ECONOMIC AND SOCIAL COMMISSION FOR WESTERN ASIA

IMPLICATIONS OF GROUNDWATER REHABILITATION ON WATER RESOURCES PROTECTION AND CONSERVATION: ARTIFICIAL RECHARGE AND WATER QUALITY IMPROVEMENT IN THE ESCWA REGION

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The study introduces the various rehabilitation techniques that need to be applied in order to combat groundwater pollution in the ESCWA region. It is hoped that it will encourage ESCWA Member States to give serious consideration to the issue of groundwater protection and rehabilitation and enhancing the technical capacity of their water professionals in these areas.

Abstract

Over the last three decades, social and economic development in ESCWA Member States has required the provision of increasing water supplies to all sectors. In order to meet increasing demand, shallow and deep aquifers have been developed and now serve as the major source of water in many parts of the region. Groundwater is a major source of drinking water for urban centres in Jordan, Syria, Lebanon, Palestine, Saudi Arabia, Oman and Yemen and for most rural communities. It is also the major source of water for irrigation in Jordan, Palestine and Syria and the countries of the Arabian Peninsula. This development has put great pressure on groundwater resources and resulted in varying degrees of depletion and contamination.

There has been little systematic investigation of groundwater contamination in ESCWA Member States, so there is little published data, but this report presents a general description of the relevant pollutants and their sources, as well as a number of case studies. The main sources of groundwater pollution in the region are discharge of wastewater, return flow of drainage water, fertilizers, pesticides and the disposal of solid and liquid industrial waste, including hazardous waste, into rivers and wadis. These pollutants infiltrate the soil profile or leak through fractures to reach shallow aquifers. Other sources of pollution are the injection of brine water from oil production into aquifers, especially in the GCC countries, and salt water intrusion caused by over-abstraction of coastal aquifers. These activities have resulted in a deterioration in water quality in many parts of the region, especially along rivers and wadis. Major pollutants found in groundwater are nitrates, phosphates, sodium chloride, sulphates, heavy metals such as chromium and lead, and faecal bacteria. Contamination has made some groundwater resources unsuitable for human consumption and therefore further reduced the availability of safe water supplies in the region.

There are many viable remediation techniques for the removal, flushing or disintegration of contaminants through treatment of water inside or outside aquifers. Remediation methods may consist of in situ and on-site or off-site physical and chemical treatments. Natural attenuation or enhanced natural attenuation which keep interference with the natural environment to a minimum is another new approach to groundwater remediation. While numerous widely approved techniques, as well as new approaches, are described in this report, the selection of a suitable remediation technique depends on particular natural and social conditions, type of pollutants, and financial constraints.

The application of remediation techniques in the ESCWA region has been limited because of lack of awareness of groundwater pollution, lack of experience and financial resources, and lack of commitment by decision-makers. One issue that has received some attention is salt water intrusion resulting from excessive pumping of coastal aquifers.

Since groundwater remediation is usually very costly and sometimes impossible, preference should be given to prevention. This requires the development, implementation and enforcement of policies and legislation to minimize the risk of groundwater pollution through, for example, land use restrictions, control of wastewater discharge and disposal of hazardous waste. Groundwater monitoring programmes, groundwater vulnerability mapping and groundwater modelling facilitate decision-making on groundwater protection measures. The potential public health risk and the decreasing availability of clean groundwater make it of paramount importance that decision-makers and water professionals give adequate attention to this issue. The study also emphasizes the need to enhance capacity-building to achieve the objectives of minimizing public health risks through groundwater rehabilitation.

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INTRODUCTION

World fresh water resources are limited, particularly in arid and semi-arid regions. There is increasing competition among water-consuming sectors to meet social and economic development requirements. Increasing development activities are contributing to the diminution of freshwater resources and posing health risks in different parts of the world. Only 2.5 per cent of the world's total fresh and salt water is useable, and there are natural and technical limitations on the extraction even of this small amount of fresh water, estimated at 42 700 billion cubic metres (bcm), since only 30 per cent (12 800 bcm) can be made available for human and development consumption.

Fresh water is even more scarce in the Arab region, where only 0.62 per cent of the world's water resources are to be found. The ESCWA region is estimated to have 0.38 per cent of them, while potentially available fresh water in the region is estimated at 163 bcm, 142.5 from surface water from the major rivers and flood flow, 18.5 bcm from groundwater and 2.1 bcm from desalination facilities. Average per capita share in ESCWA Member States is just above the absolute water scarcity threshold of 500 m3/capita/year. Eight countries, namely Bahrain, Jordan, Kuwait, Qatar, Palestine, Saudi Arabia, the United Arab Emirates and the Republic of Yemen, have less than 500 m3/capita/year, and six - Bahrain, Jordan, Kuwait, Qatar, the United Arab Emirates, and Yemen—have less than 200 m3/capita/year and are among the world's 15 countries poorest in water. Demand for water is rising and there is a shortage of water for human consumption in a number of countries. This has forced utilities to provide water through sea and brackish water desalination and further depletion of groundwater resources. In a number of ESCWA countries, such as those of the Arabian Peninsula and Jordan, groundwater is a vital water source for domestic consumption and irrigation. Worldwide, more than 1.5 billion people depend on groundwater for drinking and agricultural usage. Groundwater is a vital source of water in many parts of the world, particularly in the ESCWA region. Overuse has put great pressure on its further development and management, especially deep groundwater, as a result of extensive mining and increasing pollution levels.

Increasing urbanization, the use of pesticides and fertilizers in agriculture and the dumping of industrial waste have resulted in the contamination of groundwater sources, especially shallow ones, and further upset the balance between supply and demand. In many countries, the cost of developing new supplies is becoming prohibitive and no effort has been made to rehabilitate contaminated aquifers. The challenge of meeting future demand for water lies in efficient use, monitoring quantity and quality, avoiding over-consumption and pollution, and rehabilitation. Some monitoring and protection measures for both surface and groundwater are being implemented or planned, but there has been very little rehabilitation of resources, especially groundwater, perhaps because of lack of technical capacity.

Because of limited water availability in most ESCWA Member States, and the need efficiently to develop and manage all water sources, the Energy, natural Resources and Environmental Division (ENRED) of ESCWA gave water issues that need urgent attention by ESCWA Member States prominence in its programme for the 2000/2001 biennium. One of the priority issues selected was groundwater pollution and rehabilitation. Groundwater sources are being lost as a result of pollution and are posing health risks and damaging the environment. Over the last few decades, cases of groundwater pollution in the region have been reported around some major urban centres and irrigation regions. Increased salinity of groundwater in aquifers along the Mediterranean, Red Sea and Gulf coasts from salt water intrusion is also common, while the rise of the water table in some urban centres has had environmental and health consequences. There is a need to increase awareness of the problems and encourage decision-makers to explore ways of cleaning polluted aquifers in order to increase supply.

The main objective of this study is to review the status of groundwater pollution and present the techniques for groundwater rehabilitation being applied in different parts of the world, including the Arab world and the ESCWA region. It is hoped this will help to increase awareness of the issue of groundwater pollution control and the technical, financial and environmental impact of cleaning contaminated groundwater.

The study will highlight existing groundwater quantity and quality with regard to its use by different consuming sectors, pollution sources and pollutants, groundwater remediation techniques and protection measures. It summarizes the papers presented and discussed at the Expert Group Meeting held in Beirut from 14 to17 November 2000.

The study is divided into six chapters. The first reviews the quantity and quality of ESCWA groundwater resources, while the second discusses common sources of groundwater pollution in general and in the ESWCA region in particular, and the impact of pollution on health. Chapter three reviews rehabilitation techniques for contaminated soil and groundwater sources, and chapter four presents a number of rehabilitation case studies from the region. Groundwater protection using vulnerability mapping, monitoring and modelling are described in Chapter five, while chapter six summarizes the main conclusions and recommendations of the study.

I. THE STATUS OF GROUNDWATER RESOURCES

Water resource issues are probably more significant in the ESCWA region than in any other part of the world because of the scarcity of water and its mismanagement. When projected water requirements for all purposes are compared with available surface and groundwater resources, serious questions arise as to the long-term economic and environmental sustainability of existing water resource development and water usage patterns. Under existing patterns of water usage and prevailing water scarcity, it is unlikely that the expansion of irrigated agriculture can proceed without leading to water shortages, especially in the domestic sector.

Water resources consist of surface water from major rivers in Egypt, Iraq, Syria, Lebanon and Jordan, estimated at 150.7 bcm and renewable groundwater in shallow aquifers with limited reserves receiving recharge at 18.7 bcm. There are significant reserves in deep aquifers with fossil water and poor water quality. Treated waste water and drainage water is estimated at 8.3 bcm and desalinated water at 2.1 bcm. In 2000, total consumption was 150.5 bcm, use of groundwater being 30 bcm. The water resources of the ESCWA region are shown intable 1.

A. GROUNDWATER RESOURCES

Groundwater is a vital source for all sectors, the irrigation sector and rural communities, especially in the Arabian Peninsula, being heavily dependent on it. Groundwater is the main source of water for some ESCWA countries. Groundwater as a percentage of total supply varies, not only from one country to another, but also from sector to sector within the same country. It is the main domestic water supply in many rural areas of the ESCWA region, and even in GCC countries, where desalination is extensively used, groundwater sources are mixed with desalinated water to increase mineral content. It is also the main water supply for irrigation purposes in the Arabian Peninsula. A similar picture of varying degrees of reliance on groundwater also emerges for the irrigation sector in the remaining Member States. Furthermore, in terms of annual replenishment, groundwater aquifers receive and store the bulk of the annual run-off in the Arabian Peninsula and Jordan.

At regional level, groundwater accounts for about 11 per cent of total annual renewable water resources (i.e. groundwater recharge). At country level, however, groundwater can be much more significant, especially in GCC countries, Jordan and the West Bank, as is shown in table 1. In the countries of the Arabian Peninsula and part of Jordan, where there are no major renewable surface water sources such as rivers, the depletion of groundwater is demonstrated through the use of a sustainability indicator and is shown in table 2. Sustainability of groundwater is associated with groundwater recharge that may occur seasonally or intermittently. This indicator will be defined below.

Rainfall distribution and morphological, lithological and structural geological features govern groundwater occurrence, accumulation and movement. Rainfall and snowmelt are the main sources of groundwater recharge. Major geological features are the Arabian shield and shelf resulting from the split of the Afro-Arabian plate. The Neogene fold created the Taurid and Iranian mountain belts north and north-east of the Arabian shelf which extend from the Tauros and Zagros mountains in Turkey and Iran to the Oman mountains (ESCWA/BGR 1999). The shield covers one third of the Arabian Peninsula and extends from the Gulf of Aqaba in the north to the Gulf of Aden in the south. It is composed of hard igneous and metamorphic rocks, while the shelf is composed of a series of thick sedimentary formations dipping east toward the Gulf. Groundwater in the mountain belts in the north and the shield accumulates in the fractured folded and fissured formation. Significant groundwater reserves are found in the sedimentary formation of the Arabian shelf.

Groundwater in the region is found in numerous localized, regional and shared aquifer systems, such as the Paleogene aquifer in the Arabian Peninsula, the Basalt aquifer between Syria and Jordan and the Nubian Sandstone aquifer in Egypt. Major aquifers are those located in the Arabian Peninsula, part of the Syrian Arab Republic, Jordan and Iraq. The Arabian Shelf contains many major carbonate and sandstone aquifers. There are carbonate aquifers composed of limestone and dolomites of Jurassic and Cretaceous age in the western highlands and mountain ranges and in the Palmyrean Mountains. Paleogene aquifers composed of chalks limestone and dolomites extend over vast areas with mainly plateau-like landscapes in Syria, eastern Jordan, and southern Iraq, north-western and eastern Saudi Arabia, the Gulf area and the southern fringes of the Empty Quarter in Yemen and Oman.

TABLE 1. STATUS OF WATER RESOURCES (MCM)

Country/area	Conventional water resources[a/,b/,c/] Surface water	Ground-water use	Ground-water recharge	Total (mcm)	Non-conventional water resources Desalination	Waste-water and drainage reuse	Total renewable and non-conv. res., (mcm)	Water consumption	Utilization %	Groundwater dependency (%)
Bahrain	0.2	258	100	100.2	75	17.5 (3)*	192.7	350.7	181.99	73.57
Egypt	55 500	4 850	4 100	59 600	6.6	4920 (3800)	64526.6	65 276.6	101.16	7.43
Iraq	70 370	513	2 000	72 370	7.4	1500	73877.4	72 390.4	97.99	0.71
Jordan	350	486	277	627	2.5	61	690.5	899.5	130.27	54.03
Kuwait	0.1	405	160	160.1	388	30	578.1	823.1	142.38	49.2
Lebanon	2 500	240	600	3 100	1.7	2	3103.7	2743.7	88.4	8.75
Oman	918	1 644	550	1 468	51	23	1542.0	2636.0	170.95	62.37
Qatar	1.4	185	85	215	131	28	245.4	345.4	140.75	53.56
Saudi Arabia	2 230	14 430	3 850	86.4	795	131 (24)	7006.0	17 586.0	251.01	82.05
Syrian Arab Republic	16 375	3 500	5 100	6 080	2	1447 (1270)	1447.0	21 324.0	93.02	16.41
United Arab Emirates	185	900	130	21 475	455	108	878.0	1 648.0	187.7	16.41
West Bank and Gaza Strip	30	200	185	315	0.5	2	217.5	232.5	106.9	54.61
Yemen	2 250	2 200	1 400	3 650	9	52	3711.0	4511.0	121.56	86.02
Total	150 709.7	29 811	18537.0	169 246.7	1924.7	8321.5	179492.9	190 766.9		48.77

Source: Compiled by the ESCWA Secretariat from country papers, EGM and international sources 1995, 1996, 1997, and 1999.

* Volume of drainage water.

a/ The flow of the Tigris and Euphrates rivers may be reduced by upstream abstraction in Turkey.
b/ ACSAD paper submitted to the 2nd Symposium on Water Resources Development and Uses in the Arab World, Kuwait, 8-10 March 1997.
c/ Consolidated Arab Economic Report, 1997.

The major water carbonate aquifers are known as the Eastern Mediterranean aquifers, composed of carbonate formations, are in Lebanon, the Syrian Arab Republic and the highlands of Jordan. The Jabal Al-Arab basaltic aquifers are located in south-eastern Syrian Arab Republic, eastern Jordan and northern Saudi Arabia, and the Jezira tertiary limestone aquifers located in southern Turkey and the Syrian Arab Republic. Relatively deep aquifers include the upper and lower Fars formations, composed of gypsum interbedded with limestone in the Syrian Arab Republic and southern parts of Iraq.

There are sandstone aquifers of Paleozoic to Cretaceous age in the eastern part of Saudi Arabia, southern Jordan and the Rutbah area of Iraq, and deep, confined aquifers in northern Jordan and in Syria. The Disi-Saq sandstone aquifers are located in Jordan and Saudi Arabia. The Nubian aquifer, composed of thick sandstone, runs through Egypt, Libya and Sudan. This aquifer is overlain by a large carbonate aquifer which runs over the northern parts of Egypt. Groundwater from these formations is shared among a numbers of ESCWA countries. These aquifers are not usually at risk of pollution because of their great depth. Regional groundwater movement on the Arabian Shelf is directed towards several depression discharge areas of the Dead Sea-, Yermouk, El Ghab, and Azraq- Wadi Sirhan valleys, Damascus, Palmyra and Euphrates basins and the Sabkha area in the Gulf region.

Renewable groundwater is available in the Shallow quaternary wadis, flood plain and river bed deposits located in the coastal plains and inland basins, which contain groundwater of good quality that is frequently recharged by perennial river flow and flood flow. The shallow aquifers in the Arabian Peninsula, Lebanon, the Syrian Arab Republic, western Jordan, Iraq and the Nile Delta hold groundwater reserves in the alluvial deposits and limestone formations sufficient to meet water requirements. The hydrogeology of major aquifers located in each ESCWA country is briefly discussed below.

Lebanon. There are two main aquifers in Lebanon: the Jurassic limestone, with a thickness averaging 1200 metres and the Cenomanian-Turonian, with a thickness ranging from 600 to 1000 metres. In addition, the Neogene, Quaternary, and Carbonate aquifers overlie the two major aquifers. Recharge from precipitation is estimated at 2.5 bcm, and water quality ranges from 150 to 800 ppm (Country Papers 1997, 1999).

Syrian Arab Republic. The main groundwater aquifers are those of Anti-Lebanon and the Alouite Mountains. Folding and faulting of the geological layers has resulted in the mingling of the sub-aquifer systems. There are a number of springs discharging from this aquifer system, such as the Ari-Eyh, Barada, Anjar-Chamsine and Ras El-Ain. Recharge to the system occurs from intense precipitation in the mountainous regions which infiltrates through the fractures and fissures of the karstified surface layer. The estimated recharge is 5.43 bcm. Water quality ranges from 175 to 900 ppm.

The other significant aquifer system is the Damascus plain aquifers that extend from the Anti-Lebanon Mountains in the west to the volcanic formations in the south and east of the country. This system is composed of gravel and conglomerates with some clay, and is represented by riverbeds and alluvial fan deposits with a thickness of up to 400 metres. Recharge occurs from wadi and river flow, irrigation return, and leakage from the Cenomanian-Turonian aquifer estimated at 410 mcm. Groundwater quality ranges from 500 to more than 5000 ppm.

The other major carbonate Haramoun mountain aquifer is located between Lebanon and the Syrian Arab Republic. The main discharging springs are those of the Banias and Dan tributaries of the Jordan River basin. The average spring discharge from the Haramoun aquifer is estimated at 464 mcm with a recharge rate estimated at 320 mcm. Groundwater quality is estimated at 250 ppm. Other aquifers with limited potential are located in the desert areas. These consist of marl and chalky limestone of the Paleogene age. Recharge occurs mainly from flood flow. Water quality ranges from 500 to 5000 ppm depending on the source of recharge.

TABLE 2. SUFFICIENCY OF RENEWABLE WATER RESOURCES IN THE ESCWA REGION

Country/area	Renewable water resources (MCM)			Annual water per capita[b/] (m)^3			Sustainability indicator[c/] (%)		
	Surface water	Recharge	Total	1997	2015	2025	1997	2000	2025
Bahrain	0.2	100	100.2	137	131	99	309	349	608
Egypt	55 500	4 100	59 600	925	698	658	110	115	145
Iraq	70 370	2 000	72 370	2 963	1 832	1 359	68	88	118
Jordan	475	277	752	168	78	70	101	168	235
Kuwait	0.1	160	160.1	89	62	57	438	500	874
Lebanon	2 500	600	3 100	995	437	341	40	53	124
Oman	918	550	1 468	613	403	309	117	103	169
Qatar	1.4	85	86.4	98	70	60	345	580	943
Saudi Arabia	2 230	3 850	6 080	311	182	150	268	292	398
Syrian Arab Republic	16 375[a/]	5 100	21 475	1 438	948	609	46	80	110
United Arab Emirates	185	130	315	137	103	67	388	692	1 015
West Bank and Gaza Strip	30	185	215	-	-	-	205	230	600
Republic of Yemen	2 250	1 400	3 650	303	165	114	79	72	97
Total	152 335	18.5	169 372	-	-	-	-	-	-

From *Updating the Assessment of Water Resources in ESCWA Member Countries* E/ESCWA/ENR/1999/13.

a/ The flow of rivers may be reduced by upstream extraction.

b/ Water barrier index. Renewable resources/population.

c/ Sustainability indicator. Water use/renewable resource. Future sustainability is based on 2000 and 2025 water demand programmes (10-20 per cent indicate better management practices while more than 4 per cent mismanagement).

\- Data not available.

Egypt. There are groundwater resources in the Nile Valley, the Delta and the Nubian sandstone and alluvial aquifers. The Nile Valley and the Delta are two distinct formations; the Quaternary and Tertiary sandstone and gravel of the upper formation are separated from the underlying Nubian sandstone formation by a layer of clay. The thickness of the Nile Valley and the Delta aquifers averages 300 and 1000 metres respectively, depending on the location, with reasonable production capacity. Sources of recharge in the Nile Valley are percolation form irrigation water and conveyance channels, while for the Delta they are irrigation percolation and river seepage. Recharge to the Valley and Delta aquifers are estimated at 6.2 and 2.6 bcm respectively. Water quality ranges from 170 to 1700 ppm and in some areas the concentration may reach more than 6000 ppm. There is also groundwater in the extensive Nubian sandstone aquifer that extends into Libya and Sudan. Aquifer thickness ranges form 100 to 800 metres, with large potential groundwater reserves of good quality. Water-bearing formations extend into the desert area of the Red Sea and the Sinai Peninsula.

West Bank and Gaza Strip. Groundwater resources occur mainly in the Cenomanian-Turonian mountain aquifers and coastal Pleistocene sand and sandstone aquifers (ESCWA/NR/1997). The mountain aquifers in the West Bank consist of limestone and dolomite with a thickness of 700 metres. In the mountain aquifer system, three groundwater provinces have been identified in the western, north-eastern and eastern basins. These basins extend over most of the West Bank and discharge into the Yarkan River. The estimated recharge magnitude is 600 mcm. There are sandstone aquifers in the Gaza strip with a thickness ranging from 10 to 180 metres and an estimated annual recharge volume of 70mcm. Water quality ranges from 1200 to 3000 ppm.

