Groundwater Recharge and Discharge:

- **Static Water Level: Depth of water able that measured during the steady state of groundwater**
- **Dynamic Water Level: Depth of water able that measured during the dynamic state of groundwater**

The groundwater systems are in dynamic state as a result of:

1. **The replenishments of groundwater resource i.e. (Groundwater Recharge)**

2. **Discharge of groundwater by different processes**

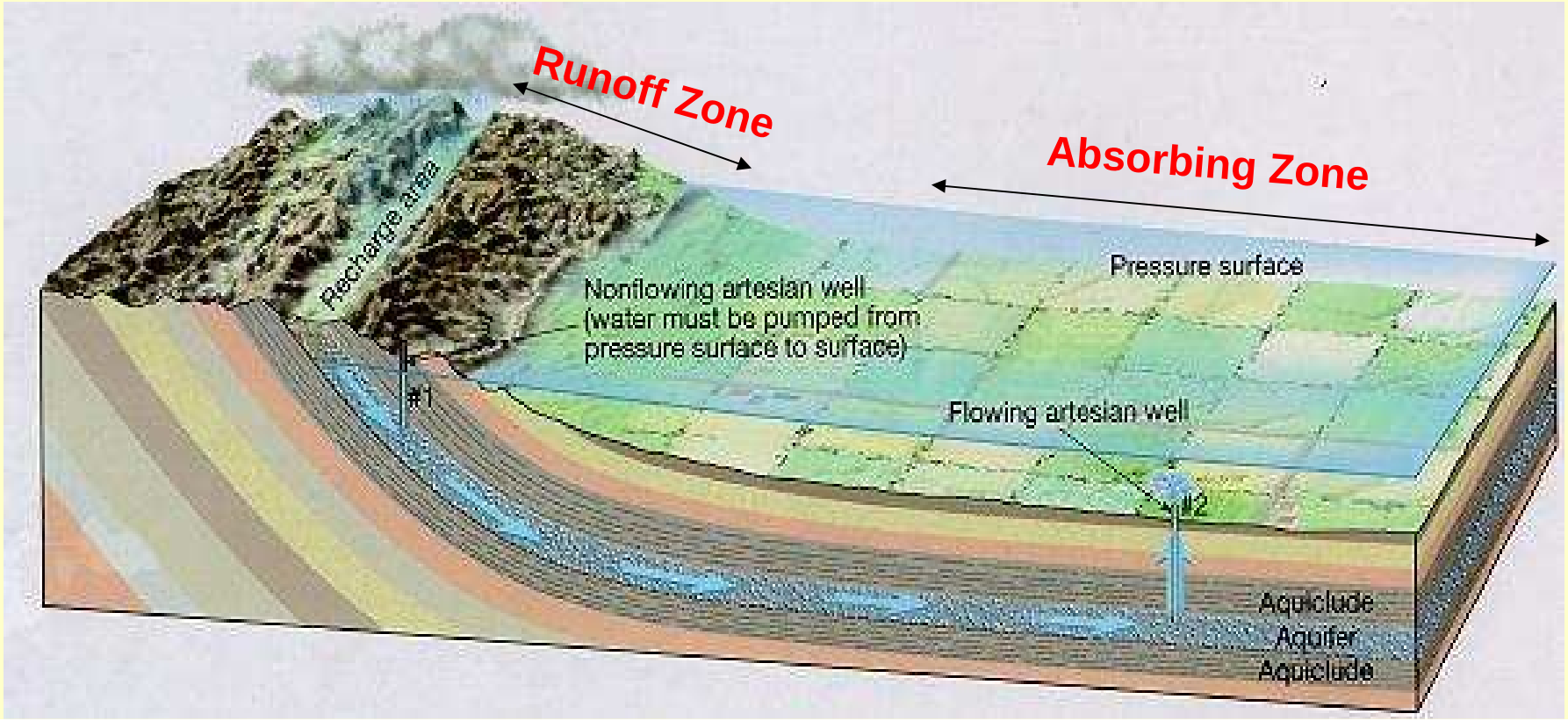
Groundwater Recharge:

The groundwater recharge can be produced by:

I. Direct Recharge:

a. Direct infiltration of rainfall in excess of the water-holding capacity of the soil

b. Direct recharge by runoff water moving through fissures and cracks of solid rocks. The direct recharge in the runoff absorbing zone is usually much greater than in the runoff producing zones.

