unrelated. As already outlined, soil degradation phenomena tend to be local and in very general terms, associated with unsuitable agricultural / forestry practices (soil salinisation) and large scale construction activities (soil erosion). Despite the low vegetation cover, vegetation degradation is a serious problem, but more from a biodiversity and conservation aspect, and this issue is dealt with elsewhere. Efforts in the UAE to "green the desert" have in general proved unsuccessful, mainly due to unsustainable practices employed and a lack of ecological understanding, despite the considerable financial resources that have been invested in such activities in the past. Promoting re-vegetation for whatever purpose can be achieved by two main approaches, namely restoration and rehabilitation (Le Houérou, 2000). Restoration implies returning an ecosystem to its pristine condition (and is also referred to as 'biological recovery'), whereas rehabilitation is the reclamation of a degraded landscape by generating a type of vegetation different from the pre-degradation phase (Le Houérou, 2000). In arid environments, restoration, *i.e.* natural re-vegetation, is regarded as the most economically and ecologically sound method of regenerating depleted ecosystems, (Schuster, 1998). In the context of Abu Dhabi Emirate, protecting and enhancing natural woodland vegetation (*Prosopis cineraria* woodland, *Acacia tortilis* woodland), and growing woodlands based on natural principles would be the obvious solution to greening parts of the desert where this is feasible, and would minimise problems such as soil salinisation and the severe effects of sandstorms, at least locally.

Potentially the most urgent issue facing the Emirate in the coming decades will be that of global climate change ("global warming"). It is still far from clear how shifts in climatic patterns will affect different parts of the world. For Abu Dhabi Emirate it could be speculated that the climate may become wetter, drier, or there could be no change at all. However, even in the latter case, the Emirate cannot insulate itself from the effects of climate change taking place far away from its borders. With the Arctic ice pack rapidly shrinking, a concomitant rise in sea-level by as much as 80cm seems inevitable during the next decades, and this will cause severe flooding in the low-lying coastal areas. A significant proportion of the population of the Emirate lives in these areas, but this may not remain a viable option in the medium to long-term, even if the actual rise in sea-level turns out to be more modest. Furthermore, even if it were possible to construct effective flood defences to protect some of the most susceptible areas, sea water intrusion will still lead to periodic flooding as well as a deterioration of coastal aquifers and soil salinisation. The implications of this rise in sea level will affect all spheres of life in low-lying coastal areas, but with respect to the physical environment, agriculture and forestry will be unfeasible due to flooding and the expansion of sabkha-type substrates and subsidence and severe damage to infrastructure will be inevitable due to flooding and salt corrosion. The breathtaking speed of development in coastal areas currently underway may well turn out to be a short-lived phenomenon, with major social and economic consequences. The problems are likely to be confounded if there is a concomitant rise in aridity *(i.e.* rising temperatures, less rainfall or a combination of the two). The effects of global climate change will invariably affect the Emirate in the medium to long-term, especially in the more amenable and heavily populated coastal regions, and it is therefore vital that the planning for all eventualities begins on a broad front now, something that has been addressed as part of the current climate change study being developed through EAD.

General policy options for management of the natural resources of the GCC States, which also apply to the Emirate of Abu Dhabi, are currently being published by UNESCO, with contributions by Brook *et al*. (2006) on water resources and Brown *et al*. (2006) on coastal and terrestrial ecosystem management issues (see also other sector papers, and especially Policies and Regulations, Water Resources, Coastal and Marine and Terrestrial Environment papers).

Acknowledgements

As always, a book represents the culmination of coordinated efforts of many - more so, when it has to do with science. This volume too is no exception.

Quite a few contributed significantly to the shaping of this title; to acknowledge each individually is tough. That we specifically mention some is no evidence of slighting the others.

Our greatest debt is, no doubt, to H.H. Sheikh Khalifa bin Zayed Al Nahyan, President of the United Arab Emirates, who has not only been the inspiration behind it all but has lent us his vision of the balanced growth of an environmentally sustainable UAE.

H.H. Sheikh Mohammad bin Zayed Al Nahyan, Crown Prince of Abu Dhabi and Honorary Chairman of the Environment Agency - Abu Dhabi, whose involvement and commitment to all matters environmental have been complete, has also given us boundless support.

H.H. Sheikh Hamdan bin Zayed Al Nahyan, Chairman of the Environment Agency - Abu Dhabi, has extended his help, without any reservation, to the AGEDI initiative, which resulted in this effort.

H.H. Sheikh Mansour bin Zayed Al Nahyan, Deputy Chairman of the Environment Agency - Abu Dhabi, also placed at our disposal his generous encouragement and assistance in all aspects connected with environmental programmes.