Iraq. Groundwater aquifers in Iraq consist of extensive alluvial deposits of the Tigris and Euphrates rivers, and are composed of Mesopotamian-clastic and carbonate formations. The alluvial aquifers have limited potential because of poor water quality. The Mesopotamina-clastic aquifers in the north-western foothills consist of Fars, Bakhtiari and alluvial sediments. The Fars formation is made up of anhydrite and gypsum interbedded with limestone, and covers a large area of Iraq. The Bakhtiari and alluvial formations consist of a variety of material, including silt, sand, gravel, conglomerate and boulders, with a thickness of up to 6000 metres. Water quality ranges from 300 to 1000 ppm.

Another major aquifer system is contained in the carbonate layers of the Zagros Mountains. Two main aquifers are found in the limestone and dolomite layers, as well as in the Quaternary alluvium deposits. The limestone aquifer contributes large volumes of water through a number of springs. The alluvial aquifers contain large volume reservoirs, and recharge is estimated at 620 mcm from direct infiltration of rainfall and surface run-off. Water quality is good, ranging from 150 to 1400 ppm.

Jordan. The major groundwater aquifers in Jordan are Wadi El-Sir of the Turonian age, Amman of the Cempanian age, and the Disi formations. The Wadi El-Sir and Amman formations consist of limestone, dolomite, chert and sandy limestone. One of these formations lies on top of the other throughout most of Jordan, with the exception of a small area in the south. The other aquifer system is a deep sandstone aquifer in the Disi formation that extends into the northern region of Saudi Arabia. Recharge takes place directly by infiltration of rainfall through fissures and karstified carbonate rocks, and from flood flow. Estimated recharge is 260 mcm. Base flow and spring discharge is estimated at 540 mcm, with water quality ranging from 500 to 3500 ppm.

Arabian Peninsula. Groundwater reserves for some of the countries of the Arabian Peninsula Saudi Arabia, Kuwait, Bahrain, Qatar, the United Arab Emirates, Oman and Yemen are found in the renewable shallow alluvial aquifers and non-renewable deep aquifers of sandstone and limestone formations (Abu Zeid 1992, ASCAD 1997, ESCWA 1996/139-1, ESCWA 1999). Alluvial deposits along the main wadi channels and flood plains of drainage basins in Kuwait, Saudi Arabia and the United Arab Emirates, Oman, Yemen and southern Jordan make up the shallow groundwater system in most of the southern ESCWA countries. Groundwater in the shallow aquifers is the only renewable water source, and is estimated at 131 bcm. Total reserves are estimated at 131 bcm, mainly in Saudi Arabia, where they are estimated at 84 bcm. Groundwater from the shallow alluvial is used mainly for domestic and irrigation purposes. The alluvial aquifer is being contaminated by the dumping of industrial and domestic wastewater.

The other main source of water for the countries of the Arabian Peninsula is the non-renewable fossil groundwater stored in sedimentary deep aquifers. These aquifers store significant amounts of groundwater that is thousands of years old. The major aquifers are the Disi/Saq, Tabuk, Wajid, Minijur-Druma, Wasia-Biyadh, Tawilah and Amran sandstone aquifers and the Dammam, Um er-Radhuma, Neogene carbonate aquifers. Other aquifers are the Aruma, Jauf, Khuff, Jilh, Sakaka, Upper Jurassic, Lower Cretaceous, and Buwaib formations. These aquifers cover two-thirds of the eastern Arabian Peninsula, with large coverage of Saudi Arabia and extending into Kuwait, Bahrain, Qatar, the United Arab Emirates, Oman, and Yemen, as well as into Jordan, the Syrian Arab Republic and Iraq.

Saudi Arabia. Major aquifer systems are the alluvial deposits, carbonate and sandstone formations. Deposits consist of mainly coarse-grained sand, gravel, silt and clay. The alluvial aquifers range in thickness from 10 to 250 metres, and contain large groundwater reserves. Groundwater recharge occurs from rainfall and flood flow, and may reach 2000 mcm per year.

Water quality ranges from 300 to 5000 ppm. The other main groundwater source is located in the deep carbonate and sandstone formations of the Saq, Tabuk, Minjur, Wasia, Wajid, Dammam, Khobar, Sakaka and Aruma aquifers. Vast amounts of groundwater stored in the deep aquifers serve as a dependable source of water for the central and northern regions of Saudi Arabia, and to a lesser extent, the other countries of the peninsula. Total dissolved solids range from 400 to 20 000 ppm. Good quality water is stored only in the Saq, Tabuk, Wajid, and Dammam aquifers.

Kuwait. Groundwater resources consist of water available from the Dibdiba, Far, Gar, Dammam, Rus and Umm er-Radhuma formations. The aquifer system is divided into two main groups: the Kuwait group, which includes the Dibdiba, composed of sand and gravel, Far of evaporite and Gar sand formations, and the Hassa group represented by the Dammam limestone, Rus anhydrite and Umm er-Radhuma limestone formations. The main formations for groundwater utilization are the Kuwait group and the Dammam formation. Groundwater recharge is estimated at 160 mcm, with water quality ranging from 400 to 4000 ppm.

Bahrain. The main aquifers in Bahrain are the Neogene, Dammam, Rus and Umm er-Radhuma. The Dammam and Umm er-Radhuma aquifers provide most of Bahrain's water, but contain saline water. The subdivisions of the Dammam formation are the Khabor (dolomite) and the Alat (limestone) formations, each containing major aquifers of average quality water which serve as an industrial and agricultural source for Bahrain. The Rus and Umm er-Radhuma aquifers contain either brackish or saline water unfit for consumption. The aquifer system in Bahrain acts as a major recharge area for tertiary carbonate aquifers located in Saudi Arabia. Recharge is estimated at 100 mcm and occurs from leakage from other aquifers, as well as from underflow from the extensions of aquifers originating in Saudi Arabia. There are other aquifers, such as the Aruma and Wasia that have high salinity. Groundwater quality in the Dammam formations ranges from 2000 to 4000 ppm, while for the Umm er-Radhuma it may reach 18,000 ppm.

Qatar. The aquifers in Qatar are in the carbonate, Umm er-Radhuma, Rus, Dammam and Neogene formations. The Aruma and Wasia formations are also present in Qatar. Groundwater from the Dammam, Umm er-Radhuma, and Rus formations is used to provide water for use in all sectors. Water quality in some locations is good, ranging from 400 to 2000 ppm, however for most of the aquifer water quality ranges from 2000 to 6000 ppm.

United Arab Emirates. There are groundwater resources in the upper clastic and lower carbonate formations located in the Bajada region in the eastern part of the country. The aquifers consist of alluvial fan deposits along the base of the Oman and Ras El-Khaymah mountains extending over a large area. The upper aquifer is composed of gravel sand and silt, the lower aquifer of limestone, dolomite and marl. Both aquifers range in thickness from 200 to 800 metres. In addition, the Damam and Umm er-Radhama formation extend into the western desert areas, with thickness ranging from 500 to 1000 metres. Groundwater quality in the two aquifer systems, particularly in the Bajada region, ranges from 600 to 2000 ppm. The Dammam and Umm er-Radhuma aquifers contain highly saline water.

Oman. The Batiniah alluvial and Bajada alluvial fan deposits and the Umm er-Radhuma and Rus tertiary carbonate formations are the major aquifer systems in Oman. The Baliniah alluvial aquifer is composed of gravel, conglomerate, medium and coarse sand, silt and clay. Thickness ranges from 240 to 600 metres. A large number of fissures drain the mountain catchment areas into the Piedmont zones. Water quality ranges from 800 to 6000 ppm. The alluvial fan aquifer of the Bajada region consists of Quaternary deposits and Fars group formations, with water quality ranging from 900 to 6000 ppm. The tertiary carbonate aquifers, represented by the Umm er-Radhuma, Rus and Dammam formations, have very poor water quality in excess of 4000 ppm.

Yemen. There are groundwater resources in the Tihama and Gulf of Aden alluvial deposits. The Tihama alluvial aquifers are an extensive system extending along the coastal plains, and range in thickness from 20 to 500 metres. The aquifers receive extensive direct recharge from rainfall and wadi flood flow. Water quality ranges from fair to good. The Gulf of Aden alluvial aquifers extend into the coastal area of the Gulf, with major wadis separated by intrusive rock, and thickness averaging 400 metres. The major aquifers are those in wadis and the Delta of Tuban, Abian, Ahwear and Meifa. Water quality varies from 600 to 2000 ppm.

The Hadramaut aquifer system consists of sandstone and carbonate aquifers in the eastern Arabian Peninsula. The system consists of the Umm er-Radhuma limestone and Mukalla sandstone formations. The aquifer is overlaid with thick alluvial deposits. Recharge from rainfall, run-off and intermittent flow is estimated at 160 mcm. Water quality from the Mukalla aquifer ranges from 440 to 1000 ppm. The other major groundwater source is contained in the highland aquifers located in the rugged volcanic and crystalline mountains in the central region of Yemen. They are located in the sub-basin and mountain plains of the centre of the country. The main aquifers are in the alluvium, the volcanic formations, and the Taqilah, Amran, Kohlan and Wajid sandstone formations. Water Quality is generally good.

B. GROUNDWATER UTILIZATION

Groundwater reserves in both renewable shallow and non-renewable deep aquifers are currently the main source of water in Jordan, the Syrian Arab Republic, Egypt, Republic of Yemen, the GCC countries and Gaza, and have been exploited to meet domestic and agricultural water requirements. Jordan, Saudi Arabia and Bahrain have been exploiting their non-renewable groundwater, while Qatar, the United Arab

Emirates, Oman and Yemen are using fossil water sources over 20 000 years old to meet rising demand in the agricultural sector. Groundwater utilization has exceeded the safe yield of the aquifers. Safe yield, which is regional groundwater recharge of the sustainable use of groundwater, is estimated at 18.5 bcm. In 1996, groundwater utilization in the ESCWA region was 28.3 bcm, compared to 18.5 bcm of groundwater recharge, with 67 per cent withdrawal in the GCC countries and Yemen.

Agriculture is the largest user of water in the region, but rapid urbanization and improved quality of life in terms of health, sanitation and social services have resulted in a sharp increase in water demand for municipal purposes. When combined with industrial and agricultural uses, high demand for water has caused an imbalance between water availability and water required for socio-economic development (ESCWA, 1999). Groundwater mining is expected to continue in order to meet growing demand in all sectors. The percentage of water requirements in he ESCWA region in the year 2000 is shown in table 3.

In the ESCWA region, groundwater quantity and quality is threatened by various development activities, and mismanagement. Groundwater has been over-exploited through excessive, uncontrolled pumping in many basins, such as those in Jordan, the GCC countries, the Syrian Arab Republic and Republic of Yemen. Groundwater quality is deteriorating as a result of seawater intrusion into aquifers under the coastal plains in Bahrain, Oman, Qatar, the United Arab Emirates and Republic of Yemen. All these factors have resulted in a progressive reduction in available groundwater resources in the region, to the extent that sustainable agricultural development may be hindered in the future.

C. GROUNDWATER QUALITY

Water utilization is influenced by water quality, whether it is abstracted for drinking, industrial, recreational or irrigation purposes. Geology (rock types and structures), hydrology (rainfall and run-off distribution and movement through the soil profile and the aquifer) and pollution (source, type and disintegration) are the major factors influencing the quality of groundwater. Humid regions tend to have good water quality due to frequent rainfall and perennial recharge, while arid regions, such as the ESCWA region, tend to have relatively good to poor groundwater because of limited rainfall. In the ESCWA region, groundwater with relatively low salinity is usually found in aquifers in areas with relatively high rainfall, while deep groundwater aquifers with good water quality may be attributed to ancient and current recharge along their outcrop areas or through infiltration of water from major river and wadi deposits. The main processes affecting groundwater quality in the region are the prevailing infiltration-recharge mechanism, over-irrigation, solid and liquid waste disposal, groundwater extraction and inter-aquifer flow as a result of the dynamic equilibrium of multi-aquifer systems.

Groundwater with low salinity extends over wide areas of the western mountain ranges and the western escarpment of the Arabian Peninsula. Groundwater salinity in most areas of the Syrian steppe and the Arabian Peninsula has total dissolved solids (TDS) ranging from one to several thousand mg/l (ESCWA 1995, ESCWA/BGR 1999). Examples of groundwater quality are shown in table 4.

TABLE 3. PERCENTAGE OF WATER REQUIREMENTS IN THE ESCWA REGION IN 2000

Country	Domestic water demand (%)	Industrial water demand (%)	Agricultural water demand (%)
Bahrain	46.8	9.2	44
Egypt	4.4	7.8	87.8
Iraq	7.4	1.7	90.9
Jordan	31.3	5	63.7
Kuwait	63.6	17.8	18.6
Lebanon	22	10.6	67.4
Oman	14.2	4.6	81.2
Qatar	42.4	4.3	53.3
Saudi Arabia	13.3	2.3	84.4
Syrian Arab Republic	7.5	2.8	89.7
United Arab Emirates	34	1.4	64.285
West Bank and Gaza Strip	52.5	3.6	43.9
Yemen	10	1.7	88.3

Source: Compiled by the ESCWA Secretariat from country papers, regional and international sources, 1992, 1994, 1995, 1996, 1997, 1999, and questionnaires.

TABLE 4. EXAMPLES OF MAJOR ION CONCENTRATIONS IN GROUNDWATER SAMPLES (*mg/l*)

Aquifer	Area	Ca	Mg	N/A	HCO_3	SO_4	Cl
A. *Sandstone aquifers*							
Disi	South Jordan	75	12	20	105	23	33
Tabuk	NE Saudi Arabia	59	23	51	54	49	113
B. *Karstic carbonate aquifers*							
Upper Cretaceous	Qaryatein, Syria	64	32	58	201	178	40
Upper Cretaceous	Arak, Syria	42	26	30	79	130	53
Um er-Radhuma	Wadi El-Miyah, east of Saudi Arabia	69	21	51	269	62	54
C. *Wadi aquifers*							
Upper Cretaceous	W. El-Minah, Syria	96	43	161	209	240	226
Tertiary	Muqat , NE Jordan	67	35	114	282	127	134
Qauternary	W. Arran, Saudi Arabia	59	33	103	194	96	199
Quaternary	W. Fatimah, Saudi Arabia	113	18	69	192	218	126
D. *Pleistocene*	Raudhatain, Kuwait	88	14	113	192	216	75
E. *Quaternary*	Fujayrah, United Arab Emirates	20	4	103	232	62	138

Sources: Hobler et al. (1991), Khouri (1982)

II. GROUNDWATER POLLUTION

A. POLLUTION SOURCES

Generally, good groundwater is available in areas with abundant rainfall, in aquifers with heterogeneous and coarse materials and areas with perennial flow. In addition to natural poor quality, increasing pollution by the consuming sectors is causing deterioration in groundwater. As the quality of water deteriorates, its uses diminish, thereby reducing groundwater supplies and intensifying shortages.

Pollution may occur Naturally or result From human activity. In general, pollution sources may be classified into the following types:

1. *Point source*

Point source pollution is inputs of pollutants from Individual discharge points. Typical point sources are leakage of hazardous substances from storage tanks, spills at industrial installations and farmyards, or Leaching from landfills and waste disposal sites. It also includes discharges of industrial, domestic or municipal Wastewater. Infiltration of untreated industrial wastewater Can increase concentrations of various substances above drinking quality values Such as total salinity, major constituents, organic compounds, and trace metals. Leakage of untreated wastewater from sewers and septic Tanks into shallow aquifers may increase Groundwater salinity and particularly nitrate concentrations, faecal bacteria and viruses.

2. *Diffuse source*

Diffuse pollution is inputs of pollutants into the aquatic environment over a large area, especially agricultural pollution sources. Irrigation return flow can cause an on-going increase in the salinity of groundwater affecting its further use for irrigation, while residues of fertilizers and pesticides in irrigation return flow may endanger drinking water quality. Infiltration of domestic wastewater from areas depending on percolation pits and septic tanks for sewage disposal and the use of untreated wastewater in irrigation may seriously contaminate water supply wells and springs, particularly with bacteria and viruses and elevated levels of nitrogen compounds.

Deposition of atmospheric contaminants is another diffuse source. Pollutants which are emitted to the air, such as sulphur dioxide and ammonia, may be transported for hundreds of kilometres, before they precipitate as acid rain.

3. *Accidental pollution*

Accidental pollution is the release of pollutants from a source due to an accident or unforeseen circumstances.

The level of groundwater pollution differs from one country to another depending on the intensity of social and economic development activities, the infiltration-recharge mechanism and hydrogeological conditions. Potential groundwater pollution sources are shown in figure I. Groundwater degradation in the ESCWA region is the result of a number of factors, the most important being:

(a) Increases in the discharge of untreated or inadequately treated domestic and industrial water in open areas, rivers and wadis;

(b) Discharges from agro-processing plants and a high level of agrochemicals in rivers, wadis and dump sites;

(c) Discharge of hazardous and toxic industrial waste in inadequate dump sites;

(d) Infiltration of saline agricultural drainage from large-scale irrigation into shallow aquifers;

(e) Over-exploitation of groundwater, causing rapid movement of saline groundwater lenses and salt water intrusion;

(f) Unmanaged pumping leading to hydrodynamic disturbance which may cause groundwater mixing among multi-aquifer systems;

(g) Overuse of fertilizers and pesticides in agriculture and their migration to the shallow groundwater formation;

(h) Injection of brine and hydrocarbon by-products from oil production and refinery operation into aquifers;

(i) Naturally occurring pollutants such as radium, radon and other radioactive elements.

Untreated wastewater, toxic industrial and medical waste, irrigation return flow and accidental spills of hazardous material are the major sources of groundwater pollution in the ESCWA region and have caused groundwater contamination in many areas, especially of shallow alluvial aquifers, but also of some deep aquifers, as a result of injection operations or fast water movement in karstified limestone formations. The degree of pollution depends on many factors, including the physical and chemical characteristics of the soil profile, the underlying aquifer and the pollutant itself, the flow dynamics and depth to the water table. The absence of enforceable regulations has encouraged the easy disposal of pollutants into surface and ground water bodies.

B. EXAMPLES OF GROUNDWATER POLLUTION IN THE ESCWA REGION

While few systematic investigations of groundwater pollution in ESCWA Member States have been carried out and published, evidence of groundwater contamination has been reported for a number of aquifers.

Groundwater pollution is especially prevalent in shallow aquifers beneath rivers, for example, in the Nile Delta, southern Iraq, Jordan and the Damascus basin in Syria. The discharge of industrial and domestic wastewater and irrigation return flow into rivers are the main sources of contamination of these aquifers, as a result of river-groundwater hydraulic interconnection. The development of major irrigation schemes and industrial and domestic wastewater facilities along the four major rivers - the Nile, Tigris, Euphrates and Jordan - has led to a deterioration of water quality in the connecting shallow aquifers. Fractured limestone aquifers in Lebanon and Syria are also especially prone to contamination and the use of septic tanks in mountainous limestone areas is a major pollution source. Extensive agriculture in Saudi Arabia, Oman, the United Arab Emirates and Republic of Yemen, and to a certain extent in the remaining countries, has caused high nitrate and other fertilizer compound concentrations in the soil and shallow groundwater sources. Fertilizer and pesticides leaching from irrigated fields are often found in shallow alluvial aquifers of the Arabian Peninsula, while the discharge of untreated or semi-treated wastewater into dry wadis and its reuse in irrigation is another common pollution source in all countries of the peninsula. An overview of exposure to contaminants in the ESCWA region is shown in table 5.

Nitrogen, which is overused in the form of manure, sewage sludge and chemical fertilizer, is a major groundwater pollutant in the ESCWA region. As an essential plant nutrient, it is an important fertilizer, but high levels of nitrate in drinking water have a major health impact. Furthermore, too much nitrate in the soil leads to the destruction of organic matter by oxidation, thus increasing the amount of nitrate leached by infiltrating rain and decreasing the self-purification capacity of the soil and the unsaturated zone near the surface.

Pesticides are widely used in agriculture and industry. The use of synthetic organic pesticides has grown rapidly since the 1950s because, when used in conjunction with fertilizers, they increase crop yields. Pesticides are, however, a risk to human health. Some soluble pesticides can move fast through the unsaturated zone, but their progress may be delayed by adsorption and biological degradation processes. Rapid flow in fractured aquifers is a high risk.

Figure I. Groundwater pollution sources

Potential pollution sources

- Industrial
  - Handling of hazardous substances
  - Accidental spills
  - Hazardous waste
  - Mining waste
  - Surface mining
  - Wastewater treatment plants
    - - Effluent
    - - Sludge
    - - Injection wells
  - Oil field brine
  - Pipeline leakage
- Domestic and
  - Underground storage tanks
  - Septic
  - Percolation pits
  - Domestic waste
  - Construction waste
  - Municipal landfill
- Agricultur
  - Fertilizer
  - Manure
  -
  - Irrigation with untreated wastewater
  - Irrigation return flow
  - Animal waste
  - Crop debris
-
  - Over abstraction leading to saltwater intrusion from
    - - sea water
    - - deeper brackish or saline groundwater
  - Improper well design resulting in short-circuiting be

In the Beqa'a plain, a major agricultural region in Lebanon, the overuse of fertilizers and the reuse of wastewater have caused soil and groundwater pollution. These activities have resulted in elevated levels of nitrate and heavy metals, such as chromium, nickel, cadmium, lead and zinc in the Beqa'a soil profile and shallow groundwater aquifer (Darwish et al.., 2000). The aquifer is vulnerable to contamination, including by heavy metals, as its depth below the soil surface is in some locations very shallow with a minimum of only 0.5 metres. Heavy metal concentration in the soil profile decreases with depth (Darwish et al., 2000) with highest reported values of 0.28, 28.5, 93.6, 28, 72.8, 15.5 and 97.2 mg/l for cadmium, copper, chromium, cobalt, nickel, lead and zinc, respectively. In the groundwater, concentrations of 13.9, 6.4, 0.06, 115.2, 0.86 μg/l of Ni, Cr, Cd, Zn, and Pb respectively were found at a depth of 2 metres, and similar levels of 12.5, 5, 0.03, 219.5, and 0.95 μg/l at a depth of 8 metres, while in the 70-metre deep well, concentrations were significantly lower at 5, 4, 0.02, 36.8 and 0.4 μg/l, respectively, as shown in tables 6, 7 and 8. Although these values indicate elevated levels of heavy metals, all concentrations are still well below WHO drinking water quality standards. In contrast, nitrate concentration in the groundwater was sometimes above the WHO drinking water quality standard of 50 mg/l, reaching maximum values of more than 200 mg/l.