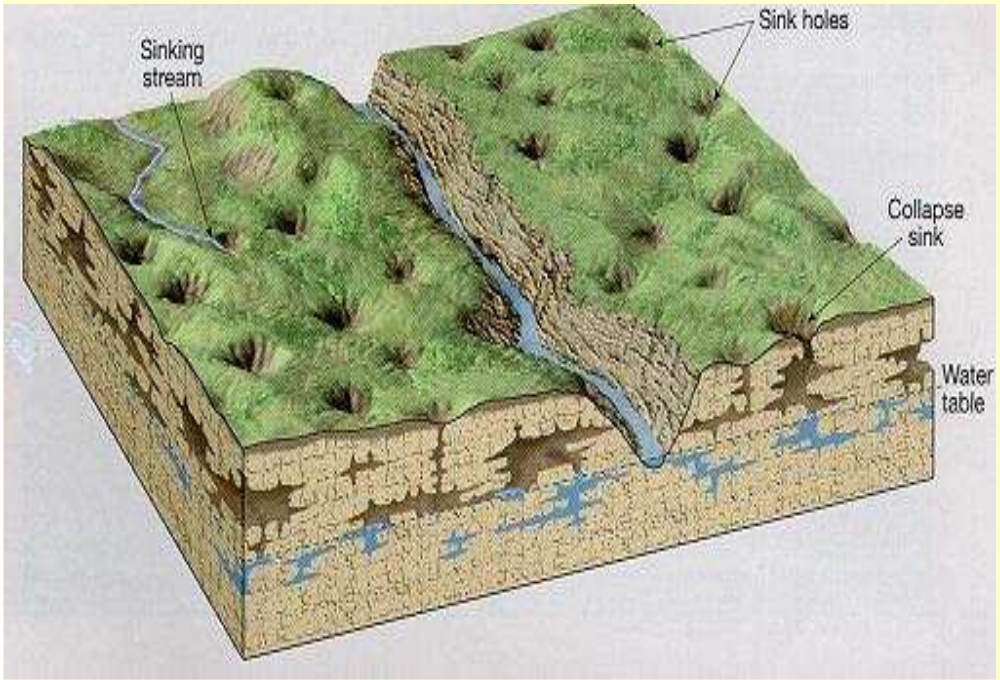


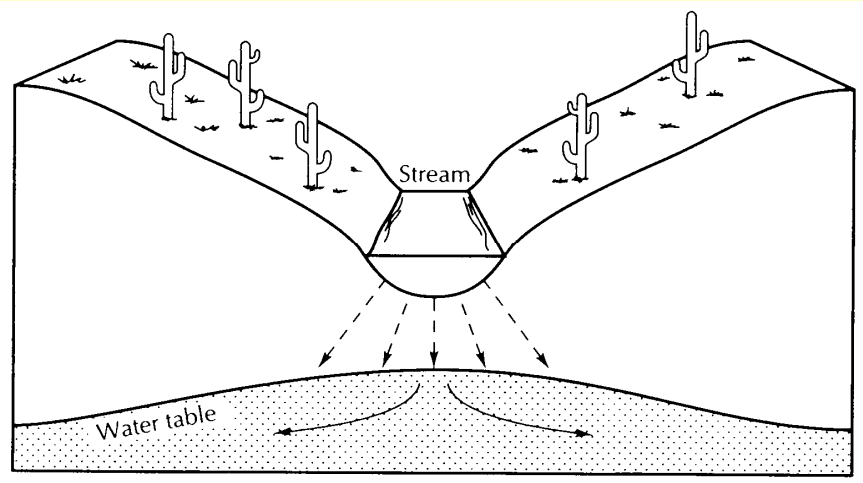
2. Indirect Recharge:

a. Recharge of groundwater by infiltrating surface water from wadis:

It is the main form of of natural groundwater recharge in Yemen. i.e.

- **Less recharge in the steep and relatively impermeable catchments** "Runoff producing zones"
- **High recharge in the flat and permeable terrains** "Runoff absorbing zone"