H. E. Mohammed Al Bowardi, Managing Director of the Environment Agency - Abu Dhabi, has led us in our pursuits with unique finesse in the implementation of the AGEDI initiative.

I consider it a great privilege to acknowledge my immeasurable gratitude to these eminent personages.

H.E Majid Al Mansouri, Secretary General of the Environment Agency - Abu Dhabi, is thanked for his abiding loyalty to the cause of protection, management and conservation of the environmental assets of the Emirate of Abu Dhabi.

As for Mohammad Al Jawdar, the pains he took in steering the course of the initiative to its set goal against occasional adverse winds are prodigious.

To them all, I offer with warmth a bouquet of thanks.

Mr. Mark Sorenson, Senior Consultant and Principal of Geographic Planning Collaborative, and his colleagues have rendered matchless contribution through the introduction of the concept of sector papers into the AGEDI programme and the conduct of workshops for collating data for the sector papers including this one. I record with pleasure and gratitude our appreciation of their invaluable work.

To Dr. Ken Glennie, Hussan Raafat, Mike Brook and Dr. Shahid Shabbir, authors of the chapters on Geology, Climate, Hydrology and Soil respectively- each of proven competencies in the respective areas - our gratitude is immense. Dr. Gary Brown's watchful eyes monitored the overall venture and it is a pleasure to acknowledge his role here. The paper profited greatly from the critical review of Prof. Essam Abd El Gawad and Dr. Mahmoud Abdelfattah (Soil Chapter).

Lastly, we record with appreciation the unstinted assistance of Jane Glavan, Ahlam Al Marzouqi and May Chafati, without which this work would not have been possible.

Anil Kumar Lead,
Physical Geography Sector paper

Environment Agency – Abu Dhabi (EAD)
P.O Box 45553
Abu Dhabi
UAE
T: +9712- 4454777
F: +9712- 4463339
www.ead.ae
customerservice@ead.ae

Design & Layout by: Rob Barnes

List of Authors and Contributors

Name	Organization	Role
Dr. Shahid Shabbir	International Centre for Biosaline Agriculture (ICBA), Dubai	Author, Soils Chapter
Michael Brook	Environment Agency - Abu Dhabi	Author, Hydrology Chapter
Prof. Kenneth W. Glennie	University of Aberdeen, UK	Author, Geology Chapter
Hussain Raafat	Dept. of Meteorology, Ministry of Communication, UAE	Author, Climate Chapter
Dr. Gary Brown	Kuwait Institute of Scientific Research (KISR), Kuwait	Author, Introduction & Conclusion
Prof. Essam Abd El Gawad	Dept. of Geology, UAE University	Overall Review
Dr. Mahmoud Abdelfatah	Environment Agency - Abu Dhabi	Reviewed Soil Chapter
Anil Kumar T P	Environment Agency - Abu Dhabi	Lead, Sector Paper Compilation & Overall Review

References

Administrative Report 95-001, 1 sheet, scale 1:200,000, prepared for the National Drilling Company, Abu Dhabi.

Al Ain Municipality & Agriculture -Agriculture Extension Service 2001 Annual Report on Groundwater Salinity.

Ali Hamid A Ali, (1997) Statistical analysis of Meteorological events in the Arabian Peninsula and the Arabian Gulf. PhD thesis.

Al-Husseini, M. I., 2000. "Origin of the Arabian Plate Structures: Amar Collision and Najd Rift", GeoArabia 5(4), pp 527-542.

Al-Husseini, M., Amthor, J., Grotzinger, J. & Mattner, J. 2003. "Arabian Plate Precambrian-Cambrian Boundary Interpreted in Oman's Ara Group", GeoArabia 8(4), pp 578-580.

Al Mardi, H.A. & Al Aidrous, A., 1985. Regional aquifer geology, onshore Abu Dhabi. Abu Dhabi Company for Onshore Operations. Report No. 210572/573. 9p.

Alsharhan, A. S., 1989 "Petroleum Geology of the United Arab Emirates", Journal of Petroleum Geology, 12(3), pp 253–88.

Alsharhan, A.S. et al., 2001. Hydrogeology of an Arid Region: The Arabian Gulf and Adjoining Areas, Elsevier, New York.

Alsharhan, A. S. & Whittle, G. L., 1995. "Carbonate-Evaporite sequences of the Late Jurassic, southern and south-western Arabian Gulf", American Association Petroleum Geologists Bulletin, 79 (11), pp 1608–30.