A water quality study in Saudi Arabia reported a relatively high nitrate concentration in shallow aquifers located at a depth ranging from 30 to 50 metres (Al Zubari, 2000). It was reported that the sampling of 388 wells located in the six regions of Saudi Arabia in 1989 had nitrate levels ranging from 0.01 to 95 mg/l. The ammonia level in eight per cent of the wells reached more than 0.05 mg/l, with some values as high as 5 mg/l. Faecal coliform bacteria were present in 21.4 per cent of the wells. Another field study (Abdulrahman, 2000) carried out in the eastern part of Saudi Arabia investigated pollution from the application of fertilizers and herbicides. The main pollution sources were nitrogen, phosphorus and potassium fertilizers and organic nitrogen from manure. Pesticide and herbicide concentrations in the shallow aquifer were below detection levels. Because of its great depth, the deep aquifer showed no sign of pollution. The sampling of the shallow aquifer indicated high levels of nitrate and sulphate and trace elements of boron, iron, and copper.

The nitrate values indicated seasonal variation, with the highest values of 620 mg/l in the winter and 568 mg/l in the summer. The high sulphate values ranged from 7 690 in the summer to 5990 mg/l in the winter, while for boron the range was from 18.7 in the summer to 24 mg/l in the winter. The highest fluoride values also ranged from 5.4 in the summer to 15.4 mg/l in the winter (Abdulrahman 2000).

In Egypt, the application of nitrogen, phosphorus and potassium fertilizers increased by 62, 81, and 115 per cent, respectively, between 1976 and 1996 (Shamrukh et al., 2001). Extensive application has resulted in pollution of the shallow Nile aquifer, Nile Delta and Nile Valley aquifers located at depths of 30-70 metres. Concentrations were 20-350 for nitrate, 7-34 for phosphate, 7-28 for potassium and 96-630 mg/l for sulphate. The permissible limits are 0.25-3.5 for phosphate, 12 for potassium and 250-400 mg/l for sulphate.

TABLE 5. REPORTED TYPE OF WATER SOURCE UTILIZATION, QUALITY AND EXPOSURE TO CONTAMINANTS IN THE ESCWA REGION

Bahrain	Groundwater (GW) Desalinated sea water	Poor -fair N/A	Excessive exploitation – brackish water
Egypt	Surface water (SW) Groundwater (GW)L	Good Fair	Municipal: overloaded sewerage disposal systems Industrial: discharge of untreated effluents Agriculture: pesticides
Iraq	Surface water (SW) Groundwater (GW)	Poor-good	Excessive construction in neighbouring countries Saline water intrusion Municipal: overloaded sewerage systems Industrial: discharge of treated effluents Agricultural: water drainage and run-offs
Jordan	Groundwater (GW)	Variable	Excessive exploitation – brackish water, saline water intrusion. Industrial: uncontrolled discharge of untreated effluents Agriculture: irrigation water drainage, pesticides and toxic materials
Kuwait	Groundwater (GW)	Poor	Excessive exploitation – brackish water, saline water intrusion, transboundary underflow Industrial: oil pools

TABLE 5 (*continued*)

Lebanon	Groundwater (GW) Surface water (SW)	Good Good	Municipal: solid waste disposal, sewerage systems Industrial: management of waste Silent trade: transboundary movement, dumping of hazardous industrial wastes
Oman	Surface water (SW) Groundwater (GW)	Good	Excessive exploitation – brackish water, saline water intrusion, transboundary underflow Industrial: oil pools
Qatar	Groundwater (GW) Desalinated sea water	Fair N/A	Excessive exploitation – brackish water, saline water intrusion
Saudi Arabia	Groundwater (GW) Surface water (SW) Desalinated sea water	Good N/A	Excessive exploitation: brackish water-, saline water intrusion
Syrian Arab Republic	Surface water (SW) Groundwater (GW)	Fair-Good N/A	Industrial: disposal of industrial and other types of waste water
United Arab Emirates	Surface water (SW) Groundwater (GW) Reclaimed water	Fair N/A N/A	Over-exploitation (alluvial aquifers), saline water Industrial – oil spills and oil-sludge
Yemen	Groundwater (GW) Surface water (SW)	Fair-good	Over-exploitation (alluvial aquifers), saline water Sewage disposal systems

Source: UNESCWA, 1995 *Assessment of Water Quality in the ESCWA Region*. United Nations, New York, (E/ESCWA/ENR/1995/14), chapter II and III.

Pollution of the ESCWA coastal aquifers from saltwater intrusion is the result of the pumping of groundwater exceeding recharge. This is happening in the coastal aquifers of Egypt, Syria, Lebanon, the Gaza Strip and all countries of the Arabian Peninsula. One of the major groundwater pollution sources in Lebanon is salt water intrusion along the coastal zone as a result of overpumping of groundwater. The karstified coastal aquifers were exposed to increased sea water intrusion and chloride content increased from 250 mg/l in 1968, to 1200 in 1973 and 2000 mg/l in 2000 (Lebanon Country Paper, 2000). In eastern Saudi Arabia salt water intrusion was observed with reported values of 15000 to 21 00 mg/l total dissolved solids (Abdulrahman 2000). A similar situation was observed in Bahrain, the United Arab Emirates, Oman and Yemen, with high chloride content as a result of salt water intrusion.

TABLE 6. HEAVY METAL ACCUMULATION IN THE BEQA'A VALLEY UPPER SOIL LAYERS WITH LOW QUALITY IRRIGATION WATER
(*After Darwish et al., 2000*)

Profile ID	Soil depth cm	Cd mg/kg	Co	Cr	Cu	Ni	Pb	Zn	Water table depth cm
Za-3	0-20	0.28	28.5	93.6	28.6	72.7	15.5	95.7	
	20-150	0.26	28.1	93.5	28.3	72.8	13.2	97.2	800
	150-200	0.24	17.9	60.7	19.2	48.8	7.2	64.4	

TABLE 7. ANALYSIS OF WATER FROM WELLS IN THE CENTRAL BEQA'A VALLEY
(*mg/l*)
(*After Darwish et al., 2000*)

Source	Ni	Cr	Cd	Zn	Pb
Shallow open water reservoir, 2m depth nourished from water table seepage.	13.9	6.4	0.06	115.2	0.86
Superficial well (Arab well) 8 m.	12.5	5	0.03	219.5	0.95
Deep well 70 m.	5	4	0.02	36.8	0.4
Level of Intervention*	15-37	1-26	1.5-6	150-290	15- to be defined
WHO drinking water quality standard	20	50	3	3 000	10

* The level beyond which measures should be undertaken to limit hazards of heavy metal input to the soils.

TABLE 8. THE STATUS OF NITRATES AND SALTS IN THE DEEP WELLS OF THE CENTRAL BEQA'A VALLEY
(*After Darwish et al., 2000*)

Number of wells	NO3 mg/l	No. of wells	Electrical Conductivity dSm/m	Total dissolved solids mg/l
10	>200	13	1.0-2.0	650-1300
6	100-200	4	0.6-1.0	400-650
8	40-100	13	<0.6	<400
6	10-40			

Highly toxic organic pollutants have also been found in groundwater in some ESCWA countries. The sources of these pollutants are petrol spillage, brine from oil refinery by-products and medical waste. In the GCC countries, injection wells are frequently used to discharge brines into the deep zones. In addition to their high salinity, brines are usually contaminated by hydrocarbons, their content depending on the efficiency of the process used to separate oil from water. Injection wells can cause groundwater contamination if the injected fluid enters overlying fresh water aquifers as a result of poor well design or vertical migration through cracks, fault zones and abandoned well casings. In Bahrain and eastern Saudi Arabia, brine has been injected into the Rus - Umm er-Radhuma aquifers (Al-Zubari, 2000). The injected brine in Bahrain had an average oil content of 260 mg/l, equivalent to 60 000 cubic metres of crude oil (Al-Zubari, 2000). Because of its serious environmental impact, this type of pollution is not being reported. Treatment of such waste before injection is very costly.

In northern Bahrain, petrol leakage from storage tanks has resulted in a petrol plume 0.5 km wide and 1.5 km long floating over the shallow groundwater sources (Al-Zubari, 2000). There is a similar problem in the industrial city of Jubail in Saudi Arabia. Petrol pollution is common in most urban centres because of lack of monitoring and poor design.

Pollution is further compounded by failure to implement appropriate groundwater monitoring and protection programmes. This brief discussion gives only an indication of the type and extent of pollution from different activities. Groundwater contamination is taking place in all ESCWA countries, but limited data make it very difficult to estimate the total extent of pollution. In this study, the limited information available in papers presented at the Expert Group Meeting on groundwater rehabilitation held in November 2000, as well as other sources, provide a few examples of soil and groundwater pollution. There are believed to be many other cases of pollution in the ESCWA region, with varying environmental and health impacts. The documented cases of groundwater pollution demonstrate that serious efforts are required to implement protection measures. In some cases, remediation of contaminated soil and aquifers may also be advisable.

C. GROUNDWATER POLLUTION - HEALTH IMPACT

Contaminated drinking water is the main cause of illness and death in the world. Ingestion of, or exposure to, contaminated water causes a number of diseases. Others may be caused by exposure to naturally found harmful chemicals or man-made pollutants in ground water. The morbidity and mortality rates of water-related diseases that may result from pollution are shown in table 9. There are short-term and long-term health risks associated with contaminated water. These may be microbial (bacteria, viruses, parasites), chemical (metals, pesticides, disinfectants by-products, etc.) or toxin-related (toxins produced by micro-organisms), as shown in tables 10 and 11. Contaminants in irrigation water can also affect agricultural products and cause health problems by entering the food chain. Consequently, the absence of proper astewater collection systems and the persistence of open channels or pools of wastewater will serve as breeding grounds for many diseases.

Illness resulting from water consumption may be caused by chemical contamination, such as radio-active material, arsenic, cadmium, lead etc. or biological contamination by viruses, parasites and bacteria. The symptoms of illness caused by groundwater contaminants include the following:

(a) Symptoms of chemical poisoning may include mental confusion, dementia, mental retardation in babies, etc. Long-term exposure may be carcinogenic. Industrial and agro-industrial pollution, particularly by hydrocarbons and heavy metals, can cause severe health damage;

(b) Biological contaminants can lead to uncontrollable outbreaks of disease, especially in developing countries. Symptoms may include diarrhoea, gastro-intestinal manifestations, fever, etc. Infectious diseases caused by pathogenic bacteria, viruses and protozoa or by parasites are the most common and widespread health risks associated with drinking surface and groundwater. Water can carry a number of infectious diseases, such as viral hepatitis, Norwalk virus, cholera, typhoid fever, camphylobacteriosis, gastro-enteritis, amoebic dysentery, giardiasis and cryptosporidiosis. Water-borne infectious diseases can be fatal: globally, two million people die from diarrhoea every year;

(c) Illness may also be caused by water containing naturally occurring trace elements, which may be beneficial to health at low concentrations, but are very harmful in high dosages. Lead, arsenic, fluoride, and radioactive isotopes are the most dangerous of these.

Table 9 classifies water-related disease.(Jurdi, 2000).

For many years a ban on human morbidity and mortality data operated by some countries made it difficult to trace the effect of poor environmental conditions on human health. These restrictions have now been lifted, but it is still difficult to collect data because methods are not standardized.

Adequate, safe water supply and treated wastewater can reduce the occurrence of water-related diseases and death. Some preventive measures are shown in table 12 (Jurdi, 2000).

TABLE 9. ESTIMATED MORBIDITY AND MORTALITY OF WATER-RELATED DISEASES
(*After Jurdi, 2000*)

Disease	Morbidity (episodes/ year, or as stated)	Mortality (deaths/year)	Relationship of disease to water supply and sanitation
Diarrhoeal disease	1 000 000 000	3 300 000	Strongly related to unsanitary excreta disposal, poor personal and domestic hygiene, and unsafe drinking-water.
Infection with intestinal helminths	1 500 000 000[a/]	100 000	Strongly related to unsanitary excreta disposal, and poor personal domestic hygiene.
Schistosomiasis	200 000 000[a/]	200 000	Strongly related to unsanitary excreta disposal and absence of nearby sources of safe water.
Dracunculiasis	100 000[a/,b/]		Strongly related to unsafe drinking water.
Trachoma	150 000 000[c/]		Strongly related to insufficient face washing, often in the absence of nearby sources of safe water.
Malaria	400 000 000	1 500 000	Related to unsatisfactory water management, water storage, operation of water points and drainage.
Dengue fever	1 750 000	20 000	Related to unsatisfactory solid waste management, water storage.
Poliomyelitis	114 000		Related to unsanitary excreta disposal, poor personal and domestic hygiene, and unsafe drinking-water.
Trypanosomiasis	275 000	130 000	Related to the absence of nearby sources of safe water.
Bancroftian filariasis	72 800 000[a/]		Related to unsatisfactory water management, water storage, operation of water points and drainage.
Onchocerciasis	17 700 000[a/,d/]	40 000[e/]	Related to unsatisfactory water management in large-scale projects.

a/ People currently infected.
b/ Excluding Sudan.
c/ Active Trachoma. There are approximately 5 900 000 cases of blindness or severe complications of the disease annually.
d/ Includes an estimated 270 000 blind people.
e/ Mortality resulting from blindness.

TABLE 10. CLASSIFICATION OF WATER-RELATED DISEASE (*After Jurdi, 2000*), TYPE OF PATHOGENIC AGENT AND RECOMMENDED ENVIRONMENTAL INTERVENTION

Category	Infection	Pathogenic agent	Recommended environmental intervention
Water-borne (faecal-oral)			
Diarrhoeas and dysenteries	Amoebiasis	Protozoa	Improve water quality
	Camphylobacter gastro-enteritis	Bacterium	
	Cholera	Bacterium	
	E. Coli diarrhoea	Bacterium	Prevent casual use of unauthorized water sources
	Giardiasis	Protozoa	
	Rotavirus	Virus	
	Salmonellosis	Bacterium	
	Shigellosis	Bacterium	
Enteric Fevers	Typhoid	Bacterium	
	Paratyphoid	Bacterium	
	Poliomyelitis	Virus	
	Ascaiasis (giant roundworm)	Helminth	
	Trichuriasis (whipworm)	Helminth	
	Strongyloidiasis	Helminth	
	Taenia solium taeniasis (pork tapeworm)	Helminth	
Water-washed	Infectious skin disease	Miscellaneous	Improve water quality
	Infectious eye disease	Miscellaneous	Improve water quality
	Louse-borne relapsing fever	Spirochaete	Improve hygiene
Water-based	Schistosomiasis	Helminth	Regulate the need for water contact
	Dracunculiasis	Helminth	Control snail population
	Clonorchiasis	Helminth	Improve water quality
	Others	Helminth	Improve water quality
Water-related insect vector	Trypanosomiasis	Protozoa	Improve surface water
	Malaria	Protozoa	Eliminate breeding sites of insect
	Yellow fever	Virus	Control water storage
	Dengue fever	Virus	Improve design of water storage vessels
	Other	Virus	

- Adapted from R.G Feachman, 1984 "Infection Related to Water and Excreta: The health dimension of the decade" in P.G Bourne (ed). *Water and Sanitation*. Academic Press Inc. , Orlando, Florida, pp. 21-47.

- Adapted from Cairncross, Sandy et al. *Evaluation for village water supply planning*. Chichester, New York Published in association with International Reference Centre for Community Water Supply by J. Wilev IRC.

TABLE 11. A SAMPLE CLASSIFICATION OF WATER-RELATED DISEASES BY AGENT, INCUBATION PERIOD AND SIGNS AND SYMPTOMS
(*After Jurdi, 2000*)

Disease entity	Agent	Incubation period	Signs and symptoms
Cadmium poisoning	Cadmium	<1hr	Upper gastrointestinal symptoms predominate (nausea, vomiting)
Fluoride poisoning	Sodium fluoride		
Arsenic poisoning	Arsenic		
Cholera	Vibrio cholera	<1week	Lower gastrointestinal symptoms predominate (abdominal cramps, diarrhoea)

TABLE 11 (*continued*)

Disease entity	Agent	Incubation period	Signs and symptoms
Camphylobacter gastro-enteritis	Camphylobacter foetus jejuni	<1week	Lower gastrointestinal symptoms predominate (abdominal cramps, diarrhoea)
Viral agents enteritis	Variety of viral Agents (Coxackiek's-adenovirus, rotavirus)	<1week	Lower gastrointestinal symptoms predominate (abdominal cramps, diarrhoea)
Amoebiasis	Entamoebia histolytica	<1week	Lower gastrointestinal symptoms predominate (abdominal cramps, diarrhoea)
Giardiasis	Lamblia	<1week	Lower gastrointestinal symptoms predominate (abdominal cramps, diarrhoea)
Lead poisoning	Lead and lead salts	Variable/dose dependent	Lower gastrointestinal symptoms predominate (abdominal cramps, diarrhoea)
Hepatitis A	Hepatitis A virus	<1week	General infection (fever, chills)
Typhoid fever	Salmonella typhoid	<1week	
Methaemoglobania	Nitrates	Variable/dose dependent	Cyanosis
Organophosphate poisoning	Organophosphate compounds, insecticides	<1 hr	Neurological symptoms (visual disturbances, tingling paralysis)
Chlorinated hydrocarbon poisoning	Chlorinated hydrocarbons, insecticides	1-6 hrs	Paralysis
Pseudomonas auruginosa infection	Pseudomonas auruginosa	<1week	Paralysis
Schistosoma dermatitis	Schistosoma larvae (many species)	<1week	Neurological Symptom (visual disturbances, and/or tingling).
Schistosoma dermatitis	Schistosoma haematobium	<1week	

Source: Balance, R.C. and Glun, R.A. (1984)). "Drinking–water and sanitation projects: criteria for resource allocation". World Health Organization WHO Chronicle, 38(6), pp. 243-248 (1984).

General signs and symptoms should be carefully investigated, in addition to disease specific spectrum.

TABLE 12. IMPORTANCE OF WATER SANITATION-RELATED INTERVENTIONS AND DISEASE CONTROL

	Intervention				
Disease	Water quality	Water quantity convenience	Personal and domestic hygiene	Wastewater disposal drainage	Excreta disposal
Diarrhoeas					
Viral diarrhoeas	++	+++	++	0	++
Bacterial diarrhoeas	+++	+++	+++	0	++
Protozoa diarrhoeas	+	+++	+++	0	++
Poliomyelitis and Hepatitis A	+	+++	+++	0	++
Worm infections					
Ascaris, Tricharis	+	+	+	+	+++
Hookworm	+	+	+	0	+++
Pinworm, dwarf tapeworm	0	+++	+++	0	++
Other tapeworm	0	+	+	0	+++
Schistomiasis	+	+	+	0+	+++
Guinea-worm	+++	0	0	0	0
Other worms, with aquatic hosts	0	0	0	0	++

TABLE 12 (*continued*)

Disease	Intervention				
	Water quality	Water quantity convenience	Personal and domestic hygiene	Wastewater disposal drainage	Excreta disposal
Skin infections	0	+++	+++	0	0
Eye infections	+	+++	+++	+	+
Insect-transmitted diseases					
Malaria	0	0	+	+	0
Urban yellow fever, dengue	0	0	+	++	0
Bancroftian filariasis	0	0	0	+++	+++
Onchocerciasis	0	0	0	0	0

Source: Adapted from Balance, R.C and Glun, R.A (1984). "Drinking-water and sanitation projects: criteria for resource allocation". World Health Organization, WHO Chronicle, 38(6), pp. 243-248 (1984).

Notes: Degree of importance of intervention:
+++ high,
++ medium,
\+ low,
0 negligible

D. GENDER IMPACT

Women can play an important role in the management of water resources especially in the domestic sector in urban and rural areas. It is usually they who collect water from taps or wells for domestic use and apply irrigation water. Women and children provide nearly all the water for households in rural areas in many developing countries. In some cases, women recycle grey water for washing and irrigation, and use run-off for livestock. Women therefore have considerable knowledge about water resources, including quality and reliability, restrictions and acceptable storage methods. Although they are so closely involved in water use and disposal, women have been ignored in the planning and execution of water programmes.

Women make multiple uses of water resources and attempt to avoid their pollution. If water resources become contaminated, it is women and children who have to walk further to obtain safe water. Thus poor water access and polluted water create hardship for women in rural communities. For example it is reported that approximately 30 per cent of women in the rural areas of Egypt walk over an hour a day to collect water for domestic water needs. In some parts of Africa, women and children spend eight hours a day collecting water.

In many cases, water resource policies and programmes have proven detrimental to women's water rights and therefore to sustainable water management and use. Interventions such as irrigation habitually fail to take into consideration the existing imbalance between men's and women's ownership rights, division of labour and incomes. By raising the value of the land, irrigation brings about social change, which usually favours men. It is now recognized that the exclusion of women from the planning of water supply and sanitation schemes is a major cause of their high rate of failure. International initiatives, such as the International Drinking Water Supply and Sanitation Decade and the United nations Conference on Environment and Development (UNCED), have been instrumental in promoting the role of women in water management. Programmes were suggested to train women in the use and maintenance of water pumps and to promote their leadership role in the participatory process of water users' association. If such programmes are to be successful, local participation in project design is essential, and discussions should be held at each phase of project planning with different segments of rural communities, such as village leaders, adult women and youth.

