Water Resources in Oman

Ministry of Regional Municipalities, & Water Resources, Sultanate of Oman
“Of all the gifts with which God has blessed us, water is the greatest. It must be cherished and husbanded. Every effort must continue to be made to develop this resource. If extravagance is forbidden by Islam, it is even more applicable to water. Indeed, Islam emphasises in its teachings that it is our duty to conserve it. We cannot stress too strongly the need to observe the conservation measures laid down by the Government in this respect. The use of this vital resource throughout the world can have a great impact on future development strategies, and indeed could become a decisive factor in political tension and thus world security.”

from the speech of HIS MAJESTY SULTAN QABOOS BIN SAID SULTAN OF OMAN On The 21st Anniversary of Oman’s National Day 18 November 1991
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Introduction

Water is the spring of life and a basic resource required for human existence. It is a vital source for various developmental activities. Underlining the importance of this vital resource right from the time of Creation, God said: “we made from water every living thing.”

Both history and current state of affairs confirm that the survival of people and development are closely connected with this natural renewable resource. They also confirm that water is the fundamental source of the welfare and prosperity of human beings and the foremost support for the achievement of development goals.

Water receives great international attention and is considered one of the most pressing problems that all countries have to deal with. The current situation manifests the magnitude of the problem particularly in arid and semi-arid regions and in many other areas which suffer long periods of drought and water stress.

It is clear that increasing water consumption in various sectors, insufficiency of water resources, lack of balance between supply and demand, depletion of water resources and absence of prompt, integrated water policies, have led to this critical situation. Several studies and indicators confirm that the world, in the next years, will face a lot of challenges and more complicated situations relating to water.

The Middle East in general and the Gulf Region in particular are considered amongst the areas that suffer from scarcity of water resources especially the countries that lie in the arid and semi-arid zones like the Sultanate. This situation has prompted the concerned countries to improve the standard of water management and conservation, to look for new water resources and to implement intensive awareness programs in order to emphasize the importance of conservation of this important resource.

On account of the Sultanate’s deep-rooted history, attachment of its people to their rich cultural heritage and their appreciation of water in various aspects of living, the Sultanate has dealt with the challenges imposed by water situation through the adoption of an approach which seeks to harmonize the requirements of development and the available water resources. This is carried out within the framework of the main objectives of sustainable development which aim at conservation and rational exploitation of natural resources for the benefit of present and future generations.

The important achievements in the field of water during the years of the Blessed Renaissance and the ambitious plans and policies set to face the current and future water challenges may require a historical pause to depict all of these achievements together with the water environment in the Sultanate.

The Water Atlas of Oman is a comprehensive reference which can be relied on for clear understanding of the Sultanate’s water environment, together with milestones attained over the years in different aspects of water resources development and management.
CHAPTER 1

Geographical & Hydrological Features
The Earth’s Water Budget

Storage and Fluxes

The oceans contain 97.5% of the earth’s water, land 2.4%, and the atmosphere holds less than .001%, which may seem surprising because water plays such an important role in the status of weather. The annual precipitation for the earth is more than 30 times the atmosphere’s total capacity to hold water. This fact indicates the rapid recycling of water that must occur between the earth’s surface and the atmosphere.

To visualize the quantity of water contained in these storages, imagine that the entire amount of the earth’s annual precipitation fell upon the state Texas. If this was to occur, every square inch of that state would be under 1,841 feet, or 0.3 miles of water! Also, there is enough water in the oceans to fill a five-mile deep container having a base of 7,600 miles on each side.

Water appears to be one of the most abundant molecules in the Universe. It dominates the environment of the Earth and is a main constituent of numerous planets, moons and comets. On a far greater scale it possibly contributes to the so called “missing mass” of the Universe and may initiate the birth of stars inside the giant molecular clouds.

The Earth, a “water planet”, contains some 0.07% water by mass or 0.4% by volume. The table opposite shows the summary of water resources of the Earth. Large quantities of water, estimated to be the size of two World Oceans, are also contained in the crust and the mantle of the planet. The origin of water on Earth is by no means certain and numerous theories have been proposed. They fall into three basic groups: condensation of the primary atmosphere, outgassing of the interior, and extraterrestrial fallout. The condensation theory, once universally sanctioned, has fallen into disfavour as current models of the primordial nebula and evolving Earth assume that the primary atmosphere consisted mainly of hydrogen, helium, ammonia and methane. This atmosphere would have been blown away by the intense solar wind during the so called T-Tauri stage of the proto-Sun.

Present composition shows that our atmosphere is secondary, and suggests both a geological and biological origin. Similarly, the hydrosphere is believed to be outgassed and condensed from the interior of our planet. However, this theory needs further investigation, as in fact there should be some 20 to 40 times more water on Earth, depending on which meteorite material would have been its main component. In this respect we should not ask: “Where does the water come from?” but rather “Where is the missing water?”

The questions of outgassing and of tectonic movement of water are of importance for hydrologists in refining global water balance calculations. It is also of prime interest for planetologists, as the volatile contents and especially the water content of planetary mantles and the rate of volatile release are important in controlling the amount of melting, fractional crystallisation trends and the viscosity of planetary interiors which in turn affect the rate of convection and heat loss which are important in terms of evolutionary state. Some 0.1km³/year of water is thought to be presently outgassed by volcanic eruptions which predominantly consist of water vapour: most of this water is, however, probably recirculated on a geological time scale.
It is now well established that our planet both in geological and present times is exposed to various cosmic collisions. An extraterrestrial origin of the Earth’s water is, therefore, possible, and comets are commonly targeted as our potential water supplier. Estimates of the quantity of water acquired in this way in the early stages of the evolution of our planet range from 4 to 40%. How long will the water on Earth last for. At present there are no grounds to speak about any significant positive or negative water exchange between the Earth’s atmosphere and space. The present atmosphere is marginally stable with respect to water and, with the present escape rate, it will take some 7 billion years to lose the World Ocean. This corresponds to a water escape rate of $7m^3/s$. Because the Sun is currently increasing its luminosity by about 1% every 100 million years, the critical solar flux for water loss could be reached within about one billion years, much shorter than the five billion years during which the Sun is expected to remain on the main sequence.

### Table: Estimate of World Water & Water Statistics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Volume $Km^3 \times 10^6$</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceans &amp; Seas</td>
<td>1370</td>
<td>93.77</td>
</tr>
<tr>
<td>Rivers, Lakes &amp; Swamps</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Groundwater</td>
<td>60</td>
<td>4</td>
</tr>
<tr>
<td>Icecaps and Glaciers</td>
<td>30</td>
<td>2</td>
</tr>
<tr>
<td>Atmospheric Water</td>
<td>0.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Biosphere Water</td>
<td>0.01</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>

**FACT FILE**

- More than half of the world population is concentrated in the cities and on only 4% or less of the total land of the Earth.
- 1.1 billion (25%) of the world population has a shortage of safe drinking water.
- There are 261 international rivers in the world, which means rivers cross borders and their water resources are shared.
- 70% of the world water is used for agriculture. And it accounts for a maximum of 90% of the water supply in many countries.
- Some 600–700 billion $m^3$ of water, almost 20% of the quantity of water intake around the world, is annually.
- There is only a limited volume of fresh water on Earth, but people on every continent are pumping enormous quantities of groundwater from the main aquifers. 1.5–2 billion people around the world are dependent on groundwater supplies.
- 80% of the diseases impoverished developing countries are due to dirty water.
- In this century, water will become a flash of conflict.
- The term groundwater is refers to the sub-surface water that occurs beneath the water table in soils and geological formations that are fully saturated.
Geographical Parameters

It is Oman’s destiny to be both at the crossroads, and in the centre of, world affairs. Few areas on Earth have a location and history so vivid and colourful. Geologically, Oman is at a tectonic intersection: the spectacular mountains and coastlines of northern Oman result from the collision and interaction of four crustal plates. The climate is also shaped by competing atmospheric influences from many remote lands and seas. And as a crossroad for civilisations of three continents, Oman has both experienced and influenced the ways of many nations.

The Sultanate of Oman is picturesquely located in the south-east of the Arabian Peninsula. The Musandam Peninsula consists of limestone mountains rising to 2100 meters, deeply dissected by wadis. Occasional heavy storms here produce very rapid runoff, of which a large portion is lost to the sea. The northern part of Oman is mostly mountainous. The Hajar Al Gharbi range runs parallel to the coast and separates the fertile Al Batina region from the Interior: the highest peak of this magnificent mountainous range is Jabal Shams whose altitude reaches more than 3000m above sea level. The Al Batinah coastal plain is the key region for agriculture, industry and settlement, and can be divided into two geomorphological units.

The northern front of Al Jabal Al Akhdar is drained by a series of deeply incised wadis transforming coastwards into gravel terraces, and finally the coastal plain, which consists of alluvial deposits, scattered sabkhas, strips of fertile soils and coastal sand dunes.

South and west of Al Jabal Al Gharbi there is a vast region of coalescing gravel plains. In the western part they slope towards Umm as Samim sabkha, a large topographic depression and ground water discharge area at the border of Oman, Saudi Arabia and the United Arab Emirates.
The Central Plateau is a flat table of carbonate sediments with occasional scattered sand dunes. The extensive sand deserts of Ar Rub Al Khali and Ash’ Sharqiya, and widespread gravel plain covering large areas of the country are extremely arid.

A second mountain belt is located in the southern part of the country. The Dhofar Mountains are up to 1800m high, and near Salalah they frame a small but important coastal plain with a unique climate.
The Hydrologic Cycle

The Sun puts our whole living system in motion. The hydrological cycle is the most important process on our planet; it distributes the water of life to all corners of the globe. The search for an explanation of springs, streamflow, and the occurrence and movement of groundwater persisted for millenia. Some hints on the ceaseless circulation of water may be found in Ecclesiastes (c.350BC) and Lu’Shi Chun Qiu (239BC) and the real wealth of consideration on water issues is contained in the Holy Quran.

Scientific approach to the water balance is attributed to Mariotte who, in 1684, conclusively proved that rainfall is the source of water discharged by springs and rivers. From that time the concept of the hydrological cycle evolved but it was a further 200 years before the concept was fully assimilated by the scientific community.

However, it may be argued that this wisdom was acquired by the Omanis much earlier, since almost simultaneous occurrence of rainfall and runoff in the form of wadi flow can be readily observed during flash floods which originate in the mountains of arid lands. It is one of the most important processes on Earth. It transports water around the globe, maintains the heat balance of the planet, shapes the geology and surface relief, cleans our water supplies and is essential for maintaining life. The cycle is continuous and involves evaporation, condensation of water in the atmosphere giving rise to rainfall, runoff, surface water flow to the sea and recharge to the groundwater reservoirs.
Geologically, Oman is a land of exceptional variety and beauty. It is an open book of the finest geological examples because most of its past is clearly visible on the surface. There are many excellent books on the geology of Oman: it is important to briefly introduce this subject through the eyes of a hydrologist, to develop an understanding of how hydrological processes shape the land.

Geology is the study of Earth through its rocks. Rock, in a physical sense, is a supercooled liquid, and geologically, mountains are as transient as clouds. They emerge and disintegrate quite rapidly - in geological terms - and while their existence is greatly affected by water, they also affect hydrological and hydraulic properties of the land at any given time. In a dynamic sense, geology is the scene of the balancing of three phenomena: crustal movements, erosion and deposition. Crustal movements, in which plate tectonics are an important player, fold and mix the rock, exchanging some material with the interior of the Earth. Erosion and deposition contribute to the production of new rock blends, and flatten the relief of the globe. It is estimated that, in the absence of crustal movements, rainfall would obliterate mountains in about ten million years: land would disappear under the world ocean, some three kilometres deep.

Some 400 million years ago they were submerged beneath a warm and shallow tropical sea. About 80 million years ago, plate movements and interactions caused the massive slab of ocean floor to rise above the coastal shelf: the collision of sea and land crust produced an amazing mixture of rocks which were then buckled and lifted into mountain ranges. Several stages of uplifting were followed by erosional and depositional cycles, with alluvial, terrestrial and raised beach deposits being formed up to the present.

Weathering of mountains by water in the recent past was a final touch to the creation of the spectacular landscapes which we see in Oman today. From a hydrological point of view, geology sets the scene for the land phase of the hydrologi-
The Main Geological Sequences in the Sultanate include:

**PRE-PERMIAN BASEMENT ROCKS**
comprising granites, gneisses, partly metamorphosed siliciclastic and carbonate sediments and metavolcanics.

**THE HAJAR SUPER GROUP**
which is made of carbonate sediments, limestone, dolomites, and marls of mid-Permian to late Cretaceous age.

**THE SUMAINI GROUP**
which is made of locally thrusted sedimentary sequences of Permo-Triassic limestone, dolomites, sandstones and marls.

**THE SAMAIL OPHIOLITE**
covering extensive areas of northern Oman, is the world’s largest intact and best exposed obduction ophiolite, a slice of oceanic lithosphere, 75 to 95 million years old.

**LIMESTONES**
widespread throughout Oman with common development of karst terrain especially during wet periods.

cal cycle. It dictates how much rainfall reaches the sea as surface runoff, how much go via a subsurface (groundwater) route and how much evaporates into the atmosphere. The foundation of this differentiation is established by water which, in time and through a variety of processes, sorts out material from the monoliths of mountain peaks to grains of sand in valleys. This is a purely physical process, which in arid countries like Oman is not obscured by ecological systems, so dominant in temperate regions. A combination of geological setting with present arid climatic conditions gives unique hydrological characteristics to Oman and sets a scene for the life of people on the land.
Climate

The Sultanate is characterised by hot and dry summers and mild winters, except for the Dhofar region in the south of the country, which is affected by monsoon climate from June to September each year. Summer starts in May and ends by October. Usually, a thermal low is established over the region with the core over north-western India, Pakistan and Oman. This thermal low contributes to the dynamics of the south-westerly circulation over the Indian Ocean and the Arabian Sea, such that, once it is established, it generates the south-westerly monsoon. Having travelled a long way over the Indian Ocean, the south-westerly winds are warmer, moist and unstable. During the summer season the average temperatures range between 27-37°C at As Seeb, 17-23°C at Saiq on Al Jabal Al Akhdar, and 24 and 30°C at Salalah.

During this season, the southern region of Oman experiences monsoonal weather. This is because of its location in the fringes of the strong southwesterly monsoon winds which originate far out in the Indian Ocean. More extensive rains are also experienced around the mountains and the nearby area of northern Oman in the form of thunderstorm activity triggered by the moist monsoon current entering this region due to the westward movement of the seasonal trough across Oman.

The winter season extends from November to April. During this season the Arabian Peninsula is dominated by a high pressure ridge extending from Siberia over central Asia. The main air flow associated with this system is not itself rain-bearing. The prevailing condition is generally relatively cool with comfortable dry continental air.

The trajectory of this air flow is however modified by two other factors before reaching Oman. The first is the Zagros mountains in the south of Iran which act as an obstacle to the air flow, and the second is the warm water of the Gulf of Oman. That is why by the time this air reaches Oman, it will already be modified to a warm temperature which is usually prevailing in the northern coastal areas.

Although the predominating weather is dry during the winter, rainfall sometimes occurs in association with migratory low pressure systems from the west. The average temperatures range between 20–28°C at As Seeb, 19–26°C over the interior, and 20–27°C at Salalah. Lower temperatures occur at higher altitudes. Temperatures on Al Jabal Al Akhdar range between 8 and...
140°C, depending upon the elevation above sea level. Skies over the Sultanate are mostly clear: Muscat averages nearly ten hours of sunshine a day. Both to a native resident and a visitor alike, it is clearly visible that the Sun is a dominant force of nature.

Evaporation

Evaporation is a process by which liquid water is transformed into a gaseous state. Annually, about half a million cubic kilometres of water evaporates from the oceans and land surfaces into the atmosphere. The energy necessary to convert this amount of water into vapour consumes more than one-third of the solar radiation absorbed by the whole Earth. Evaporation cools our planet down and helps to transfer huge amounts of energy from the equator to temperate and polar regions.

On a global scale, evaporation equals rainfall. The annual potential amount of evaporation varies from practically zero at the poles to more than 3,000mm in hot deserts. Although globally evaporation is a hugely beneficial process, on a local scale - and especially in arid areas - we see it rather as a loss, since it depletes the available resources of fresh water. The Sultanate of Oman lies in an area that has both the lowest rainfall and highest potential evaporation in the world.

Evaporation depends mainly on temperature, wind speed and moisture deficit in the air. In the Sultanate, with high temperature and low humidity common, conditions for evaporation are very favourable. Potential evaporation is estimated between 3,000mm in the Interior, through 2,100mm on Al Batinah coast, to some 1,700 mm on the Salalah plain. These high potential evaporation rates apply to open water surfaces, which in the Sultanate are few. Actual evaporation is dependent on the available supply of water. Thus, if an area receives 100mm of rain per year, some 95mm of this rain may evaporate, and 5mm may be transferred from the runoff producing zones to runoff absorbing zones.

Direct measurements of evaporation are extremely difficult even at one point, let alone a large area. Therefore, many indirect methods including pan evaporation, meteorological formulas, and recently, remote sensing are used as substitutes for direct measurements. Practically, there is no technology available...
at present for the reduction of evaporation from large free water surfaces. The few available methods: floating plastic covers, thin layers of methyl alcohol over the surface, or sheltering of the reservoir by vegetation, may cause many undesirable side effects like rising temperature of water, pollution and increased biological activity. Furthermore, these methods are usually not effective in high winds, and their maintenance is difficult. Avoiding evaporation by storing water underground is very effective and has led to the development of various schemes that will augment recharge to the groundwater reservoirs.

**Atmospheric Water**

We think little about atmospheric water. However, this is the only component which accompanies us everywhere - the most reliable companion of water in our bodies. The amount of water in the atmosphere is comparatively small in comparison to other sources of water. The atmosphere contains only 0.001% of all water resources of the Earth, however, it can be argued that this small amount has more effect on our planet than all others.

Firstly, atmospheric water is in perpetual motion. Its residence time is only 9 days, which means that it can carry materials and transport energy throughout the globe. Secondly, atmospheric water is the source of all rain. And we should remember that however big our human achievements are, we owe our very existence to two phenomena: the top two inches of soil, and the fact that it rains. Thirdly, atmospheric water distributes the heat from the Sun around the planet. Without the water-induced transport, the Equator would be unbearably hot, and temperate regions unbearably cold. There would be not much room to live on the Earth.

The amount of vapour that will saturate the air increases with a rise in temperature: at 0°C, one cubic metre of air contains a maximum of 11g of water vapour; at 40°C one cubic metre of moist air contains a maximum of 45g of water vapour.

When the atmosphere is saturated with water, the level of discomfort is high because the evaporation of moisture from the body as perspiration, with its attendant cooling effect, is impossible. The weight of water vapour contained in a volume of air is known as the absolute humidity and is expressed in grams of

**Evaporation Conditions in the Sultanate**

In the Sultanate, with high temperature and low humidity common, conditions for evaporation are very favourable. Potential evaporation is estimated between 3,000mm in the Interior, through 2,100mm on Al Batinah coast, to some 1,700mm on the Salalah plain. These high potential evaporation rates apply to open water surfaces, which in the Sultanate are few. Actual evaporation is dependent on the available supply of water. Thus, if an area receives 100mm of rain per year, some 95mm of this rain may evaporate, and 5mm may be transferred from the runoff producing zones to runoff absorbing zones.
water vapour per cubic metre. Relative humidity, given in weather reports, is the ratio between the actual vapour content of the atmosphere and the vapour content of air at the same temperature saturated with water vapour. If the temperature of the atmosphere rises and no change occurs in the vapour content of the atmosphere, the absolute humidity remains the same but the relative humidity is lowered. A fall in temperature increases the relative humidity, producing dew.

Atmospheric humidity, which is the amount of water vapour or moisture in the air, is another leading climatic element, as is precipitation. All forms of precipitation, including drizzle, rain, snow, ice crystals, and hail, are produced as a result of the condensation of atmospheric moisture to form clouds in which some of the particles, by growth and aggregation, attain sufficient size to fall from the clouds and reach the ground.
Classification of Clouds

High clouds are composed of ice particles, found at average levels of 8km or more. The family contains three principal genera. Cirrus clouds are isolated, feathery, and thread-like, often with hooks or tufts, and are arranged in bands. Cirrostratus clouds appear as a fine, whitish veil; they occasionally exhibit a fibrous structure and, when situated between the observer and the Moon, produce halo phenomena. Cirrocumulus clouds form small, white, fleecy balls and wisps, arranged in groups or rows.

Middle clouds are composed of water droplets and range from about 3 to 6km above the Earth. Two principal genera are included in the family. Altostratus clouds appear as a thick, grey or bluish veil, through which the Sun or Moon may be seen only diffusely, as through a frosted glass. Altocumulus clouds have the appearance of dense, fleecy balls or puffs somewhat larger than cirrocumulus. The Sun or Moon shining through altocumulus clouds may produce a corona, or coloured ring, markedly smaller in diameter than a halo.

Low clouds, also composed of water droplets, are generally less than 1.5km high. Three principal forms comprise this group. Stratocumulus clouds consist of large rolls of clouds, soft and grey looking, which frequently cover the entire sky. Because the cloud mass is usually not very thick, blue sky often appears between breaks in the cloud deck. Nimbostratus clouds are thick, dark, and shapeless. They are precipitation clouds from which, as a rule, rain or snow falls. Stratus clouds are sheets of high fog. They appear as flat, white blankets, usually less than 500m above the ground. When they are broken up by warm, rising air, the sky beyond usually appears clear and blue.

Clouds of this type range in height from less than 1.5km to more than 13km above the Earth. Two main forms are included in this group. Cumulus clouds are dome-shaped, woolpack clouds most often seen during the middle and latter part of the day, when solar heating produces the vertical air currents necessary for their formation. These clouds usually have flat bases and rounded, cauliflower-like tops. Cumulonimbus clouds are dark, heavy-looking clouds rising like mountains high into the atmosphere, often showing an anvil-shaped veil of ice clouds, false cirrus, at the top. These thunderclouds are usually accompanied by heavy, abrupt showers. An anomalous, but exceptionally beautiful, group of clouds contains the nacreous, or mother-of-pearl, clouds, which are 20 to 30km high, and the noctilucent clouds, 50 to 55km high. These very thin clouds may be seen only between sunset and sunrise and are visible only in high latitudes. The development of high-altitude aircraft has introduced a species of artificial clouds known as contrails (condensation trails). These are formed from the condensed water vapour ejected as a part of the engine-exhaust gases.
CHAPTER 2

Water Resources
Surface Water

The average annual amount of rainfall run-off or surface water – wadi flow is estimated to be about 1,050 Mm$^3$. During flood flows in wadis, significant quantities of water infiltrate the coarse wadi gravels and replenish the shallow alluvial aquifers. Some of the balance is intercepted by newly-constructed dams; the rest, estimated nationally to be about 119 Mm$^3$/year, is lost to the sea.

Rainfall

Rainfall is the principal source of all freshwater on earth. Average annual rainfall over the surface of the planet is some 1000 mm and is relatively constant on a global scale from year to year because it is dictated by solar radiation constantly. Most individual summer storms in Oman cover only limited area, no more than several tens of square kilometres, while winter storms are generally much more widespread. Orographic effects strongly control this special pattern of rainfall and there is often great differences in the amount of rainfall over short distances. Mean annual rainfall throughout most of Oman is relatively low, less than 100 mm, and sporadic but in mountain areas rainfall is greater, up to 350 mm, and relatively frequent. Droughts of two or three years duration are not uncommon. The variability of rainfall is demonstrated by the long-term record for Muscat (histogram). The total average annual amount of rain falling on Oman is estimated to be about 19,250 Mm$^3$. Of this total, some 80% is evaporated leaving just over 1,400 Mm$^3$ as effective rainfall generating run-off and direct infiltration to the groundwater reservoirs.