Al-Silwadi, M. S., A. Kirkham, M.D. Simmons, and B.N. Twombley, 1996. "New insights into regional correlation and sedimentology, Arab formation (Upper Jurassic), offshore Abu Dhabi", GeoArabia, 1(1), pp 6–27.

Barth, H.J. & B?er, B., 2002. Sabkha Ecosystems. Volume I: The Arabian Peninsula and Adjacent Countries. Kluwer Academic Publishers.P. 354. ISBN 1-4020-0504-0.

Besler, H., 1982. "The north-eastern Rub al-Khali within the borders of the United Arab Emirates", Zeitschrift für Geomorphologie, N.F. 26(4), pp 495–504.

Beydoun, Z. R., 1991. "Arabian Plate Hydrocarbon Geology and Potential – a plate tectonic approach", AAPG Studies in Geology, 33, pp 1–77.

Bordenave, M.L., 2008. "The Origin of the Permo-Triassic Gas Accumulations in the Iranian Zagros Fold Belt and Contiguous Offshore Areas: a Review of the Palaeozoic Petroleum System", Journal of Petroleum Geology 31(1), pp 3-42.

Blum, W. E. H. 1997. Basic Concepts: Degradation, resilience, and rehabilitation. In: Methods for Assessment of Soil Degradation, eds. R. Lal, W. E. H. Blum, C. Valentin and B. A. Stewart, 1-16. Advances in Soil Science series. New York: CRC Press.

Bohn, L. H., B. L. Mc Neal and G. O'Connor. 1985. Cation retention. In Soil Chemistry Edited by Bohn et al., (1985) Second Edition, John Wiley and Sons, New York. P. 153-183.

Boulton, G.S., 1993. 'Ice Ages and Climatic Change' in P. McL. D. Duff (Editor), Holmes' Principles of Physical Geology (4th edition) London, Chapman & Hall, pp 439–69.

Bridges, E. M. 1997. World Soils. 3rd ed. Cambridge: Cambridge University Press.

Bristow, C.S.. 1999. 'Aeolian and sabkha sediments of the Miocene Shuweihat Formation, Emirate of Abu Dhabi' in: P.J. Whybrow and A. Hill (Editors.), Fossil Vertrbrates of Arabia. Yale University Press p. 50-60.

Bright, D.J. & Silva, Eric, 1998. Hydrogeology of the surficial aquifer system in northeastern Abu Dhabi, United Arab Emirates: U.S. Geological Survey Administrative Report, 2 sheets, prepared for the National Drilling Company, Abu Dhabi.

Brook, M, Houqani, H & Al Mugrin, A. (2006) The Current Status and Future Requirements of Water Resources Management in the Arabian Peninsula. - United Nations University Bahrain / UNESCO Doha (in press).

Brook, M.C., 1994. Preliminary Assessment of the Fars Aquifer in the Dhahirah Region of Oman. Ministry of Water Resources Technical Report.

Brook, M.C., 2001. History of the Al Masarrat Aquifer Water Supply Scheme, Sultanate of Oman (Proc. Geology of Oman Conference, Oman 2001).

Brook, M.C., 2006. The current status of Aflaj in the Al Ain Area, U.A.E.

Brown, G., Peacock, J., Loughland, R. & Alhadrami, G.A. (2006): Coastal and terrestrial ecosystem management requirements in the Arabian Peninsula. - United Nations University Bahrain / UNESCO Doha (in press).

Dincer, T., Al Mugrin, A., Zimmerman, U., 1974. Study of infiltration and recharge through the sand dunes in arid zones with special reference to stable isotopes and thermonuclear tritium: Journal of Hydrology, v. 2, p 79-109.

Ditchfield, P.W., 1999. Diagenesis of the Bunaynah, Shuwaihat and Upper Dam Formation Sediments Exposed in the Western Region, Emirate of Abu Dhabi, United Arab Emirates' in P.J. Whybrow and A. Hill (Editors.), Fossil Vertebrates of Arabia. Yale University Press p.61-74.

EAD, 2005. Chances for Big Quake Here Slim. An article written by Kevin Dean for Gulf News, 24 December 2005. http://www.ead.ae/en/?T=4&ID=494

EAD (Environment Agency - Abu Dhabi). 2005. Terrestrial Environment of United Arab Emirates. Published by the Environment Agency - Abu Dhabi.

EAD-ICBA. 2006. Soil Survey for the Emirate of Abu Dhabi - Action Plan. Terms of Reference and Scope of Work (Project Proposal) jointly prepared by ICBA and EAD.