Women should be trained in water resource planning and technology in order to improve water use efficiency and help protect the environment. The empowerment of women with respect to water resources, especially groundwater, is the key to raising nutrition levels, improving the production and distribution of food, improving the living conditions of rural populations and preserving water quality. They should have access to water technology, and take up leadership positions in order to raise awareness of groundwater quality and the scarcity of groundwater resources.

III. GROUNDWATER REMEDIATION TECHNIQUES[1]

When dealing with contamination, attention must be given to both the saturated and unsaturated zones. In most cases a contaminated soil unsaturated zone acts as a secondary pollution source with regard to groundwater and therefore has to be included in remediation work. When planning remediation, it should be remembered that no single technology works every time and that more than one technology may be required. The rate of success in restoring contaminated aquifers to drinking water quality is very low for the following reasons:

(a) The contaminated site is inadequately characterized before undertaking the remedial action (reasons for failure include aquifer heterogeneity and spatial variability of geohydraulic parameters);

(b) Insufficient scientific knowledge of the interaction of the contaminants with the geologic matrix;

(c) Gaps in the engineering knowledge required to design and complete successful actions;

(d) The presence of any immiscible fluid phases is not known and therefore not removed.

A. SOIL PROFILE REMEDIATION METHODS

Excavation is an unsophisticated remedial option. Depending upon the depth and extent of contamination, the only requirement is earthmoving equipment and trucks. If the polluted soil is considered hazardous waste, it must be land-filled or treated, e.g. burned.

Containment and sealing of the soil is the placement of a barrier to the movement of the contaminants. For soil contamination, the containment may include surface sealing by asphalt, concrete, or the construction of a specially designed surface cap that includes membrane liners. Lateral migration is often prevented by constructing a slurry wall or other barrier around the edge of the contamination source. Truly effective containment designs will include consideration of a natural barrier (e.g. thick clay deposits) at the bottom of the containment walls. Surface sealing will reduce the potential for downward movement of the contaminants by reducing the downward movement of water through the soil.

Encapsulation and solidification are closely related. Both rely on mixing the soil with cement, asphalt, silicate, or plastic to form a solid product that resists the release of the contaminant by modest abrasion, pressure, and crushing, or chemical attack. The acceptability of a solidified or encapsulated material can be determined by laboratory procedures. Specific chemical formulations are effective only against a limited number of chemical compounds. Cement and silicate formulations are generally not effective in solidification of petrol-contaminated soils.

Vitrification is a relatively new process and not much is known about its long-term viability. The process converts soil into a silicate matrix by electrical melting in place. The heating of the soil is accomplished by burial of carbon electrodes and resistance heating of the soil by generating electric currents or microwaves.

Incineration is the high-temperature thermal oxidation and processing of a soil. The process generally destroys all organic matter in the soil. It is not effective in the destruction of inorganic materials such as lead, chromium or other metals. Before the soil can be processed, it must be excavated and screened.

Soil washing is the physical removal of contaminants by flushing the soil with water, detergents, solvents, or nutrients. The process may occur as a by-product of bioremediation or be performed to enhance the bioremediation process. The emphasis is on the physical removal of the contamination from the soil by the action of washing liquid. Soil washing may be conducted in situ or on the surface. It is difficult to achieve in silty and clayey soils, and its effectiveness is limited when used as a remedial option by itself.

[1] This chapter relies heavily on the paper by Mr. B. Toussaint, consultant to the ESCWA/BGR project for the EGM on Groundwater Rehabilitation, Nov. 14-17 2000.

Vapour stripping is the removal of volatile materials from the soil (and groundwater) by inducing a movement of air through the soil. Vapour stripping will effectively remove the most volatile fraction of the petrol or volatile halogenated hydrocarbons in a soil, but will not remove diesel and fuel oil (because they contain relatively small proportions of volatiles). If vapour stripping is accomplished by the installation of a vacuum well in the unsaturated zone above the groundwater table, it may also have some benefit in the treatment of a contaminated groundwater plume, but it is not an effective technology when used solely for contaminated groundwater.

Biological treatment is the mainly aerobic process of using micro-organisms to consume the hydrocarbons in the soil (and groundwater). naturally occurring micro-organisms or naturally or artificially adapted micro-organisms from other sources may be used. The treatment can be classified by type of container or location of application. Contaminated soil that has been excavated or is quite shallow is generally treated by applying water, fertilizer, and manure. The different technologies are described below.

Biopile/Composting is a controlled biological process for converting contaminants to low toxicity by-products. In most cases, degradation is achieved by indigenous micro-organisms. The composting system is designed to provide optimum temperature, moisture content, aeration, and nutrient conditions to promote rapid biodegradation. The composting system is typically operated so that material temperature rises to between 40 °C and 55 °C as a result of biodegradation. Water content should be sufficiently high to support biological activity, but not so high as to fill pores completely and block air movement. The material should have a good structure and porosity to provide a high percentage of voids, allowing efficient air movement. Fertilizer is added to the soil to provide an optimum balance of carbon, nitrogen, and phosphorous. Bulking agents may be required if soil porosity is low or recalcitrant contaminants are being treated. Composting can be performed using windrows, aerated static piles, or specially designed composting vessels. A windrow process involves forming long piles (windrows) turned by specially designed machines.

Temperature and aeration are controlled by the natural convection currents in the windrow and the frequency of turning. The aerated static pile is constructed to allow forced airflow so that the oxygen supply can be more accurately controlled. The material is piled over perforated pipes connected to a blower to withdraw air from the pile. Contained vessel composting systems use tanks, boxes, or silos provided with equipment to aerate and mix the material. Contained systems typically allow treatment to be completed in less time than the windrow or aerated pile by providing better control of composting conditions. Rapid treatment time is offset by the high initial cost of the composting reactor.

The principle behind *land application* technology is simple. Waste containing low concentrations of organic contaminants is spread over a large area and allowed to interact with the soil and climate at the site. The waste, soil, climate, and biological agents interact dynamically as a system to degrade, transform, and immobilize waste constituents. Any land application site must be managed properly to prevent both on-site and off-site problems with groundwater, surface water, air, or food chain contamination. Adequate monitoring and environmental safeguards are required.

Land tilling is a full-scale bioremediation technology in which shallow layers of contaminated soils, sediments, or sludges are periodically turned over or tilled to aerate the waste matrices. The conditions of the waste matrices are often controlled to optimize the biodegradation rate of associated contaminants. Conditions normally controlled include moisture content (usually by irrigation or spraying), oxygen level (by mixing the soil using tilling or aerating), nutrients, primarily nitrogen and phosphorus (by fertilizing), pH (increased slightly by adding lime), and soil bulking (by adding material and mixing by tilling, etc.).

Constructed wetlands use natural geochemical and biological processes inherent in a man-made wetland ecosystem to accumulate and remove metals from influent waters. The treatment system incorporates the principal ecosystem components found in wetlands, including organic materials (substrate), microbial fauna, and algae. Influent waters with low pH and contaminated with high metal concentrations, flow through the aerobic and anaerobic zones of the wetland ecosystem. Metals are removed by ion exchange, adsorption, absorption, and precipitation via geochemical and microbial oxidation and reduction. Ion exchange occurs as metals in the water contact humic or other organic substances in the soil medium. Oxidation and reduction reactions that occur in the aerobic and anaerobic zones, respectively, precipitate metals as hydroxides and sulphides. Precipitated and adsorbed metals settle in quiescent ponds, or are filtered out as the water percolates through the soil or substrate.

Bioventing stimulates the natural in situ biodegradation of petroleum hydrocarbons in soil by providing oxygen to existing soil micro-organisms. In contrast to soil vapour extraction, bioventing uses low airflow rates to provide only enough oxygen to sustain microbial activity. Oxygen is most commonly applied by directing air into residual contamination in soil. In addition to degradation of adsorbed fuel residuals, volatile compounds are biodegraded as vapours move slowly through biologically active soil. Cometabolic bioventing differs from bioventing in that biodegradation of contaminants such as chlorinated solvents is sought. For this to occur, a primary substrate, such as fuel hydrocarbons, must already have been present at the site or must be added. The primary substrate must be present for biodegradation of the chlorinated compounds to occur.

B. GROUNDWATER REMEDIATION METHODS

When a contaminant is released on or into the ground, it divides into one or more phases: vapour or gaseous phase, free phase or liquid pools of contaminants, adsorbed or residual phase on soils and dissolved phase in groundwater. Dissolved phase contamination is directly related to the other three phases, creating a persistent and complex problem in terms of remediation. Technologies for controlling groundwater contamination generally fall into one or more of three categories: 'pump and treat' systems, which pump the groundwater to the surface for treatment, plume containment through groundwater pumping, groundwater injection, and/or the use of subsurface barrier walls, and passive treatment using chemically or biologically reactive barrier walls. A precondition of the effectiveness of all remediation systems is the prior recovery of free products (DNAPLs—dense, non-aqueous phase liquids—or LNAPLs—light, non-aqueous phase liquids). In the case of volatile materials present in the unsaturated and/or saturated zone, vapour stripping by inducing air movement through the soil is recommended as an additional clean-up measure.

1. *“Pump and treat” systems*

Pump and treat systems have been used extensively for capturing contaminant plumes under widely varying conditions. The technology removes contaminated groundwater from the subsurface through the use of extraction wells. Once at the surface, groundwater can be treated in a variety of ways. The physical and chemical properties of each contaminant are evaluated to determine the appropriate treatment technology to meet effluent criteria. Effluent criteria depend on how the water is to be disposed of. Disposal options include storage in tanks, discharge to a wastewater treatment facility, and reinjection through wells, trenches, leach fields, or recharge basins.

There are two general classes of pumping wells used for groundwater recovery: suction lift wells and deep wells. Suction lift wells are used at sites where groundwater is within 5 to 8 metres of the surface. Individual shallow wells or multiple well point systems can both be implemented using suction lift pumps. Well point systems consist of a number of closely spaced, shallow wells each connected to a main header pipe, attached to a centrally located suction lift pump. Deep well systems are used at sites where groundwater is found at depths greater than 8 metres. Since a wide variety of pumps is used for deep well extraction, it is beyond the scope of this paper to describe each one.

Pump and treat can also be accomplished by a trench system perpendicular to the direction of groundwater flow or longitudinally along the plume of contamination. A perforated collection pipe is placed in a trench to collect groundwater and divert it to extraction wells/sumps. An impermeable liner made of synthetic material can be installed along the downstream face of a trench to facilitate groundwater recovery and aid plume control. Trench systems are generally used at sites with shallow water table conditions (< 5 m) and soils with low permeability.

Experience with pump and treat has proven that the effectiveness of the technology is generally limited to removal of the highest contaminant concentrations from the groundwater at or near the original contaminant source area. This is mainly due to a combination of the following factors:

(a) In most aquifers, the pattern of water flow is not uniform. In addition to collecting groundwater which contains dissolved phase contamination, pump and treat systems rely on water to remove and carry contamination in the residual and adsorbed phases present in the soil. Since groundwater flow characteristically occurs along main flow paths, water does not come into contact with all areas of the aquifer where contamination is present. Although contaminant and site specific criteria affect the amount of residual contamination present, a significant portion of contamination is typically present in the adsorbed and residual phases;

(b) Contaminants that have been in the ground for an extended period of time have diffused (i.e., moved) into less permeable areas of the aquifer (so-called matrix diffusion). Since the majority of water pumped comes from the most permeable zones of the aquifer, clean-up times are significantly extended under these conditions;

(c) The ability of pump and treat systems is severely limited by the solubility of the contaminants in water. It is estimated that it could take more than 1000 years to remove perchloroethane by using water as the carrier. More soluble compounds may take less time.

At some sites, water injection wells have been installed upgradient of the pumping wells in an attempt to aid in flushing the contamination towards the extraction wells. This technique has offered limited improvement to the pump and treat process in many cases. Innovative modifications to the concept include the use of surfactants and chemical enhancements to facilitate the flushing effect. These techniques are still in the experimental phase and are not fully understood.

To summarize, the natural conditions of an aquifer work together to impede remediation through the use of pump and treat systems. The prevailing opinion is that plume containment a more appropriate use of pump and treat technology.

2. *Containment systems*

As we have seen, it may not be feasible or technically possible fully to remediate an aquifer using pump and treat technology. This is especially true at sites where the source of contamination cannot be located and removed. For such aquifers, hydraulic or physical containment may be the most viable long-term solution. This can be accomplished by groundwater pumping, groundwater injection, or the installation of a cut-off wall. Plume containment through groundwater pumping is achieved by installing one or more wells or by using existing wells to pump only enough water to capture the plume. Trenches can also be used for plume containment. Since there is no need to maximize the amount of water extracted, the volume of water pumped may be less than that needed for full site remediation. Pumping is generally performed for an extended period, sufficient to allow for natural degradation of the plume so that containment or removal actions are no longer necessary. The pumped water is generally treated prior to disposal, or reinjected upgradient to recirculate through the aquifer. Water may also be reinjected downgradient to create an artificial ridge of higher hydraulic head which forces the plume to change direction. This may be a desirable technique for use during initial response or when a short-term groundwater diversion is needed.

Physical barriers made of low permeability materials are also widely used for containment of a groundwater plume. These systems are most commonly used in conjunction with pump and treat or other remediation technologies or as interim measures while remediation alternatives are considered. Sheet piling, grout curtains and slurry walls are the most common forms of low permeability barriers. Sheet piling involves driving lengths of steel that connect together into the ground to form a thin, impermeable barrier to groundwater flow. Experience has shown that corrosion is not a concern at most sites but, when the barrier is to be left in place for extended periods of time, the steel is generally coated to protect it from corrosion. One great advantage of sheet piling is that the sections can be removed and reused.

Grouting is the process of injecting a liquid, slurry, or emulsion under pressure into the soil. The fluid moves away from the point of injection to occupy void or open spaces in the soil. After a time, the injected fluid solidifies creating a low permeability barrier. Grouts can be classified as particulate or chemical, depending on the materials used. Particulate grouts consist of water and particulate materials that solidify in the subsurface, while chemical grouts consist of two or more liquids that gel as they come into contact with each other. Slurry walls encapsulate an area to prevent groundwater pollution or restrict the movement of a contaminated groundwater plume. The technology involves digging a trench around an area and backfilling the excavation with an impermeable material. Slurry walls are generally constructed with a cement-bentonite mix or a soil-bentonite mix.

3. *Free product recovery*

When a contaminant is released on or into the ground, it divides into one or more phases: vapour or gaseous phase, adsorbed or residual phase (in soil), dissolved phase (in groundwater), and free or liquid phase. Liquid phase or pure phase contamination, also known as free product, is characterized by having sufficient volume to saturate the soil such that it accumulates on the water table and can readily flow into wells or excavations. When the free product is immiscible in water (i.e. does not readily dissolve in water), it is referred to as a non-aqueous phase liquid or NAPL. NAPLs consist of both a residual (non-drainable) portion and a portion which is recoverable (drainable). Light non-aqueous phase liquids (LNAPLs) float on the water table, whereas dense non-aqueous phase liquids (DNAPLs) sink, since they are heavier than water.

Free product on or below the water table serves as a continual source of contamination by dissolving, volatilizing and smearing onto soils and groundwater. Mobile free product is free to move and 'pancake' outward from the source area and migrate downgradient along the groundwater flow direction away from the source area. For these reasons, expedited recovery of free product is an extremely important aspect of site remediation. Free product recovery is generally accomplished by installing a trench/drain system, implementing a recovery well system, or by using a dual phase extraction system. Trenching or drain systems can be operated actively through the use of pumps or skimming equipment located in wells or sumps along the trench. Passive operation is accomplished by using the natural hydraulic gradient to recover the free product. Recovery well systems may be designed to recover only NAPL or NAPL and groundwater. Equipment used in recovery wells includes skimmers, filter separators, product recovery pumps and groundwater pumps. Dual phase extraction systems use one or more pumps to induce a subsurface vacuum in order to recover both free product and vapours.

4. *Soil vapour extraction*

Organic contaminants that are released into the subsurface distribute themselves into four phases: adsorbed phase (on soil surface), vapour/volatilized phase (in soil gas), dissolved phase (in groundwater) and free phase (pure contaminant, also known as non-aqueous phase liquid or NAPL). Soil vapour extraction is a physical means of removing or reducing concentrations of volatile compounds. This technology targets the adsorbed, vapour and free (NAPL) phases of the volatile contaminant present in the unsaturated (vadose) portion of the subsurface.

Traditionally, soil and groundwater contamination has been remedied by excavating the contaminated soil and pumping and treating the groundwater. Frequently, soil excavation does not extend to the water table, so a significant mass of contamination can remain in the unsaturated zone above it. These residual contaminants may act as a lingering source of groundwater contamination during seasonal water table fluctuations or from infiltrating recharge water. For this reason, corrective action systems may be needed to address remediation of unsaturated zone soils as a source of contamination.

Recognition that source removal is the key to site remediation has led to the development of technologies which target soils in the unsaturated zone, namely soil vapour extraction, also known as soil venting or vacuum extraction. Dissolved contamination found beneath the groundwater table is not directly addressed by using vapour extraction. The soil vapour process involves applying a vacuum to contaminated soils in the unsaturated zone in order to induce air flow in the subsurface. The volatile fraction of contaminants stuck to soil particles evaporates and is swept away to extraction wells. Those contaminants that have already volatilized, or ‘weathered’, are also carried to extraction wells. If volatile NAPLs are floating or pooled on the groundwater table, they are also carried away in a way similar to a fan blowing past a pool of petrol.

A typical vapour extraction system consists of one or more vapour extraction wells connected by a header pipe. The extraction wells can be placed vertically or horizontally, depending on depth to groundwater and other site specific characteristics. The piping system is often placed underground, allowing for more efficient operation during the winter months and also providing extra protection from accidental damage. A blower or pump is connected to the header system, depending on the flow and vacuum desired. An air/water separator and/or filter is required prior to the vacuum pump in order to protect equipment from moisture and particulates drawn into the system. Discharge from the blower/vacuum pump is either vented to the atmosphere or connected to an off-gas treatment system, depending upon air emission requirements and the nature and extent of contamination.

In some cases, subsurface soil conditions can be modified to facilitate and enhance the application of vapour extraction technology. At some sites it may be necessary to lower the groundwater table in order to enlarge the unsaturated zone. The extracted groundwater may require treatment prior to disposal. To enhance airflow through zones of maximum contamination, it may be desirable to install air inlet and/or air injection wells. Air inlet wells operate passively, while injection wells force air into the subsurface and can be operated as a closed loop system (i.e. air is injected from the vapour treatment system or directly from the blower). Controlling airflow to a vapour extraction system can also be accomplished by installing a cap or impermeable barrier at the soil surface, potentially widening the horizontal distance under the influence of the extraction wells. The surface may be sealed with plastic sheeting, clay, concrete or asphalt; existing surface structures can also be incorporated as soil caps.

C. GROUNDWATER TREATMENT TECHNOLOGIES

The utility of groundwater as drinking water or industrial water (process, heating and cooling water) depends on its natural physical or chemical properties, the most important of which are: approximately constant thermal consistence within a broad temperature range, natural heat and dirt transportation medium, the most universal solvent fluid, etc.

Water quality is an especially critical factor determining the usability and reliability of any particular water source. Anthropogenically uninfluenced groundwater, usually germ-free, contains various minerals which improve its quality, such as calcium or magnesium, but cause technical problems, as these substances are directly related to the hardness of the water. Traditional public health practices emphasize the need to use the best quality sources available for municipal supplies and implement source protection measures to maintain high quality raw water sources. Where raw water supplies are of less than pristine quality, greater reliance must be placed on treatment technology.

To transform lower quality raw water sources into reliable water supply options, basic water treatment technologies (chemical procedures, such as coagulation, flocculation, cation and anion exchanges, acid dosage, inhibitor dosage, or physical procedures, such as filtration, reverse osmosis, magnetic field method, electrostatic method) have to be used. “Normally” mineralized groundwater can be treated without difficulty and therefore at low cost, thus meeting requirements for civil or industrial usage. In the case of polluted groundwater, remediation measures are eminently more cost-intensive (equipment costs, installation costs, operating costs, labour costs, capital costs, etc.) if the goal of obtaining usable water is to be reached.

Abstracted groundwater has to be treated before any disposal to sewer or surface water or re-infiltration into the ground. There are a number of ways of removing contaminants shown in table 13. The technique chosen depends on the type of contamination, the concentration of pollutants, and economics. The different treatment technologies have advantages and disadvantages depending on which contaminants are to be removed. A combination of procedures may therefore be appropriate. While developing anthropogenically influenced groundwater is relatively cheap, costs can increase significantly if there is a need to provide complex water treatment to remove contaminants, especially in the case of long-term remediation. Long-term remediation is undertaken if less soluble contaminants are present in the form either of free product, such as floating petrol, or as residuals in the unsaturated or saturated zone of the aquifer.

1. *Chemical treatment*

In general, chemical treatments alter the structure of the groundwater pollutants to render them less hazardous. When using chemicals and chemical reactions, the objective is to immobilize, mobilize for extraction, or detoxify the contaminants. A chemical technology may achieve one or all of the above tasks. Before describing any of the treatments in detail, a few points must be emphasized.