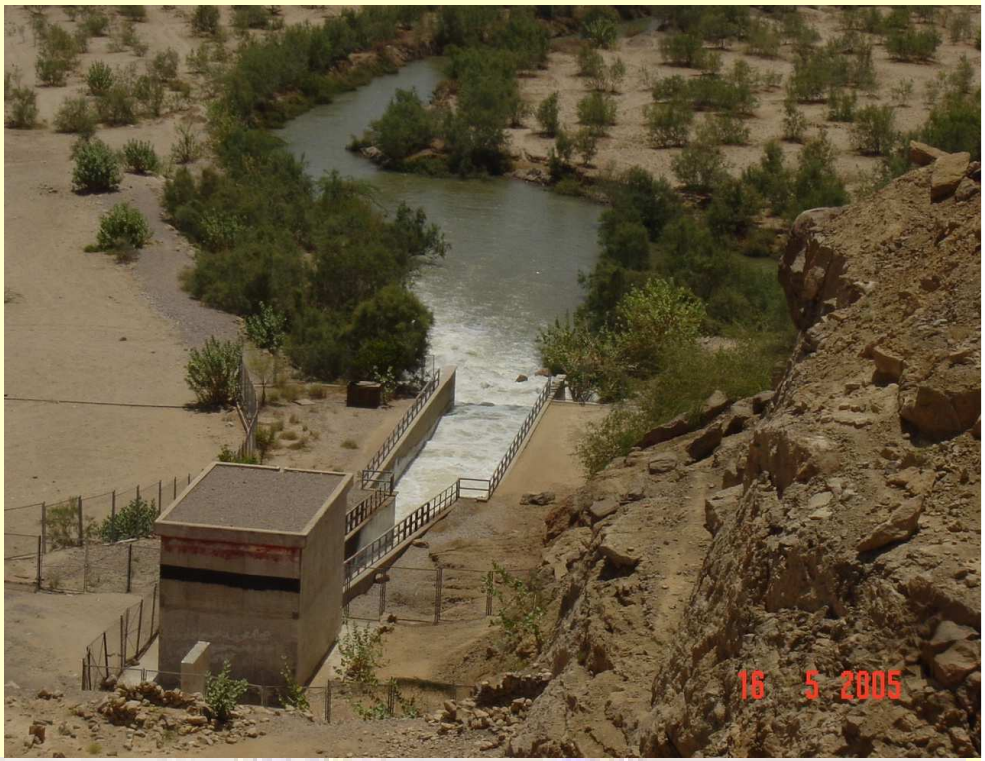


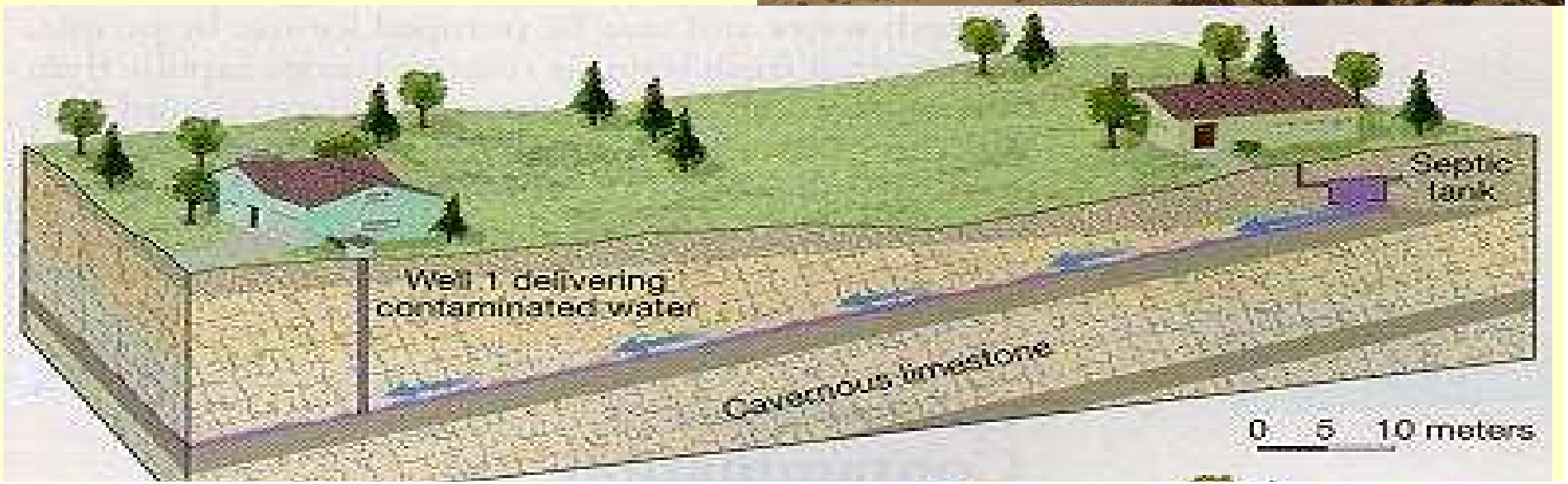


Cross section of a losing stream, which is typical of arid regions, where streams can recharge groundwater