El-Bershamghy, A. and S. Al-Tamimi. 2003. Feasibility study on the "Use of saline water for agricultural production in Al-Ain Region. Unpublished Report of Ministry of Agriculture and Fisheries Central Laboratories Al-Ain.

El-Keblawy, A. A. 2003. Effects of protection from grazing on species diversity, abundance and productivity in two regions of Abu Dhabi, United Arab Emirates. In Desertification in the Third Millennium. Edited by A. S. Alsharhan, W. W. Wood, A. S. Goudie, A Flower and E. M. Abdellatif. Swets & Zeitlinger Publishers, Lisse, The Netherlands, p. 217-226.

Elschami, F., 1990. The hydro-geochemistry of the spring at Ain bu Sukhanah, UAE. Arabian Journal for Science and Engineering, Volume 8 (1), 33-49.

ERWDA. 2000. Abu Dhabi Coastline Oil Spill Protection Priorities. Published by the Environmental Research and Wildlife Development Agency, Abu Dhabi, United Arab Emirates.

ERWDA, 2002. ERWDA Water Resources Statistics Bulletin. Water Resources Department, Environmental Research and Wildlife Development Agency, P. O. Box 45553, Abu Dhabi, UAE.

ERWDA, 2003. Water Resources Statistics bulletin for Abu Dhabi Emirate 2002.

ERWDA, 2004. Assessment of the Water Situation in Abu Dhabi Emirate.

ERWDA, 2004. Water Resources Statistics bulletin for Abu Dhabi Emirate 2003.

Evans, G. & Kirkham, A., 2002. The Abu Dhabi Sabkha in Sabkha Ecosystems. Volume I: The Arabian Peninsula and Adjacent Countries. Kluwer Academic Publishers.P. 354 ISBN 1-4020-0504-0.

Evans, G., C.G.St.C. Kendall and R. Skipwith, 1964a. "Origin of the Coastal Flats, the Sabkha, of the Trucial Coast, Persian Gulf", Nature, v.202, pp 759-761.

Evans, G., D.J.J Kinsman and D.J. Shearman, 1964b. 'A Reconnaissance Survey of Recent Carbonate Sedimentation Along the Trucial Coast, Persian Gulf', in L.M.J.U. van Straaten (Editor), Deltaic and Shallow-Marine Deposits. Elsevier, Amsterdam, pp 129-135.

Evans, G and A. Kirkham, 2002. 'The Abu Dhabi Sabkha', in Barth and Boer (Editors) Sabkha Ecosystems, Pt. 1. Distribution of Sabkhat within the Arabian Peninsula and the Adjacent Countries. Kluwer Academic Publishers, The Netherlands, pp 7-20.

Evans G., A. Kirkham and R.A. Carter, 2002. "Quaternary Development of the United Arab Emirates Coast: New Evidence from Marawah Island, Abu Dhabi", GeoArabia, v.7, no. 3, pp 441-458.

Faloci, M.L. & Notarnicola, V., 1993. Egyptian Sinai Peninsula - Aquifer recharge is possible with an annual rainfall of only 100mm: Journal of Environmental Hydrology, Vol 1, No. 4, p.17-25.

FAO. 1976. A framework for land evaluation. FAO Soils Bulletin No.32. Rome: Food and Agriculture Organization.

FAO. 1995. Planning for sustained use of land resources: Towards a New Approach, Rome: FAO.

FAO-UNEP-UNESCO. 1979. A provisional methodology for soil degradation. 84pp. Rome: FAO.

FEA-UAE. 2002. Summary on the Second UAE National Report to the UNCCD. April 2002, p.7.

FEA-UAE. 2003. Strategies and national action plan to combat desertification in the United Arab Emirates. Arabic Version.

Foth, H. D. 1984. Fundamentals of Soil Science. 7th ed. New York: John Wiley and Sons.

Fitterman, D.V., Menges, C.M., Al Kamali, A.M., & Jama, F.E., 1991. Electromagnetic mapping of buried paleochannels in eastern Abu Dhabi Emirate, U.A.E.: Geoexploration, v.27, p.111-133, Elsevier Science Publishers B.V., Amsterdam.

Friend, P.F., 1999. 'Rivers of the Lower Buynaynah Formation, Emirate of Abu Dhabi, United Arab Emirates', in: P.J Whybrow & A. Hill (Editors) Fossil Vertebrates of Arabia. Yale University Press, pp 39-49.

Gray, L. C. 1999. Is land being degraded? A multi-scale investigation of landscape change in southwestern Burkina Faso. Land Degradation and Development 10: 329-343.