Wadis

The term wadi is a familiar term throughout the world and a household name used by inhabitants of the Arabian Peninsula. It describes both a water-made cut through a mountain range and a river of gravel distinguishable on a wider alluvial plain that stores fresh surface water originating from a mountain range. This water slowly gravitates towards the sea and is a major, sometimes the only, source of water for most of the time when the countryside is dry. Historical accounts list two permanent rivers in Oman “one near Qurayt and one near Seeb, which flowed all year long” in the nineteenth century, or even as recently as mid-of-
Muscat Rainfall

Variability of Muscat Rainfall 1895 - 2003

Flood Risk Zones

The map above shows areas of high (red), medium (blue) and low (yellow) flood risk zones. The high risk zones are defined as those being inundated by a flood that on average would occur once in a five year period, termed the “5-year flood”. Likewise, the medium risk area would be that covered by the 20-year flood; and the low risk area being covered by the 100-year flood. The 20-years flood is considered the “Index” or “Design” flood for general planning purposes.
The four principal mechanisms that cause rainfall in the Sultanate:

1. **Convective Rain Storms**
   - Which can develop any time of the year but mostly during the summer months.

2. **Cold Frontal Troughs**
   - Originating over the Atlantic Ocean or Mediterranean Sea, which are common during winter and early spring.

3. **Onshore Monsoon Currents**
   - Which occur from June to September that bring a complex regional circulation and result in frequent drizzle, the khareef along Dhofar extending from Dhalqut to Mirbat and the adjoining mountains.

4. **Tropical Cyclones**
   - Moving in from the Arabian Sea, which occur on average about once in five years in Dhofar and once in ten years in Muscat.

Flood Studies

Floods in Oman often occur with little warning, causing property damage, community disruption, and at times, loss of life. In order to reduce the future loss of lives and damage to properties from floods, the Supreme Committee for Town Planning has established guidelines for development in the flood-prone risk areas of Oman. The Ministry of Regional Municipalities, & Water Resources has the task of investigating and analyzing the hydrologic conditions of flood events and producing maps showing flood risk zones under its Nationwide Flood Study Programme. The Nationwide Flood Study Programme was initially proposed in 1987 by the former Council for Conservation of Environment and Water Resources. The programme of work for the areas under study consists of two phases. The Phase 1 reports consisted of the delineation of high risk flood zones only, to be used as interim guides for planning, the Phase 2 reports, based on more detailed study, are considered final as of the date of completion and they supersede the Phase 1 reports.
Groundwater

Groundwater, in a broad sense, is all water that occurs below the land surface. Groundwater occurs in the interstices of surface sediments (such as unconsolidated sands and gravels commonly found in alluvial valleys, coastal plains and dunes) and sedimentary rocks (such as limestone, sandstone) and within the fractures of hard rocks. A rock formation that stores and can transmit water is called an aquifer. Aquifers may be described as unconfined – where the water contained is under normal atmospheric pressure – or confined – where an overlying layer of low permeability prohibits flow and the water is under greater pressure than atmospheric.

Groundwater resources may be considered as renewable or non-renewable. Renewable resources describe aquifers that receive replenishment – or recharge – from rainfall or infiltration of surface water flows. Non-renewable resources receive little or no modern-day recharge; most owe their existence to historic times when the climate was much wetter than it is now. Renewable groundwater resources occur in areas of moderate to high rainfall and/or where surface water flows are common. In such locations, rainfall or runoff can readily infiltrate the subsurface where permeable strata exists at surface. Where such recharge occurs, water levels rise. The elevated water levels sustain groundwater flow though the aquifers with general movement from the highlands to the coastal or interior lowlands. Groundwater discharge may occur naturally from direct evaporation in areas where depth to water is very shallow such as may be found within wadi beds or sabkhas. At the coast, groundwater flow may provide seepage in the tidal zone or be lost by submarine discharge offshore.

The rate of groundwater flow in an aquifer is low; the passage of groundwater from highlands to lowlands can take hundreds or even thousands of years. During this period, when the groundwater is continually in contact with rock material, it is not uncommon for chemical processes to result in water quality deterioration.

At a generalised scale, major groundwater flows in Oman are from the Al Hajar Al Gharbi and from the Dhofar mountains both towards the sea and towards the Interior. In both mountain areas, alluvial deposits in wadi beds typically form excellent aquifers and contain renewable resources of good quality groundwater on account of regular recharge from rainfall, surface water flow and locally the inflow of groundwater from adjacent hard rock aquifers. This is

Aquifers in the Sultanate

There are several important aquifers in Oman. The main aquifer systems include alluvial aquifers, regional Quaternary aquifers, aquifers of the Hajar Super Group in Northern Oman, aquifers of the Hadramawt Group and the aquifers of the Fars Group. Some of these aquifer systems are part of large-scale regional systems that extend throughout the Middle East.
reflected by the groundwater salinity map for shallow aquifers shown below. The seaward flows recharge the extensive alluvial aquifers of the coastal plains. Flows to the interior provide similar local replenishment to shallow aquifers and converge at topographic lows, such as Umm As Samim, from whence groundwater discharge occurs through direct evaporation.

The non-renewable groundwater resources of Oman largely occur within the Interior basin where thick Tertiary carbonate formations occur that have a total thickness of several hundred metres and store vast quantities of water. Groundwater quality tends to be brackish generally deteriorating away from the northern and southern mountains where the rocks are exposed or at shallow depth and where recharge occurred in past times.

Nationally, total recharge to our groundwater reservoirs is estimated to average almost 1,300Mm$^3$/year the bulk of which 70% results indirectly from infiltration of surface water flows and the balance from direct rainfall recharge. With settlement and development, the demand for water has led to ever-increasing interception of groundwater flow by, and abstraction from, dug wells and aflaj. Such interception and use has modified the natural balance; in some areas the rate of abstraction now exceeds the rate of replenishment. In such areas, water levels decline signifying a reduction in the volume of water stored in the aquifer. In some coastal areas, the lowering of water levels has reversed the natural groundwater flow direction with consequent movement of sea water inland.

In many areas, demand for water exceeds availability. Where this situation exists the demand is met by withdrawals from aquifer storage and is evidenced by declining groundwater levels. This situation currently occurs in Al Batinah, Salalah and the inland areas of Ad Dhahirah, Ad Dakhliyah and Ash Sharqiyah. In coastal areas, declining groundwater levels has locally induced saline intrusion.

In addition to the renewable resources, Oman is also fortunate in having significant reserves of ‘non-renewable’ resources. These reserves occur throughout the Interior and are typically brackish. Whilst the total volume of ‘non-renewable’ resources has been estimated to be several billions of cubic metres, they are finite resources, needing a carefully planned approach to their development.
Springs

A spring is a natural discharge point of groundwater at the surface of the ground. Water that emerges at the surface without a perceptible current is called a seep. Water in springs and seeps originates from rainfall that has soaked into the soil and percolated into underlying rocks. This simple fact was not recognised in ancient times: spring water was thought to originate from some mythical underground ocean. Springs have played an important role in the settlement pattern of arid lands, where they have served as a local source of water supply and irrigation. Water from mineralised and thermal springs has also long been used for its therapeutic value.

The extreme relief and structure of the northern Oman mountains give rise to many springs in the valleys. Springs in Oman discharge their water from two major geologic systems, Al Hajar limestones and the ophiolites. The limestones are porous, with flow through fractures and faults, and usually bear good quality water. The ophiolites are less permeable, tend to be low yielding and may yield alkaline water: many such springs exist in Ad Dakhliyah, Ad Dhahirah and Al Batinah, where sometimes they form ‘blue pools’ as a result of calcite precipitation when alkaline water mixes with wadi water containing bicarbonate. In general, the pH of spring water in Oman ranges from 7.4 to 11.9. Some of the springs are fed by percolating water that has reached considerable depths and been heated before it finally emerges at the surface. Springs on the northern side of the northern Oman mountains are often hot and have had local importance for therapeutic purposes for many years.

Natural Springs in the Sultanate

There are several hundred springs in Oman and most of them are located in the mountainous areas. These springs vary according to their discharge, temperature and water quality. The most famous are the hot springs of Al Kasfah at Rustaq, Al Thawara at Nakhl and the cold spring of Razat in Salalah area. Ain Al Kasfah is well known for its strategic location while Ain Al Thawarah is characterized by its unique landscape. Both springs yield good quality water, which has been used over the centuries for water supply, irrigation and therapeutic purposes. Ain Razat is known for its attractive landscape and its high water yield, which has been used for crop irrigation. The quality of spring water depends on the chemical properties of the minerals forming the rocks through which water infiltrates into and through the ground. With the advent of the Renaissance, recreation facilities were established near these springs turning them into attractive sites for citizens, residents and tourists alike.
CHAPTER 3

Water Structures
Ancient water structures are living monuments of the ingenuity of our predecessors: aqueducts of the Roman Empire, dams of Persia, the gardens of Alhambra or aflaj of Oman testify to the importance which they attached to water. Throughout the centuries the Omanis contributed much to the world’s civilisation, working out some of the finest examples of sustainable water development. Archaeological evidence suggests that early irrigation practices in Oman existed 4,000–5,000 years ago.

Initially they involved the direct use of surface runoff and shallow hand-dug wells - Al Zaghira - then more sophisticated techniques, including terracing based on the use of spring water in Al Jabal Al Akhdar and, finally, the falaj. The establishment and maintenance of our larger settlements demanded assured water supply; this was typically provided by aflaj in the rocky mountainous and foothills areas whereas supply from wells predominates in coastal areas where...
There are still people who follow the old ways, and who talk of ancient glory, when frankincense was king and all the world sought it. In ancient days, the Romans called this land Arabia Felix, or Fortunate Arabia. Today, it belongs mostly to the wildlife. The ancient city of Ubar which flourished along the frankincense route was positioned around a major waterhole. The ancient city was discovered in 1992 with the aid of remote sensing data. Archeologists believe Ubar existed from about 2,800BC to about 300AD and was a remote desert outpost where caravans were assembled for the transport of frankincense across the desert.

There is no question that water was key here. In this desert, Ubar could have been hidden anywhere in, say, 200,000 square kilometres. But it is located in Shisur because there is water, permanent water here. It is likely that this is the only major site in the whole area. With water, the fortress would have made a fitting home for a kind like King Shaddad. It would have had a processing and storage facility for the frankincense. And high, thick walls to withstand a siege. But Ubar was far more than a fortress. It would have been surrounded by thousands of tents, set in a vast oasis. King Shaddad’s imitation of paradise, now turned to sand. To the northeast, there are remnants of campsites where most people lived. This is how Ubar may have looked in its time of glory: about 150 people would have lived within the fortress walls: family and servants of the king, administrators and record-keepers of the frankincense trade.
Al Zaijrah

Al Zaijrah is a mechanical means by which the water is extracted from a dug well, historically by beasts of burden. It was the main traditional method of lifting water for agriculture from dug wells till the introduction of pumps in the fifties.

The Zaijrah consists of one or two Manjur (well-wheel) which is made from individual wedge-like sections of Acacia wood, which are fitted around a central hub and bound tightly with strips of leather or shark skin. It is believed that each Manjur has its own individual sound. The main advantage of Al Zaijrah is that it can be constructed in any formation which contains groundwater. The main disadvantage is that mechanical power is needed to extract water from the ground.

The Quantity of Water available from Al Zaijrah is related to:

- Topography & Geology
- Infiltration into Alluvium and Lateral Formations
- Hydrogeological Properties of the Formations Wherein the Ground Water is Stored
- Human Activities (wells, diversions)
Aflaj

Aflaj (plural of falaj) are conduits which are dug in the ground to convey water by gravity from one place to another; there are more than 3,000 active aflaj in the Sultanate of Oman. It is believed that this technique of tapping ground water resources originated from Central Asia and Iran and spread to other semi-arid areas which have appropriate physiographic conditions - in the Sahara, China and even South America. However, recently, the Italian mission has referenced the origin of aflaj to Oman. In these areas village communities tapped into groundwater aquifers with the help of long, gently sloping channels when surface flows were intermittent or unreliable. The time of the construction of the first falaj in the world is shrouded in antiquity. Early written accounts on ground water occurrences and the engineering and surveying techniques involved in exploiting them is provided by Mohammed bin Al Hasan Al Karaji in 1,017 in the fascinating work “Kitab inbat al miyah al khafiya”, or Book of the Extraction of Hidden Waters.

Many of the aflaj in Oman have existed for over 1,500 years and some of them may date back over 2,500 years. Some aflaj have been constructed relatively recently: aflaj in the Ibra - Mudharib area were constructed some 150 years ago. The galleries excavated in solid rock may continue their work in collecting seepage unattended for hundreds of years. In many cases, even the location of the mother well is uncertain, since after successful completion of the scheme, entrance openings were closed. Most aflaj are found in the wadis of Al Hajar Al Gharbi. These mountains are characterised by bold relief and paucity of soil and vegetation: surface runoff is therefore rapid, but short-lived. In past centuries, aflaj were the only means to enable people to have a constant water supply.

Day and Night Distribution

The day Muhadhara means the distribution of the falaj water among shareholders during day time. The Falaj people used the movement of a shadow cast by the Sun - in effect a sundial to distribute the shares of the falaj among owners. The idea is to select a flat area and anchor a stick three metres high. The area in the west and east of the stick is divided into 24 parts. These divisions are equal to one athar which is 30 minutes. Nowadays, the clock is used for timing. The actual duration of night Muhadhara is between the Sun setting and rising.

The Discharge of the Falaj is related to:

- Rainfall intensity and frequency
- Topography and geology
- Infiltration into alluvium and lateral formations
- Hydrogeological properties of the formations wherein the ground water is stored
- Hydraulic properties of a falaj
- Human activities (wells, diversions)
Over time it was agreed to use the star’s movement for this purpose. The ancient people knew all the stars that were used for falaj water distribution during the night time. They knew their rising, setting and what time they were in the dawn. It has to be noted however, that most of the ancient knowledgable people used shadow for their water distribution and the stars for night water distribution. Since the rising time of the stars is variable, this system affects the athar duration. This variability of athar under this system was one reason for the falaj people’s to adopt a 30-minute athar.

Water Trade (Qa’ad)

The sale of water of a falaj can take place in a number of ways. Qa’ad means selling of falaj water shares during every circulation. Since the circulation of falaj is every seven days, any person who has an extra amount of water can go and sell it for just one irrigation application only. This is done by auction. The sellers and buyers meet in a place used for this purpose. The auction starts at a low price and goes up. The prices of one athar may vary between 200 baisas during wet season to 35 Rials during periods of drought. Selling a share permanently is not influenced by the sequence of dry and wet seasons. It is influenced by the stability of the falaj flow. Any person who owns a share of water from the falaj can mortgage his share. The method of mortgage is to sell the share for a certain amount of money. The seller has the right to return money to the buyer during any time between 10 and 20 years. The buyer can benefit from this share either by using it for irrigation or by selling it by quod.
DAUDI FALAJ  
(Underground)

The first, called daudi or iddi-falaj, is constructed as an underground tunnel with a series of vertical access shafts, starting from the mother well to the conveyance channel, and finally to the irrigated areas. (Fig. 1)

GHAYLI FALAJ

The second type is the ghayli falaj which collects water from base flow of the wadi through an open channel and transports it to the distribution section. The well-known falaj in Mazara is of this type. In this particular case the supply is totally dependant on the surface flow. During prolonged dry seasons, the discharge of such a falaj decreases, and sometimes ceases temporarily. (Fig. 2)

AINI FALAJ  
(Spring fed)

The Aini Falaj is fed directly from springs. Many springs which rise out of limestone in the mountain areas are reliable sources of good quality water. (Fig. 3)
Birkats

Birkats are cisterns; a traditional system designed to collect and store rainfall generated flows typically comprising an excavated chamber or naturally occurring hollow structure. For centuries, the utilization of birkat has been vital for the survival and development of many remote settlements in Musandam where they serve as the only source of water to meet domestic and livestock requirements.

The topographical, hydrological and hydrogeological features of many mountainous areas can impose major constraints on the availability and development of natural water resources. With the absence of perennial surface water flows and limited aquifer potential, the construction of birkat to harvest rainfall and local runoff presents the only means to establish a water supply to support settlement.

An inventory of birkat was undertaken in the Musandam Governorate through the period February–July 2001 with a view to establishing location, assessing structural status and water use, and determining maintenance requirements together with estimated cost. A total of 967 birkat were located through visits to 385 localities; of the total inventoried, 80% were found operational. No birkat were found in the wilayat of Madha; the different hydrogeological environment there provides more ready access to groundwater by way of aflaj, springs and wells. Most birkat (86%) are man made (dug); natural birkat have been developed in structures like openings, joints and fissures in hard rocks but their storage capacity tends to be limited to less than 500m³; excavation and construction work is required to provide a storage capacity adequate to sustain supplies through the typical 7 dry summer months (April to October). The total storage capacity of the birkat inventoried is of the order of 78,000m³; individual capacity ranges from <1 to 2,540m³ but most (79%) are small with capacity <100m³. Birkat can be classified according to the water use.

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Results with regard to current Usage:

- The primary use of water from birkat is for raising livestock (information from 254 birkat visited indicated a goat population in excess of 20,000).
- The use of water for domestic purposes is limited and transitory; few, if any, existing permanent households are entirely dependent on Birkat as a primary source of supply.
- The use of water for agricultural purposes is limited being heavily constrained by lack of continuity of supply and land/soil availability.
Dams

Recharge Dams

In hot and arid climates, potential evaporation can exceed rainfall by several orders of magnitude. Surface storage in such a situation is impractical due to large water losses. The idea then emerged to store flood waters underground. This process is called artificial recharging, or Aquifer Storage and Retrieval (ASR), and may be defined as follows: the planned activity of man whereby surface water from a wadi is made to infiltrate the ground, commonly in rates and in quantities many times in excess of natural recharge.

Artificial recharge is most commonly executed with the help of either injection wells, recharge ponds or recharge dams. Although the concept of a recharge dams is relatively new, it is rapidly gaining wide acceptance. Many recharge dams have already been constructed in Arab countries and throughout the world. Many more schemes are planned. Artificial recharge to underground storage yields several benefits. Ground water storage capacity exceeds that of most surface structures; the method is relatively cheap; silting difficulties are largely avoided; water supplies are naturally purified for drinking purposes and evaporation losses are minimised.

In Oman, an additional and very important benefit of storing flood waters underground is the reduction of sea water intrusion in coastal areas, which has become a serious problem in many parts of the country, especially on the Al Batinah plain.

Principles

A dam built across an alluvial channel stores water during the flood. The stored and clarified water is then released slowly, so it can infiltrate thick alluvium downstream of the dam and in time be withdrawn for use. Contrary to popular belief, recharge mainly occurs downstream of the dam, and not in the reservoir itself. The reservoir bed becomes quickly sealed by silt so the recharge through it becomes low. However, water released from the reservoir has little sediment, and easily infiltrates into gravel aquifers downstream of the dam.

The parameter which is perhaps the most difficult to quantify is the percentage recoverability of the increased recharge that is induced by the dam structure. The dams are designed in such say that the maximum discharge of outlets
ensures that the total wetted contact area in the channel downstream is sufficient to infiltrate the total release volume. The rate of infiltration into the alluvium downstream therefore does not usually present a constraint in utilising all the available water for recharge. Usually there is more than sufficient storage capacity in the alluvium for a single recharge event. Preferred locations can accommodate several recharge events in a short period of time. For illustration, an aquifer with the porosity of 10% measuring ten by ten kilometers could store ten million cubic metres of water with a one metre rise in the water table. Due to slow ground water movement, most of this water may be in time withdrawn for use.

**Components**

**Reservoir:** Due to topography, recharge dams have relatively small capacity reservoirs. The current tendency is to design storages that can contain a flood that can occur, on average, once every five to ten years. An ‘average’ recharge dam in the Sultanate is ten metres high and has a crest 3.5km long; it has an ‘average’ reservoir of four million cubic metres, which, in an ‘average’ year, stores more than four million cubic metres of water. The period of water retention in the reservoir is usually less than fourteen days, which is dictated by health requirements.

**Construction Materials:** Principally the construction materials available govern the types of dams. Thus, in Oman, the structures are typically in the form of permeable sand and gravel embankment dams with gabion protection, or gabion weir structure. Gravels are abundant at dam sites: they are usually widely graded, but are also occasionally well sorted. Cobbles and boulders occur more frequently near to the jabal, and are frequently used as a construction material there. Some of the dams require special design. Thus Tanuf Dam, due to the necessity of passing very high discharges through a narrow spillway, is a gabion-constructed dam, with a bitumen impermeable upstream facing layer and downstream concrete spillway and energy dissipation-stilling basin.

**Spillway:** A spillway is a part of the dam designed to safely pass floodwaters. The spillway is designed for overtopping, whereas the remainder of the dam is usually
## Recharge Dams in the Sultanate

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**Total Capacity:** 84.48
not. The spillways of the recharge dams in Oman need to be large because the dams are generally in the lower reaches of the wadis with relatively large catchment areas of the arid mountains. Flash floods produce extremely high flow peaks in these conditions. It is beneficial to avoid concentration of flow over a small cross-section downstream of the dam, because it increases erosion and flood risk. Therefore, if practical, a large portion of the dam should be designed as a spillway. This leads to the adoption of an overtoppable embankment of gabion structures.

**Flood protection:** Each dam that has an ungated spillway reduces the incoming flood peak. How much the peak is reduced depends on the size of the reservoir and the magnitude of the flood. Typically, recharge dams in Oman are designed to fully contain a flood that is likely to occur, on average, every five to ten years. Larger dams are effective in reducing floods that statistically occur once in a century, and to a lesser extent reduce more rare floods.

**Monitoring:** A dam monitoring network is essential to know the quantity of water that comes, and when. It is indispensable for the operation of dams, evaluation of their effectiveness, providing proper safety measures, and deriving conclusions for construction of new, improved objects. All recharge dams are instrumented. The hydrological network of dams includes 47 rainfall stations, 18 falaj stations, 31 wadi flow stations and 264 monitoring wells. Data records are intensively studied and show that, in an average year, the cumulative storage of all recharge dams in the Sultanate is slightly greater than their total combined capacity; presently this amounts to more than 84 million cubic metres. Most of this water recharges the aquifer – an amount similar to the annual production of the Al Ghubra sea water desalination plant.

**Storage Dams**

Due to low runoff and high evaporation losses, the potential for storage dams in Oman is limited. Studies have established however that a major storage dam is feasible on Wadi Dayqah which has perennial flow over much of its length. A number of small storage dams have been constructed in remote areas of Al Jabal
## Storage Dams in the Sultanate

<table>
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Al Akhdar to support isolated communities. Construction materials comprise stone and cement mortar and storage size is about 750,000 m³. Phase 1 of this programme was completed in 1994 and involved construction of 27 dams. Phase 2 involved construction of 31 dams Jabal Al Kawr, Jabal Shams and Jabal A’ Surah and Jabal Dhofar.