(a) The feasibility of chemical treatment is dependent on site and pollution characteristics. Therefore, a careful study of site hydrology and geology must be conducted before choosing a technology;

(b) Many chemical treatments involve delivery of a fluid to the subsurface. Care must be taken to avoid the migration of treatment reagents since they may themselves be toxic;

(c) Chemical treatment can be applied to both organic and inorganic pollutants. However, a detailed study of pollutants must be carried out so that the wrong reagents are not mixed with the pollutants, thus increasing toxicity.

2. *Physical treatment*

The basic objective of physical treatment is the manipulation of the physical properties of the pollutants in order to immobilize them, detoxify them, or render them less harmful. Some of these technologies may apply physical forces to the pollutants to separate them from their medium. The chemical characteristics of the hazardous compounds remain constant during physical treatment. Physical treatment often produces residues that require further treatment prior to disposal. Chemical or thermal technologies may be applied to these residues in order to dispose of them in an environmentally safe way.

3. *Biological treatment*

Biological treatment is the process of using naturally occurring living organisms to degrade, stabilize and destroy organic contaminants. These micro-organisms use them as their source of energy and carbon. Biological treatment technologies are restricted to organic compounds, and therefore have limited application. It is appropriate at this point to review some principles of biological processes.

All living organisms require a source of energy and carbon to be able to develop and reproduce. Many organisms (autotrophic) obtain carbon from inorganic compounds (such as CO_2), while other organisms (heterotrophic) use organic compounds to obtain carbon. Aerobic and anaerobic metabolic pathways are used by micro-organisms to degrade organic pollutants. During aerobic respiration, the organism uses oxygen to break down complex organic compounds into simple inorganic salts, carbon dioxide and water. These micro-organisms require an electron acceptor (oxygen in the case of aerobic), nutrients such as nitrogen (N) and phosphorous (P), and other trace elements. Some common aerobic bacteria are pseudomonas, arthrobacter, and flavobacterium. Various micro-organisms require different conditions for optimal growth. For example, anaerobic bacteria break down organics in the absence of oxygen. These bacteria use other molecules (such as nitrates) as the electron acceptor.

TABLE 13. GROUNDWATER REMEDIATION TECHNOLOGIES

Method	Process
In situ physical/chemical treatment	
Air sparging	Air is injected into saturated matrices to remove contaminants through volatilization.
Directional wells (enhancement)	Drilling techniques are used to position wells horizontally or at an angle in order to reach contaminants not accessible via direct vertical drilling.
Dual phase extraction	A high vacuum system is applied simultaneously to remove liquid and gas from low permeability or heterogeneous formations.

Table 13 (*continued*)

Method	Process
In situ physical/chemical treatment	
Free product recovery	Undissolved liquid-phase organics are removed from subsurface formations, either by active methods (e.g. pumping) or a passive collection system.
Hot water or steam flushing/stripping	Steam is forced into an aquifer through injection wells to vaporize volatile and semivolatile contaminants. Vaporized components rise to the unsaturated zone where they are removed by vacuum extraction and then treated
Hydrofracturing (enhancement)	Injection of pressurized water through wells cracks low permeability and over-consolidated sediments. Cracks are filled with porous media that serve as avenues for bioremediation or to improve pumping efficiency.
Passive reactive walls	These barriers allow the passage of water while prohibiting the movement of contaminants by employing such agents as chelators (ligands selected for their specificity for a given metal), sorbents, microbes, and others.
Slurry walls	These subsurface barriers consist of vertically excavated trenches filled with slurry. The slurry, usually a mixture of bentonite and water, hydraulically shores up the trench to prevent collapse and retards groundwater flow.
Vacuum vapour extraction	Air is injected into a well, lifting contaminated groundwater in the well and allowing additional groundwater flow into it. Once inside the well, some of the volatile organic compounds (VOCs) in the contaminated groundwater are transferred from the water to air bubbles, which rise and are collected at the top of the well by vapour extraction.
Co-metabolic processes	An emerging application involving the injection of water containing dissolved methane and oxygen into groundwater to enhance methanotrophic biological degradation.
Anaerobic biotreatment	Nitrate is circulated throughout groundwater contamination zones as an alternative electron acceptor for biological oxidation of organic contaminants by microbes.
Biological denitrification	Micro-organisms are put in contact with the water supply containing nitrates and an added carbon source (e.g. methanol or acetic acid) in an anoxic environment. In the process, nitrates are converted into nitrogen gas which is harmless.
Oxygen enhancement with air sparging	Air is injected under pressure below the water table to increase groundwater oxygen concentrations and enhance the rate of biological degradation of organic contaminants by naturally occurring microbes.
Oxygen enhancement with hydrogen Peroxide	A dilute solution of hydrogen peroxide is circulated throughout a contaminated groundwater zone to increase the oxygen content of groundwater and enhance the rate of aerobic biodegradation of organic contaminants by microbes.
On-site/off-site physical/chemical treatment (assuming pumping)	
Air stripping	Volatile organics are partitioned from groundwater by increasing the surface area of the contaminated water exposed to air. Aeration methods include packed towers, diffused aeration, tray aeration, and spray aeration.
Filtration	Filtration isolates solid particles by running a fluid stream through a porous medium. The driving force is either gravity or a pressure differential across the filtration medium.

Table 13 (*continued*)

Method	Process
On-site/off-site physical/chemical treatment (assuming pumping)	
Ion exchange	Ion exchange removes ions from the aqueous phase by exchange with innocuous ions on the exchange medium.
Macro Porous Polymer Extraction	The contaminated water is passed through a column packet with polymer particles. An extraction liquid immobilized within the polymer matrix removes the hydrocarbons from the water. Regeneration of the extracted liquid containing particles is accomplished periodically in situ with low-pressure steam.
Granular activated carbon adsorption (liquid phase)	Groundwater is pumped through a series of canisters or columns containing activated carbon to which dissolved organic contaminants adsorb. Periodic replacement or regeneration of saturated carbon is required.
Precipitation	This process transforms dissolved contaminants into an insoluble solid, facilitating the contaminant‘s subsequent removal from the liquid phase by sedimentation or filtration. The process usually uses pH adjustment, addition of a chemical precipitant, and flocculation.
Surfactant flushing	Surfactant flushing of non-aqueous phase liquids (NAPL) increases the solubility and mobility of contaminants in water, so that the NAPL can be biodegraded more easily in the aquifer or recovered for treatment above ground by a pump-and-treat system.
UV oxidation	Ultraviolet (UV) radiation, ozone, and/or hydrogen peroxide are used to destroy organic contaminants as water flows into a treatment tank. An ozone destruction unit is used to treat off-gases from the treatment tank.
On-site/off-site biological treatment (assuming pumping)	
Bioreactors	Contaminants in extracted groundwater are put into contact with micro-organisms in attached or suspended growth biological reactors. In suspended systems, such as activated sludge, contaminated groundwater is circulated in an aeration basin. In attached systems, such as rotating biological contractors and trickling filters, micro-organisms are established on an inert support matrix.
Other treatment	
natural attenuation	Natural subsurface processes , such as dilution, volatilization, biodegradation, adsorption, and chemical reactions with subsurface materials, are allowed to reduce contaminant concentrations to acceptable levels.

4. *In situ treatment – physical/chemical*

Passive reactive walls

In its simplest form, a reactive barrier consists of a trench in the path of a dissolved chlorinated solvent plume. This trench is filled with a reactive material, such as granular iron. As the groundwater passes through the reactive barrier, the chlorinated organics come in contact with the reactive medium and are degraded to potentially non-toxic dehalogenated organic compounds and inorganic chloride. The main advantage of this system is that no pumping or aboveground treatment is required; the contaminated water passively moves through the barrier. Because there are no aboveground installed structures, the affected property can be put to productive use while it is being cleaned up.

A common reactive barrier configuration is the funnel-and-gate system. Wider plumes or heterogeneously distributed contamination can be captured with impermeable funnel walls or wings on either side of the treatment trench, which direct the plume towards the permeable reactive cell, or gate. At some sites, this configuration can provide better control over reactive zone emplacement and plume capture.

Although a variety of reactive media could be used to treat groundwater contaminants, the most commonly used media are zero-valent metals, particularly granular iron. As the zero-valent metal in the reactive cell corrodes, the resulting electron activity can reduce the chlorinated compounds to potentially non-toxic products. Granular iron is the only reactive medium that has been used so far in field applications and the mechanism of chlorinated solvent degradation with zero-valent iron has been the most widely studied and reported to date. Other zero-valent metals may exhibit similar reactions with differing reaction rates.

Reactive barriers can be used to remediate groundwater contaminated with chlorinated organic compounds (solvents, pesticides, polychlorinated biphenyls [PCBs]. Depending on the site conditions, a funnel-and-gate system can be installed to handle large volumes of contaminated water without hydraulic control via pumping.

5. *In situ treatment – biological*

Anaerobic biotreatment (nitrate enhancement)

Bioremediation is a rapidly expanding field with considerable research and development taking place, especially in the USA and Europe. Bioremediation offers the ability to destroy or render harmless various organic contaminants using natural biological activity. As such, it uses relatively low cost, low technology techniques, which generally have high public acceptance and can often be carried out in situ. It will not always be suitable, however, as the range of contaminants on which it is effective is limited, the time scales involved are relatively long and the residual contaminant levels achievable may not always be appropriate. Although the methodologies employed are not technically complex, considerable experience and expertise may be required to design and implement a successful bioremediation programme because of the need thoroughly to assess a site for suitability and optimize conditions to achieve a satisfactory result.

In situ biological treatment uses micro-organisms to remove organic compounds such as petroleum hydrocarbons in water through metabolic processes. Bioremediation involves establishing in a contaminated environment conditions that allow appropriate micro-organisms to flourish and carry out the metabolic activities that detoxify the contaminants. It is preferable to use indigenous microflora. Biostimulation means encouraging the biodegradation activity of indigenous microflora and supplementing nutrients and other favourable conditions. During bioremediation, micro-organisms may use the contaminants (hazardous chemicals) as nutrients or an energy source or they may be degraded by co-metabolism.

Establishing suitable conditions for bioremediation may mean adding nutrients to promote the growth of particular organisms, adding a terminal electron acceptor (preferably NO_3), adjusting moisture conditions or raising the temperature, etc. The basic concept is to provide critical environmental requirements that may be adverse in a particular site. The entire area then acts as a bioreactor.

In situ biotreatment is usually part of a pump and treat system. One or several collector wells abstract the contaminated groundwater. After pretreatment on the surface (in a bioreactor, etc.), supplementing with nutrients and perhaps with useful micro-organisms, the abstracted groundwater is re-introduced by injection into the subsurface through wells or trenches upgradient of pumping well(s). Thus water circulation is installed which enables a high groundwater flow velocity and flux that helps flush contamination towards the extraction wells. It is important that nitrate or nutrients are prevented from escaping by a hydraulically controlled groundwater flow field, commonly predicted by a prior application of a numerical groundwater model.

Sometimes, one or more additional protecting wells are installed in which water of drinking quality is injected or infiltrated into the underground creating a water divide between the nutrified water in the depression cone around the abstraction well(s) and the unaffected groundwater.

In situ bioremediation provides a potentially significant benefit for volatile organic compounds (VOCs) and other contaminants that are held up in adsorptive soils or less permeable sediments and clays that act as sinks. The main limitation of this technology when compared with baseline methods is the difficulty of designing and implementing an effective subsurface treatment system for highly heterogeneous media. Several key technical issues have prevented widespread use of bioremediation for organic and inorganic subsurface contaminants. These are adequate nutrient delivery systems, effective mixing for contacting micro-organisms, nutrients, contaminants, control of biofouling or excessive microbial growth, and adequate tools for designing, predicting, and monitoring the performance of in situ technologies in heterogeneous subsurface environments.

6. *On-site/off-site treatment – physical/chemical*

(a) *Air stripping*

Air stripping is a full-scale technology in which volatile organics are partitioned from groundwater by exposing a large surface area of contaminated water to clean air flow. Aeration methods include packed towers, diffused aeration, tray aeration, and spray aeration.

Air stripping involves the mass transfer of volatile contaminants from water to air. For groundwater remediation, this process is typically conducted in a packed tower or an aeration tank. The typical packed tower air stripper includes a spray nozzle at the top of the tower to distribute contaminated water over the packing in the column, a fan to force air countercurrent to the water flow, and a sump at the bottom of the tower to collect decontaminated water. Auxiliary equipment that can be added to the basic air stripper includes an air heater to improve removal efficiencies, automated control systems with sump level switches and explosion-proof components, and air emission control and treatment systems, such as activated carbon units, catalytic oxidizers, or thermal oxidizers. Packed tower air strippers are installed either as permanent installations on concrete pads or on a skid or trailer.

Aeration tanks strip volatile compounds by bubbling air into a tank through which contaminated water flows. A forced air blower and a distribution manifold are designed to ensure air-water contact without the need for any packing materials. The baffles and multiple units ensure adequate residence time for stripping to occur. Aeration tanks are typically sold as continuously operated skid-mounted units. The advantages offered by aeration tanks are considerably lower profiles (less than 2 metres high) than packed column towers (5 to 12 metres high), where height may be a problem, and the ability to modify performance or adapt to changing feed composition by adding or removing trays or chambers. The discharge air from aeration tanks can be treated using the same technology as for packed tower air discharge treatment.

A recent innovation is the low-profile air stripper. These units have a number of trays that are set almost horizontally. Water is cascaded over the trays to maximize air-water contact while minimizing vertical space. Because they are not so visible, they are increasingly being used for groundwater treatment.

Air strippers can be operated continuously or in batch mode where the air stripper is intermittently fed from a collection tank. Batch mode ensures consistent air stripper performance and greater energy efficiency than continuously operated units because mixing in the storage tanks eliminates any inconsistencies in feed water composition.

Air stripping is used to separate volatile organic compounds (VOCs) from water, and is ineffective for inorganic contaminants. Henry's Law Constants are used to determine whether air stripping will be effective. Generally, organic compounds with constants greater than 0.01 atmospheres (m^3/mol) are considered amenable to stripping. Some compounds that have been successfully separated from water using air stripping include BTEX and the halogenated aliphatic hydrocarbons chloroethane, dichloroethene (DCE), trichloroethene (TCE) and tetrachloroethen (PCE).

(b) *Granular activated carbon adsorption-liquid phase*

Granular activated carbon adsorption is a full-scale technology in which groundwater is pumped through a series of vessels containing activated carbon to which dissolved contaminants adsorb. When the concentration of contaminants in the effluent from the bed exceeds a certain level, the carbon can be regenerated in place, removed and regenerated at an off-site facility, or removed and disposed of. Adsorption by activated carbon has a long history in treating municipal, industrial, and hazardous wastewater.

The two most common reactor configurations for carbon adsorption systems are the fixed bed and the pulsed or moving bed. The fixed-bed configuration is the most widely used for adsorption from liquids. Suspended solids in a liquid stream may accumulate in the column, causing an increase in pressure drop. When the pressure drop becomes too high, the accumulated solids must be removed, by backwashing, for example. The solids removal process necessitates adsorber downtime and may result in carbon loss and disruption of the mass transfer zone. Pretreatment for removal of solids from streams to be treated is, therefore, an important design consideration.

Carbon can be used in conjunction with steam reforming. Steam reforming is a technology designed to destroy halogenated solvents (such as carbon tetrachloride [CCl_4] and chloroform [$CHCl_3$]) adsorbed on activated carbon by reaction with superheated steam in a commercial reactor.

The target contaminant groups for carbon adsorption are semi VOCs (SVOCs) and explosives. Limited effectiveness may be achieved on halogenated VOCs, fuels, and pesticides. Granular activated carbon adsorption is effective for removing contaminants at low concentrations (less than 10 mg/l) from water at nearly any flow rate, and for removing higher concentrations of contaminants from water at low flow rates (typically 2 to 4 litres per minute). Carbon adsorption systems are particularly effective for polishing water discharges from other remedial technologies to attain regulatory compliance. Carbon adsorption systems can be deployed rapidly, and contaminant removal efficiencies are high. Logistic and economic disadvantages arise from the need to transport and decontaminate spent carbon.

7. *On-site/off-site treatment – biological*

Bioreactors

Onsite/off-site technologies include a wide variety of bioreactors, ranging from small (1-5 m^3) portable units to large plant built specifically for a polluted site. When contaminated groundwater is to be treated, this method is desirable. Groundwater is pumped to the surface and treated under controlled conditions in the bioreactor. The cleaned water is then returned to the ground or discharged into surface water or sewer. Bioreactors are used either to reduce nitrate in groundwater/drinking water or to remove hydrocarbons from abstracted groundwater.

The nitrate reducing bioreactor approach involves adding a carbon source (methanol, butane gas, etc.) which leads to the consumption of dissolved oxygen. When water becomes anoxic and both organic carbon and nitrate are abundant, some bacteria switch from oxygen-based respiration to nitrate-based respiration. In the latter mode, the carbon is converted into microbial biomass and CO_2, and nitrate is converted into a gaseous nitrogen compound (usually N_2, but also N_2O or NO gas). This mode of respiration is only slightly less efficient than aerobic respiration. From a process point of view, it is important to maintain conditions which minimize re-oxygenation of the water. Methanol or butane are probably more economic as a carbon sources than glucose, but ethanol or butane result in a more stable process. Alternatively, any high BOD-processing waste could work (BOD = biological oxygen demand). Water with residual organic carbon returned onto the heap could result in sliming and plugging of channels. This can be avoided by carefully controlling the dosing of organic carbon.

Bioreactors removing organic compounds from contaminated groundwater are biochemical processing systems designed to degrade contaminants in water with micro-organisms through attached or suspended biological systems. In suspended growth systems, such as activated sludge, fluidized beds, or sequencing batch reactors, contaminated groundwater is circulated in an aeration basin where a microbial population aerobically degrades organic matter and produces CO_2, H_2O and new cells. The cells form a sludge, which is settled out in a clarifier, and is either recycled to the aeration basin or disposed of. In attached biofilm systems, such as upflow fixed film bioreactors, rotating biological contactors, and trickling filters, micro-organisms are established on a support matrix to degrade water contaminants aerobically. One promising methodology includes the use of adsorption media, such as activated carbon, which adsorbs contaminants and slowly releases them to the micro-organisms for degradation. The microbial population may be derived either from the contaminant source or from an inoculum of organisms specific to a contaminant.

Bioreactors are used primarily to treat non-halogenated VOCs and SVOCs, including petrol, diesel fuel, JP-4, JP-5 and heavy fuels in extracted groundwater. Co-metabolites may be needed to treat PCBs, halogenated VOCs, and halogenated SVOCs. Bioreactors with specially adapted micro-organisms are used to treat halogenated SVOCs, pesticides, PCBs, and ordnance compounds. Sequential anaerobic/aerobic bioreactors are used primarily to treat halogenated VOCs, SVOCs, pesticides, PCBs and ordnance compounds.

8. *Treatment costs*

Because of quite different site characteristics and pollution conditions, the costs of treatment technology vary widely. The examples below (Table 14), resulting from an Internet search should be regarded as giving only the vaguest idea of cost, particularly as most refer to US Super Fund sites and therefore may not be generalized. In most cases, treatment costs in a narrower sense could not be separated.

TABLE 14. EXAMPLES OF REMEDIATION TECHNOLOGY COST

Treatment technology	Pollutants	Cost in $US (Equipment, design, engineering, labour)
Groundwater stripping with thermally enhanced soil vapour extraction (SVE)	VOCs	4.3 million
Air sparging and SVE	VOCs	265 000
Density-driven groundwater sparging with SVE	BTEX, diesel, petrol fuels	153 000
Dynamic underground stripping	BTEX, petrol, fuel hydrocarbons	5.4 million
Groundwater sparging	VOCs	100 000
In situ air stripping with horizontal wells	VOCs	350 000
Continuous permeable wall	VOCs	250 000 – 700 000
Funnel and gate	VOCs	400 000
Hanging wall reactive barrier	Cr VI	350 000
Filtration (operation)	heavy metals, PAHs, smaller phenolics	200 000 – 1 200 000/yr
Membrane separation (operation)	PAHs, creosote, smaller phenolics	60 – 400/m^3
Pump and treat with air stripping (operation)	VOCs	0.20/m^3
Pump and treat with granular activated carbon (GAC)	BTEX, free petroleum product	1 million
Pump and treat	BTEX, petroleum free product, VOCs	800 000
Pump and treat with thermal oxidation and GAC	VOCs	5 million
Pump and treat with oxidation	VOCs, BTEX, PCBs	1.7 million
Pump and treat with fluidized bed reactor	VOCs	4/m^3
Pump and treat with solids removal and air stripping	VOCs	2 million
In situ air sparging plus pump and treat with GAC	petrol, fuel oil, kerosene, petroleum free product	1.2 million
Incineration plus pump and treat with GAC	PAHs, creosote, phenoles, PCBs, dioxins, pesticides	47.5 million

TABLE 14 (*continued*)

Treatment technology	Pollutants	Cost in $US (Equipment, design, engineering, labour)
Rotary kiln incineration plus pump and treat with GAC	PAHs, creosote	110 million
SVE plus pump and treat with GAC	VOCs	1.4 million
Pump and treat with GAC	VOCs, BTEX, acetone	300 000 – 400 000
Pump and treat with GAC plus in situ SVE	VOCs	1.9 million
In situ remediation and pump and treat with GAC	BTEX, PAHs	2.5 million
Land treatment of soil plus pump and treat with incineration	PCPs, creosote	11.9 million
Rotary kiln incineration plus pump and treat	PCPs, PAHs, dioxins	4.3 million
Land treatment of soil with incineration and pump and treat with GAC	PCPs, PAHs, VOCs	55 million
Land treatment of soil with bioventing, chemical fixation and pump and treat with GAC	PCPs, PAHs, BTEX, dioxins, furans	15 million groundwater

D. FUTURE INNOVATIVE TECHNOLOGIES

Innovative of emerging in situ groundwater and soil remediation technologies (as compared to the standard "pump and treat" approach for groundwater or soil excavation and treatment) are described in this section. Many of these remedial activities do not require groundwater extraction, but ways of enhancing pump and treat are also addressed.