Glennie, K.W. and B.D. Evamy, 1968. "Dikaka: Plants and Plant-root Structures Associated with Aeolian Sand" Palaeogeography, Palaeoclimatol., Palaeoecol., 4, pp 77–87.

Glennie, K. W., 1970. "Desert Sedimentary Environments", Developments in Sedimentology 14, Amsterdam, Elsevier.

Glennie, K. W., 1995a. (2nd edition, 2005a). The Geology of the Oman Mountains: an Outline of Their Origin, Beaconsfield, Scientific Press.

Glennie, K.W., 1995b. The Geology of Abu Dhabi, in: Osborne, P.E. (Editor) Desert Ecology of Abu Dhabi. Pisces Publications, Newbury. pp 16-35.

Glennie, K.W., 2000. 'Cretaceous Tectonic Evolution of Arabia's Eastern Plate Margin: A Tale of Two Oceans', in: A.S. Alsharhan & R.W. Scott (Editors) Middle East Models of Jurassic/Cretaceous Carbonate Systems. SEPM Special Publication No. 69: pp 9-20.

Glennie, K.W., 2005b. The Desert of Southeast Arabia. Gulf Petrolink, Bahrain.

Glennie, K.W., M.W. Hughes Clarke, M.G. Boeuf, W.F.H. Pilaar and B.M. Reinhardt, 1990. 'Inter-relationship of Makran – Oman Mountains Belts of Convergence', in A.H.F. Robertson, M.P. Searle, and A.C. Ries (Editors) The Geology and Tectonics of the Oman Region. Geological Society Special Publication No. 49: pp 773-786.

Goodall, T. M., 1995. The Geology and Geomorphology of the Sabkhat Matti Region (United Arab Emirates): a Modern Analogue for Ancient Desert Sediments from North-West Europe, Ph.D. thesis, University of Aberdeen.

Gradstein, F.M., J.G. Ogg, & A.G. Smith, 2004. International Stratigraphic Chart. Cambridge University Press.

Gulf News. (2003). Sands of time-Heritage. In Friday Magazine August 1-7, 2003. Published in United Arab Emirates, p.12-15.

GTZ/Dornier Consult/ADNOC, 2005a. Status Report Phases IXa, IXb and IXc for Groundwater Assessment Project Abu Dhabi.

GTZ/Dornier Consult/ADNOC, 2005b. Combined Artificial Recharge and Utilization of the Groundwater Resource in the Greater Liwa Area. Pilot Project Final Technical Report.

Hadley, D.G., 1995. Surficial geology Al Ain area, Emirate of Abu Dhabi, United Arab Emirates: U.S. Geological Survey

Hailwood, E.A & P.J. Whybrow, 1999. 'Palaeomagnetic Correlation and Dating of the Baynunah and Shuwaihat Formations, Emirate of Abu Dhabi, United Arab Emirates', in P.J Whybrow & A Hill (Editors) Fossil Vertebrates of Arabia. Yale University Press, pp 75-87.

Hastenrath, S., 1995. Climate Dynamic of the Tropics. Kluwer Academic Publishers.

Houghton, P. D. and P. E. V. Charman, 1986. Glossary of Terms Used in Soil Conservation, Sydney, Australia: Soil Conservation Service of New South Wales.

Johnson, D, and L. Lewis, 1995. Land Degradation: Creation and Destruction. Blackwell: Oxford.

Johnson, D.L., S. H. Ambrose, T. J. Bassett, M. L. Bowmen, J. S. Isaacson, D. E. Crummey, D. N. Johnson, P. Lamb, A. M. Saul and A.E. Winter-Nelson, 1997. "Meanings of Environmental Terms". Journal of Environmental Quality 26, pp 81-589.

Kirkham, A., 1998. "Pleistocene Carbonate Seif Dunes and their Role in the Development of Complex Past and Present Coastlines of the UAE", GeoArabia, v.3, no. 1, pp 19-32.

Khalifa, M.A., 1997. 'Hydrogeology of the Geothermal Fractured-Rock Well Field at Jabal Hafit, Abu Dhabi Emirate'. Water Sciences & Technology Association, Proceedings of the Third Gulf Water Conference, March 8-13, Muscat, Oman, v.1, Water Resources Planning and Management, pp 125-140.

Khalifa, M.A., 2004. Hydrogeologic Setting and Characterization of the Aquifer System in Al Wigan Area, South Al Ain, UAE. UAE University, Deanship of Graduate Studies, Master of Water Resources.

Kirkham, A, 2004. The Geology of Jebel Hafit in S. Aspinall and P. Hellyer (Editors), Jebel Hafit: A Natural History.