**Wadi Dayqah**

Wadi Dayqah presents unique opportunities for construction of a major storage dam. The wadi flows most of the year in its middle reach and, on occasions, discharges enormous quantities of water to the sea. Recently, in its major floods Wadi Dayqah flows in Al Mazara were 192, 84, 95, 121 and 260 Mm³ in 1982, 1987, 1990, 1996, and 1997 respectively. The average annual flow of Wadi Dayqah is about 60 Mm³ per year which is equivalent to about 2 Mm³/s. About 10 Mm³ of this water flow is consumed for domestic and irrigation purposes within the three villages - Al Mazara, Hail Al Ghaf and Dagmar - that host 6,000 people and 112,000 trees on 400 hectares of irrigated land adjacent to the lower reaches of the wadi. The remaining 50 Mm³ is lost through infiltration in the wadi bed and direct discharge to the sea.

Wadi Dayqah has been the subject of a number of technical studies that have assessed the potential for construction of a dam to arrest and store the excess flood volumes. Technical evaluations of hydrology, hydrogeology and geology completed in 1993 confirmed the potential for a dam and quantified yield potential to be of the order of 40 Mm³ per year. With commitment to ensuring continuing supply of water to the existing downstream users, about 35 Mm³ per
year would become available to augment priority domestic supply in the Capital Area (20Mm$^3$/yr) and to provide the wilayat of Qurayat with both domestic and irrigation water supplies (15Mm$^3$/yr). Of six sites investigated, the preferred location for the dam was at Al Mazara where the water tightness of foundation material was found the most favourable. The economic viability of the scheme was subsequently examined with several options of dam and reservoir size. A full Feasibility Study was commissioned in 2002 which included detailed site investigations in the dam and reservoir areas, potential quarry and borrow areas, irrigation areas and along potential pipeline routes. Recently, the first phase of the project has been tendered and construction is expected to start early 2006.

Flood Protection Dams

Floods can cause loss of life and much damage to property. The fact of life is, however, that often the best areas for agriculture are subject to flooding. River valleys attract human settlement, and proper measures have to be taken to defend these areas against floods. Many dams in the world are built specifically for flood protection, and most other dams have a degree of flood protection in their duty statement. In Oman, a combination of high, step and bare mountains mixed with an arid climate and highly variable rainfall, gives one of the highest flood peaks in the world for catchments of comparable size. Wadis are capable of providing flood peaks of the order of 20m$^3$/s/km$^2$, and possibly more during extreme events. Time from the occurrence of rainfall to a flood is measured in minutes. As a consequence, flood protection dams have to be durable, and their spillways able to withstand ferocious floods of very high magnitude. Hydrological and hydraulic factors for dam design and evaluation of the largest possible flood able to pass a dam without damage are complex. Each catchment requires a separate study to determine the rainfall runoff relationship as there is often great variation of rainfall-runoff relations between neighbouring catchments. Details of flood protection dams constructed to protect settlement areas, infrastructure and utilities in Muscat and Musandam are shown on the right.

A combination of high, step slopes and bare mountains mixed with highly variable rainfall in Oman, gives one of the highest flood peaks in the world. As a consequence, flood protection dams are very important.
### Statistics

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Desalination Methods

DISTILLATION

- **Multiple-effect Distillation:**
salt water is heated and vaporized in long vertical tubes. The hot vapour is used to heat salt water entering the next evaporator; in doing so, the vapour is cooled and condensed into fresh water. Because the multiple-effect evaporator reuses heat, it requires less fuel to treat incoming water than a single evaporator.

- **Flash Evaporation:**
heated seawater is sprayed into a tank kept under reduced pressure. At this reduced pressure, the water vaporizes at a lower temperature, so that flash evaporators require less heat and thus less fuel.

- **Multistage-flash Distillation:**
systems consist of a series of flash chambers operating at decreasing pressures.

MEMBRANE PROCESSES

- **Reverse Osmosis:**
saline water is subjected to pressure, and forced against a membrane; fresh water passes through while the concentrated mineral salts remain behind.

- **Electrodialysis:**
uses electrical potential to drive the positive and negative ions of the dissolved salts through separate semi-permeable membranous filters, leaving fresh water between the filters.

Desalination Plants

Desalination of seawater or saline/brackish groundwater has become an important contributor to water supplies where natural water resources are unavailable or inadequate. Desalination is the process of removal of excessive dissolved salts from water which renders such otherwise unusable water fit for human consumption, irrigation, industrial applications, and various other purposes. Nowadays, desalination is seen as a proven and reliable alternative for the development of new water resources. Existing desalination technology requires a substantial amount of energy, and so the process is expensive. For this reason, it is generally used only where sources of fresh water are not economically available.

In the later 20th century, more than 8Mm$^3$ of fresh water were produced each day by several thousand desalination plants throughout the world. Distillation processes are used in about half of all the plants and accounts for roughly three-quarters of the world’s desalinated water. Most of the other plants employ membrane processes. The world’s desalination capacity expanded rapidly during the 1970s and 1980s as the hyper-arid countries of the Middle East improved their standard of living, with attendant changes greatly increasing the consumption of fresh water. The Middle East countries produce about 75% of all the world’s desalinated water. The United States produces about 10%, and Europe and Africa each account for approximately 5%. The world’s largest desalination plants are in the Arabian Peninsula. The Al Ghubra electricity and desalination plant commenced operation in 1976, with a production capacity of 26 MW and 10Mm$^3$ of water per year; this has since been upgraded to an installed capacity of 58Mm$^3$/yr. Construction, as a first stage, of a 200 MW generating plant at Barka together with a desalination plant of 20Mm$^3$/yr capacity, primarily for the supply of Muscat, has recently been completed. Additionally, plants have been installed by MOD, PDO and MEW. They are located both on the coast and in the Interior, primarily to provide potable water to communities but also to supply industry.

A number of domestic desalination units have also been installed at private wells on the Batinah coastline to improve the quality of groundwater now being abstracted. Over 90% of the total desalination capacity is installed at the co-generation plant at Al Ghubrah for the Capital Area water supply. Its present production is about 52Mm$^3$/yr while production from the remaining water supply plants totals about 5Mm$^3$/yr.
Wastewater Treatment Plants

Most domestic wastewater in Oman is disposed of through septic tanks and in towns where there is very little garden watering about 90% of the water supplied will return to the aquifer. This factor is reduced for greater evaporation losses in areas where there is sewage collection, either from a piped system or by tanker from holding tanks, and treatment. There are collection and treatment systems for some 25% of the Muscat municipal population. The treated wastewater is being used very effectively for municipal greening in some urban areas and is a valuable resource. Current supplies are of the order of 12Mm³/year.

A major wastewater treatment and re-injection scheme has recently been commissioned on the Salalah Plain. As at August 2003, approximately 80% of the Salalah town was connected to the scheme. The total scheme capacity is currently in the order of 20,000m³/day with two further stages planned to more than double the initial capacity. The effluent is treated to a tertiary level, chlorinated and then injected as recharge into tubewells in a line parallel to the coast in an attempt to stabilise the encroaching sea water interface. Additional facilities are being installed and commissioned in Khasab, Ibrī, Buraimi, Samail, Nizwa, Ibra, Sur, Rustaq and Saham. Similarly there are plants for the industrial estates at Rusayl, Sohar and Raysut. With the future development of water and wastewater systems there will be considerable potential for increasing its use particularly for aquifer recharge and irrigation.

Of major importance is the Muscat Municipality plan to extend its sewage collection and treatment system. The first stage by 2006 should generate 70,000m³/day of effluent, eventually increasing to an estimated 270,000m³/day (100Mm³/yr). The Municipality plans to use up to 50,000m³/day on extensions of its present greening practice and thereby replace the use of potable tubewell water.
CHAPTER 4

Water in the Regions
In the Sultanate of Oman, groundwater usually occurs in the alluvial deposits in wadi beds where it is exploited by wells and aflaj. Recharge to the alluvium may occur through infiltration of floods in the wadi and from groundwater inflow from adjacent hard rock aquifers. The permeability of the saturated alluvium is usually high and the quality of water good. Exceptions to these general rules occur where the alluvium is cemented or where discharges from ophiolites into the alluvium cause locally high salinity and alkalinity.

The Samail ophiolite is a locally important aquifer feeding aflaj and it stores large quantities of water. This water is released slowly into the wadi alluvium and thus it helps maintain supplies to wells and aflaj in small alluvial basins. Permeability is largely dependent on fracturing and jointing of the rock, which occurs in the upper zones in the peridotites and locally in the gabbros. Hence, these formations occasionally yield significant quantities of good quality water. However, very high alkalinity and conductivities up to 3,000μS/cm are often associated with springs emerging from the contact of the gabbros and peridotites.

Other significant sources of groundwater in the Northern Mountains are the limestones and dolomites of the Hajar Super Group. Yields of up to 30 l/sec in wells in the Wasia limestones and over 40 l/sec in the Saiq and Mahil formations have been reported. Such yields are dependent on locating open joints and fissures. The limestones also feed large geothermal springs at Nakhl and Rustaq.
The Muscat region extends over the easternmost portion of the Hajar Ash Sharqi mountain range where limestone and ophiolite bedrock formations reach elevations of more than 2,000m. The Capital Area is dominated by a narrow anticline of elevated HSG limestone flanked by more subdued Samail ophiolite and Tertiary limestone hills in the west and hills formed of Pre-Permian metamorphic rocks (Huqf Group) in the east. Quaternary to Recent alluvial deposits are largely restricted to a narrow and discontinuous coastal plain and a few small internal alluvial plains.

Mean annual rainfall ranges from 67mm at Bajriyah in Wadi Aday to 210mm in the mountains at Jabal Bani Jabir. The long-term average for Muscat, recorded in Ruwi, is 102mm/yr. More than 73% of the total annual rainfall falls within the December to March period.

Limestone rocks comprise the principal aquifers in the mountains. Hajar Super Group (HSG) carbonate rocks outcrop extensively in the mountainous upper catchment and piedmont/plain zones and may locally exhibit high permeability due to fracturing and karst development. The HSG is an important source for aflaj; the presence of numerous aini and ghaily aflaj on or adjacent to outcropping HSG formations indicates the importance of these rocks for water supply. The Eastern wellfield in Wadi Aday gorge which contributes to water supply in the Capital Area is constructed in HSG limestone and dolomite. Tertiary Limestones also forms an important aquifer locally as demonstrated by the Central wellfield (Lansab and Bawshar wellfields) and the former MOD wellfield (MAM Camp). Alluvial deposits comprise significant aquifers on the coastal plain and in the upper reaches of Wadi Aday. Alluvial deposits are typically less than 20m thick but greater thicknesses (up to 300m) occur in the north western part of Wadi Rusayl on the edge of the Batinah Plain. Groundwater discharges at the coast through direct evaporation in some coastal plain areas with sabkha development and increased groundwater salinity. At other locations some groundwater discharge is likely to occur through submarine outflow.

Water demand for domestic requirements in the region is mostly met by the Muscat Area Water System. This distributes water via a reticulated water mains system supplemented by water tankers to serve unconnected areas and is serviced mainly by:

Key Issues identified within the Muscat area:

- Development of water supplies to meet predicted increases in demand for domestic, industrial and municipal water.
- Collection, treatment and reuse of municipal waste water for landscape and agricultural irrigation and possibly for groundwater recharge also.
- Implementation of conservation measures for domestic and industrial water use.
- Implementation of leakage detection and remediation programmes to reduce water losses from municipal supply networks.
- Management and monitoring of solid and liquid waste treatment facilities.
- Prevention of groundwater contamination.
- Development of integrated environmental audit and monitoring programmes.
- Monitoring and control of rising ground water levels in urban areas.
- Improvement in farm practices and introduction of further wastewater collection/treatment facilities to reduce water quality hazard.
- Prevention of contamination by new and existing industrial development.
- Improved management of existing waste disposal sites.
- Location and protection of secure potable supplies for all major rural settlements.
- Maintenance and protection of falaj supplies.
- Optimum development of Wadi Dayqah surface water resources.
- Investigation assessment and development of surplus groundwater resources.
The multistage flash-evaporation desalination plant at Ghubra.

The Eastern Wellfield: located in Wādi Aday gorge. It consists of 29 production wells which currently abstract about 4 – 5 Mm$^3$/yr.

The Central Wellfield: consists of the smaller Lansab and Bawshar wellfields, each of which has five production wells. Abstraction ranges from about 0.3 Mm$^3$/yr to < 0.02 Mm$^3$/yr.

The Western Wellfield: includes the old Government, Seeb and Al Khawd wellfields which collectively comprise some 42 production wells clustered around the Al Khawd recharge dam. These wellfields tap the Batinah Plain alluvial aquifer system and commenced production in 1968 (old Government), 1974 (Seeb) and 1984 (Al Khawd).

Production from the Western wellfield has stabilised at about 8 Mm$^3$/yr.

Wastewater treatment is effected by numerous plants most of which employ the extended aeration activated sludge process. Plant flows range from 10,800 (Darsayt plant) to less than 10 m$^3$/day. An effluent treatment plant in Wādi Lansab treats trucked waste water and produces about 9.6 Mm$^3$/yr of treated effluent the majority of which is reticulated by a separate non-potable distribution system, for irrigation of roadside gardens throughout the Capital Area and beyond to Barka.
Al Batinah

The Al Batinah region comprises two distinct geomorphological zones - the mountain/piedmont area of the Al Hajar Al Gharbi range and the alluvial plain to the north. In the south, the mountains comprise the northern anticline limb of the Jabal Al Akhdar where elevations attain 2,500m. The mountains consist of Cambrian Huqf Group siltstone, greywacke and limestone and Hajar Super Group (HSG) carbonates, siltstone and sandstone. Carbonates dominate and are typically massively bedded and resistant to erosion. Hawasina Nappes, composed of limestone, siltstone and siliceous sediments, have relatively limited and discontinuous exposure in narrow bands on the northern flanks of the jabals. Extensive thrust faulting is evident at the contact of these rocks with HSG rocks and Samail Nappe ophiolites and appears to control a number of springs and aflaj. To the north, mountain peaks are lower and ophiolites predominate upper catchment geology. Valley-fill alluvium of late Tertiary to Quaternary age lines upper catchment wadi channels. Sediment thickness is generally less than 50m. Small exposures of Tertiary limestone, calcarenite and marl occur in the piedmont zone.

The alluvial plain varies in width from 30km to 15km. In upper alluvial fan systems, older gravel and sand ridges are interspersed with and incised by more recent wadi channels. Towards the coast, the terrain becomes flatter and wider old and new channel systems interlink. Wadi channels tend to narrow towards the sea sometimes forming multiple, small outlets. Adjacent to the coast, aeolian and beach sand deposits occur juxtaposed with sabkha, clay and silt deposits.

Rainfall in the mountains may exceed 300mm in the south but reduces to the northwest. Numerous large wadis drain mountainous tributaries to discharge on the coastal plain where mean annual rainfall is typically <100mm. For the larger wadis, mean annual flows range from <1 to 17Mm³/yr; in historic times, wadi flows during extreme events have caused extensive damage and discharged millions of cubic metres of flood waters to the sea.

In an endeavour to reduce such loss and provide protection from flood waters, 11 major recharge dams have been constructed on the Batinah since 1985 - on wadis Ma’awil, Taww, Ajal, Fulajj Dam, Bani kharous, Mistal, Hawasinah, Fara, Hilti, Jizi and Ahin; storage capacities ranging from 0.6-6.8Mm³. A number of smaller storage dam structures have also been constructed for local supplies.
in the upper reaches of some wadis. Alluvial sediments associated with upper catchment wadi courses and the alluvial fan/plain zone comprise the principal aquifers in the area. All yields vary considerably depending on the nature of the deposits, their saturated. In upper catchment areas, wadi channel alluvium is typically 10 to 15m thick with a saturated thickness of only a few metres, except after major recharge events. Aquifer potential is limited by small saturated thickness and restricted areal extent. It is now recognised that flow in this shallow alluvial system is supplemented by seepage from adjacent bedrock areas. Significant groundwater resources are found in the much thicker (>300m) alluvial deposits found in the alluvial fan/plain zone.

Along the highland front, Tertiary carbonates may locally show limited karst development and may locally contain useful supplies of groundwater. Within the mountains, Hajar Super Group (HSG), Samail Nappe ophiolite and older Huqf deposits all may locally contribute good supplies and sustain numerous aini aflaj and shallow well abstractions where permeability is enhanced due vari-
Key Resource Issues in the Al Batinah Region:

- Reduction in current water use and development of a detailed water resources management plan to establish a sustainable level of development in coastal areas.
- Control of seawater intrusion. Location and protection of secure potable supplies for all major settlements.
- Improvement in farm practices and introduction of further waste-water collection and treatment facilities to reduce water quality hazard.
- Prevention of contamination by new and existing industrial development.
- Improved management of existing waste disposal sites.
- Maintenance of falaj supplies.
- Provision of water supplies for planned industrial development in the Sohar area.
- Remediation of the contamination plume in Wadi Suq and prevention of further contamination by mining operations.

From karst development, fracturing and/or weathering in association with major fault zones. Hawasina Nappe sediments generally exhibit relatively poor open fracture development and have limited groundwater potential.

Seepage of water from mountainous bedrock sequences has been established to be an important if not dominant component in the replenishment of adjacent alluvial aquifers. Evidence includes high temperature springs at Nakhal, Rustaq and elsewhere along the highland front, the presence of upward hydraulic gradients within deeper alluvial sequences beneath the plain, hydrochemical and isotopic data which show that groundwater on the alluvial plain has the same composition as high elevation rainfall and groundwater recorded on Jabal Akhdar. Potable water can be found throughout the mountain/piedmont upper catchment zones although high pH waters, associated with ophiolites, occur locally and contamination due to leakage from a tailings dam has occurred in Wadi Suq.

The demand for water has increased dramatically in recent times in response to agricultural development and population growth. Numerous large farms have been established inland. This development has had a corresponding dramatic impact on groundwater levels and quality with significant storage depletion and saline intrusion now occurring in many coastal areas. A pronounced decrease in vegetation near the coast shows that increasing agricultural water use on the plain has led to rapid seawater encroachment and a large contraction in the area of traditional farming north of the coastal highway. By comparison in mountain/piedmont upper catchment areas, groundwater levels and falaj flows appear to be generally quite stable with temporary declines evident during dry periods and good recovery occurring during ensuing wetter periods. Wellfield Protection Zones (WPZ) have been established to protect municipal supplies from the Barka, Musanah, Rustaq, Sohar, Liwa and Shinas wellfields.
Historically, agricultural development in this area of the Southern Al Batinah region (Wadis Al Manumah, At Taww and Al Ma’awil) was limited to a relatively narrow (less than 5km) strip along the coast where shallow groundwater occurs, and to isolated areas inland, where depths to groundwater were minimal and aflaj could be constructed. Abstraction of groundwater from hand-dug wells satisfied domestic and stock requirements and provided water for only limited agriculture. Total consumption of water for all purposes at that time was undoubtedly much less than the natural replenishment which has been estimated to be in the order of 80Mm$^3$/yr. The availability and use of new drilling equipment and techniques have enabled deeper water resources to be exploited through boreholes and facilitated development of areas away from the coast. At the same time, mechanical pumps, which became available for use in the deeper boreholes, increased the consumption of water and initiated the overdraft conditions.

The National Well Inventory has confirmed that the current level of abstraction on the coastal plain of this part of the Southern Al Batinah far exceeds the natural recharge to the groundwater in the area. Water use has increased from an estimated 34Mm$^3$/yr, before 1970, to about 161Mm$^3$/yr in 1995. This is twice the estimated natural recharge and falling groundwater levels and rising salinity result. The security of domestic water supplies and the sustainability of current levels of irrigation are threatened. Due to over-pumping, groundwater levels have fallen significantly below sea level in many areas. A ‘trough’, enclosing areas where this depression of the water table is greater than 5m below sea level, has an axis running parallel to the coast, some 6km inland and extending 10km east and west of Barka. This has led to low yields from dug wells and to the repeated requirements for well deepening in parallel with deterioration of water quality. Wells drilled and constructed within the newer farms further inland penetrate far below the water table and the water level declines experienced to date have had less immediate impact. However, if such over-abstraction continues in the present manner, the problems will extend into the inland agricultural areas.

As the volume of abstracted water has increased, and the water levels have declined, sea water has moved landwards because the natural slope of the water table (and therefore the direction of flow) has reversed. As a result, a critical deterioration in groundwater quality has taken place. Degradation of the domestic water supplies has occurred as salinity has risen to levels that render the water unfit for human consumption. The yield of the crops, including the date palms which usually tolerate higher salinities, has been affected. Farms have been abandoned as soil salinity has increased. In this part of the Southern Al Batinah, some 750 wells have been abandoned, all within 6km of the coastline. This highlights the need for urgent conservation measures to sustain this precious wealth.

The National Well Inventory

<table>
<thead>
<tr>
<th>The National Well Inventory located all wells, determined cropped areas and water use as follows:</th>
</tr>
</thead>
<tbody>
<tr>
<td>■ Total Number of Wells: 8,664</td>
</tr>
<tr>
<td>■ Number Operational Wells: 6,043</td>
</tr>
<tr>
<td>■ Number of Agricultural Properties: 3,915</td>
</tr>
<tr>
<td>■ Farm Area: 13,224 ha</td>
</tr>
<tr>
<td>■ Cultivated Area: 8,210 ha</td>
</tr>
<tr>
<td>■ Present Water Use: 161Mm$^3$/yr</td>
</tr>
</tbody>
</table>

Of the 2,621 non-operational wells located, some were abandoned and others not yet used. Of the operational wells, 4,321 were dug wells and 1,722 drilled.
Ad Dhahirah

The Dhahirah region is located on the western side of the Al Hajar Al Gharbi mountain range where an alluvial fan/plain zone extends from the mountain/piedmont through the central and lower reaches of all catchments, forming an extensive gravel plain which is partly covered by sand dunes in the southern and western border regions. Elevations range from greater than 2,500m in the mountainous upper catchments in the northeast to less than 500m near the international borders.

The upper catchments in the north, around Mahdah, are characterised by relatively low Ophiolite mountains. In their middle and lower reaches irregular hills and narrow ridges of ophiolite, Hawasinah Nappes, Tertiary limestones or Aruma Group rocks are interspersed with flat alluvial plain areas. Narrow gaps, cut through these bedrock outcrops, permit wadi flows to pass downstream onto permeable alluvial fans and plains and on towards the UAE border.

To the south, the upper catchments are characterised by elevated outcrop areas of Samail ophiolite and Hawasina bedrock. An extensive area of Tertiary limestone outcrop occurs near Dank with smaller limestone outcrops forming a discontinuous piedmont ridge between the upper mountainous catchments and the alluvial fan/plain zone that becomes more extensive southward. The Tertiary limestone extends under much of the plain at depths of several hundred metres and is overlain by Fars Group marls and conglomerates and a thin veneer of alluvium which thickens nearer the piedmont. Upper Fars Group conglomerates comprise a regional aquifer system (Al Massarat aquifer) and thicken within a north-south trending trough which parallels the highland front and extends through the central and lower parts of all catchments.

Recorded rainfall in the region ranges from 77mm at Tanam to 280mm at Jabal Khawr with the 3 wettest months from February to April typically accounting for more than 50% of the total annual rainfall. A 9m high dam with capacity of 0.5Mm³ was constructed in 1990 on Wadi Kabir (tributary of Wadi al Ayn) near Dariz, about 15km northeast of Ibri to arrest wadi flood waters. Records show inflows since construction have, an average, exceeded twice the storage. About 3km upstream of the dam, a diversion embankment has been constructed which buts onto the small Jabal al Hasi to ensure that part of the Wadi Kabir flood flows do not bypass the dam by flowing westwards into Wadi Khuwaybah/Aridh.