1. *In situ physical/chemical remediation*

(a) *Air Sparging* or *in situ air stripping* is the process of injecting gas (usually air or oxygen) under pressure into well(s) installed within the saturated zone to volatilize contaminants dissolved in groundwater, present as non-aqueous phase liquid, or sorbed to the soil matrix. Volatilized contaminants migrate upward and are removed upon reaching the vadose zone, typically through soil vapour extraction. This is most applicable for volatile organic contaminants in relatively moderate to high permeability geologic materials. This technology is commonly used in conjunction with soil vapour extraction systems, allowing for treatment of vadose zone soils, saturated zone soils and groundwater in the saturated zone. Implementing an air sparging system without soil vapour extraction may create a net positive pressure in the subsurface, inducing contaminant migration into previously uncontaminated areas;

(b) *In-well aeration* involves injecting air into the bottom of a well or trench screened in the saturated zone. As the injected air travels upward through the water column, bubbles form which remove volatile and semi-volatile organic compounds. The upward movement of air also produces an airlift pump effect, as groundwater is pulled into the well from deeper screened portions and out of the well from shallower screened portions. Contaminant concentrations are reduced as groundwater circulates through the well, eliminating the need for pumping and treating the water at the surface;

Similar to this technology is air lift technology with a combined abstraction and injection well. Advanced *bio air lift* technology offers the possibility of in situ bio-remediation.

(c) The *blast-enhanced fracturing* technique is used at sites with fractured bedrock formations to improve the rate and predictability of recovery of contaminated groundwater by creating "fracture trenches" or highly fractured areas by detonating explosives in boreholes (shotholes). Blast-enhanced fracturing can be distinguished from hydraulic or pneumatic fracturing in that the latter technologies do not involve explosives, are generally conducted in the overburden, and are performed within individual boreholes;

(d) *Directional wells* are trenched or directly drilled wells installed at any non-vertical inclination for purposes of groundwater monitoring or remediation. They are especially useful when the contaminant plume covers a large area and has linear geometry, or when surface obstructions are present. This technology can be used in the application of various remediation techniques such as groundwater and/or non-aqueous phase liquid extraction, air sparging, soil vapour extraction, in situ bioremediation, in situ flushing, permeable reactive barriers, hydraulic and pneumatic fracturing, etc.;

(e) *Groundwater recirculation wells* create a groundwater circulation "cell" by the injection of air or inert gas into a zone of contaminated groundwater through the centre of a double-cased stripping well which is designed with upper and lower double screened intervals. The injection of air creates an "airlift pumping system" due to density gradient, causing groundwater with entrained air bubbles to rise and partition volatile contaminants from dissolved to vapour phase. Water exits the upper screen beneath a divider, where vapours are drawn off through annular spaces between well casings by vacuum pump, and groundwater re-enters the contaminated zone, where it is again drawn into the stripping well. In this manner, groundwater is recirculated through the stripping well until remediation goals are reached. There are several commercial types of in-well vapour stripping which seek to make the general process more efficient or use the process to enhance bioremediation or metals fixation by taking advantage of circulation cell development. The technology is most applicable to volatile organic contaminants; modifications of the basic remedial process are proposed for application to semivolatile organic compounds, pesticides and inorganics. The technology may be used in unconfined or confined aquifers, and has been applied to geological materials of wide ranging permeability;

(f) *Vacuum-vaporizer well* A comparable technology is the as yet relatively new hydraulic system for in situ remediation of volatile contaminants in groundwater and possibly in the unsaturated zone. It is an alternative to conventional pumping, off-site cleaning and reinfiltration. The contaminated groundwater is tripped by air under the groundwater table in below atmospheric pressure in a special well with two screen sections. The vertical well discharge initiates a circulation flow in the region surrounding the well. Stripped air passes through a ventilator and across activated carbon where the contaminants are adsorbed;

(g) *Hydraulic and pneumatic fracturing* techniques create enhanced fracture networks to increase soil permeability to liquids and vapours and accelerate contaminant removal. They are especially useful for vapour extraction, biodegradation and thermal treatments. Hydraulic fracturing involves injection of high pressure water into the bottom of a borehole to cut a notch. A slurry of water, sand and thick gel is pumped at high pressure into the borehole to propagate the fracture from the initial notch. The gel biodegrades, leaving a highly permeable sand-filled lens that may be up to 20 metres in diameter. Pneumatic fracturing involves injection of highly pressurized air into consolidated sediments to extend existing fractures and create a secondary fracture network. The technology is most applicable for unconsolidated sediments or bedrock;

(h) *Flushing* means injection or infiltration of a solution into a zone of contaminated soil/groundwater, followed by downgradient extraction of groundwater and elutriate (flushing solution mixed with the contaminants) and above ground treatment and/or re-injection. Solutions may consist of surfactants, co-solvents, acids, bases, solvents, or plain water. Any variety of configurations of injection wells, directional wells, trenches, infiltration galleries and extraction wells or collection trenches may be used to contact the flushing solution with the contaminated zone. An excellent understaning of the hydrogeologic regime is essential. The method is best applied to moderate to high permeability soils and may be used for a variety of organic contaminants, including non-aqueous phase liquid;

(i) *In situ stabilization/solidification* is also known as in situ fixation, or immobilization. It is a process of rendering organic or inorganic contaminants innocuous and/or immobile by injecting or infiltrating stabilizing agents into a zone of contaminated soil/groundwater. Contaminants are physically bound or enclosed within a stabilized mass (solidification), or their mobility is reduced through chemical reaction (stabilization). An excellent understanding of the hydrogeologic regime is essential. The technology is best applied to moderate to high permeability soils and may be used for a variety of organic and inorganic contaminants;

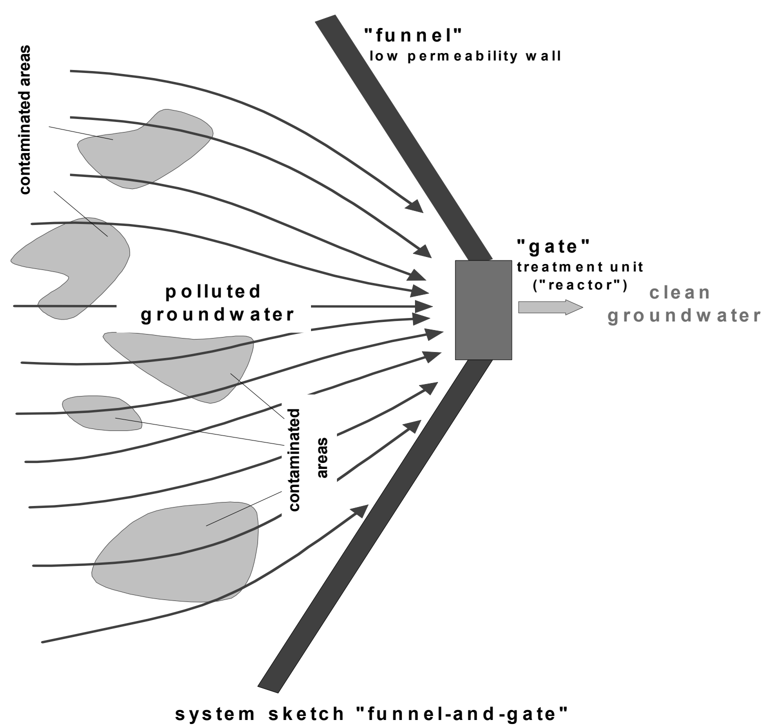
(j) *Permeable reactive barriers* are passive barriers, passive treatment walls, treatment walls or trenches. The technology is in its infancy with limited field scale trials reported. An in-ground trench is backfilled with reactive media to provide passive treatment of contaminated groundwater passing through the trench. A treatment wall is placed at a strategic location to intercept the contaminant plume and backfilled with media such as zero-valent iron, micro-organisms, zeolite, activated carbon, peat, bentonite, limestone, saw dust or other.

Physical barrier walls (i.e., sheet piling, grout curtains or slurry walls) can be incorporated to channel groundwater through the reactive treatment wall. This combination of physical barrier walls with passive treatment walls is often referred to as a funnel-and-gate system. An example of a typical funnel-and-gate system is shown in figure II.

The treatment processes, which occur within the treatment wall, are typically contaminant degradation, sorption or precipitation. The technology is applicable to a wide range of organic and inorganic contaminants, so the choice of media for the treatment wall depends on the specific contaminant. For chlorinated ethenes (PCE and TCE) the products are mostly fully dechlorinated (e.g. little vinyl chloride was observed), although some chlorinated alkanes produce partial dechlorination products that can be problematic. The zero-valent metal is the bulk reducing agent in these systems. However, corrosion of iron metal yields ferrous iron and hydrogen, both of which are possible contaminant reducing agents.

The hydrogeological setting is critical. Geologic materials must be relatively conductive and a relatively shallow aquitard must be present to provide a “basement” to the system. Groundwater flow should have a high degree of preference, and groundwater quality must support the desired reaction without imposing additional loading of the reactive media or creating undesirable by-products.

Figure II. System sketch “funnel and gate”



Source: Toussaint, 2000.

(k) *Thermal enhancement* uses steam, heated water, radio frequency (RF) or electrical resistance (alternating current - AC) to alter temperature-dependent properties of contaminants in situ to facilitate their mobilization, solubilization, and removal. Volatile and semivolatile organic contaminants may be vaporized. Vaporized components then rise to the vadose zone where they are removed by vacuum extraction and treated. Steam is best applied to moderate to high permeability geologic materials,; RF and AC heating may be applied to low permeability, clay-rich geologic materials as the clay will preferentially capture the RF or AC energy. An excellent understanding of hydrogeologic conditions is essential for all applications. The technology is used for a variety of organic contaminants and non-aqueous phase liquid and may also have applications for some inorganic contaminants;

(l) *Electrokinetics* is an in situ process involving the application of low intensity direct electrical current across electrode pairs implanted in the ground on each side of a contaminated area of soil, causing electro-osmosis and ion migration. Contaminants migrate toward respective electrodes depending upon their charge. The process may be enhanced by using surfactants or reagents to increase contaminant removal rates at the electrodes. Heavy metals, radionuclides and organic contaminants are separated and extracted from saturated or unsaturated soils, sludges and sediments. The technology may be used in both low and high permeablility soils and is applicable to a broad range of organic and inorganic contaminants.

2. *In situ biological remediation*

(a) *Bioslurping* uses vacuum-enhanced pumping to recover light, non-aqueous phase liquid (LNAPL) and initiates vadose zone remediation through bioventing. In bioventing, air is drawn through the impacted vadose zone via extraction wells equipped with low vacuums to promote biodegradation of organic compounds;

(b) Intrinsic bioremediation means natural, non-enhanced microbial degradation of organic constituents by which complex organic compounds are broken down to simpler, usually less toxic compounds through aerobic or anaerobic processes. For environmental applications, it remains to be demonstrated that current biodegradation rates are sufficient to control or degrade a contaminant plume or zone without creating an unacceptable risk to human health or the environment;

(c) *Monitored natural attenuation* (encompassing intrinsic bioremediation) relies on a variety of physical, chemical and biological processes (within the context of a carefully controlled and monitored site clean-up approach) that, under favourable conditions, act without human intervention to reduce the mass, toxicity, mobility, volume or concentration of contaminants in soil or groundwater;

(d) *Phytoremediation* means the general use of plants to remediate environmental media in situ and includes rhizofiltration (absorption, concentration, and precipitation of heavy metals by plant roots), phytoextraction (extraction and accumulation of contaminants in harvestable plant tissues such as roots and shoots), phytotransformation (degradation of complex organic molecules to simple molecules which are incorporated into plant tissues), phytostimulation or plant-assisted bioremediation (stimulation of microbial and fungal degradation by release of exudates/enzymes into the root zone), and phytostabilization (absorption and precipitation of contaminants, principally metals, by plants). The technology may or may not involve periodic harvesting of plants and is applicable to a wide range of organic and inorganic contaminants. Phytoremediation is most appropriate for sites where large volumes of groundwater with relatively low concentrations of contaminants must be remediated to strict standards. The best effect is given where groundwater is within three metres, and soil contamination within one metre, of the surface.

3. *On-site/off-site physical/chemical remediation*

The *macro porous polymer extraction* system removes contaminants with boiling points up to 250 °C (aliphatic, aromatic and chlorinated hydrocarbons) from water. The hydrocarbon-contaminated water is passed through a column packet with porous polymer particles. An extraction liquid immobilized within the polymer matrix removes the hydrocarbons from the water. Regeneration of the extracted liquid-containing particles is accomplished periodically in situ with low pressure steam. During regeneration, the volatile hydrocarbons are removed from the polymer particles, while the immobilized non-volatile extraction is retained in the pores of the polymer. After condensation of the vapour phase, an organic and an aqueous phase are obtained. The aqueous condensate, containing a small amount of hydrocarbons, is returned to the feed of the extraction column. The organic phase is separated for re-use or disposal. A continuously operating automated unit is achieved through columns in parallel allowing simultaneous extraction and regeneration.

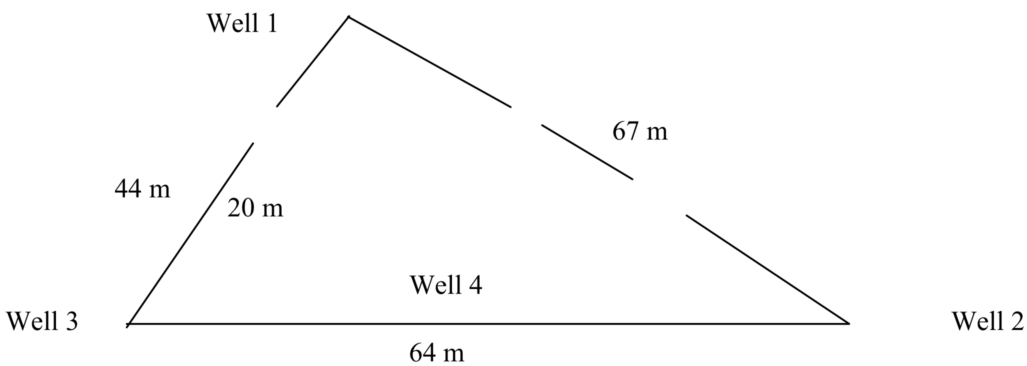
IV. CASE STUDIES OF GROUNDWATER REHABILITATION IN SELECTED ESCWA COUNTRIES

A. Removal of manganese from groundwater in Beheira, Egypt

The groundwater extracted from the Nile Delta aquifer generally contains iron (Fe^{2+}) and manganese (Mn^{2+}). In the Com Hammed and Tay al-Barred areas of Beheira governorate, (northern Egypt), the average concentration is 0.41 and 1.1 mg/l, respectively. Since chlorination began in 1990, problems began to arise from precipitation of manganese oxides in the distribution systems. A programme was needed to flush the system on a monthly basis. In summer, there is twice monthly flushing in some places in order to maintain bacteriological quality and guarantee a minimum chlorine concentration for drinking water.

The investigation has focused on to what extent iron and manganese can be removed from groundwater in the subsoil itself using natural processes. To this end, a test was carried out on the groundwater extraction site of Kom Hamada. It was successful and is now being tested and implemented on other sites as well (Warda, 2000). The Kom Hamada treatment plant is situated in the Nile Delta 35 kilometres south-east of Damanhur, (30° 45' 50'' N and 30° 42' 30'' E). The site has four production wells in a layout shown in figure III.

Figure III. Well Sites at Kom Hamada



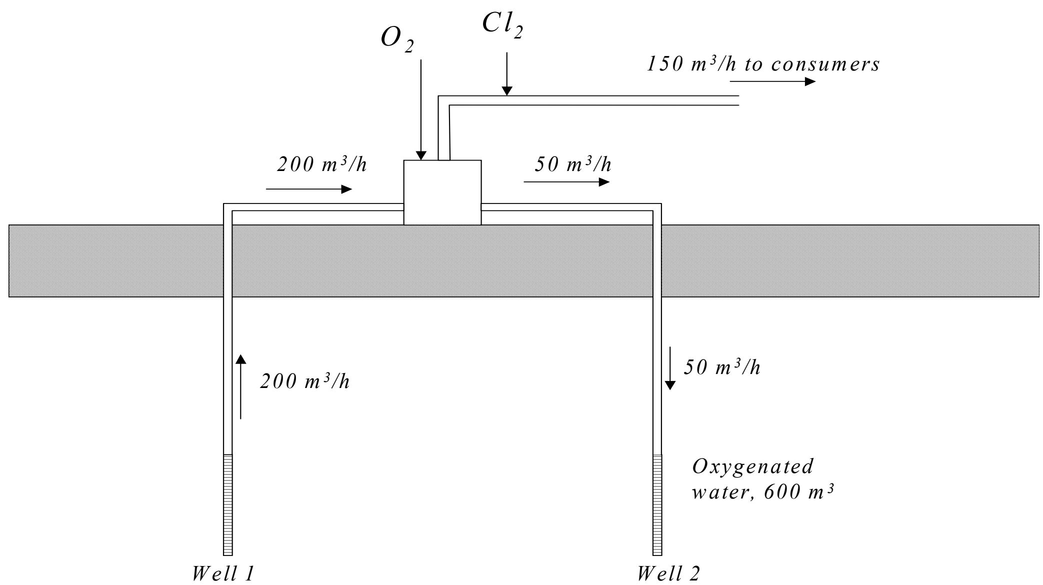
Wells 1 and 2 were drilled in 1987 and are 50 metres deep. Wells 3 and 4 were drilled in 1958 and are 55 metres deep. All have a screen of around 20 metres. The wells tap the Nile Delta aquifer, which, in Kom Hamada, reaches down to 350 metres below mean sea level. The aquifer consists of sands and gravels with embedded clay layers of different composition. Pumping tests on the site revealed high transmissivities of about 7500 m^2/d. The aquifer is covered by a top layer consisting of clay, loam and sand, which is about six metres thick at Kom Hamada. Typical chemical analyses of the groundwater in the area are given in table 15.

TABLE 15. TYPICAL GROUNDWATER QUALITY ANALYSES IN THE KOM HAMADA AREA

Well name	NH4 mg/l	CO_2 mg/l	Cl mg/l	SO_4 mg/l	Fe mg/l	Mn mg/l	Ca mg/l	Mg mg/l	EC mg/l	TDS mg/l	pH
Zawyet Mo	0.34	18.6	87	37	0.02	0.46	48	20	609	406	7.53
Ebioka	0.26	14.6	62	47	0.1	0.92	42.5	18.5	725	486	7.49
El Tod 2	0.19	22	82	60	0.1	0.36	295	36.5	1 088	728	7.36
El Tod 1	0.25	17.2	67	108	0.12	0.73	36	?	678	453	7.34
K.Zeyada	0.17	17	37	60	0.66	0.25	325	17	510	340	7.37
K.Zeyada	0.23	17	27	25	1.3	0.25	48	7.5	540	361	7.34

While in most places in the world iron concentrations tend to be much higher than those of manganese, the opposite is true in this area. The field site experiment consisted of trying to oxidize the two cations Fe^{2+} and Mn^{2+} (iron and manganese) in the subsoil by injecting a fixed volume of aerated water into a well, then extracting from the same well until the iron and/or manganese concentration rose to a fixed norm. A schematic of the arrangement is shown in figure IV.

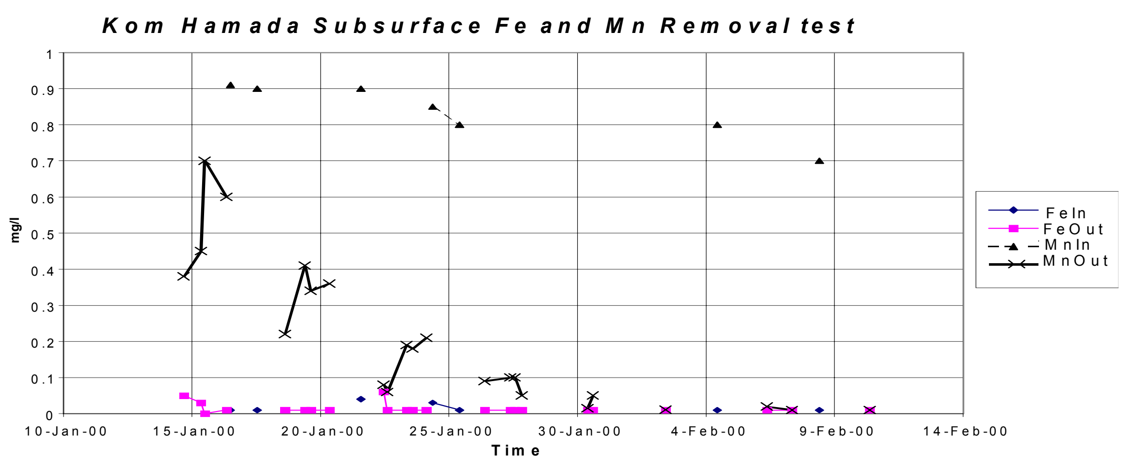
Figure IV. The experiment at Kom Hamada



Source: Warda, 2000.