Le Houérou, H.N., 2000. "Restoration and Rehabilitation of Arid and Semiarid Mediterranean Ecosystems in North Africa and West Africa: A Review", Arid Soil Research and Rehabilitation 14, pp 3-14.

Lindskog, A., and A. Tengberg, 1994. Drylands, Sustainable Use of Rangelands into the Twenty-First Century. Technical report. International Fund for Agricultural Development (IFAD) Rome.

McClusky, S., S. Balassanian, C. Barka and 25 others, 2000. "Global Positioning System constraints on plate kinematics and dynamics in the eastern Mediterranean and Caucasus", Journal of Geophysical Research, 105(B3): pp 5695-5720.

McClusky,S., R. Reilinger, S. Mahmoud, D. Ben Sari and A. Tealeb, 2003. "GPS Constraints on Africa (Nubia) and Arabian Plate Motions", Geophysical Journal International 155 (1), pp 126-138.

Membury, A. 1982, "A Documented Case of Strong Shamal Wind Shear", Weather 37, pp 19-23.

Middleton, N. and D. Thomas, 1997. World Atlas of Desertification, UNEP/Arnold.

Moreland, J.A., 1998. Activities, findings, and conclusions of the Ground-Water Research Project for the Emirate of Abu Dhabi 1988-1997: U.S. Geological Survey Administrative Report, prepared for the National Drilling Company, Abu Dhabi.

MWR, 1998. Ministry of Water Resources, Sultanate of Oman, Water Attachment position paper.

National Drilling Company (NDC) - United States Geological Survey, 1993. Groundwater Research Project. Groundwater Resources of Al Ain Area, Abu Dhabi Emirate. US Geological Survey administrative report prepared in cooperation with NDC, October 1993.Phase II).

Noweir, M.A., 2000. "Back-thrust Origin of the Hafit Structure, Northern Oman Mountain Front, United Arab Emirates", GeoArabia 5(2): pp 215-228.

Paton, T. R (Editor), 1983. The Formation of Soil Material. George Allen & Unwin (Publishers) Ltd. London, UK.

Peacock, J.M., Ferguson, M.E., Alhadrami, G.A., McCann, I.R., Al Hajoj, A., Saleh, A. & Karnik, R., 2003. "Conservation Through Utilization: a Case Study of the Indigenous Forage Grasses of the Arabian Peninsula", Journal of Arid Environments 54: 15-28.

Perrone, T.J., 1979. Winter Shamal in the Persian Gulf. NEPRF Technical Report 1979.

Petit-Maire, N., 1994. 'Natural Variability of the Asian, Indian and African Monsoons Over the Last 130 ka.', in M. Debois, and Desalmand (Editors) Global Precipitation and Climate Change, NATO ASI Series vol 126, Berlin, Springer Verlag. pp 3-26.

Resources en Eaux Minerales (REM), 2004. Qualitative Valuation of Mineral Water Resources in the Area of Al Ain, UAE.

Ramezani, J., 2004. Earthquakes in Iran: A Geological Perspective. Payvand's Iran News. January 2004. http://www.payvand.com/news/04/jan/1109.html

Richards, L. A (Editor), 1954. 'Diagnosis and Improvement of Saline and Alkali Soils', United States Salinity Laboratory Staff, USDA Handbook No.60, pp 158.

Rizk, Z.S., 1998. "Aflaj of the United Arab Emirates: Geological Setting and Hydrogeological Characteristics", Arabian Journal for Science and Engineering, Volume 23, Number 1C, pp 3-25.

Rizk, Z.S, Alsharhan, 2003. 'Hydrogeology, Groundwater Chemistry and Isotope Hydrology of the Quaternary Liwa Aquifer in the Western Region of the United Arab Emirates', in Proceedings of Sixth Gulf Water Conference, Riyadh, Saudi Arabia.

Rizk, Z.S, H,K. Garamoon and H.A. El Etr, 1998. "Morphometry, Surface Runoff and Flood Potential of Major Drainage Basins of Al Ain Area, United Arab Emirates", Egypt Journal of Remote Sensing & Space Sciences. Vol 1, pp 391-412.

Sanford W.E. and W.W. Wood, 2001. "Hydrology of the Coastal 'Sabkha' of Abu Dhabi, United Arab Emirates". Hydrogeological Journal 9, pp 358 - 366.

Sanlaville, P., 1992. "Changements climatiques dans la péninsule Arabique durant le Pléistocène supérieur et l'Holocène", Paléorient, 18, pp 5–26.