Ancient settlements to modern cities, water has always been a vital factor in human existence and survival.
As elsewhere, alluvial deposits collectively form the main developed aquifer within the mountain/piedmont upper catchment zone and are regularly replenished with recharge from direct infiltration of rainfall, wadiflow infiltration and bedrock runoff and seepage. The saturated thickness of many of the alluvial aquifers however is limited and supplies are severely jeopardised in times of drought when complete dewatering of the alluvial aquifer can occur locally.

The fractured Tertiary carbonates that outcrop over a large area in the upper reaches of Wadi Dank and along the piedmont contain significant amounts of water in storage but investigations completed to date indicate low yield potential for individual wells. Water quality tends to be good throughout the mountainous region and in the northern plains areas with local anomalies caused variously by agricultural and effluent disposal practices and seepage from ophiolites. A general increase in groundwater salinity is evident in the middle and lower reaches of catchments in the southern plains area with groundwater becoming brackish to saline along the international border. The domestic water demands of most of the rural population are currently met through use of aflaj or private well supplies. Potable water demands of the Ibri, Dank and Yanqul areas are now being met by supplies from the Al Massarat Groundwater Supply Scheme.

The relatively thin alluvial aquifer systems that occur throughout the mountainous upper catchment areas are extensively developed for agriculture. There are a number of areas where installed capacity and water use exceeds mean annual recharge causing serious temporary depletion. The water situation in these areas is naturally exacerbated during droughts when aquifer dewatering may occur on the margins of the alluvial channels. Elsewhere in upper catchment areas, water levels show no evidence of significant long-term decline, but the large number of falaj support wells indicates that falaj flow has been affected by increased local pumping in many areas.

The development of oil industry in the central and western plains area has created significant demand for water for use in reservoir flooding and enhanced oil recovery. Demand is largely being met with use of the brackish and saline waters from the Upper Fars Formation. A protection zone has been established for the Al Massarat aquifer to protect the wellfields from pollution and depletion. Protection Zone will be established to protect from pollution the wellfields for the supply of water to the township of Mahdha.
he Dakhiliya region links Muscat and Al Batinah coast with the rest of the country through the Samail gap. It is a region of great beauty with a rich history. The geomorphology of the region is dominated by the rugged mountains of the Jabal al Akhdar and the wadis draining from these mountains. The longest of them, Wadi Halfayn extends nearly 200km, and on rare occasions discharges at the coast opposite Masira Island. Other well known wadis include Mu’adin, Ghul and Tanuf; many wadis flow into the desert, toward the Umm as Samim ‘sink’.

The mountain ranges of Dakhiliya expose limestones of the Hajar Super Group (HSG) with an extensive, more subdued area of Samail ophiolite hills in the east. Within the piedmont/plain zone, outcrops of Hawasina sediments are interspersed with small alluvial fans and plains, incised by active wadi channels. To the south, a ridge of HSG outcrop extends east and west of Adam township constricting groundwater and surface water flow to narrow gaps through which discharge to an extensive gravel/desert zone occurs.

Annual rainfall generally exceeds 300mm in the mountains; the mean annual rainfall recorded at Jabal Shams (2,820 masl) is 387mm. Within the piedmont zone, where elevations are typically in the range 500 – 1000m masl, mean annual rainfall tends to fall within the range 100 – 200mm declining to 68mm at Adam and 30mm at Fuhud (elevation 170m masl). There is no distinct wet season, but the average rainfall pattern is characterised by two ‘wetter’ periods. The main wet period is the 3-month period February to April, which accounts on average for about 40% of the total annual rainfall. The second wet period is from July to August, accounting for another 30%, which results from the effects of the khareef/monsoon blowing from the south.

The Late Tertiary and Quaternary alluvial sediments associated with wadi courses comprise the principal aquifers in the area. Low to moderate yields may also be obtained from the Hajar Super Group units (notably the karstic and fractured Wasia limestones) and upper, weathered ophiolite horizons. The indurated Hawasina sediments generally exhibit relatively poor open fracture development and hence have limited water potential; the exceptions are the limestones/dolomites/basalts. In the south and lower catchment areas, Tertiary marine, lacustrine and continental deposits host brackish to saline water and, generally, have limited aquifer potential in this area. Tertiary carbonates and marl formations

Past and present settlements have followed the course of water.
of the Hadhramaut Group are exposed at Natih and Fahud and underlie a large part of the lower catchments of Wadis Umayri and Aswad.

Potable water occurs throughout the middle and upper reaches of wadi courses. Groundwater quality deteriorates southward becoming saline to hypersaline within the desert lower catchment areas. Pockets of fresher groundwater associated with the major wadi channels do occur locally. Local anomalies in groundwater chemistry have been identified and assigned, variously, to hyperalkaline inflows, domestic pollution, irrigation returns, local recharge and carbonate precipitation.

Nizwa township, the capital of the Ad Dakhiliya region, obtains its municipal water supply from two wellfields – Izz and Al Abyad. The supply of water to the town has increased four-fold since 1985. A marked increase in supply is evident from early 1994 coincident with the installation of a piped reticulation network within the town centre. Current municipal water demand stands at about 4,500,000m$^3$/yr with monthly demands varying seasonally from about 250,000m$^3$ (winter) to about 400,000m$^3$ (summer). The demand is met largely from the Abyad wellfield (>80%). Water from the Izz wellfield is of inferior quality and requires blending with the better quality Abyad water; as a consequence supply from Izz is limited to 20% or less of the total.

Several recharge dams have been constructed in the region – Quriyat, Ghul and Tanuf. The construction of Wadi Quriyat Recharge Dam was completed in February 1986. This was the first dam constructed in the Interior; it is a composite of gabion, earthfill and rockarmour, 5.3m high with crest length 1,620m. The dam is located on Wadi Sayfam about 12km northwest of Bisyah and has a storage capacity of 0.13Mm$^3$. The construction of the Wadi Ghul Recharge Dam was completed in June 1989. It is located in the relatively narrow gorge of Wadi Ghul about 1.4 km upstream of the motherwell for Falaj Al Hamra. The dam is built from gabions as a cascade weir with height 7.6m, crest length 415m and effective reservoir capacity 0.45Mm$^3$. A 17m high dam was also constructed in 1989 on Wadi Tanuf, just upstream of Tanuf township. It has a capacity of 0.68Mm$^3$. The construction of Wadi Maudyn recharge Dam was completed in December 2002, with 10m high and capacity of 2.5Mm$^3$.

Two small recharge dams, Al Ala and Rahba, were built on Wadi Al Ala in 1996, both with catchment areas of about 10km$^2$. They are both gabion
structures of about 190m crest length; their heights are 4.5 and 5.5m respectively, and their effective reservoir capacities are 0.035 and 0.05Mm³ respectively. A very small storage reservoir has also been constructed in the upper reaches of Wadi Al Ala to supplement local water supplies. Its name is Ras Al Wadi, a small dam of 18 m length and 4.2m height, with a storage of 700m³. Numerous small storage structures have also been constructed throughout the mountain ranges to supplement village supplies. They range in height from 4 to 8m and are constructed of stone and cement mortar. Storage capacity varies from 1,000 to 10,000m³. Current studies have identified and proposed the establishment of the Abyad, Al Ayn, Manah, Sfaiyah and Adam Wellfield Protection Zones (WPZ) to protect wellfield supplies for major settlements.

Key Issues identified within the Dakhiliya region:

- Locating and protecting secure potable supplies for all major settlements.
- Delineation and implementation of protection zones for all potable supply wellfields.
- Widespread water quality deterioration.
- Augmentation of potable water supply to major cities.
- Repair and maintenance of falaj supplies.
- Relief of stress on alluvial aquifers.
- Improvement in farm practices.
- Maintaining continuity of water supply to small isolated communities in mountainous upper catchment areas, many of which experience short term water supply problems.
Ash Sharqiya

Ash Sharqiya lies 100km south of Muscat, on the southern flanks of the Al Hajar Ash Sharqi mountain range, and extends over an area of 40,000km². With eleven wilayats and a total population in excess of 300,000, Sharqiya is the third most densely populated region in Oman. The major inland settlements in the region lie on the courses of Wadi Andam and Wadi Al Barha - two long basins which drain from the ophiolite mountains to the Arabian Sea, flanking the western and eastern sides respectively of the Ash Sharqiya sands. Both wadis originate from a series of generally south flowing tributaries which rise in the Ash Sharqi Mountains. Very little of the substantial flows generated in these wadi actually reach the sea as a result of high infiltration within upstream alluvial fan and wadi alluvium.

Rainfall in the mountains of Ash Sharqiya is generally in excess of 200mm reducing to less than 100mm in the alluvial plains and in the Eastern Sands. For most of the region the three wettest months are February to April, which account on average for more than 60% of the total annual rainfall. In some areas, a second but less pronounced relatively wet period occurs between July and August, which results from the effects of the khareef/monsoon blowing from the south.

Tertiary and Quaternary alluvial deposits collectively form the main aquifer and supply the majority of groundwater in the region. These sediments generally provide good yields and are the easiest to develop. Well yields do vary considerably locally depending upon the nature of the wadi deposits, their saturated thickness and degree of sorting and cementation. In Wadi Al Barha, the alluvium is typically less than 40m thick around Ibra and ranges in composition from clay to boulder and in many instances has been weakly- to strongly-cemented. Downstream the alluvium thickens to more than 600m with a significant increase in clay content. The alluvium receives recharge from direct infiltration of rainfall, wadiflow infiltration and bedrock seepage. For smaller wadis, the alluvial cover is generally quite thin (< 20m) away from the main wadi channels.

In the northern Sharqiya Quaternary aeolianite overlies the alluvium, attaining a maximum thickness of about 100m. The aeolianite contains a large body of fresh groundwater. This groundwater is largely ‘fossil’ groundwater derived during a wetter climatic period, several thousand of years ago. Recharge to the aeolianite is limited to direct infiltration of minor amounts (< 2%) of rainfall. Within the mountains, fractured Tertiary carbonates have development potential locally but
their location often makes them relatively difficult to develop and yields from these rocks are variable and unpredictable. Ha-wasina Nappe sediments generally exhibit relatively poor open fracture development and have limited groundwater potential. Groundwater quality is typically good in the middle and upper catchment areas with TDS of less than 1,500mg/l. Water quality deteriorates significantly, however, in the vicinity of all major townships and agricultural developments due to recycling and agricultural and domestic pollution. Higher TDS values also occur in the alluvium of coastal areas and probably reflect upconing of sea water. The alluvial aquifer is now highly developed with several hundred aflaj systems and several thousand wells. Two areas of groundwater depletion have been identified near Butaymah and Kamil. While both zones are quite extensive, they are also predominantly quite shallow.

A major recharge dam (Al-Fulaj Dam) was constructed in December 1991 and is situated on the lower Wadi Rafsah upstream of Sur. The dam is designed to enhance recharge, limit outflow losses to the sea and assist in controlling saline intrusion. A desalination plant with a design capacity of about 2,590m³/day supplies Sur; a wellfield exists in Wadi Al Fulaj to provide contingent groundwater supplies. Smaller units, capacity <60m³/day, meet potable requirements at Ras Al Had and Aseelah. Studies have identified the need for the establishment of a Wellfield Protection Zone (WPZ) to protect the Ibra and Sur wellfields from pollution.

Key Issues identified within the Ash Sharqiya region:

- Strategic development and management of the Eastern Sands groundwater resources.
- Locating and protecting secure potable supplies for all major settlements.
- Preservation and management of the prosopis forest and Eastern Sands.
- Maintenance of falaj supplies.
- Improvement in farm practices and introduction of urban wastewater collection and treatment facilities to reduce water quality hazard.
- Control of seawater intrusion in coastal agricultural areas.
Dhofar

Dhofar, spelled also Zufar, is an historical region in southern Oman, extending from Ash Sharbathat on the coast of the Arabian Sea south-westward to the Oman-Yemen border. The region is separated from the rest of Oman by a huge stretch of open desert, stony plains and sand dunes. Wooded mountain ranges - the Al Qara Mountains - rising to about 1500m, form a crescent in southern Dhofar behind a long, narrow coastal plain on which is located the provincial capital of Salalah. Behind the mountains, gravel plains gradually merge northward into the Ar Rub Al Khali desert.

Dhofar accounts for almost one third of the surface area of Oman. It is divided into nine wilayats. The geographical, social and economic diversity is based on three natural landscapes: the coastal strip, the mountain district, and the Nejd. The coastal strip is around 560km long, having an area of 1500km$^2$, or 1.2% of the total area of the Governorate. All along the coastal plain are well-populated towns and villages. The Salalah coastal plain, about 60km long and from 2 to 20km wide, facing the Arabian Sea, is considered one of the most beautiful in Arabia, particularly in its southwestern part, because of its monsoon climate and temperate vegetation and bird life. Throughout the three autumn months much of the province wears a lush cover of grass and low green vegetation beneath an umbrella of mist and light drizzle.

Most of the agricultural development in Dhofar is in the Salalah Plain where fresh groundwater beneath the plain, and springs which issue from the mountain foothills, are used for irrigation. Major crops include coconuts, alfalfa, sorghum, bananas, and vegetables. Dhofar is the world’s leading source of frankincense and is Oman’s main cattle-raising area, primarily for milk. There are oil fields in the northeast.
Jebel Dhofar

The Green Mountains of Dhofar consist of a high sierra 400km long, west to east, approximately half of this being the contribution of the Jabal Al Khadra, which rises up from the western frontier adjoining the Yemen and run eastwards across Dhofar. This ridge of mountains is around 23km wide and occupies a total area of 2,300km$^2$. This highland area receives the monsoon rains which are caused by cooling of the very humid and warm south-westerly trade winds as they pass over the cold upwelling sea and are drawn over the one kilometre high Jabal Al Qara by the interior low pressure system. The rains are accompanied by dense clouds and mists which are almost continuous throughout July, August and September. The fog bank is approximately 180km long and less than 40km wide from the coast to the northern watershed where it abruptly dissipates.

After the rains, numerous springs appear within the foothills, covering the ground with a carpet of grass and small plants. A number of springs continue to provide plentiful water for many months of the year. There is a dense ground cover of woody shrubs as well as other vegetation in the wadis. The local inhabitants use the branches of these shrubs as roofing material for their homes, and they manufacture timber door and window panels from the trunks. In this part of the region the olibanum or frankincense trees grow and there is abundant pasture vegetation for the local herds and production of dairy products and meat. These constitute a principal source of income for the Dhofaris and contribute in a fundamental way to raising their standard of living.

The rural environment in the Dhofari mountains, and other districts and regions where water and vegetation are plentiful, provides a suitable habitat for settlement and from centuries past the mountain dwellers have divided this region amongst the various tribes, each tribe living in a specific area with its individual lifestyle, with water and pasture for their herds as well as caves to which they retired in the winter to shelter from torrential rains and the regular assaults of gales and storms. They also make huts from the branches of trees which they then cover with a layer of dried vegetation, and these are habitable once the weather stabilises and daily life returns to normal.

This wide network of modern roads has been constructed in the Dhofar mountains during the Renaissance of Sultan Qaboos. A number of administra-
tive centres have been established in the mountain areas to provide the local inhabitants with a range of essential services. These include administrative offices, schools, health clinics, mosques, and goods stores maintained under government supervision as represented by the office of the Minister of State and Governor of Dhofar.

Salalah Plain

The Salalah Plain is triangular in shape, reaching from the foot of Jabal al Qara to the Arabian Sea and from the coastal town of Taqah in the east to the port of Raysut in the west. It extends along the coast for 40km, inland for about 12km at its widest point and covers an area of 240km². Salalah is located on the coast in the central part of the plain. It is the main residential, commercial and agricultural centre of Dhofar, while Taqah is of secondary importance. Traditional agriculture extends along a narrow strip between the coast and the urbanised area. Large scale agricultural development occurs to the north and east of the town. Water for agricultural use is pumped mostly from dug wells and boreholes located between the town wellfields and the sea. Additional water for agricultural use is carried by aflaj from four springs located at the foot of the jabel, though aflaj are relatively uncommon in Southern Oman.

The Salalah Plain is underlain by limestones of the Taqah Formation, with a mostly thin covering of wadi alluvium and calcarenite. The alluvium reaches thicknesses of up to 40 metres under major wadi channels. Groundwater is contained extensively in the alluvium and the limestones. It is however primarily related to the fissured and karstic zones of the uppermost, member of the Taqah Formation. The hydrogeological characteristics of the aquifer are complex, with wide variations in transmissivity throughout the area.

The groundwater resources of the Salalah Plain depend on a tongue of fresh groundwater which extends through the centre of the plain to the coastal margin. This area is flanked to east and west by more brackish groundwater. Saline intrusion is occurring along the coastal margin. The brackish waters to east and west appear to have a geologic origin and to be unrelated to present saline intrusion along the coastal margin. Smaller zones of freshwater occur within the brackish water areas, which are related to major wadis.
Nejd

Nejd, meaning highland, is one of the major physiographic features of the Arabian Peninsula. The western part, known as Upper Nejd, lies within the Arabian shield with an average elevation of 1200m; the eastern part falls within the sedimentary province with the city of Ar Riyadh, near the eastern edge, having an elevation of about 600m. Nejd constitutes the greater part of the Governorate of Dhofar; it covers an area of some 50,000km$^2$ north and west of the Jebal Dhofar. The mountains of Dhofar could be termed nature’s dividing line, determining the distribution of water between the mountain region and the Nejd. In time the clouds coming in from the direction of the coast have traversed the Dhofar mountains, they have discharged the greater part of their moisture in the form of rainfall on the southern foothills. Those clouds which succeed in crossing the mountains generate a formidable rise in the humidity of this desert region.

Mean annual rainfall in the Nejd ranges from 40 to 71mm with an average overall of 49 mm per year. Such averages can be misleading as in many areas the only falls are associated with cyclones that occur every 7 to 10 years. Thumrait may be used as an example: 227mm of rain was recorded in 1989-90 which is about 6 times the average. In the following year only 6mm was recorded and in the year after that zero. The principal drainage of Nejd consists of a number of northerly and northeasterly-trending wadi systems that carry water only seasonally. The wadis have cut deeply incised canyons into thick limestone sequences along the southern, mountainous margins. Immediately north of the mountains, foothills merge with a relatively undissected, limestone plateau of gentle to moderate slope. This plateau is overlain by an extensive sand dune system in the north and northwest (Rub Al Khali) and merges with the Jidat Al Harisis plateau in the west.

There are no perennial wadis. Some ungauged flows enter the region from Yemen. Wadis on the plateau generally remain dry throughout the year, but occasional cyclonic events may generate large, short term flows. Large wadi flows are infrequent even in the southern Jabal areas; average flows are generally less than 1Mm$^3$/yr. Infiltration of runoff to highly permeable karstic features (sink holes, caves, solution channels etc.), in upstream mountainous catchment areas is likely to be significant and an important recharge process throughout.
Key Issues identified within Dhofar:

- Optimal development of water reserves for agricultural or other uses.
- Treatment and disposal of dehydration water from the oil production wellfields in the Marmul area.
- Reduction in fluoride levels in domestic supplies.

The Nejd has reserves of fresh and brackish water stored over a long period of time.

The southern Jabals comprise Tertiary carbonates which comprise a 500m thick, flat lying, ‘layer-cake’ sequence, which dips gently to the northeast at 0.5–1°C. Aquifers occur within the Tertiary Dammam, Rus and Umm Er Radhuma (UER) formations of the Hadramaut Group. The UER contains large reserves of fresh and low brackish groundwater and is the most extensive and important regional aquifer. In the Jabals, Hadhramaut Group aquifers are essentially unconfined. Although potential exists for some modern-day recharge, isotope data clearly shows that recharge to the UER is minimal under the present climatic regime and that groundwater in storage within this large regional aquifer is essentially derived from recharge during past pluvial periods.

In the southern Jabals, domestic (and livestock) water supplies for the small, nomadic rural population were traditionally obtained from springs, many of them only seasonal. Now, most of the domestic and livestock demand in the Jabals is provided via government wells and pipeline networks which transfer water to reservoirs and supply points. Water quality is moderate to good except in the north eastern Jabal Qara area where salt concentrations and fluoride levels can locally exceed quality standards.

To the north, in the plateau area and extending beneath the Rub Al Khali, the Umm Er Radhuma (UER) formation aquifer becomes confined with contained water under artesian pressure. Water quality deteriorates along the northerly and northeasterly flow paths from marginally fresh in the southern jabals to brackish in the north. All Nejd groundwaters and particularly the UER, show high fluoride levels and are frequently aggressive and corrosive to metals due to the common presence of H2S and other corrosive sulphides.

PDO currently generates about 6.2Mm³/yr of oil dehydration water in the Marmul area. About 1Mm³/yr of this volume is injected back into the producing horizons with the balance disposed of. This water represents both a potential pollution source and resource for reuse, possibly in agriculture. A pilot study has been commissioned at the Rahab Farm, Marmul to investigate the use of reed beds as a water treatment method.

The extent of water resources underlying the Nejd is vast. These reservoirs can be used for future agricultural development. Flowing wells near Dauka discharged freely for many years with little apparent loss of pressure, indicating the potential to sustain developments over a long period. Only small water level
changes have been recorded in wells serving the farms at Marmul. On the other hand, abstractions at Thumrait have caused falls in the water table approaching 100 metres from 1974 to 1990.

Development potential is significant. Careful water management is demanded however with a high degree of aquifer confinement and limited recharge. Under such conditions, abstraction is accompanied by widespread reduction in water pressure which can cause significant declines in well water levels – a major determinant in the cost of pumping and thus the economics of agricultural development.
Both the history and geography of the Governorate of Musandam set it aside from the other regions of the Sultanate. This rugged mountain range traces its origin to the Cretaceous and Miocene ages, about 1,850 million years ago. Those who read about the birth of the wondrous mountains in Musandam will be amazed. The story begins with vast changes in the topography of the world. Some areas separated from their original land mass and others collided, causing the formation of two of the most important mountain chains, the Alps in Europe, and the Zagros mountains to which the mountains of Oman belong. In the following age the mountains of Oman separated from the Zagros mountain range. This occurred at the same time as most of the continents appeared and the volcanoes around the Pacific Ocean and the Red Sea became active. The earthquakes which occurred explain how the mountains of Oman broke away from the Zagros, they also caused the Earth’s crust to fall away in the area of the present Strait of Hormuz. This in turn caused the rending of the Zagros mountain chain so that it divided into two mountain chains, one of them being the mountains of Oman. With rugged mountains rising up to 1,800m and a coastline with a spectacular fjord-like appearance, this region is rightly becoming a tourist venue. Roads have been built. Before 1970 the only means of transport was by donkey or foot. Even camels could not take the paths which were much too steep for them. One excellent way to discover Musandam, its fjords and hidden creeks, so deep that they cannot be seen from the sea, is of course by boat.