The experiment was carried out using an old recovery well and began on January 12, 2000 using aerated water from Well 1, which showed an Mn concentration of between 0.7 and 1.0 mg/l. A number of injection-extraction cycles were carried out. Each cycle consisted of an injection and a pumping phase, with a rest period of several hours in between. In all, about 13 cycles were executed. Injection took place at a rate of 25 m^3 /hour, infiltrating a total of 1000 m^3 at each cycle. After a rest period of several hours, extraction began at a rate of 50 m^3 /hour. The amount extracted from cycle to cycle was from 2000 m^3 to 5000 m^3.

Figure V. Results of the first eight cycles of the Kom Hamada subsurface iron and manganese removal experiment



Source: Warda, 2000.

The results are shown in figure V. The injection water had a concentration of 0.7 to 0.9 mg Mn^{2+}/l. Already, after the first cycle, a substantial reduction in concentration was obtained. Clearly, Fe^{2+} also decreased, but the much lower concentration meant it was relatively unimportant at this site. As can be seen from the figure, manganese concentration was reduced further with each cycle. After four cycles, it was almost completely removed, having fallen as low as 0.01 mg Mn^{2+}/l, almost a hundred times lower than the natural groundwater.

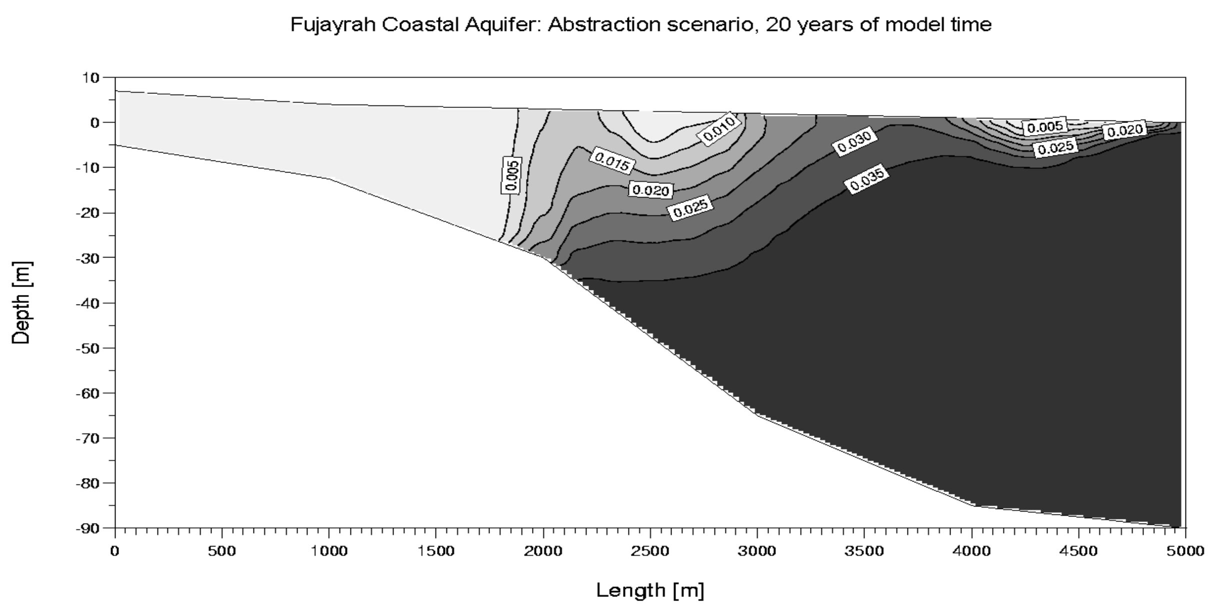
B. Control of salt water intrusion in the coastal aquifer, United Arab Emirates

In many ESCWA countries, fresh water is obtained from coastal aquifers which supply water to the often urbanized areas on the coast, as well as remote areas. Saltwater intrusion has become a crucial issue as increased groundwater abstraction has caused the fresh water/salt water interface to advance inland. A numerical model was applied to the coastal area near Al Fujayrah in the United Arab Emirates to study the salt water intrusion problem and assess options for counteracting the intrusion (Schelkes, 2000).

Various geohydraulic simulation programmes are available for planning sustainable withdrawal from coastal aquifers. They make it possible to assess scenarios with different well locations or artificial recharge. Finite difference or finite element models, such as HST3D, SUTRA, FEFLOW, and SALTFLOW, are most frequently used. In this case, the numerical groundwater model Sim Coast was applied, which is based on a simplified, sharp-interface approach and was developed to simulate the time-dependent behaviour of coastal aquifer systems in porous rock in cross-sectional models (Brunke and Schelkes, 1998). It was used to model the advance of salt water assuming continued groundwater abstraction, and to assess the impact of groundwater recharge from a dam at Wadi Ham on the location of the fresh water / salt water interface. The effect of over-abstraction was clear: salt water intruded far into the aquifer. The modelling results showed that, although the dam across the wadi discernibly affects the groundwater system, the current rate of artificial recharge is not enough to prevent sea water from intruding into the coastal aquifer.

A comparative study (ESCWA, 1999 c) was carried out for the same area of Al Fujayrah, this time using the two-dimensional SUTRA code (Voss, 1984), which is based on a system of partial differential equations with variable groundwater density. In order to save computation time, the modelled part of the cross section was shortened to five kilometres of the coastal plain, because it was only in this part of the aquifer that interaction between fresh and salt water was expected. The general trend in the results compared well with the results using the simpler Sim Coast model. The effect of continued groundwater abstraction on salt water intrusion as projected using the SUTRA model is shown in figure VI. It shows the distribution of salt concentrations after 20 years without countermeasures. The upwelling of salt water at the location of the well fields is clearly visible.

Figure VI. Development of salt concentration (kg/kg) in the coastal aquifer near Al Fujayrah Using the SUTRA Model



Source: ESCWA, 1999 b.

The simulation results of several abstraction/infiltration scenarios showed that sea water might be expected to stop intruding or even retreat if measures are taken to reduce abstraction and increase infiltration from the recharge dam.

C. Measures to control salt water intrusion: Sultanate of Oman

Salt water intrusion has been on-going on the Batinah coastal plain of northern Oman since the late 1970s, caused mainly by a rapid expansion in the number of farms and irrigated area, with a consequent increase in demand on shallow groundwater resources. Strategies have been implemented to limit the expansion of demand for water with the introduction of well permit regulations and restrictions on the allocation of new farmland. A case study of Wadi Taww illustrates the impact of saline intrusion on farm production, income and depreciation of assets, as well as on domestic water supplies for coastal villages. A number of strategies have been proposed to reduce demand to sustainable levels, including reducing cropped areas and growing different types of crops, land purchase, water allocation and the development of alternative drinking water supplies. The impact of salt water intrusion was particularly evident in catchment areas of the southern Batinah, with a deterioration in water quality, declining water levels and the abandonment of traditional farms near the coast.

Since the 1990s, a number of strategies have been implemented to limit the expansion of demand, increase water supplies and improve efficiency of use, including:

(a) The introduction of well permit regulations to limit the allocation of permits for the construction of new wells and deepening and/or modifying existing wells;

(b) The construction of nine recharge dams on the Batinah with a total storage capacity of 47 million cubic metres;

(c) Limiting allocation of new land for agricultural development.

The impact of salt water intrusion is reflected in a case study of the catchment area of Wadi Taww. From the mid 1970s to the early 1990s, there was a great increase in the number of farms and irrigated areas on the lower coastal plain. During this period, the number of farms increased by about 150 per cent, with a fivefold increase in cropped area.

The impact of salt water is often most obvious on crop health and farm productivity. Farm productivity is affected by irrigation water quality in a number of ways, such as yield reduction, deterioration of fruit quality, toxicity to specific elements, induced nutrient deficiencies and toxicities, and foliar damage.

The southern Batinah in particular has been the subject of a number of studies to define the problem more precisely and identify strategies for reducing water demand to a sustainable level and the provision and protection of domestic water supplies. The essential elements of these strategies are to develop measures to reduce water abstraction for irrigation and alternative water supplies for coastal villages. The recommended measures have include:

(a) Purchasing 4900 hectares and removing them from production;

(b) In tandem with the land purchase scheme, introducing a water allocation programme, with the installation of water meters, for wells supplying irrigation water;

(c) A shift from high water demand perennial crops to winter vegetable crops has the potential both to reduce water demand and improve productivity and returns per unit volume of water. Such a shift could reduce water demand by about 20 per cent;

(d) Modern irrigation methods have been promoted and could contribute to an overall reduction in water demand of 14 per cent;

(e) The development of desalination could ultimately reduce the cost for the coastal communities;

(f) The development of a water supply and protection scheme based on upstream well fields and distribution mains to the coast;

(g) The development of inland well fields has the advantage of providing relatively low-cost water, and moving supplies from the direct impact of salt water intrusion and other potential pollution sources.

V. GROUNDWATER PROTECTION

If groundwater becomes polluted, it is difficult and usually very costly to rehabilitate. Low microbial activity, and slow flow rates, which reduce mixing, mean that self-purification of groundwater is very limited. Degradation processes, which take days or week in surface water, are likely to take decades in groundwater systems. It is therefore advisable to prevent or reduce the risk of groundwater contamination rather than have to deal with the consequences of pollution. Groundwater protection should therefore be the top priority.

A. GROUNDWATER VULNERABILITY

The soil and unsaturated zone covering an aquifer protects groundwater from pollution. The degree of protection depends on numerous factors, such as the characteristics of the soil and the unsaturated zone, climatic conditions, the type of pollutant and the properties of the aquifer itself. Groundwater vulnerability is the likelihood of contaminants present in the soil or the unsaturated zone reaching the underlying aquifer and accumulating in the groundwater. It is a measure of protection from pollution. The risk of groundwater contamination is high where weak protection coincides with the presence of hazardous substances on the soil surface or in the unsaturated zone. This means that the risk of pollution from a given activity is greater in some areas than others.

Groundwater vulnerability mapping is a useful tool for:

(a) Formulating policies, by showing where action is most needed;

(b) Building government and public awareness of groundwater protection issues;

(c) Regional land use planning, as it can be used to assign acceptable land uses for different areas (zoning), or to search for suitable sites for a certain land use (screening);

(d) programme management, as it helps identify hot spots and set priorities, e.g. where to intensify monitoring or where to start with groundwater rehabilitation measures.

Groundwater vulnerability mapping is intended to be of practical use. For this reason, it should be possible to complete and update the assessment procedure in a limited amount of time and with a limited budget. It should therefore be based on data that is already available or can quickly be assessed on a regional scale. The purpose of vulnerability mapping is less to predict groundwater contamination precisely than to distinguish areas where groundwater pollution from potential contamination on the soil surface is more likely from areas where it is less likely.

The vulnerability of an aquifer depends on the biochemical and hydraulic properties of the groundwater cover (the soil and the unsaturated zone) and its thickness, the hydrological regime (amount and distribution of rainfall, infiltration) and the hydraulic characteristic of the aquifer. The protective groundwater cover plays an important role in delaying the travel time of contaminants to the groundwater surface and in the degradation of hazardous compounds. Degradation of contaminants predominantly takes place in the soil. Once a contaminant has leached past the root zone, degradation rates are strongly reduced, as microbiological activity decreases. The more the transport of a contaminant is retarded the longer it is exposed to degradation and dilution. One can therefore differentiate between a groundwater cover of low protective potential (e.g. thin sandy strata), intermediate protective potential (e.g. clayey sandy soil) and high protective potential (e.g. soils with a high clay content). A deep unsaturated zone of low permeability gives good protection from groundwater pollution, while areas of outcropping karstified limestone are highly vulnerable to pollution (figure VII).

Numerous methods of assessing groundwater vulnerability have been developed over the past 20 years. All of them base assessment on selected parameters describing climatic, soil and hydrogeological properties known to affect the leaching of contaminants. Typical parameters considered in groundwater vulnerability assessment are listed in table 16.

TABLE 16. PARAMETERS TYPICALLY CONSIDERED IN GROUNDWATER VULNERABILITY ASSESSMENT

Parameters most widely used	Parameters used less often
Recharge rate (rainfall, irrigation, artificial recharge)	Absorption (e.g. organic matter and clay content, pH)
Depth to water table	Biodegradation potential (e.g. temperature, pH, organic matter content in the soil)
Hydraulic conductivity of the soil	Lateral flow velocity within the aquifer
	Topography (slope)

Of the numerous existing methods, relatively easy to apply qualitative assessment methods have so far been used most frequently. These methods follow a procedure of combining maps from which parameters included in the groundwater vulnerability assessment can be deducted (soil, geology, groundwater table, rainfall etc.) to create zones of equal properties. In a second phase, scores or qualitative ratings are assigned to relevant attributes affecting vulnerability. Some much-used methods are DRASTIC (Aller et al., 1985), the common approach of the German Geological Surveys (Hölting et al., 1995), or EPIK (Doerflieger, 1996), which was developed in Switzerland especially for groundwater vulnerability assessment in carbonate (karst) regions.

More sophisticated quantitative methods have also been developed, such as deterministic and probabilistic process based methods, which are based on mathematical descriptions of physical, chemical and biological processes occurring in the soil, the unsaturated zone or the aquifer. However, their application has so far been limited to pilot areas and research as the effort and data availability required is high in comparison with the simpler qualitative methods.

Groundwater vulnerability assessment is an issue of spatial distribution and therefore typically carried out using geographic information systems (GIS). Even when using a simple qualitative method, the complex processing of spatial information is completed faster using GIS than compiling the map by hand. Map overlay techniques can be used to combine different thematic maps (e.g. soil type, geology, depth to groundwater table) with the aim of defining homogeneous areas in terms of vulnerability. The resulting vulnerability map can be combined with a map of actual or expected hazards (e.g. intensive agricultural areas, industrial areas, landfills, waste disposal sites) to infer maps indicating risk of groundwater pollution.

The application of GIS in vulnerability assessment has the following advantages:

(a) Calculations can be made on geographic data (combine spatial information);

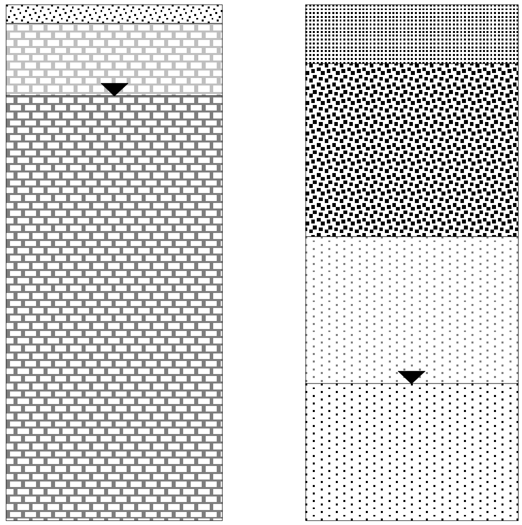
(b) High transparency as to how resulting classifications have been obtained;

(c) Clear presentation of results, which enables a quick impression of the situation and enhances the essential communication between scientific experts, decision-makers and the public;

(d) It allows "What happens if..." analyses by subsequently running calculations with changed conditions.

The map scale selected for presentation depends on the accuracy and scale of available data (information density) and the method applied. A typical scale of groundwater vulnerability maps for regional planning is 1:25,000 to 1:100,000. Groundwater vulnerability maps show which areas are likely to be more vulnerable to groundwater contamination than others, but it is not possible to infer whether or not a certain pollutant introduced to the soil surface will reach the groundwater. As vulnerability maps are prepared on a regional scale, they represent a screening method and should not be substituted for detailed site investigations where precise and accurate information is needed.

Figure VII. Examples of high and low groundwater vulnerability



Source: Toussaint, 2000.

B. Groundwater monitoring

Groundwater monitoring is an effective method of groundwater protection and pollution control. Monitoring can be defined as the "action of observing changes in a system through a systematic approach". The aim is to provide information which helps in the protection and rehabilitation of groundwater resources. Before a monitoring programme is designed, information requirements need to be identified precisely so that the are helpful to decision-making (see flow chart, figure VIII).

Groundwater monitoring can serve various purposes: it can be used to gain general knowledge about regional differences in water quality and the natural background concentrations of substances; it is useful for the early detection of groundwater pollution and the observation of trends in concentration changes; it is often used to observe existing contamination in order to control the movement of contaminant plumes and indicate whether intervention is needed or to check on the impact of remediation measures.

Monitoring can provide the following information:

(a) Changes in water fluctuation and the hydrogeologic characteristics of the groundwater system; the direction of groundwater flow and movement (travel time) of pollutants;

(b) Water balance components and exploitable reserves;

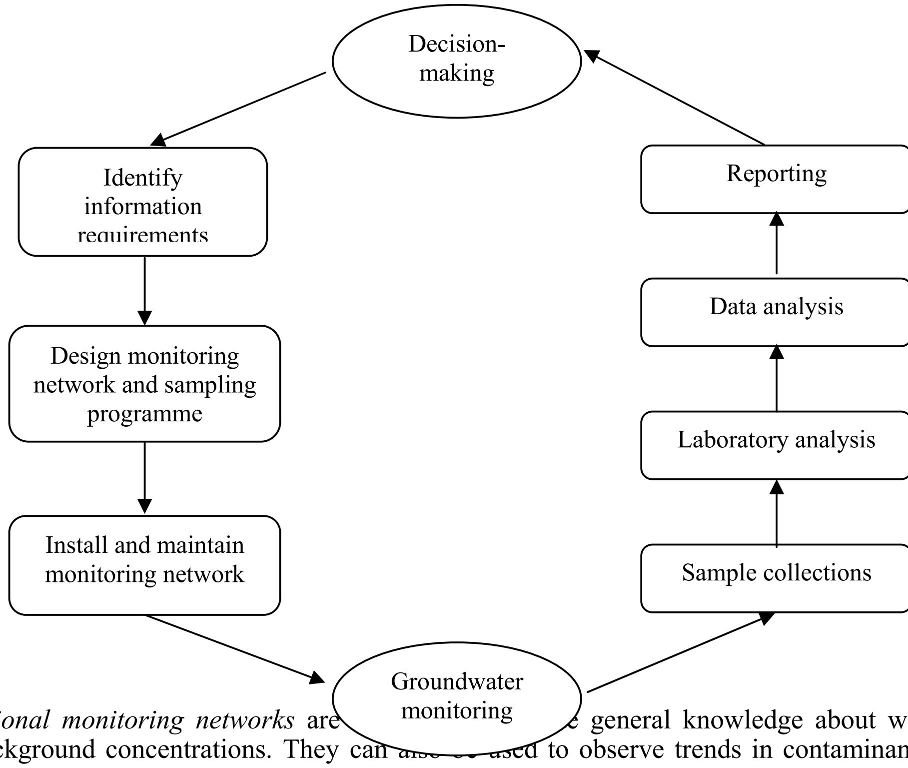
(c) Contact with mineralized bodies of groundwater, especially the fresh water / salt water interface in coastal aquifers;

(d) Information needed for the calibration of groundwater models;

(f) Environmental impacts of water projects.

The monitoring strategy, i.e. the location and design of observation wells and the sampling programme, depends on the objectives of the monitoring programme, but surveillance of the status of groundwater quantity and quality in terms of time and space must always be systematic and continuous.

Figure VIII. Groundwater monitoring flowchart



Regional monitoring networks are general knowledge about water quality and natural background concentrations. They can also be used to observe trends in contaminant concentrations from diffuse sources, such as atmospheric deposition. In regional monitoring networks, observation wells are located so that influence from local pollution sources is kept to a minimum.

Well protection monitoring networks serve as an early warning system for groundwater abstraction. Their purpose is to indicate contamination in the catchment area and the advance of contaminants towards the abstraction wells. The observation wells are positioned within the catchment area upstream of the abstraction wells.

Pollution control monitoring networks are designed to observe existing or expected groundwater pollution from known sources. Observation wells are located downstream of pollution sources, oriented according to the geometry of the pollutant plume in the aquifer.

With respect to *well design*, fully screened wells are common in regional monitoring networks according to figure IX, configuration 1. The screen arrangement yields depth-integrated sampling, mainly focused on the aquifer nearest the surface. Wells in deeper aquifers are screened if used for public drinking water supply. Shallow wells with short screens are recommended to control the input of diffuse contaminants in recharge areas (Toussaint, 2000).

Where there is a groundwater flow field with significant vertical gradients, screening the total length of a thick aquifer is not good practice because of the danger of cross flow, down flow in the recharge area and up flow in the discharge area (figure X, Wells B and D); a short filter is correct (Well C). (Toussaint, 2000). Short screens at the bottom meet this hydrodynamic feature, but not fully screened monitoring (Wells B and D), as cross flow cannot be excluded. Only in Monitoring Well A are the piezometric head and groundwater surface identical.

Contamination with non-aqueous phase liquids (NAPLs) is a challenge to the design of monitoring wells, as they can spread over long distances, floating on the groundwater in the case of light NAPLs such as petrol, or in different depths of the aquifer in the case of dense NAPLs, such as halogenated hydrocarbons. In the event of pollution with these contaminants, depth-dependent monitoring wells are strongly recommended (3, 4 and 5, figure IX).