Sarnthein, M. 1972. "Sediments and history of the postglacial transgression of the Persian Gulf and northwest Gulf of Oman", Marine Geology, v.12, pp 245-266.

Schuster, J.L., 1998. 'Restoring structure and function of degraded rangeland ecosystems' in S.A.A. Omar, R. Misak, D. Al-Ajmi and N. Al-Awadhi (Editors.) Sustainable Development in Arid Zones. Volume 2. Management and Improvement of Desert Ecosystems. Balkema, Rotterdam. pp. 373-382.

Seber, D., D. Steer, E. Sandvol, C. Sandvol, C. Brindisi and M. Barazangi, 2000. "Design and development of Information Systems for the Geosciences: an Application to the Middle East", GeoArabia 5(2): pp 269-296.

Shackleton, N. J., 1987. "Oxygen Isotopes, Ice Volume and Sea Level", Quaternary Science Review, 6, pp 183–190.

Sharland, P.R., R. Archer, D.M. Casey, R.B. Davies, S.H. Hall, A.P. Heward, A.D. Horbury and M.D. Simmons, 2001. "Arabian Plate Sequence Stratigraphy", GeoArabia Special Publication 2.

Shahid, S. A., 2004. National Project for the Assessment of Affected Agricultural Lands for Sustainable Use. Proposal submitted by Ministry of Agriculture and Fisheries of the UAE to the National Committee on Environmental Strategies, UAE.

Shahid, S. A. and M. A. Abdelfattah, 2005. Soils of Abu Dhabi Emirate. Book Chapter in the Terrestrial Environment of United Arab Emirates. To be Published by the Environment Agency - Abu Dhabi.

Shahid, S. A., S. A. S. Omar, and S. Al-Ghawas, 1999. "Indicators of Desertification in Kuwait and their Possible Management", Desertification Control Bulletin, No. 34:61-66.

Shahid, S. A., and S. A. S. Omar, 2001. 'Causes and Impacts of Land Degradation in the Arid Environment of Kuwait' in E. M. Bridges, I. D. Hanman, L. R. Oldeman, F. W. T. Penning de Vries, S. J. Scherr and S. Sombatpanit., Responses to Land Degradation, pp 76-77.

Shahid, S. A., S. A. S. Omar, and S. Al-Ghawas, 2001. 'Evaluation of aeolian soil movement mechanisms as a function of particle size analysis'. KISR Annual Report 5851, pp 37-40.

Shahid, S. A., S. A. S. Omar, R. Misak, and H. Abo-Rezq, 2003. 'Land resources stresses and degradation in the Arid Environment of Kuwait', in A. S. Alsharhan, W. W. Wood, A. S. Goudie, A. Fowler and E. M. Abdellatif (Editors) Desertification in the Third Millenium, Swets & Zeitlinger, Lisse, The Netherlands, pp 351-360.

Shahid, S. A., M. A. Abdelfattah, K. R. Arshad, M. Muhairbi, Y. R. A. Othman, A. Al Haji, M. Al Radha Al Mansouri, S. Ahmad, A. Siddiqui, A. L. Sekaly and B. S. Al Qubaisi, 2004. Soil Survey for the Coastline of Abu Dhabi Emirate. 2 Volumes (Volume 1: Reconnaissance Survey and Volume 2: Soil Maps). Unpublished Report, the Environmental Research and Wildlife Development Agency (ERWDA), Abu Dhabi, UAE.

Shinn, E. A., 1983. 'Tidal Flat Environment' in P.A. Scholle, D.G. Bebout, and C.H. Moore (Editors.) Carbonate Depositional Environments, American Association Petroleum Geologists Memoir 33, pp 171–210.

Smith, A. G., A.M. Hurley, and J.C. Briden, 1981. Phanerozoic Palaeocontinental World Maps. Cambridge University Press.

Soil Conservation Service. 1971. Guide for interpreting engineering uses of soils. USDA, Soil Conservation Service, 87p.

Soil Science Society of America, 1987. Glossary of Soil Science Terms. Madison, Wisconsin: Soil Science Society of America.

Sutherland, R. A., Y. Wan, A. D. Ziegler and C.T. Lee. 1996. "Splash and wash dynamics: an experimental investigation using an Oxisol", Geoderma 69:85-103.

Terratest Ltd, 1974. Abu Dhabi Mineral Survey. Stage II Detailed Investigation of Promising Areas Progress Report. Phase I Ain bu Sukhanah.

Terratest Ltd, 1975. Abu Dhabi Mineral Survey. Stage II Detailed Investigation of Promising Areas Progress Report. Phase II Ain bu Sukhanah.