Musandam is slightly wetter than most parts of the Sultanate, its average annual rainfall being about 180mm. Flash floods from the relatively small and steep catchments can be a problem for coastal communities, which are usually situated on the alluvium at wadi outlets to the sea. Water supplies in Musandam are drawn almost entirely from wells and boreholes in the coastal alluvium. In some inland areas, small communities derive their domestic supplies from rainfall collected in cisterns or birkats. The groundwater storage in the coastal deltas is generally limited and is therefore vulnerable to droughts. Traditional agriculture has been constrained to match the reliably available water supplies. In some areas, pumping to meet the needs of recently-increased agricultural areas has put a strain on the traditional water supplies, and saline intrusion has resulted locally.

At the Khasab municipal wellfield, five kilometres from the coast, water levels have been generally stable due to enhanced recharge resulting from the...
three Wadi Khasab flood protection dams constructed in 1986. The small municipal wellfield at Daba is only 2.5km from the coast. It is threatened by saline intrusion caused by excessive pumping. There has been a notable downward trend in groundwater levels since at least 1985. To limit further degradation, declaration of a protection zone around the wellfield is planned and the potential for artificial recharge through small recharge/flood control dams is being investigated.

In view of the mountainous features of Musandam Governorate and the lack of aquifer systems, the people of Musandam have for a long time devised systems for harvesting water, known as ‘Birkat’ or Cisterns.
Al Wusta

Al Wusta lies to the south of Ad Dakhliya and Al Dhahira in the east, the Arabian Sea, the Kingdom of Saudi Arabia to the west and in the south the Governorate of Dhofar. The region covers about one quarter of the country and is sparsely populated; it comprises four distinct areas: Al Huqf, Central Plateau, Ar Rub al Khali desert, and Umm as Samim sabkha.

The region is a gravel desert with escarpments running down to the coast where the main occupation is fishing. Inland lie Oman’s oil, gas and mineral deposits. Although mostly hot, dry desert, the region has a number of special characteristics, geographical formations and natural locations that are of great interest and provide a suitable environment for a wide range of fauna including the graceful gazelle, desert rabbits, the sand and red fox and the mountain goat and about 130 types of birds, including the golden falcon, the spotted plover, the lark and the bustard.

The indigenous population is the Harasis. Within their extensive stony and sandy territory, water could only be found along the Awta, an escarpment near the coast, between Duqm and Al Hajj. Water was rationed and they compensated for this deficiency by drinking large quantities of goat or camel milk. They spent winter in the Jiddat where their herds found food. In summer they left this plateau to return to Awta and the springs in the south. The oryx like the Harasis have always lived in this great inhospitable desert. They too could live without water for long periods, being content with the dew left by the early morning fog and covering kilometres to find some pasture.

Since the Renaissance, there have been major improvements in the development of the region with infrastructure and establishment of an administrative centre in Haima including schools and a hospital. Rural life for the Harasis has also been facilitated by construction of many water wells and local employment opportunities offered with the presence of oil companies.

Mean annual rainfall in the Al Wusta region is less than 50mm; storm events are infrequent and, in many areas, precipitation is limited to extreme cyclonic events. Groundwater flow in the region emanates from recharge zones in the mountainous areas in northern and southern Oman. The main regional aquifer system is the Umm er Raduma (UeR) Formation which typically occurs at depths of more than 200m. Throughout most of the region groundwater quality in the UeR and shallower formations is brackish to saline. Regional ground-
water discharge occurs in the Umm as Samim sabkha and in the Huqf to the east, where highly fractured pre-Tertiary basement outcrops border the Arabian Sea.

The largest discharge feature is the legendary Umm as Samim sabkha spanning the western borders of Oman, where halite caps the shallow saline groundwater. This is generally regarded as the major discharge point of flow within the UeR originating both from the north and from the south.

Fresh groundwater is relatively uncommon in the region but can occur as narrow lenses overlying the saline regional groundwater. The lenses are scattered throughout Al Wusta and adjacent regions, and are the only natural sources of potable water. The lenses are recharged locally, wherever the landscape and surface topography permits water to concentrate along wadis or in closed depressions, during the rare recharge events. The evaluation of the potential of freshwater lenses has been a high priority in groundwater investigations across Al Wusta.

Detailed studies have been undertaken along Wadi Rawnab and near Ma’abar, both of which involved investigation drilling. Improved understanding of the runoff/recharge processes was facilitated by the study of the tropical cyclone which passed over Al Wusta during early October 1992 producing heavy rain over a wide area. During and after the rainfall period, samples of rainfall, runoff and wadi flow waters were taken for chemical and isotopic analysis. The results showed that, during the short period on the surface, evaporation was minimal and the runoff/recharge water was virtually fresh (less than 500μS/cm) with salinities similar to those observed in the freshwater lenses.
Umm as Samim

Umm as Samim, a great inland sabkha lake is Oman’s largest sabkha. It is a terminal point for floods flowing from the western part of Al Jabal Al Akhdar and a discharge area for regional groundwater flow systems.

Sabkhas or playa lakes form in natural depressions of inland centered drainage systems, when the evaporation is greater than water inflows from tributaries. They are numerous in all arid areas, with Umm As Samim having some semblance to Australian dry lakes Eyre, Torrens and Gairdner.

As in Australia, the surroundings of Umm As Samim are inhospitable: the surface of such sabkhas are treacherous and threaten to drag intruders into a bottomless mud of fine sediments brought from the mountains. The shallow groundwater is highly saline, and there is not much to see and look for. However, such areas are of significant scientific interest. They are good indicators of climatic changes, form a very specific environment, the subject of numerous studies on limnology, hydrology, geology and related sciences. Oil exploration and production is the only human activity here, on the northern edge of the sands of Rub Al Khali.

After major floods Umm Al Samim sabkha temporarily becomes a shallow lake. With the present surface area of 2,000km$^2$, an average depth of 1m of water would provide storage of some 2km$^3$ of water. With the annual evaporation rate of 2,00mm it would take less than a year for the lake to evaporate. Some natural recharge of the underlying formations also takes place.

Satellite images reveal an ancestral Greater Umm as Samim, which existed under past pluvial regimes, thousands of years ago. Its surface area was several times larger than the present sabkha, and with greater and more regular inflows and lower evaporation, it may well have been a permanent body of water at that time.
Accurate records of water use in Oman can only be derived for those supply schemes that meter water delivery. In practice, this relates only to urban systems operated by the Government and some private sector industries. Completion of the National Well and Falaj Inventories has, however, for the first time enabled derivation of reasonable estimates for water use throughout the country. The water use determined for supplies provided by wells and aflaj is shown in the figure below. The total withdrawal of groundwater in Oman is estimated to be 1131 Mm$^3$/yr of which about two-thirds is withdrawn via wells and one-third from aflaj.

The vast majority of water withdrawn is utilised for agricultural purposes. For both well and falaj irrigation, traditional methods of flood irrigation remain most common and a significant proportion of the groundwater abstracted returns to the groundwater reservoir through leakage in irrigation channels. This identifies major inefficiencies in irrigation practice but not a loss of water from the system. Real water loss comes through evaporation and consumption for beneficial agricultural, domestic or other purposes.

**The Objectives of the National Well Inventory:**

- **Agricultural Water Use:** The total volume of water used for agricultural purposes is estimated to be 1,131 Mm$^3$/yr of which about 70% is for beneficial use.

- **Domestic, Commercial, Municipal and Industrial Use:** The present water supply for domestic, commercial, municipal and industrial purposes in the Sultanate is estimated as 169 Mm$^3$/yr of which two-thirds is derived from groundwater and the balance from the desalination of seawater. It is estimated that three quarters of the present supply returns to the hydrological system as wastewater and pipework leakage, although 12 Mm$^3$/yr is collected and reused for municipal greening. Total water consumption is currently estimated to be about 44 Mm$^3$/yr.

- **Environment:** Water may also be used under natural conditions. There are a number of localities within the Sultanate where natural vegetation directly consumes groundwater. Of particular note are the Prosopis cineraria forests in Ash Sharqiyyah and the lush tropical vegetation found in secluded valleys within the Dhofar mountains.
Human beings need only about 5 litres of water each day for cooking and drinking according to the World Health Organisation, however, good health and cleanliness require a total daily supply of 30 litres per person; this amounts to 11 cubic metres per year. The United Nations recommends 75 litres per person as the minimum limit for the acceptable domestic water standard. Industrialised countries, which have usually developed in water-rich areas, tend to use much more than this.

Water consumption levels vary widely between different countries but also between sections of society within individual countries. In the developed countries, for instance, daily domestic per capita water consumption varies from a low of 100 to a high of 2,000 litres, with the overall average daily use around 300 litres per person in the year 2000.

Total water demand of the system is the total quantity of water entering the area divided by the total population served. It includes domestic, commercial and industrial use of water and leakage of water from the distribution network upstream of the individual consumer’s connections. The term water consumption refers to the water delivered to the consumer, generally measured at the boundary of his property. Total water consumption of an area is based on meter readings, where available, or is estimated from sample metering or by other means. There is a tendency for consumption to increase with convenience of supply.

**FACT FILE**

- The number of people lacking access to clean drinking water worldwide is 1.3 billion, or 23 percent of the world population.
- Throughout the world the annual withdrawal for domestic and municipal usages is 52 m$^3$ per person.
- A preliminary agricultural phase of intensive food gathering in the Middle East about 9,000-7,000 BC, when man passed from hunting and gathering to food producing or agriculture.
- The use of irrigation for agricultural purposes is an ancient practice. It can be traced to the early Egyptians, who were irrigating fields with water from the Nile River by 5,000 BC. Evidence shows that other ancient civilizations, such as those of the Babylonians and the Chinese, also developed largely as a result of irrigation-based agriculture.
- The largest areas under irrigation are located in China, India, Pakistan, and the United States.
A rcheological evidence confirms that Omanis have engaged in industrial activity for many centuries. Copper was extracted in Sohar 5000 years ago, smelted, and exported to Sumeria, Iraq, Mesopotamia and other countries. There are numerous written accounts which refer to Oman as the land of palms and copper mines. These mining operations continue in Sohar today. In 1998, the Sultanate produced 24,360 tonnes of copper, 1560kg of gold and 4,692kg of silver. Other mined and quarried materials include marble, limestone, gypsum, salt, chromite and building materials. The proven reserves of copper, gold, silver, chromite, coal and silica are significant, and, therefore, this sector is expected to increase from 0.3% of GDP to 2% GDP in 2020. These industries require water for washing, cleaning or concentrating their product.

With the advent of the Renaissance, the petroleum industry has continued to increase production to meet demands. Oman ranks seventh in the league of Arabian oil producers, with a present output capacity of one million barrels per day. The Sultanate’s future status as an energy producer and exporter also lies with ongoing exploration and development of its natural gas reserves. The Sur Liquefied Natural Gas plant is technologically among the most advanced in the Middle East. Its annual output capacity is 6.6 million tons, for which long term export contracts have been signed.

The oil and gas industries are actually net producers of water. However, this water is generally of poor to very poor quality being contaminated with hydrocarbons, salt and a range of toxic chemicals, particularly heavy metals. This water, which is an unwelcome by-product of oil and gas extraction, may be re-injected to enhance oil recovery but where this is not possible it presents a dangerous pollution hazard requiring careful containment and disposal. Trials are being conducted to investigate biological methods of cleaning this water so that it may become

**Industrial Use**

**Water in Industrial Processes**

1. **PETROLEUM REFINING**

Petroleum refining is a distillation process. The crude oil is heated to boiling and each product is separated in accordance to its boiling temperature in a fractionating tower where vapour is condensed and cooled by water. Many of these petroleum fractions must be specially treated by cracking or reforming molecules, then redistilled to make products which will meet the required specifications. All of this takes considerable heat, followed by quick cooling with water. Fresh water is needed for steam generation, to replace evaporation and blow-down from cooling towers, and for washing the gases and liquids in the process streams. Steam is used for a number of purposes in a refinery, in the generation of electrical power for operation of the plant, in chemical reactions, and in providing heat in certain chemical processes. Recently, there has been substantial increase in the rate of recirculation and reuse of the initial intake supply by refineries before the deterioration of water quality requires its discharge.
a useful resource. In the Nimr, Rima and Marmul areas, the salinity of some of the water is relatively low and may be reusable locally if the pollutants can be removed at a reasonable cost. PDO is now building a pilot project at Nimr using reed bed technology that will remove toxic elements from the oil production water and make it suitable for irrigation of certain salt tolerant crops and to produce industry-quality salt as a by-product.

Water is used in many technological processes. Because uses of water in the industry are so different, the quality of water can vary accordingly. The food processing industry, for example, requires large volumes of clean water which meets potable water standards, because raw foods must be clean and wholesome for human consumption and food processing plants must be sanitary at all times. Many commercial and industrial activities are carried out within the boundaries of the municipalities, but on a larger scale they are located in Industrial Estates. Water supply is provided by both public and private sources and the supply is monitored by both the Public Establishment for Industrial Estates and the Ministry of Commerce and Industry. The Ministry of Commerce and Industry requires all new business ventures to obtain a No Objection Letter from the Ministry of Regional Municipalities, and Water Resources and it encourages them to use water-efficient techniques.

### Water in Industrial Processes cont.

#### 2. CHEMICAL INDUSTRIES

The separation and purification of substances with the use of water are also fundamental operations in the chemical industry. Large volumes of water are often required to extract heat from products or to use the water as a reactant which is chemically or physically combined with other substances. For example, water reacts with calcium carbide to form acetylene, the basic material for a large organic chemicals industry. Another type of reaction is the hydrolysis of animal fats to produce glycerine and fatty acids for soap manufacture. The list of water use functions in chemical or chemical-related industries is endless.

#### 3. STEEL INDUSTRIES

Cooling and process water also play prominent roles in the steel industry. The reduction of iron from its ore, the compounding of this iron into pig iron, wrought iron, carbon steel, and alloy steels, and, finally, the forging of these products into usable shapes, are all done at very high temperatures. Water is used for cooling parts of the furnaces, the rollers, and skid rails. Hot billets are descaled by means of high-pressure water jets which provide a combination of thermal shock and mechanical action. Steel is pickled in a strong acid solution to remove mill scale and then rinsed with water. When the metal is to be tinned, galvanized, or chemically coated for corrosion protection, it is passed through successive tanks containing alkaline detergent solutions and rinsed in water.

As impressive as the many uses of water in industrial processes may be, however, the greatest use of water by industry is for cooling, not processing.
Since time immemorial people have been engaged in the cultivation of plants and the domestication of animals. Production of food has always required more water than any other activity, since as they say, it is not earth that bears fruit but water. Water is the governing factor for human activities, and this is especially true in arid countries.

Water dictated where settlements could be found and how their inhabitants earned their income. The size of the communities was also clearly related to the availability of water. The availability of water is a critical factor for Omani agriculture.

Historically, falaj fed agriculture developed where higher elevation water sources such as springs, qanats or wadis could be intercepted by diversion or small catchment dams and then conveyed by gravity to the point of use or the construction of the dawoodi aflaj in areas of shallow water table. More recently, however, dug wells have been used to supplement falaj water. This is especially the case in the coastal areas where many hand-dug wells and tubewells have been constructed.

Data from the National Aflaj Inventory indicates a net cropped area of the order of 18,000ha. Date palms occupy nearly 60% of the area irrigated; citrus, mango and other trees occupy a further 15%. Fodder crops occupy 9% and the remaining 6% is made up of cereals (mainly barley, wheat and sorghum) and vegetables. From the the National Well Inventory it has been established that 59% of the total number of operational wells support agriculture with total net cropped area irrigated of the order of 38,000ha with two-thirds on Al Batinah. About 40% of the well-irrigated area is occupied by dates, 25% by citrus, banana, mango and other trees, 25% by alfalfa and Rhodes grass with the remaining 10% predominantly under vegetables.

**Dates: the gold of the Desert**

Date palm *(Phenix dactylifera)* plantations occupy approximately 50% of the cultivated land in Oman: some 35,000ha of land are planted with 17 million date palms. The Omani people have lived with this tree for centuries. The date palm is invaluable for the dwellers of the desert because of its adaptivity and the wide range of its benefits. Date palm provides the family with many of
How many dates are harvested from one palm tree?

<table>
<thead>
<tr>
<th>Quantity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>World Average</td>
<td>20kg</td>
</tr>
<tr>
<td>Al Batinah</td>
<td>34kg</td>
</tr>
<tr>
<td>Very good Palm</td>
<td>300kg</td>
</tr>
<tr>
<td>World Record</td>
<td>400kg</td>
</tr>
</tbody>
</table>

Agriculture, especially date palms, consumes the largest portion of available water.
Irrigation

Irrigation is the artificial application of water to land. In temperate and tropical regions, which have usually 500–2,500 mm of rainfall per year, vegetation grows on soil watered by rain. In arid countries rainfall is insufficient and erratic, and all agriculture is based on irrigation. There are numerous methods of irrigation but they can be classified into three groups, as shown on the left. Each method has its benefits and drawbacks.

- Flood irrigation is the oldest method and is used extensively in all countries throughout the world. In the flood system, water is applied at the edge of a field and allowed to move over the entire surface to the opposite side of the field. The method works well when water is abundant. Losses to evaporation are quite large, and usually some form of drainage is required to remove excess water. Salinisation may become a problem.

- Spray irrigation requires little preparation, application rates can be controlled and the system allows the application of chemicals. Many automatic or semi-automatic moving sprinkler systems travel over the field applying water. The main drawback is that much more water has to be used than the plants actually require. Losses to evapotranspiration are quite significant and use of water with higher salt contents is likely to cause a salinisation problem in the longterm.

- The concept behind micro-irrigation is to deliver to each plant the correct amount of water. Therefore, water is delivered to each plant separately. The most advanced system delivers drops of water at the root level. Very little water is lost to evaporation, and losses to transpiration of plants are kept to the minimum. Higher costs of installation are quickly offset by lower water use.
The water balance of the Sultanate may be considered as the local version of the hydrological cycle. Annual average amount to the 100mm, around 80% (7585mm) of which is lost through evaporation, 50% (474mm) is discharged to the sea and 15% (1422mm) percolates into the ground as national recharge.

Surface water (rainfall, springs and falaj) constitutes about 35% of the total water resources, while groundwater which is considered as the main source, constitutes about 65% of available water resources. Water deficit throughout most of the Sultanate is estimated at 378mm per year. Available data indicate that consumption of water in the Sultanate exceeds national recharge of groundwater storage by 25%. The steady increase in population and the expansion of agriculture, industrial and tourism activities besides the introduction of modern technology for borehole drilling and water pumping and the application of traditional irrigation methods, constitute a heavy burden on water balance. Water resources are exploited nearly up to the maximum in some areas, practically in Al Batinah coasts where water obstruction has largely exceeded the rate of groundwater recharge, a matter which has lead to continuous lowering of water tables and salinity intrusion.

### Virtual Water

The current availability of water from indigenous natural renewable resources and desalination, estimated to be about 970Mm³/year, is equivalent to about 390m³/capita/year. International indices regard this level as a condition of extreme water stress. The quality of life in Oman is not supported by the water sector solely through the exploitation of indigenous water. Every year, imports of food and other consumer products account for a major water contribution as a "virtual water" import. This is currently about four times Oman’s limited renewable water resource and equivalent to about 1,700m/capita/yr.
CHAPTER 6

Water Strategy
Water as a vital element of development has received priority attention from His Majesty since the early years of the Blessed renaissance. A number of Royal Decrees and Ministerial Decisions were issued to inaugurate and specify the duties of councils and authorities responsible for water resources sector as follows:

1. In 1975, His Majesty Sultan Qaboos bin Said promulgated Royal Decree (RD 45/75) forming the first Water Resources Council to undertake responsibility for water resources protection, the preparation of long term plans and the issuing of well permits.

2. In 1979, the Public Authority for Water Resources was formed following the issuance of Royal Decree (RD 45/75). The main responsibilities of the Council consisted of the setting of water resources policies and the issuing of regulations.

3. The year 1985 witnessed the promulgation of Royal Decree (RD 104/85) forming the Ministry of Environment and Water Resources, responsible for protecting the environment, setting policies on the environment and water resources and issuing necessary regulations.

4. Following the promulgation of Royal Decree (RD 44/89) in 1989, the Public Authority for Water Resources took over the water sector responsibilities for the Water Sector from the Ministry of Environment and Water Resources.

5. In 1985, the Ministry of Water Resources was established following the issuance of Royal Decree (RD 100/89). In line with the centralization of duties related to water resources under one body, the responsibilities and duties related to recharge dams and Aflaj were transferred from the Ministry of Agriculture and Fisheries to the Ministry of Water Resources.


7. Royal Decree 93/2007 created the Ministry of Regional Municipalities and Water Resources.
In order to protect and conserve water resources in the sultanate, number of Royal Decrees and Ministerial Decisions were issued with the aim of controlling the drilling of wells and the rate of water use as well as impeding the intrusion of saline water resulting from over abstraction. The laws were also meant to protect wellfields from pollution. The Decrees are as follows:

1. The year 1988 witnessed the promulgation of Royal Decree No 82/88 which declared the Sultanate’s water a national resource. This Decree is one of the most far-reaching and important legislation on water resources as it gave the State the right to take any necessary action to develop, protect and conserve underground water.

2. Royal Decree No 29/2000 defines water as national wealth to be protected and regulates activities related to wells and aflaj, and use of wells for desalination.

3. Royal Decree No 114/2001 on Conservation of the environment and Prevention of Pollution regulates the disposal of solid and hazardous waste, pollution control and issuing of permits for discharge of untreated wastewater.

4. Royal Decree No 115/2001 regulates the disposal of solid and liquid wastes.

5. Finally, in 2001, several ministerial decisions were issued on implementation of wellfields Protection Zones regulations in various areas of the Sultanate.
Overview of the Strategy

A National Water Resources Master Plan was prepared in 2000 to establish a strategy and plan for the period 2001-2020, for the sustainable development, management and conservation of water resources in the Sultanate of Oman. The Plan was based on general and resource studies, economic studies and some limited social studies as well as institutional and implementation support studies. The technical basis for the Plan comprises the assessments of water availability, development potential and demand for water.

In general terms, it was established that there is a requirement for an additional supply and/or adjustment of water use to yield, collectively, about 330Mm³/yr to meet future additional priority demands and restore the existing deficit through the Master Plan period. Development options and costs were examined for water supply and associated wastewater systems and the potential for the development of aflaj and farms irrigated from wells was assessed in the context of the water availability and demand for water. In view of the current high levels of water consumption by farmers using wells, demand management and water quality conservation measures were investigated in order to determine how consumption could be reduced to sustainable levels and the implications of the measures were evaluated. Some of these measures would need the support of a legislative, regulatory or institutional nature delivered at a national or regional level.

In developing a unified approach to water resources development and management, appropriate to each water assessment area, a generic list of potential water resources measures was prepared during the studies. This has ensured development proposals for the individual water assessment areas examined are compatible. It has allowed regional inferences to be drawn so that the findings from the assessment areas can be integrated into a national plan. The measures or potential ‘actions’ have provided the building blocks for developing the water resources strategy; grouped under three divisions as shown on the right. Different qualitative factors relate to the three divisions so the actions have been grouped into a matrix according to three further categories:

- Developmental or technical actions.
- Market and allocative actions.
- Supporting actions of an institutional, legal, regulatory and educational nature.
The sustainability ethic is incorporated within the Plan through adoption of the following basic principles:

■ Development of the country’s water resources should be sustainable in the long-term, not just technically but also economically, environmentally and socially.

■ Where resources are already being degraded due to over-consumption or pollution, the water balance of the aquifer should be restored to sustainability by 2020 by taking appropriate measures.

■ Saline intrusion in coastal areas should be halted by 2020. In areas where there is already severe saline intrusion, stabilising the intrusion during the period 2000-2020 will require controls on consumption.