Figure IX. Selection of differently designed monitoring wells

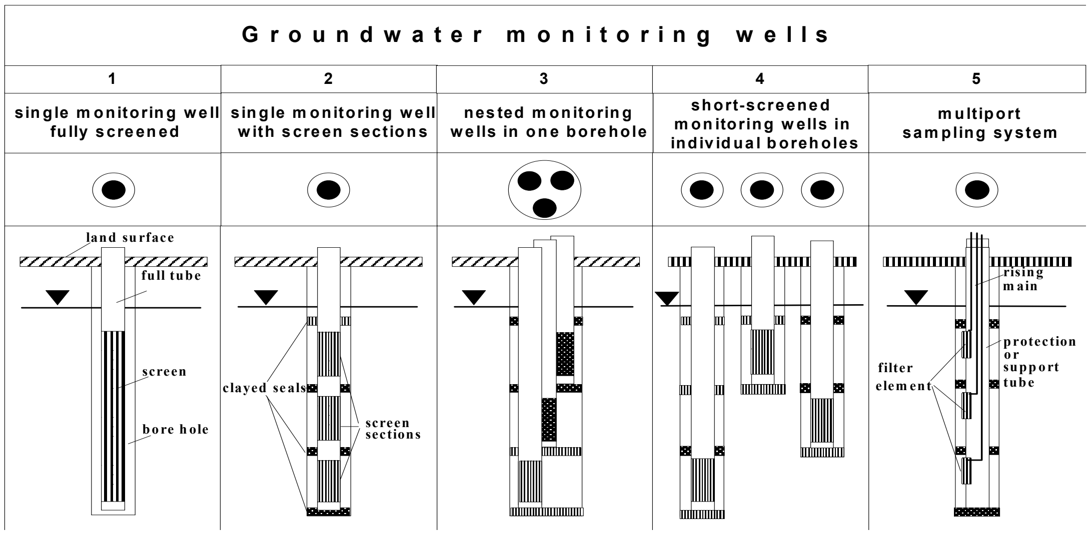
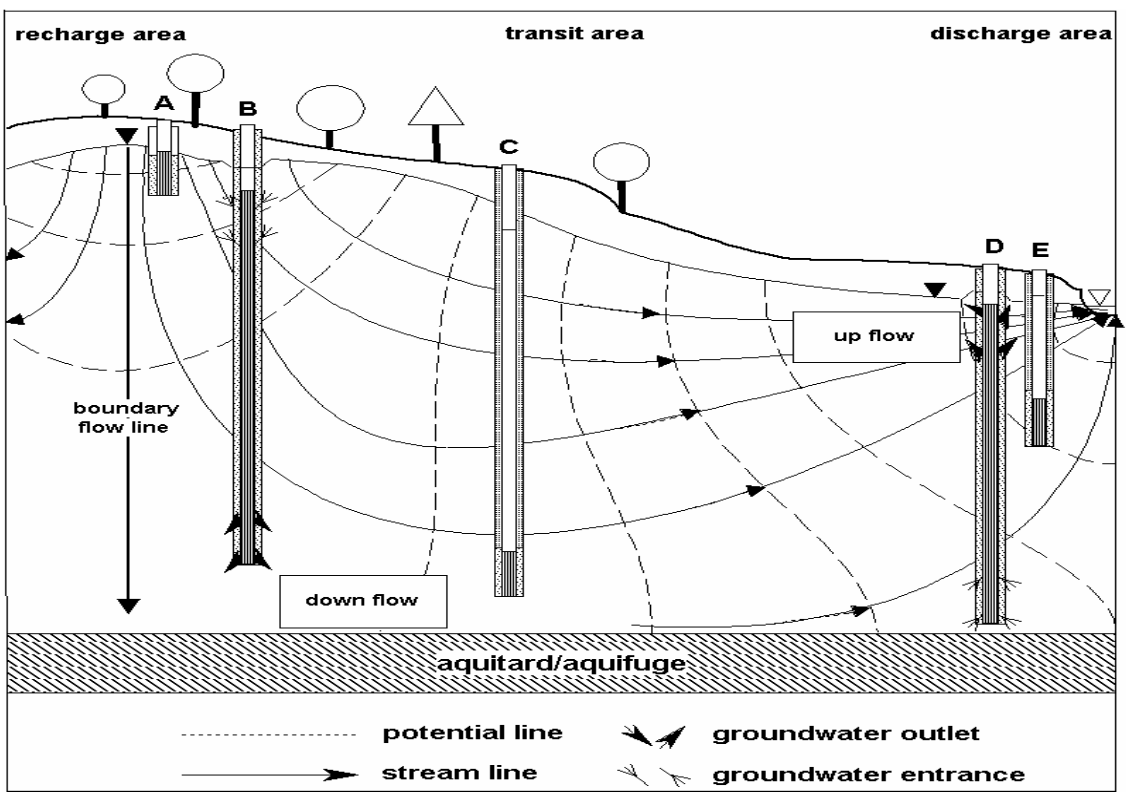


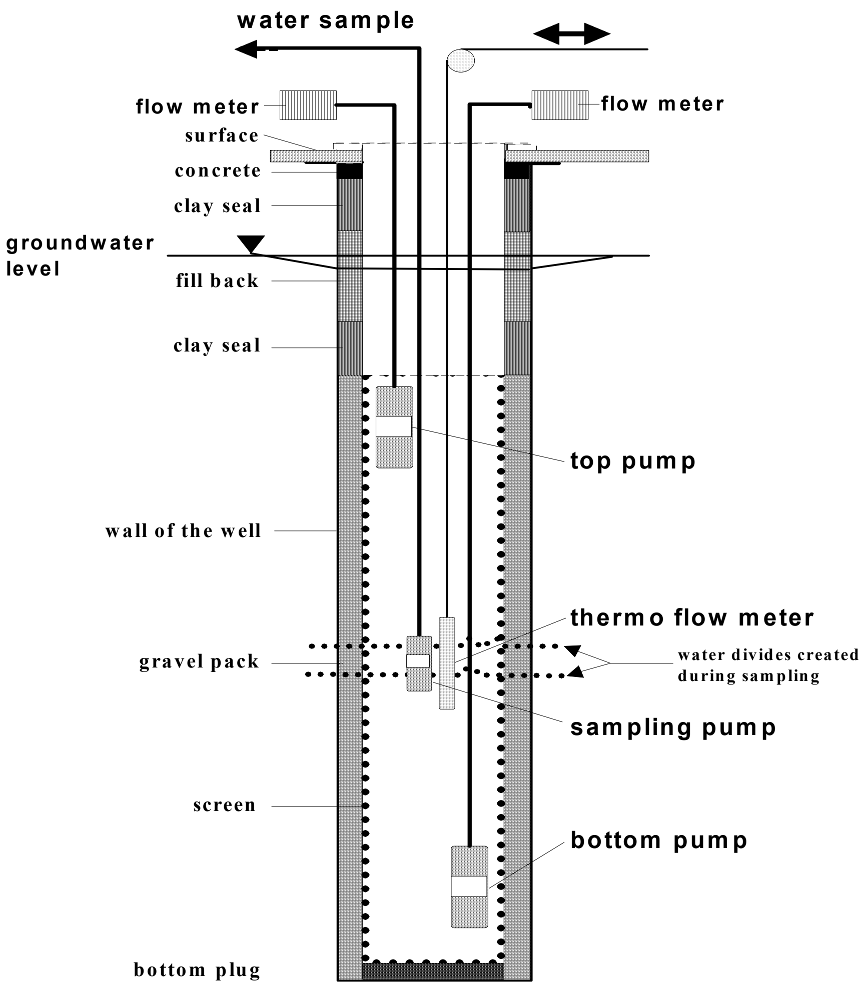
Figure X. Groundwater flow field with vertical hydraulic gradients (monitoring wells A,C and E)



One important aspect of groundwater monitoring is the selection of appropriate sampling techniques, which depends on groundwater characteristics, cost and the intended purpose of monitoring.

One modern sampling method is the *separation pump*. This technique uses two pumps to separate groundwater flow in the well into two partials, as shown in figure XI. A water divide is created in the well, its position depending on distribution of transmissivities of the aquifer and the ratio of the two pumping rates. The instrument used for locating the water divide is a thermo-flow meter. Above the water divide, the water flows to the top pump and, below it, the water moves towards the bottom pump. The difficulty lies in locating the position of the water divide and pumping water from this level at a rate of less than 1 per cent of the total rate. This will cause a zone within two new water divides, created by the sampling pump. Changing the ratio of the two main pumping rates, thereby moving the water divide to a new position, samples different levels of the aquifer. Through a series of top/bottom pumping ratios, the entire hydrochemical profile of the aquifer can be sampled.

Figure XI. Schematic illustration of separation sampling



C. GROUNDWATER MODELLING

Numerical groundwater modelling has been used to solve geohydraulic and hydrogeological problems for about 20 years. The application of flow models for groundwater management is now standard practice, while the application of contaminant transport and chemical reaction models is still being developed. Transport models can be used for many groundwater problems related to the behaviour of substances in the aquifer. They can, for example, help to interpret data from chemical analyses of groundwater in terms of the transport history of the analyzed substance. Other applications are the prediction of the behaviour of pollutant plumes, intrusion of salt water into coastal aquifers, the impact of a potential or existing pollutant source on groundwater quality at a certain point or the impact of remediation measures (Schelkes, 2000).

Groundwater modelling is therefore very useful in finding sound solutions and making the right decisions with respect to groundwater protection and rehabilitation.

As remediation of groundwater resources can be very costly, transport models are particularly useful in selecting and designing remediation procedures. By modelling different scenarios, the effectiveness of different remediation approaches can be compared and the final design of the remediation system optimized prior to installation. Therefore the model can help in comparing the cost-effectiveness of different options. When modelling remediation options, natural attenuation should also be considered, which under certain circumstances may be a good alternative or supplementary to technical methods.

Transport models can also support groundwater monitoring, as they can be used to determine whether modifications should be made in a monitoring network, e.g. if observation boreholes are needed in additional locations.

A variety of groundwater simulation software is available, from simple analytical flow models to sophisticated numerical multiphase and solute transport models. Some available models are listed in table 17.

The tasks of groundwater modelling are highly variable, mirroring the different hydrogeological and hydrochemical characteristics of the model area and the different problems to be addressed. There are no general solutions. For this reason, it is very important to develop a comprehensive conceptual model prior to the application of any modelling software. The choice of modelling software may also depend on this concept. Similarly, the type of aquifer, flow conditions, pollutant concentration and boundary conditions must be identified as input to the model. Uncertainties have to be identified and the assessment of additional data to fill these gaps should be discussed. To save costs and computation time, possible simplifications should be considered, as they may allow analytical solutions, one-phase models, simplified multi-component or density-dependent models to be substituted for more complex numerical models. As part of the conceptual model, the scenarios that should be modelled have to be defined.

TABLE 17. SELECTED GROUNDWATER FLOW MODELS

Model name	Usage and application
SUTRA	2-D solute transport, salt water intrusion for saturated and unsaturated zones
SWICHA	3-D flow and transport models
MODFLOW	3-D groundwater flow mode (finite difference), full range of groundwater flow and contaminant transport modelling with visualization and graphics
MODFLOW-SURFACT	MODFLOW-based groundwater flow and contaminant transport model
3DFEMFAT	3-D finite element model of flow and transport through saturated and unsaturated media
AQUA3D	3-D groundwater flow and contaminant transport model
AT123D	123-D analytical groundwater transport model for long-term pollutant fate and migration
BIOF&T2-D/3-D	Biodegradation, flow and transport in saturated/unsaturated zones
BIOPLUME III	Transport of dissolved hydrocarbons under the influence of Oxygen-limited Biodegradation
BIOSLURP	Multiphase hydrocarbon vacuum enhanced recovery (bioslurping) and transport
FLOWPATH II	2-D groundwater flow, remediation and well head protection model
HST3D	3-D heat and solute transport model
KYSPILL	Unique groundwater pollution forecasting system
MARS 2-D/3-D	Groundwater multiphase area remediation simulation model
MOC	Computer model of 2-D solute transport and dispersion in groundwater
MOCDENSE	Two-constituent solute transport model for groundwater having variable density
Model GIS	Interface linking groundwater models to ARC/INFO

D. PRECAUTIONARY GROUNDWATER PROTECTION MEASURES

Preventive protection of groundwater resources is aimed at decreasing the risk of groundwater pollution and can be achieved by means of groundwater-friendly behaviour, a regulatory framework and intelligent technical precaution measures.

Since groundwater is a subsurface resource and the consequences of pollution are not immediately obvious, there is usually a lack of awareness of the importance of groundwater protection. Measures to *increase awareness* among the public and water professionals about the risks of groundwater pollution and the importance of its prevention should be part of a national policy for groundwater protection. Awareness of the potential risks of groundwater contamination and their consequences are a prerequisite for careful handling and use of hazardous substances. Failure to comply will only lead to higher costs for the treatment of groundwater, costs that are inevitably met by the customer.

Protection measures may include *regulations on the handling of hazardous substances*. High construction and operating standards must be imposed for the handling and storage of water-endangering liquids and wastes, for example:

(a) Safe storage of barrels with fresh or spent solvents: capture basins for leakage with a chemical-resistant coating (or high grade steel or ceramics), double-sided barrels (highest standard);

(b) Safe underground storage tanks: double-sided tanks with leakage indicator, cathode protection and an overflow safety mechanism;

(c) Safe solvent pipelines: double-sided tubes working below atmospheric pressure;

(d) Safe operating areas in general: coated concrete or ceramic floor;

(e) safe cleaning and distillation facilities, safe recycling plants: concrete floor with protective coating (or high grade steel or ceramics) as protection against seepage into the underground, should be encapsulated;

(f) Substitution of water-endangering liquids by less harmful or harmless liquids (e.g. dry cleaning);

(g) Safe industrial and public sewers: construction works in accordance with latest design codes without leaking sleeves and stand;

(h) It should be compulsory to report accidents that cause a release of hazardous substances to the environment to local environment authorities.

Delineating groundwater protection zones around major abstraction sites (well fields, springs) is another effective means of groundwater protection. Protection zones are aimed at regulating and limiting human activities and land uses with a high risk of releasing contaminants in the catchment area of groundwater abstraction. It is advisable to define protection zones for abstraction sites that produce water for public supply, other private potable supply, including mineral and bottled water, and for commercial food and drink production.

The extent and shape of protection zones depend on the intended amount of abstraction, the hyrogeological characteristics of the aquifer and the direction of groundwater flow. Protective zones may consist of an inner zone, an outer zone and an abstraction catchment zone. The inner protection zone is the area in the immediate vicinity of the well field or spring. It is usually several metres in diameter and is fenced off to prevent any kind of human activity which might have an immediate effect upon the resource. The outer protection zone is based on the concept of 50 days travel time from any point below the groundwater table to the abstraction site. Fifty days is the assumed time it takes for biological contaminants such as bacteria or viruses to decay in an aquifer environment and is an established standard used in many countries. The zone is not usually defined where the aquifer is confined beneath a continuous covering stratum of very low permeability since in such cases infiltration is prevented. The catchment area protection zone is designed to cover the complete catchment area of the groundwater abstraction site; all groundwater within the catchment area discharges to the abstraction site. The long-term annual groundwater recharge within this zone should equal the abstraction rate in order to avoid over-abstraction. Land use restrictions are defined and enforced for all groundwater protection zones. The extent of restrictions and prohibitions decreases from inner zone 1 to the catchment zone. No human activity is allowed in the inner zone. In the outer zone, representing the 50-day travel time distance, the handling of hazardous substances (e.g. fuel stations, power stations, industry), the application of manure, artificial fertilizers and pesticides, and residential areas not equipped with a safe means of wastewater disposal should be tightly restricted.

Precautionary groundwater protection measures need to be initiated and supported through legislative regulations and policies at national, governorate and local levels. An overview is given in table 18.

TABLE 18. POLICY OPTIONS FOR GROUNDWATER PROTECTION

Institutional level	Type of Plan	Contents	General Aims
National level	National groundwater protection plan	• Strategy and approach • Methods and tools • Monitoring and control	Prevention of groundwater pollution
Governorate Level	Provincial groundwater protection plans	• Provincial differentiation of protection • Groundwater protection areas near drinking water abstractions • Regulations in protected areas for: - Agriculture - Industry - Domestic activities - Oil pipelines, etc.	Prevention of groundwater pollution
Local Level - Districts - Municipalities - Water supply companies - Industries	Operational plans	• Environmental ranking (priority ranking according to risk) • Selection of alternative protection • Remedial measures • Monitoring and control	• Remedial measures • Measures to control spread (drainage, inspection wells)

VI. CONCLUSION AND RECOMMENDATIONS

Over the last two decades, economic and social development has brought about improved provision and extended coverage of water supply and sewerage networks, a higher standard of living, an expansion of irrigated areas and industrial activities, with consequent increases in water consumption, especially from groundwater sources, and increased pollution levels and resource depletion in all ESCWA countries. There are differing levels of groundwater pollution depending on the extent of natural protection of water resources and other factors. The enforcement of pollution control measures for surface water over a given period can contribute to substantial decreases in pollution levels, while, for groundwater, the flushing of pollutants from groundwater systems takes time. Removal of contaminants from aquifers may be very costly or impossible, so that the polluted resource has to be abandoned.

Lack of systematic monitoring of groundwater quantity and quality and the absence of comprehensive legislation and regulations and their enforcement has resulted in continuing degradation of water quality.

The geology of shallow porous alluvial and fissured and karstified limestone aquifers, which are typical aquifers in the ESCWA region, allows pollutants to move fast from their sources and accumulate in the groundwater system. Major pollutants in the region are faecal bacteria, viruses, nitrate, phosphate and heavy metals from partially treated or untreated domestic and industrial wastewater, and organic contaminants from industrial and medical toxic wastes and contaminated sites. Because of the vulnerability to pollution of many aquifers in the region, special attention needs to be given to the development of appropriate policies and regulations for their protection and the implementation of effective measures to rehabilitate the soil profile and underlying aquifers.

There are many tried and tested methods of soil and groundwater remediation, but they have been little applied in the ESCWA countries because of lack of awareness and commitment by decision-makers to addressing this critical issue, lack of experience and lack of financial resources. Considering the usually high cost of groundwater remediation, top priority should be given to precautionary measures to prevent contamination of water resources.

The groundwater issue that has received some attention is salt water intrusion, the result of excessive pumping of coastal aquifers.

Although pollution levels are increasing, only local protection and rehabilitation programmes have been formulated and implemented on a limited scale.

Increasing awareness of pollution risks was evident in the discussions and recommendations of the Expert Group Meeting held by ESCWA from 14 to17 November 2001 on the subject of Groundwater Rehabilitation for Water Resources Protection and Conservation. The meeting examined potential pollution sources and pollution levels in various parts of the region, recommended a number of remediation methods and discussed groundwater monitoring and protection measures

In view of the increasing competition for water among different consuming sectors and increasing pollution of groundwater, which further reduces available water resources, there is a need to formulate and implement programmes to protect and rehabilitate groundwater systems in the countries of the ESCWA region. Without such programmes, groundwater quality will continue to deteriorate, resulting in more serious water shortages. Some programme components should emphasize the identification of the areas most vulnerable to pollution, monitoring fluctuations in water quantity and quality over time and space and the development and enforcement of legislation and regulations. On the basis of all this, the following recommendations are made:

1. Practical groundwater management policies should be formulated that can realistically match each country’s situation to tackle depletion and prevent further contamination of water, especially by hazardous substances, in order to protect public health and preserve the environment.

2. Groundwater management policy components should address the issues of updating and reforming existing regulatory frameworks (regulations and by-laws), the development and implementation of enforcement mechanisms that clearly define and allocate responsibilities among the various agencies concerned, and involve stakeholders in the planning, formulation and implementation processes. There is a need to formulate guidelines on the use of chemical and industrial products (e.g. agriculture pesticides, fertilizers and herbicides) known to contaminate groundwater sources.

3. The capabilities of groundwater protection departments in Member States should be enhanced by strengthening and developing groundwater quantity and quality monitoring systems, due attention being paid to developing reliable, comprehensive data bases so that pollution can be assessed or prevented and appropriate rehabilitation measures identified. The monitoring system should emphasis the preparation of groundwater vulnerability maps and their integration into geographic information systems in order to facilitate analysis and the use of this information in the decision-making process and the delineation of areas most prone to pollution.

4. There is an urgent need for increased public awareness about pollution-related health risks and losses of already scarce groundwater resources. The profile of groundwater needs to be raised to a level commensurate with its importance as a strategic resource through public awareness, emphasizing the role of women, NGOs, water-users' associations, the private sector and extension services.

5. Member States of the ESCWA region need to evaluate the "polluter pays principle" and link it to the principles of preventive action and rectification of damage at source, so that those who contribute to the pollution of groundwater sources become agents of its conservation and protection.

6. National projects should be launched in Member States to develop and strengthen the capacities of groundwater protection departments by organizing training workshops, seminars and practical field training in groundwater rehabilitation techniques, protection and conservation. ESCWA Member States should also encourage research to develop and update standards and guidelines for the assessment, monitoring, protection and rehabilitation of groundwater quantity and quality.

7. There should be investment in wastewater treatment facilities to produce treated wastewater that is not harmful to groundwater, and greater integration between groundwater development, use and management and the treatment and discharge of wastewater. Emphasis must be placed on the elimination of pathogens from municipal and other wastewater before it is discharged into the arid environment.

8. Agricultural policies and irrigation practices suitable for arid lands should be developed and adopted. Adequate attention should be given to the application of decision support systems to enable an optimum match between water quality, crop, soil and climate, optimize productivity and minimize the qualitative and quantitative impacts of agricultural activities on groundwater aquifers.

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Helpful Internet Sites:

1. http://www.fao.org/: United Nations Food and Agriculture Organization
2. http://www.gnet.org: The Global Network of Environment & Technology
3. http://www.gwrtac.org/: The Ground-Water Remediation Technologies Analysis Centre
4. http://www.rtdf.org: The Remediation Technologies Development Forum
5. http://www.unep.ch/: United nations Environment Programme
6. http://www.who.org/: World Health Organization
7. http://worldwatercouncil.org/: World Water Council
8. http://www.wria.org/: Western Risk and Insurance Association