Teller, J.T., K.W. Glennie, N. Lancaster, and A.K. Singhvi, 2000. "Calcareous Dunes of the United Arab Emirates and Noah's Flood: the Postglacial Reflooding of the Persian (Arabian) Gulf", Quarternary International, pp 297–308.

United Arab Emirates University, 1993. The National Atlas of the United Arab Emirates, Al Ain.

US Geological Survey / NDC Administrative Report 1994. Groundwater Resources of the Liwa Crescent Area, Abu Dhabi Emirate.

US Geological Survey (USGS), 1996. Groundwater resources of Abu Dhabi Emirate.

UAEU. 1993. The National Atlas of the United Arab Emirates. UAE University & GEO Project, Al-Ain, UAE.

UN. 1992. Report on UNCED, Malaysia Draft Resolution. UN General Assembly 47th session, second committee agenda item 79, 20 November.

UN, 1994. Convention of Desertification. Information Programme on Sustainable Development. New York: UN.

USDA. 1975. Soil taxonomy. A Basic System of Soil Classification for Making and Interpreting Soil Surveys. Soil Conservation Service. USDA Agriculture Handbook No.436. U.S. Government Printing Office: Washington DC.

USDA. 1993. Soil Survey Manual. Agricultural Handbook 18, U. S. Government Printing Office: Washington DC

USDA-NRCS. (1999). Soil Taxonomy. A Basic system of Soil Classification for Making and interpreting Soil Surveys.

USDA Agriculture Handbook No.436. U.S. Government Printing Office: Washington DC.

USDA-NRCS. 2004. Soil Survey Investigations Report 42, Soil Survey Laboratory Methods Manual, (Version 4 November 2004) U.S. Government Printing Office: Washington DC.

Verstraete, M.M. 1986. "Defining Desertification: a Review". - Climatic Change 9, pp 5-18.

Watt, G.A., 1977. "Severe Cyclone in The Arabian Sea". Weather, 33, pp 95-97.

Whybrow, P. J. and A. Hill, (Editors), 1999. Fossil Vertebrates of Arabia, Yale University Press.

Wilson, J.L. and C. Jordan, 1983. 'Middle Shelf', in P.A. Scholle, D.G. Bebout and C. Moore (Editors) Carbonate Depositional Environments, American Association of Petroleum Geologists, Memoir 33, pp 297-343.

Wood, W.W. and J.L. Imes, 1995. "How wet is wet? Precipitation constraints on late Quaternary climate in the southern Arabian Peninsula", Journal of Hydrology, v.164, pp 263-268.

Wood, W.W. and W.E. Sanford, 2002. 'Hydrogeology and solute chemistry of the coastal sabkha aquifer in the Emirate of Abu Dhabi' in H.J. Barth and B. Boer, (Editors) Sabkha Ecosystems, Vol 1- The 'Sabkha' of the Arabian Peninsula and Adjacent Countries. Kluwer Academic Publishers, Dordrecht.

Woodward, D.G. and A.H. Al Jeelani, 1993. "Application of reprocessed seismic sections from petroleum exploration surveys for groundwater studies, Eastern Abu Dhabi, UAE". Proceedings of MEOS 8th Middle East Oil Show & Conference, Society of Petroleum Engineers, Bahrain, Vol 1, pp 257-266.

Woodward, D.G., 1990. "Use of uphole velocity surveys for mapping hydrogeologic boundaries, Abu Dhabi, United Arab Emirates" [abs.]: Abstracts for the AGU Fall Meeting, Supplement to Eos, Transactions, American Geophysical Union, v.71, no.43.

Woodward, D.G. & C.M. Menges, 1991. Delineating aquifers in buried paleochannels using uphole velocity profiles from petroleum seismic surveys, northeastern Abu Dhabi, United Arab Emirates [abs.]: Geological Society of America, Abstracts with Programmes, 1991 Annual Meeting, v.23, no.5, p.A123.

Ziegler, M.A., 2001. "Late Permian to Holocene Paleofacies Evolution of the Arabian Plate and its Hydrocarbon Occurrences", GeoArabia, v.6, no. 3, pp 445-503.

هيئة البيئة - أبوظبي
Environment Agency- ABU DHABI

Environment Agency Abu Dhabi
PO Box 45553, Abu Dhabi, UAE

Tel: +971 (2) 445 4777
Fax: +971 (2) 446 3339
Website: www.ead.ae
customerservice@ead.ae

مبادرة أبوظبي العالمية للبيانات البيئية
Abu Dhabi Global
Environmental Data Initiative