■ The development of major aquifers that hold large volumes of groundwater but receive limited recharge (e.g. Nejd) should be planned in distinct stages with adequate intervals for evaluation of the aquifer response to pumping. The long-term strategy should be flexible and a well managed approach to the use of these resources adopted.

The Plan identified a number of opportunities to augment water resources but stressed the need to prioritise management of the existing water resources particularly in areas where consumption presently exceeds availability. If sustainable use is to be attained in these areas, then consumption has to be reduced or resources will have to be augmented. In critical areas, such as the southern Al Batinah, supply augmentation measures can only make a small contribution and the introduction of appropriate demand management measures in areas irrigated from wells will have to be introduced to overcome deficits. In addition, attention was drawn to the need for water conservation and the public awareness information and education campaigns that would be required as a preliminary action to active conservation control, of domestic, industrial and agricultural water use.
**Future Water Consumption**

Economic growth, combined with a rapidly growing population, will increase demands on the limited water resources of the country. Substantial increases in the demands from urban and rural areas are expected as a result of:

- Expansion of the productive capacity of all economic sectors.
- Increase in the number of housing units due to population increase.
- Higher consumption levels due to improvements in living standards.

Sustainability was the way of life of our ancestors: for a number of technical reasons, water use never exceeded water supply. The life was hard but sustainable. The Sultanate’s traditional methods of water management have important lessons for the future. Using water fairly in times of plenty and times of scarcity is one of these lessons. Matching water use to water availability, a fundamental characteristic of the aflaj system, will also be an essential element in water management in Oman’s climatic conditions. Protecting the quality of our water resources is another key issue. Everybody wants an abundant supply of clean, good quality water. In past ages, water was naturally purified by nature.

### Future Projections

It is projected that the total population of Oman will grow to over three and a half million by 2020. The growth of domestic and municipal water demands will depend significantly on the number of towns provided with improved water supply facilities in this period but is expected to increase by more than 50% (80-100 Mm$^3$/yr). With such increased demand projected and inevitable competition for scarce natural water resources, a comprehensive water management strategy is required to ensure security and sustainability of supply for priority use. We must further develop appreciation of the value of water and aim to maximize the use of the natural water resource in order to obtain the best return on the water used and to reduce the costs of industry.

### Present and Future Water Demands

<table>
<thead>
<tr>
<th>Year</th>
<th>Water Demand (Mm$^3$)</th>
</tr>
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<tbody>
<tr>
<td>2000</td>
<td></td>
</tr>
<tr>
<td>2020</td>
<td></td>
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</table>
Sustainability

Wise management of water resources must be achieved by a genuine commitment to ecological integrity and biological diversity to ensure a healthy environment, a dynamic economy, and social equity for present and future generations. Water is a precious and finite natural resource, one which is essential to all life and vital to ecological, economic and social well being. Yet water is often wasted and degraded. Therefore we face both individual and collective responsibilities to use and manage water resources wisely. This will only be accomplished as we recognize the intrinsic value of water and practice conscious and committed stewardship, recognizing that this precious heritage must be safeguarded for future generations. For example, increases in groundwater salinity in coastal areas are indications of aquifer over-exploitation. Such increases are occurring along much of Al Batinah coast, in northeastern Ash Sharqiya, on the Salalah Plain and in some areas of the Musandam peninsula. As saline intrusion occurs in response to adverse changes, it is always evidence that these changes have already occurred. For the situation to be restored to equilibrium the abstraction must be reduced to a value below the long term recharge. The saline intrusions now being monitored have developed over some 15-20 years; stabilisation and management and control will also take time to accomplish.

Water management principles should be based on the Sustainability Ethic. We should practice integrated water resource management by linking water quality, quantity and the management of other resources, recognizing hydrological, ecological, social and institutional systems; and recognizing the importance of watershed and aquifer boundaries.

The most widely accepted definition of sustainability, presented in 1980 in the World Conservation Strategy by the International Union for Conservation of Nature and Natural Resources, is that of:

"the management of human use of the biosphere so that it may yield the greatest sustainable benefit while maintaining its potential to meet the needs and aspirations of future generations."
Because our collective desire for water exceeds the available supply, the fundamental economic question for the allocation of water is how best to use the resources we have. Economic efficiency, which means getting the greatest net benefits (benefits minus costs) out of the use of the resource, is accomplished through the operation of a market mechanism wherein buyers and sellers come together to register their preferences for the use of the resource. The result of this process is a set of water prices which assures that water will be allocated to those uses for which need is most intense. In this regard, the market is simply an elaborate communication system enabling the myriad of individual preferences to be recorded, summarised, and balanced against one another. In such a theoretical system the allocation of water is treated no differently from any other commodity, and there is no place for the argument that water needs to be treated specially because of its importance to life and the production of goods and services.

Although the market for water shares basic similarities with other markets, it also possesses several distinctive features which distort the normal interaction of supply and demand and alter significantly the ability of the market to achieve purely economic efficiencies. The public interest in the allocation of water resources assures that social values have had an equal and sometimes predominating play in the market in relation to simply monetary values. As a result, through legislation, water is not assigned just to those who will pay the highest price for it; instead, we want to allocate our water resources to accomplish such societal objectives as the support of agriculture or the preservation of certain environmental values. There are several general principles involved in assessing the economic value of water and the costs associated with its provision. First, an understanding of the costs involved with the provision of water, both direct and indirect, is key. Second, from the use of water, one can derive a value, which can be affected by the reliability of supply, and by the quality of water. These costs and values may be determined either individually or by analysis of the whole system.

The supply of sea water for desalination is regarded to be unlimited but desalination depends on energy which is a limited and, therefore, an economic resource. In economic terms, the opportunity cost of water in Oman is generally determined by the desalination cost of the most efficient plant appropriate for a particular location or supply. To determine the value of water at another location, the water cost has to be adjusted for the cost of conveyance of the desalted water.

**Water Value**

The most economical solution to increasing water availability lies in demand management compared to supply options especially using non-conventional means. This point becomes more pertinent considering that the true value of water is the cost of desalination.
Apart from the economic value of water there is the intrinsic value of groundwater in the aquifer, fulfilling functions of the natural system. In Al Batinah for example, the original flow of groundwater to the sea stabilised the sea water interface at the coast, maintained the natural ecology of the sabkhas and provided small fresh water supplies for coastal villages. Redirecting the flow for alternative use incurs a cost that has to be borne by the tubewell users inland and by the economy at large.

Agriculture

Agricultural returns to water in Oman are low because of the high water demands of crops under Omani conditions. For dates in the Interior, for instance, the consumptive use of water of one hectare of dates is around 10,000m³/yr, and the income, excluding family labour, is minus RO 100 per hectare. The combined capital, maintenance and energy cost of pumping groundwater from a typical dug well for traditional irrigation is estimated at about RO 0.008/m³. For Modern Irrigation Systems (MIS), which require a larger pumping head, the equivalent costs are between 0.012 and RO 0.015/m³. Crop net benefits per hectare vary widely.

At present, with current agricultural practices, date palm has a negative net benefit. High net benefits, however are found for coconut an and bananas (700-1000 RO/ha), citrus (510-RO 700/ha), grasses and tomatoes (RO 300-470/ha). Net benefits from agriculture contribute only marginally to the national economy varying across Oman from negative returns where there is a high percentage of date palm to a better return of about RO 600/ha in Salalah. With improvements in cultivation techniques, crop varieties and the density of date palms net benefits with a return of between RO 200 /ha to RO 1,000/ha could be achieved. The present net return on agricultural labour is considerably lower for surface irrigation than it is for MIS. The net return to labour is relatively low. The amount of water used for irrigation depends on the type of crop and the cropping system adopted. It varies from 19,000 to 27,000m³/ha/yr on average. The net return on water from agriculture is generally marginal. The return on water in Salalah, however, is relatively good since crop water

Groundwater Supply

In Oman, groundwater is the principal source of both irrigation and domestic water supplies. At present irrigation consumes some 1,131 million cubic metres per year whilst domestic and municipal requirements, met by renewable fresh water resources and desalination supplies are less than 5% of this amount.
requirements are lower in this area, and more valuable crops like bananas and coconut are grown.

**Industry**

The vast majority of industries now in operation in the Sultanate are located within industrial zones managed by the Public Establishment for Industrial Estates (PME), established in 1993. This organisation is responsible for the estates located at Rusayl, Sohar, Raysut, Nizwa, Buraymi and Qalhat. A Free Trade Zone has been established in Salalah. The two principal water-using industrial groups in Oman, are food products and beverages and natural non-metallic products. The value-added per cubic metre of water for these two groups is between RO 54 and 90/m³. Other industries have higher value-added but they use small volumes of water. For example the value-added for refined petroleum products and medical and optical instruments exceed RO 1,500.

**Water Supply**

The unit costs of water supply are calculated for specific conditions of the area, such as distance from the source, groundwater depth and wellfield capacity. Economic unit costs are derived from the present value of total cost (capital, replacement and operating costs) divided by the present value of the amount of water produced over the project life. The unit cost of drinking water produced by desalination plants from sea water or brackish water varies widely with their size and the technology used. It ranges from RO 0.5 to 5 per cubic metre, and in recent time it is getting lower, as the desalination technology improves. For larger units, costs of the order of RO 0.75 per cubic metre are indicated. The range of economic unit costs of water, derived for different sources of supply and for various conservation measures, shows the very high cost of desalinated water compared to wellfield water or recycled wastewater for supply and the significant economic benefit of conservation. In economic terms, therefore, it is advantageous to use groundwater resources primarily to meet urban and industrial demands, rather than for irrigated agriculture, and restrict the use of desalinated water to meet demands in places where there is no other resource and advance conservation measures wherever possible.
Augmentation of Renewable Resources

The water resources that are currently available, can be augmented in a variety of ways, some of which are already being employed.

**Conventional and Non-Conventional Measures**

Measures classified as conventional are potential actions normally considered as part of water resource planning and engineering. Measures classified as non-conventional are usually considered only in situations of severe water shortage or where there are particular local conditions that make their application more attractive than is normally the case. For example, desalination is extensively used for public water supplies in Middle Eastern countries that have cheap energy sources, whereas in most countries in the world it is a method of last resort except for special high value uses. It is, therefore, grouped with the non-conventional measures.

**Storage dams:** There is potential in the mountainous regions for further small concrete storage dams to alleviate local domestic water supply problems.

**Recharge Dams:** Water balance estimates indicate that wadi flood flows lost to the sea or the desert average about 119Mm³/yr. There is scope for further construction of recharge dams to utilise at least part of this amount.

**Recharge Wells/Lagoons:** The artificial recharge of excess wadi flows or wastewater through lagoons and/or wells, rather than through construction of dams or some other method of surface spreading, has some potential in certain areas.

**Interception of groundwater losses:** Regional water balances determine a total groundwater discharge of 399Mm³/yr, to the sea or across the national border inland. A flow of groundwater to the sea is necessary to maintain a stable sea water interface. However, in some areas where natural groundwater flow still exists, it may be possible to effect reductions in flow losses to the sea by perhaps as much as 50% and still maintain a groundwater balance.

**Underground Dams:** The underground dam is a relatively new concept and typically involves the installation of an impermeable 'curtain' within an active

### Measures considered in the Master Plan:

#### CONVENTIONAL MEASURES
- Storage dams,
- Recharge dams,
- Recharge wells,
- Interception of groundwater losses,
- Reuse of wastewater,
- Water transfers.

#### NON-CONVENTIONAL MEASURES
- Desalination of seawater and brackish water,
- Sea water flushing,
- Treatment and use of oil production water,
- Fog collection,
- Cloud seeding,
- Import from overseas by bulk carrier.
groundwater flow system that would trap and store the underground flow. Several underground dams have been constructed in Japan, with capacities up to 10 million cubic metres. Underground dams can have a second (and equally important) role of stopping saline water intrusion in coastal areas.

**Reuse of Wastewater:** Wastewater from municipal areas represents an important resource to be considered as an essential element in developing a water resources strategy. Currently the greater part of the wastewater from urban centres infiltrates into the aquifer from septic tanks and latrines, since collection systems and treatment plants have limited coverage. At inland towns, the wastewater replenishes the aquifer and may contribute to the needs of agriculture or other demands downstream. In coastal towns and cities, including Muscat and Salalah, the potential exists for return water to reach the sea and become unavailable for reuse. As the coverage of collection and treatment systems expands, effluent of better quality should be used beneficially. The effluent can be treated to a quality suitable for direct use in agriculture or to recharge the aquifer through recharge lagoons. At present, part of the wastewater produced in Muscat is collected and treated, and it is used for municipal greening. Notwithstanding, wastewater seepage and leakage of potable water from distribution pipes occurs and is causing groundwater levels to rise. The possibility of making use of this excess water by pumping from shallow wells throughout the city, for public gardens and more widespread greening, needs further consideration. Such recovery would release all of the treated wastewater for more beneficial use as mentioned above. The possibilities for Muscat are considerable. The Municipality anticipates that there will be 70,000m³/day of effluent arising from Phase I of the current development of sewerage services, steadily growing to 270,000m³/day (100Mm³/year) by 2030. The treated effluent could be sold directly to farmers or it could be recharged into the aquifer, through recharge lagoons.

**Central wellfields and water transfers:** Water transfer refers to the transfer of water by pipeline or canal from an area with a surplus or good quality resource to an area of deficit or contaminated resource. The water developed at source has a low unit cost, particularly if it is of good quality and needs only minimal treatment, but the economic viability depends very much on the distance and
the transfer cost as well as the end use of the transferred water. From the assessment of a number of potential schemes, it is concluded that medium and long distance transfers cannot be justified economically for irrigation. The unit cost of the water transferred is many times greater than the gross margins obtained from agriculture. Potential may exist however where such transfers provide supplies for higher-value use.

Desalination of brackish water or seawater: The large scale desalination of sea water has been evaluated in consideration of the future water supply requirements for the Capital Area and Salalah. In the case of Muscat it was concluded that the desalination capacity should be increased whereas in Salalah, more economical measures are available. It is further expected that detailed investigations for the water supply to some inland or remote coastal towns may well conclude that desalination is the most viable option.

Seawater flushing: Sea water distribution systems to duplicate the potable water networks have been installed in some cities for sanitary flushing so that the domestic demand for fresh water supplies can be reduced by at least 30%. Both types of effluent are collected in the same sewerage system. In many coastal cities of Oman the water used for flushing is not just of potable standard but also comes from desalination. With the expansion envisaged for drinking water and sewerage systems in Oman, the use of sea water flushing should be considered as one of the options for coastal towns.

Treatment and use of oil production water: A significant volume of water some 270Mld (100Mm³/yr) – is produced in Oman as a by-product of oil production. In some fields, such water is re-injected to maintain reservoir pressure and assist oil recovery but a large balance remains. The oil water salinity is in the range of 5,000 to 15,000mg/l and it is polluted by hydrocarbons and heavy metals. Active research programmes are being sponsored into environmentally acceptable methods of treatment and reuse.

Cloud Seeding: Cloud seeding is carried out by using flares to deliver hygroscopic particles, silver iodide or sodium iodide into clouds in an appropriate storm
location. Clouds with a strong vertical development from upward air movement and a high moisture content are required. Even where seeding has produced rain-fall there is much debate about whether it has produced additional rain or just redistributed it. The additional precipitation may increase recharge to aquifers or enhance run-off to agriculture. Much testing and validation is required before cloud seeding can be carried out operationally with confidence.

Import of water from overseas by bulk carrier: The import of water by tanker or in bags could be considered a potential resource. Large bulk carriers could be employed to transfer up to 300,000 m$^3$ per shipment. A large bulk tanker could provide two to three days supply for Muscat. A recent study, considering sources as far away as Malaysia, gave an estimated cost of RO 0.770/m$^3$ for delivery, excluding the cost of storage and treatment. The import of water in this way is expensive and it is dependent on the external suppliers.
Water Conservation

Since water supply cannot be increased indefinitely, we need to use water in a way which assures a fair supply to every need. We need to conserve water. Conservation and efficient use of water are essential to the reaching of a balance between growing demands and finite supplies, and their incorporation should precede the construction of alternative supply systems. They are also a long-term, state-supported initiative to protect natural resources and enhance outdoors recreational opportunities. Over the last decades the increasing demand for water has exerted great pressure on the fresh water bodies of the country. Therefore, it is essential to save every drop of water, build an awareness of, and continual concern about water conservation into every aspect of life. Reduction of water withdrawal, consumption, and waste will reduce the negative effects of excessive use of water. For example, decreased wastage in agricultural applications has the important side effect of reducing salination and reducing waterlogging.

Water demand can also be reduced in the long term by implementing land-use and agricultural policies that encourage water conservation, and by instilling a conservation ethic in residential, commercial and industrial water users and by initiating water pricing for agricultural purpose. One stumbling block to efficient water use is that many people do not know how much water they really use. When surveyed, people in Australia estimated their daily household use at as little as 5 litres, and few thought it to be more than 200 litres. Most found it hard to believe that actual average use was from 700 to 1,100 litres a day. Therefore, raising public awareness is an important step for water saving and conservation. The cornerstone of any domestic water supply programme is conservation. Water conservation also includes using water of lower quality such as reclaimed wastewater effluent, gray water, or runoff from ground surfaces for toilet flushing or irrigation of vegetative landscape or food crops. These uses do not require the level of water quality as that needed for internal consumption, bathing, or washing. With the proper type of wastewater treatment and plumbing hardware, sea water can be used as a toilet flushing medium. The domestic water use includes water used for household purposes such as drinking, washing, bathing, flushing toilets, watering lawns etc. Key aspects of achieving overall reduction in domestic water use will be:

Agricultural water use accounts for approximately 90% of the total water use of the country. Water for agriculture either comes from wells (about 70%) or from aflaj (30%), therefore it is essential for agricultural users to fully participate in conservation and management measures.

Government Strategies:

- Creating and cultivating conservation awareness.
- Matching water use to water availability.
- Establishing an integrated programme for the conservation and management of the resources at basin level.
- Controlling saline intrusion by reducing abstraction below the long-term recharge.
- Adopting improved irrigation techniques and selecting appropriate crops to reduce agricultural water use.
- Controlling urban water losses. Increasing the use of treated wastewater and desalinated water.
- Protecting the groundwater resources in qualitative as well as quantitative terms.
- Constructing new groundwater recharge dams.

Light industry in the Sultanate of Oman has been extensively encouraged and several industrial estates have been established. Industrial water demand is small in comparison to other users of water, due to wise selection of low water demand industries. It is important that all industrial owners and workers participate in conserving and managing water resources.
# How to Conserve Water:

## HOUSEHOLD USE

- Fix leaks, replace commodes with low-flush units or urinals, install faucet aerators and low flow showerheads.  
  If you wash dishes by hand, don’t leave the water running for rinsing.  
  If you have two sinks, fill one with soapy water and one with rinse water. If you have one sink, gather all the washed dishes in the dish rack and rinse them with a spray device.  
- Use an automatic washing machine only for full loads: the automatic washer uses 100-150 litres of water in a cycle. That’s a lot of water to use for a few dresses.  
- Take shorter showers.  
- Install water saving showerheads or flow restrictors. Most showerheads put out 20 to 40 litres of water a minute, while 10-15 litres is actually enough for a refreshing, cleansing shower.  
- Plant low-water-use trees, shrubs and plants.

## AGRICULTURAL USE

- Improve irrigation by using modern irrigation methods such as drip, bubble and sprinkler systems. Install low-flow sprinklers or trickles/drip irrigation.  
- Optimize watering schedules and water placement, preventive maintenance and xeriscaping techniques.  
- Irrigate during cool hours other than peak demand.  
- Irrigate deeply and infrequently.  
- Select crops that have low water requirements.  
- Use recycled water for decorative ponds, fountains, etc, and shut water off whenever possible to reduce evaporation.  
- Install an irrigation system with controls or sensors to avoid unnecessary irrigation events.  
- To provide water directly to the turf roots use a trickle or subsurface drip irrigation system that is installed underground.  
- Implement xeriscaping techniques. It is a comprehensive water management approach to landscaping that considers the type of plants, growth and maintenance patterns, and their interaction with the climate and soil.

## INDUSTRIAL USE

- Use low quality water wherever possible.  
- Reuse water within facilities - reduce overall facility water consumption.  
- Install an automatic control to shut off the unit when the facility is unoccupied.  
- Expand the production without increasing water use.  
- Plan development strategies based on low water demand.
Water Demand Management

A need to reduce agricultural water consumption has been established in many areas. A number of measures that could be used to achieve sustainability targets have been evaluated within the development of the Master Plan and these are summarily described hereunder.

**Improve surface irrigation and promote Modern Irrigation Systems (MIS):** Significant water savings through greater efficiency can be made by the introduction of improved irrigation distribution and application. Improved surface irrigation could save up to 7% and MIS systems up to 15% (for drip/bubbler systems), compared with existing surface schemes. The introduction of water saving technology should be encouraged through public awareness campaigns and the agricultural extension services.

**Water Quotas:** Savings made by encouraging farmers to use MIS will not in themselves produce the total water savings required. With an uptake of MIS by 40% of farmers (a reasonable target), overall water savings in any area would not exceed 8% of current use. Other measures of demand control and management will be needed to meet the targets required. Water quotas could be established for all registered well owners and these should be within defined Sector allocations, based on the water balance of the aquifer in order to ensure resource sustainability. Water allocations should be set for sectors of the economy and regions of the country based on current water sector demands, hydrogeological conditions that have developed in a particular area and the local needs to return abstraction to a sustainable level.

**Change Cropping Patterns:** Water savings can be made through a change in cropping pattern by reducing the area planted with dates and other tree crops; replacing Rhodes grass and alfalfa with annual fodder crops; and increasing the cultivation of winter vegetables. Extension services will be of central importance in achieving objectives and will need strengthening so that they can assist farmers in developing appropriate cropping schedules, as well as providing advice on maximising benefits.

**Crop Area Prohibition:** Perennial fodder crops, such as Rhodes grass and alfalfa, are high water users since they require irrigation throughout the hot summer months and their consumptive use in northern Oman is in the order of 20,000m³/ha/year. Replacing such crops with annual fodder crops, perhaps just one crop or maybe two crops during the cooler months, would produce potential water savings in the range of 8,000 to 15,000m³/ha/year. If this were done, extension services would be required to advise affected farmers on how to arrange their
animal feed using annual fodder crops instead of Rhodes grass and alfalfa.

**Change Land Use**: Land could be taken out of agricultural production through its voluntary sale to, or compulsory purchase by, the Government, thereby reducing crop water consumption. In this situation, landowners would have to be compensated at commercial rates.

**Water Tariffs**: Water charges and tariffs are widely used throughout the world in connection with irrigation schemes, introduced with a variety of objectives. Tariffs could be introduced in Oman with the aim of reducing water consumption, although there is no sound international experience to show the effect of irrigation tariffs on consumption. Their introduction can provide an incentive to farmers to look more carefully at their cropping patterns and farm budgets and make decisions to maximise their returns on the water charged, without necessarily reducing consumption. If tariffs were to be introduced to farmers in Oman, the choice of tariff levels will require considerable extra social and technical studies as well as pilot projects.

**Water markets**: Intersectoral water markets are markets in which water utilisation rights are traded. They are not yet commonplace throughout the world. However, volumetric abstraction rights and charges, a precursor to the development of water trading, are applied in several countries. Water markets come into place when the trading of abstraction permits takes place. In Oman, there are currently no abstraction charges and the introduction of tradeable water rights from pumped well abstraction is not an immediate option. Nonetheless, in the case of the traditional aflaj, water trading among the aflaj community is an established practice, although only to the extent of using the water for irrigation within the command area. Thus, for the future, there is a precedent upon which to base water trading in Oman. The introduction of formal water markets in the areas currently being irrigated from wells, however, would not be feasible until well permits and abstraction licences (quotas) have been firmly established.

**Develop Water Users Associations**: Water Users Associations (WUA) are a necessary form of management for farmer groups receiving irrigation water from a common water source, be it a surface water diversion or a groundwater tubewell. This is the case for falaj irrigation that traditionally has been managed by a falaj committee. However, the well-based irrigation in Oman is an individual business with each farmer having responsibility for his cropping and water use management. Clearly, to achieve technical improvements aimed at lower water use, more efficient water use and higher farm returns it will be more effective to be able to work through a form of WUA.
National Groundwater Protection Master Plan

Groundwater is a resource which is under increasing risk from human activities. Since groundwater flow and contaminant transport are neither readily observed nor easily measured, and both processes are generally slow, there can be a lack of awareness or, in some instances, compliance among decision-makers about the risk of deterioration. Almost all human activities cause some degradation of the environment. The risks of contamination are obviously greatest near the source of water or immediately around the supply. Major pollutants are civil, commercial and industrial developments, solid and liquid waste disposals, storage tanks, landfills, sewage and drainage, burial grounds, oil wells, exploration wells and oil pipelines, agriculture, mining and quarrying, waste water injection, and septic tanks.

The first wellfield protection zone schemes for the Wadi Aday and Western Wellfields (Muscat) and Salalah Wellfield were promulgated in 1988. These sought to protect groundwater flowing into the wellfields from contamination, over-abstraction, saline intrusion and adverse development. The schemes used a colour-coded zoning system to identify specific limitations on future developments and, progressively, on existing activities. The wellfield protection programme has been extended in recent years following a major study investigating twenty four wellfields serving major towns in various regions of the country (refer to map).

Within the scope of groundwater protection, abstraction must be managed to prevent the loss of wellfield viability by over-abstraction, damage to the environment - natural vegetation, khawrs-which are dependent upon the presence or level of the groundwater table, including the unacceptable depletion of throughflow, aflaj and springs, and deterioration of groundwater quality by saline intrusion and upconing or incursion of polluted water. Under the wellfields and aquifer protection programme, control of development activities are imposed at various levels and the monitoring and policing are accomplished in the protection zones. For example, for the full prevention from pollution with management measures and contingency...
plans for emergency situations, will allow management of all potential sources of contaminants. The control of groundwater contamination sources is achieved by means of regulations, which list the degree of acceptability of potentially polluting activities for each zone and describe the recommended controls for both existing and new activities. The level of response depends on the different element of risks: the vulnerability, the value of groundwater as potable water supply in the area and the contaminant loading from proposed developments.

Regulations are developed under the above criteria for the control of development activities. Each regulation will be applicable to one or more zones. Generally speaking, the lower zone number then the stricter the regulations that apply to it. The protection plan should be followed by the cooperation and coordination of a group of the concern agencies and authorities. Periodic water quality monitoring is carried out to ensure that water quality does not degrade.

Common Causes of Groundwater Pollution

**Agricultural Development:** Agricultural development in the catchment, especially around recharge areas and along groundwater flow paths, has a two-fold negative impact on municipal wellfields. Firstly, agricultural withdrawals compete directly with those of municipal supply. Secondly, agricultural chemicals such as fertilizer and pesticide residuals can migrate to groundwater through the unsaturated zone.

**Graveyards and Burial Grounds:** Large graveyards can be a potential threat to groundwater quality and as such the establishment of new sites or extensions within Zone 1 and 2 areas would be opposed.

**Sewage Works:** Leaking septic tanks are a major source of groundwater pollution in Oman. The presence of sewage works and the associated sewage system present a risk of both bacteriological and chemical contamination of groundwater sources. Creation of new works within Zones 1 and 2 will be prohibited.
**Major Infrastructure Development:** Discharge on major roads within Zones 1 and 2, and discharge of roadsides to underground strata via soaks system are main source of pollution. Therefore, these activities are opposed in Zone 1 and restricted in Zone 2. Such developments include industrial parks, large areas of vehicle parking, garages and petrol stations.

**Future Developments:** Activities such as expansion of urban centers, industrial and commercial areas, mining and quarrying, the construction of highways, burrows, construction of impermeable barriers, exploration drilling for oil or minerals can in certain circumstances cause problems and are therefore subject to planning controls.

**Contaminated Sites:** Contaminated sites may include land currently or previously used in connection with the following activities:
- Landfill sites, and other waste disposal activities.
- Chemical/industrial sites.
- Mining.
- Sewage treatment works.
- Metal refining.
- Garages.
- Car washes/petrol stations.
- Oil refining/hydrocarbon storage.

Proposals for the siting of such activities within protection zones would only meet with approval subject to adequate measures to prevent the migration of pollutants to groundwater. Such measures would include:
- Minimisation of underground storage.
- No open storage areas.
- Secure bulk storage of potentially polluting substances with impermeable bounding.
- Adequate containments and safe disposal for spillage.
- Above ground pipe works in positions not vulnerable to accident damage.

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**List of potentially polluting Activity according to Level of Risk:**

- Acceptable subject to normal good practice.
- Acceptable in principle, but subject to certain conditions.
- Not acceptable in principle, but some exceptions may be allowed subject to certain conditions.
- Not acceptable.
A flaj are man-made structures which carry water, sometimes for thousands of years. The long history of aflaj is evidence of continuing community participation in construction, management and maintenance. Although some aflaj are practically maintenance-free, many problems are encountered in the maintenance of others.

Nowadays, the income from aflaj farms is perceived to be low: plots are relatively small, cheaper food is available in the market, and alternative sources of income can more readily be found. With the cost of maintaining aflaj systems having probably increased in recent years, aflaj communities have become increasingly dependent upon Government support. This is particularly evident during summer and dry seasons. In prolonged periods of drought, reduced flows can have a significant impact on water supply and food production which leads many aflaj communities to apply for the construction of a support well to sustain flows.

How people construct and maintain the Falaj

The main problems which are being encountered in the maintenance of aflaj include instability of walls, sections of restricted dimensions, material deposited on the gallery floor and yield deficiencies. The problems of wall instability are posed essentially in the alluvium, and are mainly related to decompression of the terrain due to the excavations, regressive erosion related to the water flow pattern in the falaj, and entrainment of fines, essentially through the roof, during wadi floods, on account of the high gradients close to the walls of the falaj, which acts as a drain. In combination, these three phenomena can locally cause
the formation of large caverns; at Al Hazm falaj a cavern 10m high, 7m wide and 15m long has developed. While some forces are making caverns, others act differently, constricting the gallery. Both the deposition of calcareous tuff on the walls, which may gradually accumulate to reduce the cross-section, and partial caving in, reduce the clearance of the gallery, to the point of complete human inaccessibility. Sometimes a small diameter is attributable to the actual construction of the gallery, when the material was either too hard, or too soft, to allow a larger cross-section.

Since most of the galleries were excavated in the alluvium, containing a proportion of fines, these are drawn through the soil by the flowing water, and deposit on the bottom of the gallery as soon as the flow rate reduces. These materials tend to deposit in the areas of water collection, clogging these zones, and thus reducing inflows. In some cases, in the section of the falaj which serves for water conveyance only, there is a reduction in the flow rate from upstream to downstream, due to infiltration in the permeable soil formations situated below the water table. Other encountered problems may be large travertine deposits, leading to a fair decrease of the section, or holes in the floor, which can lead to great depth of water.

Since aflaj are water carriers, they are first to be affected by floods. The main reasons of flooding are flash floods which the cause damage to both underground and surface channels. The lack of routine maintenance or the excavation of gravels from wadi beds where there are some underground falaj channels underneath them, however, can locally create or exacerbate flood impacts. To avoid flood damage, first of all, all head of shafts located in wadi beds should be suitably protected, as well as mother wells located in wadi beds. Access shafts to the galleries can present a problem for the overall life of a falaj. Surface flooding can seriously damage the open shafts and the result to the galleries can be catastrophic. In most well maintained aflaj, therefore, the minimum number of shafts is kept open. Newly constructed concrete shafts often have a concrete cover which can be easily removed for access. In the older stone lined or unlined shafts, a large key stone is wedged across the shaft which is subsequently covered with plastic sheeting or more traditionally, with palm fibre and dead roots. This prevents the gravel and sand cover from subsiding into the shaft.

**Maintenance Aflaj Problems:**

- **Flooding:** Flooding can cause erosion and damage to subsurface and surface channels.
- **Silting:** Silt accumulation inhibits flow, and desilting is an on-going requirement.
- **Water loss:** Water leakage in falaj channels, can reduce water availability, particularly during periods of low flow.
- **Technicalities:** Aflaj are specific structures and require a highly specialised approach to their maintenance. Traditionally, subsurface channels were maintained by Omani with skills of excavation and construction of channels. Much of this skill base no longer exists or has been superceded by other technology which is not always appropriate for the conditions or longterm maintenance of the system.

**Maintenance**

In Oman, galleries of aflaj may have four different types of lining: natural earth, dry stone, masonry - stones and mortar - and concrete. The floor is generally of natural soil, with the exception of a few concrete-lined sections. The main types of natural soil are limestone, ophiolites, conglomerates and alluvium of varying coarseness and varying cohesion.
The comprehensive development witnessed by the Sultanate in all aspects of life is a result of the efforts made by the Government through the National Development Plan with its consecutive Five-Year Plans which aimed to raise and improve the standard of living of the Omani people and build a modern country. This development needs understanding and cooperation from citizens. Public awareness has an essential and effective role in orienting the concerns of human beings and prompting them to protect their national gains.

Public awareness and education activities have included:
■ Direct communication
■ Symposia and Lectures
■ Symposia and lectures in Offices of Their Excellencies the Walis in presence of Sheikhs and Guides
■ Symposia at Schools
■ Youth Clubs and Students Work Camps
■ Omani Woman’s Associations
■ Agricultural Development Centres
■ Local Communities Development Centres
■ Military Training Colleges and Centres

Exhibitions:
■ Stationary Exhibitions
■ Mobile Exhibitions

Educational Contests:
■ Quiz Contests
■ Drawing Contests
■ Photography Competitions
■ Literary Competitions
■ Songs and Poems Contests
■ Contests for wall newspapers
■ Contests for Leaflets
■ Contests for Youth Camps
■ Sporting Tournaments supporting Water Conservation
International Conferences:
- Participation in Conferences
- Preparation of Materials

School Curricula:
- Preparation of Awareness Programmes
- Coordination with the Ministry of Education

Indirect communication:
- TV: News on MRMWR activities, Television Reports about Water, Guiding Calls about Water, Small Drama Series, TV Serials, Maintaining Audiovisual Library
- Radio: News on MRMWR activities, Rainfall Reports, Weekly Water Programmes, Instructional Calls
- Press: Technical and Scientific Reports, Instructional Calls, Special Monthly Water Page, Articles in Regional Newspapers

The Awareness Strategy for the Appreciation of the Value of Water and its Conservation is based on 3 Dimensions:

- The first dimension is to define water issues of relevance to people such as appropriate water use, over-use and pollution, embody them in plans and programmes liable to implementation.
- Secondly, we need to define modern communication means and techniques which match the Omani society and have positive effects.
- Thirdly, we have to evaluate the implemented awareness activities and identify their ability in making good behavioural changes.
CHAPTER 7

Major Achievements in Water Resources
Water Explorations

The most significant Basins:

- Al Massarat Aquifer in Ad Dahirah
- Al Ash Sharqiya Aquifer in Ash Sharqiya
- Al Wadi Al Ma’awil Basin in South Al Batinah
- Al Wadi Al Umaiyr in Ad Dhakliyah
- Al Wadi Rawnab in Al Wusta
- Al Nejd Aquifer in Dhofar

Water exploration programmes aim at locating groundwater aquifers in various areas of the Sultanate and identification of their geological and hydrogeological characteristics. They also give a clear picture of the quality and quantity of groundwater storage and its mechanism of recharge and flow. These explorations help to identify whether such groundwater storage is renewable or non-renewable and accordingly to determine its approximate age.

Exploration operations consist of several stages, the most important of which are: Geological and topographical studies, geophysical surveys, exploration drilling, pumping test and laboratory analysis. Upon completion of these operations the aquifer will be delineated and mapped and the methods of its exploitation will be determined.

The Ministry has implemented a number of exploration programs in various areas and governorates of the Sultanate during the past decades. These explorations led to the discovery of a number of groundwater aquifers, the most important of which are: Al Masarat Aquifer, Ash Sharqiya Aquifer, Wadi Al Maawil Aquifer, Wadi Ronab Aquifer and Al Najd Aquifer.
National Well Inventory Project

The National Well Inventory was a major undertaking which, for the first time, gave a clear picture of water use in the Sultanate. The project was initiated in 1991 with a Well Registration Campaign for the entire Sultanate. In total, over 160,000 well registrations were received of which 30,000 were abandoned. Following the successful completion of this campaign, the Ministry initiated its National Well Inventory project to collect the essential details of current water abstraction and demand. This major programme, initiated in December, 1992, was preceded by execution of pilot projects in Salalah, Barka and Al Buraimi which sought to develop and refine operational procedures prior to large scale, national implementation.

The Objectives of the National Well Inventory:

- To accurately locate all water wells and collect data on their physical characteristics.
- To confirm well registration details.
- To assess the distribution and quality of the groundwater resources.
- To evaluate the type, demand and use of groundwater.

Data collection for the various water use categories was phased. Highest priority was given to those areas with greatest water consumption (intense, agricultural development), areas of water shortage and areas with a potential for future development.

The collected Information provided Evaluation and Analysis for:

- The foundation for water management.
- The data required to establish whether or not existing water supplies are suitable for their present use.
- The planning of future water supplies for various uses.
Considering the importance of wells as a major water abstraction means, it became necessary to develop a reliable data base on wells and their properties for efficient planning and management.

Substantial resources were invested to ensure the successful completion of this project. This involved extensive public awareness campaigns, the recruitment and training of local personnel, acquisition and establishment of several new regional offices, and the procurement of vehicles and large quantities of field equipment. Fifty-seven field inventory teams were formed which operated from regional offices; the total project workforce comprised 242 employees with over 90% nationals. Training of all staff members was undertaken in all aspects of data collection, verification and interpretation activities.

Field teams visited every well in the Sultanate and collected information on well location, structure, yield, installed pumps and water quality. The Inventory activities identified the type of water use - agricultural, domestic and industrial - at each wellsite and data were collected to calculate current water demand. Domestic water demand was derived from an assumed per capita consumption rate. Agricultural water demand was calculated for various individual crops and crop areas and details of the irrigation methods in use were also recorded to evaluate water use efficiency.

Following quality control procedures, the data was entered into a database of the Geographic Information System to facilitate evaluation and presentation of results in a variety of tables, maps and reports.
National Falaj Inventory Project

National Aflaj Inventory was undertaken following the success of, and invaluable experience gained from, the National Well Inventory. Forty-five field teams were deployed to locate, measure and document aflaj throughout the country. This involved for each site:
The data were subjected to the same processing, quality control and reporting procedures as described above for the Well Inventory. In total, the National Aflaj Inventory identified 4,112 aflaj of which 3,017 were operational. Most of the 'dead' aflaj were of the ghayli type (54%).

The largest number of aflaj were found in the wilayats of Sohar (408), Ibri (363) and Al Rustaq (294). A total of 5,326 branches of various types were identified with a cumulative length of 2,726km. Of this length, 959km were surface channels whilst 1,767km were underground. The total command area of operational aflaj was estimated as 26,500ha. The largest demand area of an aflaj was found at Manah comprising 12,127 hectares. Most aflaj (68%) however, have demand areas of less than 2 hectares.

The Objectives of the National Falaj Inventory:

- Identification of water source.
- Location and depth of a mother well and access shafts.
- Mapping of the routes of main and subsidiary channels.
- Measurement of discharge rates.
- Water sampling and analysis.
- Measurement of demand, cropped, developed uncropped and undeveloped areas.
- Water use and consumption estimation.

The Aflaj Inventory Project:

<table>
<thead>
<tr>
<th>Region</th>
<th>Area (ha)</th>
<th>Aflaj Nos.</th>
<th>Area/Falaj</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batinah</td>
<td>5,594</td>
<td>1209</td>
<td>2.3</td>
</tr>
<tr>
<td>Ad Dakhliyah</td>
<td>7,895</td>
<td>501</td>
<td>14.4</td>
</tr>
<tr>
<td>Ad Dhahirah</td>
<td>3,527</td>
<td>473</td>
<td>9.9</td>
</tr>
<tr>
<td>As Sharqiyyah</td>
<td>4,326</td>
<td>661</td>
<td>6.4</td>
</tr>
<tr>
<td>Muscat</td>
<td>0,225</td>
<td>173</td>
<td>4.4</td>
</tr>
<tr>
<td>Total</td>
<td>21,606</td>
<td>3,017</td>
<td>7.3</td>
</tr>
</tbody>
</table>

The National Aflaj Inventory Project

The National Aflaj Inventory project, commenced in 1997, and concluded that the total recorded aflaj was 4,112 aflaj, of which 3,017 were operational. Of the total cropped area daudi aflaj comprise 57%, ayni 9%, ghayli 22% and multiple water sources 12%. Tables above show the distribution of aflaj by region and their serviced cropped area.
The Hawd Al Masarrat Project commenced in late-1993 and included the exploration, assessment and development of the Al Masarrat Aquifer, which occupies an area of about 12,560km² to the west of the towns of Ibri and Dank in the Ad Dhahira Region. The first Phase of the investigation, 1993-1994, involved regional exploration to delineate, map and assess aquifer characteristics and water. During this phase, a total of 49 wells, including 29 test wells and 20 observation and exploration wells were drilled and 27 aquifer tests were conducted. Borehole depth ranged from 80 to 220m with average 137m; the total meterage drilled was 7,063m. The maximum and average airlift yields recorded during drilling were 146 l/s and 30 l/s respectively. Assessment of the results of the Phase I exploration enabled identification of several potential sites for municipal water supply development.

The Phase II, or pre-design phase, commenced in August 1995 and was completed in May 1996; this concentrated on the acquisition of detailed hydrogeological information within two large wadi systems - Wadi Al Ayn and Wadi Bu Bukara - where aquifer conditions and water quality had been found most favourable. During Phase II, a further 86 wells were drilled and constructed, including 20 production wells, 10 test wells and 56 observation/exploration wells. In addition, 34 aquifer tests were performed, including wellfield simulation tests at two wellfield sites. Borehole depth ranged from 50 to 400m with average 127m; the total meterage drilled was 12,985m. The maximum and average airlift yields recorded during drilling were 209l/s and 33l/s respectively. The results of this Phase of work confirmed the potential for two wellfields at Wadi Al Ayn and Wadi Bu Bukara. Concurrent with the exploration work, a pre-feasibility study and Business Plan were conducted to form the basis of development of the aquifer and establishment of a water supply scheme.

Following the successful groundwater exploration and assessment programme and careful review of business plans for development, the design of the Al Masarrat Water Supply Scheme commenced in 1999 and was completed in 2002. The objective of the Scheme was to provide potable water to the main towns and villages of the Wilayats of Ibri, Dank and Yanqul via a distribution system from the Al Masarrat aquifer and to provide tanker points in the region for potable water to be supplied to other villages.
Assessment studies were initiated in the Ash Sharqiyah Region in 1991. Initial work was concentrated around Ibra. The focus of work was changed in 1992 after due consideration of the worsening water situation in the lower catchment areas around Al Kamil, Al Wafi and Ja’alan. Activity was directed toward possible reserves in the aquifers in and around Ash Sharqiyah, an area covering approximately 15,000 km². In the first phase, exploratory drilling was followed by aquifer testing in the alluvial plains. Encouraging results were obtained with several high-yielding wells and good quality water. During this period, preparation was made for large-scale exploration works in the desert. Given the difficult terrain and working environment, this demanded particular attention to logistics and safety. Preliminary geophysical surveys were completed in 1994. These indicated the extension of the aquifer system beneath the Ash Sharqiyah Sands and provided the first aerial assessment of potential aquifer thickness. In the second phase, drilling and aquifer testing within the Ash Sharqiyah Sands area commenced in October 1995. Early results confirmed the potential of the alluvial aquifer and proved the existence and significance of fresh water within overlying aeolianite (lithified sands) of the Ash Sharqiyah Sands itself. For the combined aquifer systems, a fresh water thickness in excess of 100 m was delineated over an area of about 1000 km².

A large-scale exploration programme comprising 99 boreholes and 13 long-term aquifer tests were conducted within the third phase of the project. This work was complimented by associated hydrogeologic, remote sensing, hydrochemical, borehole logging, monitoring and topographic studies. Integration, interpretation and analysis of the complete data set was completed in January 1997. The existence and significance of two major aquifers was confirmed. The gravel aquifer, which reaches thicknesses of 160 m, lies within the upper horizons of the gravel alluvium that is associated with Wadi Al Batha and which extends to depths of more than 600 m in a largely fault-bounded basin. The aeolianite aquifer attains a maximum saturated thickness of 100 m and the total volume of potable water in this aquifer is estimated to be of the order of 16,000 MMm³, approximately twice that contained within the alluvium. With significant development potential of both aquifers afforded by these vast storage quantities, further works were commissioned for development and establishment of a supply scheme to benefit local citizens.

Presently, this project is estimated to supply 79,000 people with about 3.3 MMm³/yr of potable water. By the year 2032 it will supply 196,000 people with 8.5 MMm³.
Following the successful exploration and regional assessment programme in the area, the design and construction of a scheme to supply potable water to the main towns and villages of the wilayats of Al Kamil, Al Wafi, Jaalan Bani Bu Hasan, Jaalan Bani Bu Ali and Al Askhara was instigated. The scheme envisaged construction of two wellfields and supply of potable water provided for domestic, potable, commercial and municipal use over a 30-year period. On commissioning, the total annual abstraction rate is planned to be about 3.3Mm$^3$ with an estimated 79,000 beneficiaries. This number will increase to 196,000 people by 2032 with annual abstraction peaking at almost 16Mm$^3$.

The first stage of the scheme – Main Water Supply System – was completed in 2003 and involved the construction of various projects listed above. The second phase of development is planned for network distribution within the towns and to provide individual household connections. This will involve 144km of distribution pipework within Al Kamil wa Al Wafi and 252km within the Jaalan area. HDPE pipes with diameters ranging between 100 and 400mm are to be used. An extension of the scheme, to ease the water situation in the coastal areas and settlements of Al Sowaih, Al Bander Al Jadeed, Al Hadaah, Ras Al Rowais, Al Khabbah, Al Daffah and Wadi Sal, is under design. For such extension, a further 54km of pipeline will be constructed together with associated reservoir, pumping station and tanker filling facilities.

**Main Water Supply System Projects:**

- Two wellfields (Al Kamil and Jaalan) with total 31 production wells and 19 monitoring wells.
- 3 groundwater reservoirs with capacities ranging from 3,330m$^3$ to 12,300m$^3$.
- 16km of 100mm diameter collector pipelines.
- 115km of transmission pipelines with diameter ranging from 200-800mm.
- 2 pumping stations with capacities of 8,360 and 25,091m$^3$/day.
- Water treatment facilities.
- 7 water towers with capacities ranging from 500 to 1500m$^3$.
- Numerous tanker filling reservoirs and filling stations.
Water Monitoring Network

Monitoring data is the basic for most projects for the country. This data is very important in the construction design of roads, bridges, civil and non-civil structures. The systematic water resources data collection in Oman started after 1970. Monitoring networks have been established for measuring rainfall, climate, wadi flows, aflaj flows, groundwater levels and quality.

Rainfall Stations

Muscat has the only long-term rainfall record in the Sultanate; this started in the year 1894. Followed by a station in Salalah airport (1942) and Masirah Island (1943). However, nearly all of the 341 rainfall stations for which data are available were installed since the early 1970s. The Ministry is continuously updating and expanding the network using new technologies. Now about 70% of the rain gauges are automatic recorders. Most rainfall gauges in the Sultanate are operated by MRMWR, though some are operated by other Government organisations, including the Ministry of Defence (MOD), Ministry of Agriculture and Fisheries (MAF), Ministry of Transport & Communications (MOTC), Department of Meteorology and by Petroleum Development Oman (PDO).

In Dhofar, measurements of “occult” precipitation from summer monsoon clouds have been the subject of a series of experimental efforts. There is clear evidence that occult precipitation is an important component of total precipitation in the areas affected by the monsoon, and that interception by vegetation has been an essential link in the recharge process. In some areas of sparse coverage, interpolation between rain gauges is required and this is done with use of data from weather satellites. This appears to be a useful technique and to have applications to individual, major storms as well as to longer-term data, such as monthly rainfall distribution.

Meteorological Stations

There are 11 climate or meteorological stations in the Sultanate; they are mostly located at airports and are operated by the MOTC’s Directorate of Meteorology. In addition, 7 stations are operated by MRMWR and additional data is collected at certain sites by MAF and PDO.
High Altitude Rain Gauges (HARGs)

It is well known that it rains more in the mountains, but how much more? In the mid-1980s a programme was initiated to install rain gauges at high altitude at selected locations in Al Jabal Al Akhdar. It was recognised that the extreme orographic effects caused by the Northern Oman Mountains were a very important component of the hydrologic conditions in northern Oman and it was essential to obtain quantitative data. Accordingly, between 1986 and 1994, 15 HARGs were installed at elevations of between 1,310 to 2,820 metres above sea level. The HARGs stretch over a 250 km length of the Northern Oman Mountains, with a single gauge in Musandam.

Wadi Gauging Stations

As is typical for arid regions, wadi flow measurements in the Sultanate are fraught with difficulty. Wadis tend to be wide, sediment loads high and flow channels variable. Flash floods, though relatively rare, are characterised by high velocities which can damage flow measurement instruments, and the often difficult access adds to the problems involved in developing accurate systems for recording wadi flows. Currently, the Sultanate has 136 wadi gauges. As with rainfall gauges, most wadi stations are concentrated in the populated areas of the country. Wadi monitoring began in the 1970s using different devices. Three types of water level measurement device are used: electronic recorder with pressure transducers, bubble gauges with chart recorders, and stilling well-float type gauges with chart recorders. Originally, most were of the standard float type but after repeated damage by floods, they were replaced by electronic recorders. Now, 127 are of the pressure transducer data logger type and these are proving to be much more successful. There are plans to extend the present network in due course, and to provide telemetry for a selected network of key stations.

Aflaj flow measurements

Flow measurements are made periodically in a number of aflaj. These current meter measurements are made at a designated site on each falaj, at a location up-channel from the first water diversion. It is only recently that a programme to install recorders on a small number of aflaj has begun. Installations are designed and constructed in a manner that is acceptable to the local citizens, who are rightfully protective of such a fundamental resource.

Groundwater stations

Groundwater monitoring to measure water levels and water quality initially made use of existing, privately-owned, wells. These were typically subject to fluctuations associated with local pumping and have gradually been replaced by newly drilled wells constructed and dedicated to long-term monitoring. Some are designed to allow conductivity and other water quality characteristics to be
measured throughout the vertical profile of the aquifer, particularly in areas of active saline intrusion. A small number of monitoring wells are now equipped with recorders, so that groundwater levels can be continuously measured. In addition to routine monitoring of groundwater conditions, specialised monitoring programmes are conducted adjacent to recharge dam sites.
A

Alluvium: sediments deposited by flowing rivers. Depending upon the Location in the floodplain of the river, different-sized sediments are deposited.

Anisotropy: the condition under which one or more of the hydraulic properties of an aquifer vary according to the direction of flow.

Antecedent moisture: the soil moisture present before a particular precipitation event.

Aquiclade: a low-permeability unit that forms either the upper or lower boundary of a ground-water flow system.

Arid zone hydrology: the science and art of applying hydrological principles to arid and semi-arid regions.

Aquifer Rocks or sediment in a formation, group of formations, or part of a formation which is saturated and sufficiently permeable to transmit economic quantities of water to wells and springs.

Aquifer, confined: an aquifer that is overlain by a confining bed. The confining bed has a significantly lower hydraulic conductivity than the aquifer.

Aquifer, perched: a region in the unsaturated zone where the soil may be locally saturated because it overlies a low-permeability unit.

Aquifer, semiconfined: an aquifer confined by a low-permeability layer that permits water to slowly flow through it. During pumping of the aquifer, recharge to the aquifer can occur across the confining layer. Also known as a leaky artesian or leaky confined aquifer.

Aquifer, unconfined: an aquifer in which there are no confining beds between the zone of saturation and the surface. There will be a water table in an unconfined aquifer. Water-table aquifer is a synonym.

Aquifers: an absolutely impermeable unit that will neither store nor transmit water.

Aquitard: a low-permeability unit that can store ground water and also transmit it slowly from one aquifer to another.

Artificial recharge: the process by which water can be injected or added to an aquifer. Recharge dams, dug basins, drilled wells, or simply the spread of water across the land surface are all means of artificial recharge.

B

Baseflow: that part of stream discharge from ground water seeping into the stream.

Baseflow recession: the declining rate of discharge of a stream fed only by baseflow for an extended period.

Borehole geochemical probe: a water-quality monitoring device that is lowered into a well on a cable and that can make a direct reading of such parameters as pH, Eh, temperature, and specific conductivity.

Borehole geophysics: the general field of geophysics developed around the lowering of various tools into a well.

Bores: a hole advanced into the ground by means of a drilling rig.

C

Capillary forces: the forces acting on soil moisture in the unsaturated zone, attributable to molecular attraction between soil particles and water.

Capillary fringe: the zone immediately above the water table, where water is drawn upward by capillary attraction.

Cementations: the process by which some of the voids in a sediment are filled with precipitated materials, such as silica, calcite, and iron oxide, and which is a part of diagenesis.

Climate: the average course or condition of the weather at a place usually over a period of years as exhibited by temperature, wind velocity, and precipitation.

Condensations: the process that occurs when an air mass is saturated and water droplets form around nuclei or on surfaces.

Confining beds: a body of material of low hydraulic conductivity that is stratigraphically adjacent to one or more aquifers. It may lie above or below the aquifer.

Contact springs: a spring that forms at a lithologic contact where a more permeable unit overlies a less permeable unit.

Current meters: a device that is lowered into a stream in order to record the rate at which the current is moving.

D

Density: the mass or quantity of a substance per unit volume. Units are kilograms per cubic meter or grams per cubic centimeter.

Depression springs: a spring formed when the water table reaches a land surface because of a change in topography.

Depression storage: water from precipitation that collects in puddles at the land surface.

Dew points: the temperature of a given air mass at which condensation will begin.

Diffusion: the process by which both ionic and molecular species dissolved in water move from areas of higher concentration to areas of lower concentration.

Digital computer model: a model of water flow in which the aquifer is described by numerical equations, with specified values for boundary conditions, that are solved on a digital computer.

Direct precipitation: water that falls directly into a lake or stream without passing through any land phase of the runoff cycle.

Discharge: the volume of water flowing in a stream or through an aquifer past a specific point in a given period of time.

Discharge area: an area in which there are upward components of hydraulic head in the aquifer. Ground water is flowing toward the surface in a discharge area and may escape as a spring, seep, or baseflow or by evaporation and transpiration.

Dispersion: the phenomenon by which a solute in flowing ground water is mixed with uncontaminated water and becomes reduced in concentration. Dispersion is caused by both differences in the velocity that the water travels at the pore level and differences in the rate at which water travels through different strata in the flow path.

Drainage basin: the land area from which surface runoff drains into a stream system.

Drainage divides: a boundary line along a topographically high area that separates adjacent drainage basins.

Drawdown: a lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping of ground water from wells.

Duration curve: a graph showing the percentage of time that the given flows of a stream will be equalled or exceeded. It is based upon a statistical study of historic streamflow records.

Dynamic equilibrium: a condition in which the amount of recharge to an aquifer equals the amount of natural discharge.

Drought: the phenomenon by which both ionic and molecular species dissolved in water move from areas of higher concentration to areas of lower concentration.

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G

Glacial-lacustrine sediments: silt and clay deposits formed in the quiet waters of lakes that received meltwater from glaciers.

Groundwater: the water contained in interconnected pores located below the water table in an unconfined aquifer or located in a confined aquifer.

Groundwater basin: a rather vague designation pertaining to a ground-water reservoir that is more or less separate from neighboring ground-water reservoirs. A groundwater basin could be separated from adjacent basins by geologic boundaries or by hydrologic boundaries.

Groundwater, confined: the water contained in a confined aquifer. For water pressure is greater than atmospheric at the top of the confined aquifer.

Groundwater flow: the movement of water through openings in sediment and rock, occurs in the zone of saturation.

Groundwater mining: the practice of withdrawing ground water at rates in excess of the natural recharge.

Groundwater, unconfined: the water in an aquifer where there is a water table.

Grout curtain: an underground wall designed to stop groundwater flow; can be created by injecting grout into the ground, which subsequently hardens to become impermeable.

Hardness: a measure of the amount of calcium, magnesium, and iron dissolved in the water.

Humidity, absolute: the amount of moisture in the air as expressed by the number of grams of water per cubic meter of air.

Humidity, relative: percent ratio of the absolute humidity to the saturation humidity for an air mass.

Hydraulic conductivity: a coefficient of proportionality describing the rate at which water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in determining hydraulic conductivity.

Hydraulic gradient: the change in total head with a change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head.

Hydrogeology: the study of the interrelationships of geologic materials and processes with water, especially ground water.

Hydrographs: a graph that shows some property of ground water or surface water as a function of time.

Hydrologic equations: an expression of the law of mass conservation for purposes of water budgets. It may be stated as the rate of increase or decrease in storage.

Hydrological cycle: succession of stages through which water passes from the atmosphere to the earth and returns to the atmosphere: evaporation from the land or sea or inland water, condensation to form clouds, precipitation, accumulation in the soil or in bodies of water, and re-evaporation.

Hydrology: the study of the occurrence, distribution, and chemistry of all waters of the Earth.

I

Infiltration: the flow of water downward from the land surface into and through the upper soil layers.

Injection well: a well drilled and constructed in such a manner that water can be pumped into an aquifer in order to recharge it.

Interception: the process by which precipitation is captured on the surfaces of vegetation before it reaches the land surface.

Interception loss: rainfall that evaporates from standing vegetation.

Isohyetal lines: a line drawn on a map, all points along which receive equal amounts of precipitation.

Isotopes: the condition in which hydraulically connected aquifers are equal in all directions.

K

Karst: the type of geologic terrane underlain by carbonate rocks where significant solution of the rock has occurred due to flowing ground water.

L

Limestones: a rock that is formed chiefly by accumulation of organic remains (as shells or corals), consists mainly of calcium carbonate.

M

Model calibration: the process by which the independent variables of a digital computer model are varied in order to calibrate a dependent variable such as a head against a known value such as a watertable map.

Monsoon: a secondary atmospheric circulation occurring over a wide area, characterized by a seasonal reversal of steady, prevailing wind directions and by only rate alternations of high and low pressure systems.

O

Observation well: a nonpumping well used to observe the elevation of the water table or the potentiometric surface. An observation well is generally of larger diameter than a piezometer and typically is screened or slotted throughout the thickness of the aquifer.

Ophiolites: these are slices of the ocean floor that have been thrust above sea level by the action of plate tectonics. In various places in the world, the entire sequence of oceanic crust and upper mantle is exposed. The mountains in Oman are the best example of ophiolites in the world.

Overland flow: the flow of water over a land surface due to direct precipitation. Overland flow generally occurs when the precipitation rate exceeds the infiltration capacity of the soil and depression storage is full. Also called Horton overland flow.

Phreatic caves: a cave that forms below the water table.

Phreatic water: water in the zone of saturation.

Piezometer: a nonpumping well, generally of small diameter, that is used to measure the elevation of the water table or potentiometric surface. A piezometer generally has a short well screen through which water can enter.

Pluvial lake bed found in arid and desert regions in the lower part of an enclosed valley whose drainage is centripetal or inward. The lake is usually dry, except after heavy rainstorms, when it may be covered by a thin sheet of water which quickly disappears through evaporation. In Arabic lands is called sifah.

Pollutants: any solute or cause of change in physical properties that renders water unfit for a given use.

Porosity: the ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.

Porosity, effective: the volume of the void spaces through which water or other fluids can travel in a rock or sediment divided by the total volume of the rock or sediment.

Potentiometric maps: a contour map of the potentiometric surface of a particular hydrogeologic unit.

Prior-appropriation doctrine: a doctrine stating that the right to use water is separate from other property rights and that the first person to withdraw and use the water holds the senior right. The doctrine has been applied to both ground and surface water.

Public trust doctrine: a legal theory holding that certain lands and waters in the public domain are held in trust for use by the entire populace. It is especially applicable to navigable waters.

Pumping cone: the area around a discharging well where the hydraulic head in the aquifer has been lowered by pumping. Also called cone of depression.

Pumping test: a test made by pumping water for a period of time and observing the change in hydraulic head in the aquifer. A pumping test may be used to determine the capacity of the well and the hydraulic characteristics of the aquifer. Also called aquifer test.

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P

Radial flow: the flow of water in an aquifer toward a vertically oriented well.

Rainfall-runoff models: a mathematical model which, using appropriate hydrological principles expressed in mathematical equations, relates the volume and rate of runoff to the causative rainfall intensity and duration.

Rating curves: a graph of the discharge of a river at a particular point as a function of the elevation of the water surface.

Recharge: process, natural or artificial, by which water is added from outside to the zone of saturation of an aquifer, either directly into a formation, or indirectly, by way of another formation.

Recharge area: an area in which there are downward components of hydraulic head in the aquifer. Infiltration moves downward into the deeper parts of an aquifer in a recharge area.

Recharge basin: a basin or pit excavated to provide a means of allowing water to soak into the ground at rates exceeding those that would occur naturally.

Recharge dam: a structure built across an alluvial channel to temporarily store flood waters. The clean water is then released slowly, so it can infiltrate thick alluvium downstream of the dam and in time be withdrawn for use. The period of water detention in the reservoir is usually only a few days, to avoid losses and health hazards.

Recharge well: a well specifically designed so that water can be pumped into an aquifer in order to recharge the ground-water reservoir.
Recovery: the rate at which the water level in a well rises after the pump has been shut off. It is the inverse of drawdown.

Riparian doctrine: a doctrine that holds that the property owner adjacent to a surface-water body has first right to withdraw and use the water.

Rock, igneous: rock formed by the cooling and crystallization of a molten rock mass called magma.

Rock, metamorphic: rock formed by the application of heat and pressure to preexisting rocks.

Rock, plutonic: igneous rock formed when magma cools and crystallizes within the earth.

Rock, sedimentary: a rock formed from sediments through a process known as diagenesis or formed by chemical precipitation in water.

Rock, volcanic: an igneous rock formed when molten rock called lava cools on the earth’s surface.

Root zone: the zone from the land surface to the depth penetrated by plant roots. The root zone may contain part or all of the unsaturated zone, depending upon the depth of the roots and the thickness of the unsaturated zone.

Runoff: the total amount of water flowing in a stream. It includes overland flow, return flow, interflow, and baseflow.

Safe yield: the amount of naturally occurring ground-water that can be economically and legally withdrawn from an aquifer on a sustained basis without impairing the native ground-water quality or creating an undesirable effect such as environmental damage. It cannot exceed the increase in recharge or leakage from adjacent strata plus the reduction in environmental damage. It cannot exceed the ratio of the volume of contained water in a soil to the volume of the voids of the soil.

Specific capacity: an expression of the productivity of a well, obtained by dividing the rate of discharge of water from the well by the drawdown of the water level in the well. Specific capacity should be described on the basis of the number of hours of pumping prior to the time the drawdown measurement is made. It will generally decrease with time as the drawdown increases.

Specific discharge: an apparent velocity calculated from Darcy’s law; represents the flow rate at which water would flow in an aquifer if the aquifer were an open conduit.

Specific electrical conductance: the ability of water to transmit an electrical current. It is related to the concentration and change of ions present in the water.

Specific yield: the ratio of the volume of water a rock or soil will yield by gravity drainage to the volume of the rock or soil. Gravity drainage may take many months to occur.

Storage, specific: the amount of water released from or taken into storage per unit volume of a porous medium per unit change in head.

Storativity: the volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storativity is equivalent to the specific yield. Also called storage coefficient.

Saturated zone: the zone in which the voids in the rock or soil are filled with water at a pressure greater than atmospheric. The water table is the top of the saturated zone in an unconfined aquifer.

Saturation ratio: the ratio of the volume of contained water in a soil to the volume of the voids of the soil.

Sediments: an assemblage of individual mineral grains that were deposited by some geologic agent such as water, wind, ice, or gravity.

Seepage velocity: the actual rate of movement of fluid particles through porous media.

Seismic refractions: a method of determining subsurface geophysical properties by measuring the length of time it takes for artificially generated seismic waves to pass through the ground.

Sinkhole springs: a spring created by ground-water flowing from a sinkhole in karst terrain.

Soil moisture: the water contained in the unsaturated zone.

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Storm hydrograph: a graph of the discharge of a stream over the time period when, in addition to direct precipitation, overland flow, interflow, and return flow are adding to the flow of the stream. The storm hydrograph will peak owing to the addition of these flow elements.

Stream, gaining: a stream or reach of a stream, the flow of which is being increased by inflow of ground water. Also known as an effluent stream.

Throughflow: the lateral movement of water in an unsaturated zone during and immediately after a precipitation event. The water from throughflow seeps out at the base of slopes and then flows across the ground surface as return flow, ultimately reaching a stream or lake.

Time of concentration: the time it takes for water to flow from the most distant part of the drainage basin to the measuring point.

Tortuosity: the actual length of a ground-water-flow path, which is sinuous in form, divided by the straight-line distance between the ends of the flow path.

Transmissivity: the rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of properties of the liquid, the porous media, and the thickness of the porous media.

Transpiration: the process by which plants give off water vapor through their leaves.

Turbidity: cloudiness in water due to suspended and colloidal organic and inorganic material.

Turbulent flow: that type of flow in which the fluid particles move along very irregular paths. Momentum can be exchanged between one portion of the fluid and another. Compare with Laminar flow.

Unsaturated zone: the zone between the land surface and the water table. It includes the root zone, intermediate zone, and capillary fringe. The pore spaces contain water at less than atmospheric pressure, as well as air and other gases. Saturated bodies, such as perched ground water, may exist in the unsaturated zone. Also called zone of aeration and vadose zone.

V

Vadose cave: a cave that occurs above the water table.

Vadose water: water in the zone of aeration.

Vadose zone: see unsaturated zone.

Viscosity: the property of a fluid describing its resistance to flow. Units of viscosity are newtons seconds per meter squared or pascal-seconds. Viscosity is also known as dynamic viscosity.

W

Wadi gauging: operation of measuring the velocities, depths and widths for the purpose of determining the discharge.

Water balance: an evaluation of all the sources of supply and the corresponding discharges with respect to an aquifer or a drainage basin.

Water content: the weight of contained water in a soil divided by the total weight of the soil mass.

Water equivalent: the depth of water obtained by melting a given thickness of snow.

Water quality criteria: values for dissolved substances in water based upon their toxicological and ecological impacts.

Watertables: the surface separating the upper unsaturated from lower saturated soil.

Watertable map: a specific type of potentiometric-surface map for an unconfined aquifer; shows lines of equal elevation of the water table.

Well development: the process whereby a well is pumped or surged to remove any fine material that may be blocking the well screen or the aquifer outside the well screen.

Well screen: a tubular device with either slots, holes, guaze, or continuous-wire wrap; used at the end of a well casing to complete a well. The water enters the well through the well screen.

X

Xerophyte: a desert plant capable of existing by virtue of a shallow and extensive root system in an area of minimal water.

Z

Zone of aeration: see unsaturated zone.
# Glossary of Arabic Terms

| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z |
| **A** | **J** | **K** | **L** | **M** | **N** | **O** | **P** | **Q** | **R** | **S** | **T** | **U** | **V** | **W** | **X** | **Y** | **Z** |
| abu | jabali | khabura | ligil | mazara | tahr | ghayli falaj | jilab | mazari | rabiya | sabkha | thuqaba | umm | wadi | zakat |
| father well, a term used less frequently than umm - the mother well. | mountain. | the basic unit of shareholding on a falaj. | a cistern. | permanently cultivated gardens. | a residential area. | type of falaj in which water is derived from wadi baseflow. | individual plot of land. | the water diviner. | an agricultural labourer with particular duties, plural: bayadir. | water shares allocated to the falaj administration. | salt flat, playa. | a shaft. | the mother well. | valley or drainage channel in an arid region, which carries flash floods. | Islamic tax. |
| aflaj | jilabs | mazara | muganni | maful | zabaa | ghayli falaj | jilab | bidar | rabiya | sabkha | thuqaba | umm | wadi | zakat | type of falaj originating from a mother well, a type of a horizontal well. | same as daudi falaj. | salt flat, playa. | a shaft. | umm al falaj | Arbid | waqf | wilayat | zaht | |
References

A substantial work has been done on water resources of the Sultanate of Oman, regarding their hydrology, hydrogeology, and their management. The resources can be divided into two main categories. The first one is Arabic references and the second one is the English references.

There are many Arabic references which have covered the subject of aflaj under different titles like ‘Ahkam al aflaj’ aflaj rules and ‘Ahkam al muṣrāj’ water rules. The main subjects they cover are the solution of the dispute between the share owners of a falaj and the dispute among the owners of different aflaj. The rules are derived from Sharia, the Islamic Law. The main rule they use is “La dhāna kalas dhīma” which means there is neither harm for you nor harm for others.

Bader bin Salim Al Abri in 1993 wrote a book about aflaj called ‘Al Ḥaybān fi Ba’dh Aflaj Oman’. He described the falaj construction and the way of shares distribution among the owners. Some Arab researchers also wrote about aflaj and their hydrology and construction like Agha from ACSAD and Sa‘īd.

There are many references in English written about aflaj, the most prominent of them by Wilkinson. In his studies (1974, 1977), he represented the distribution of water among shareholders and social impact of aflaj on the community. Beaumont (1968, 1989) studied qanats in the Middle East and Iran. He gave a hydrogeological explanation about qanats and the influence of wells on them. Dutton has been studying aflaj since early seventy’s till now. He is concentrating on the prediction of flow recessions. Yvonne Parks had tried to apply mathematical model in aflaj for the prediction of flow recessions.


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