b. Recharge by “Irrigation Water Losses” and waste water

- **It is the most important form of indirect groundwater recharge in Yemen**



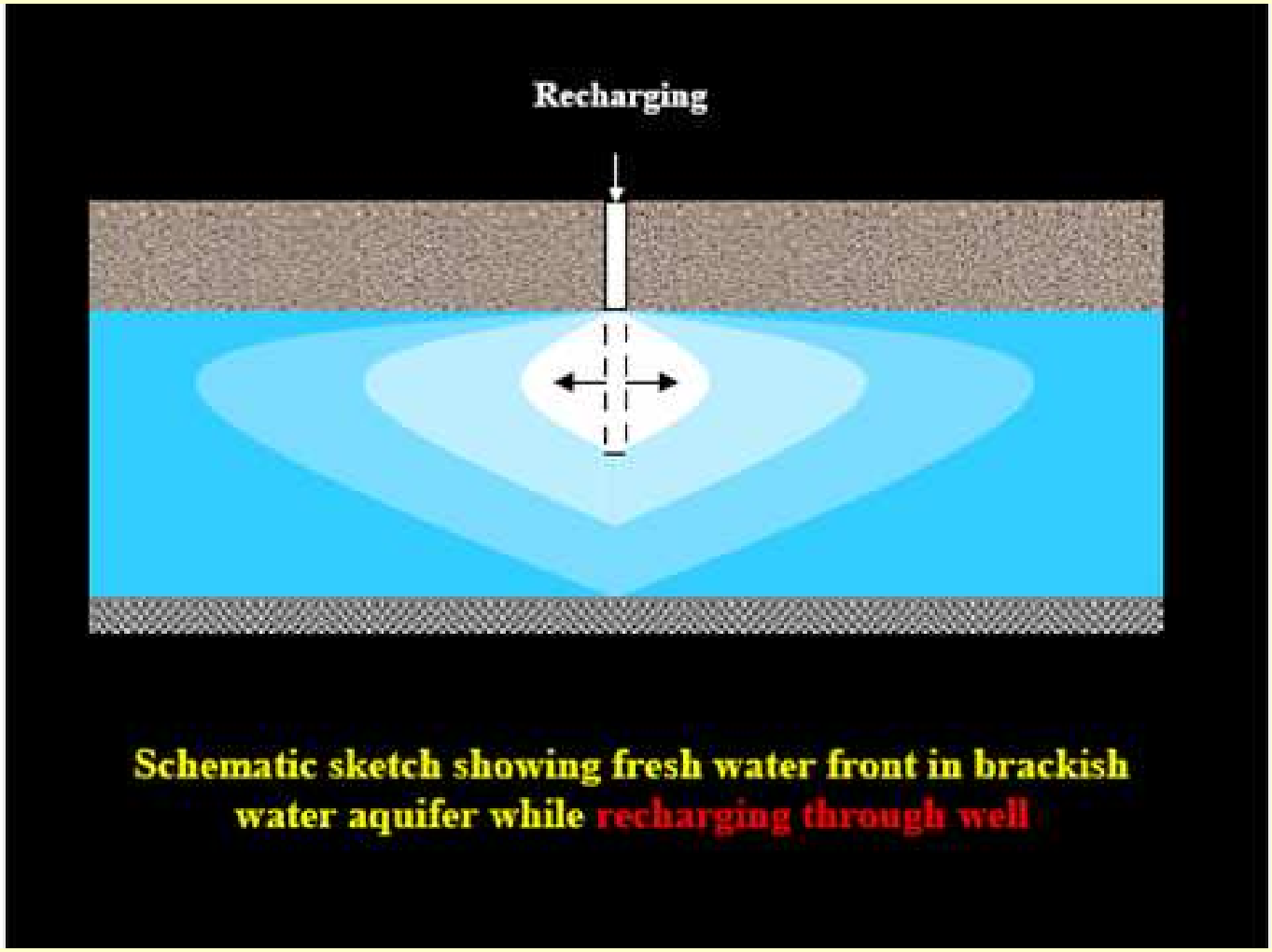


C. Artificial Recharge :

1. By Recharge Dams

- **It is usually produced by human interference with the purpose of recharging groundwater system**

C. Artificial Recharge : 1. By Injection Wells



Schematic sketch showing fresh water front in brackish water aquifer while recharging through well

Groundwater Discharge:

Groundwater Discharge can be classified into:

a. Natural Discharge

b. Human Induced Discharge

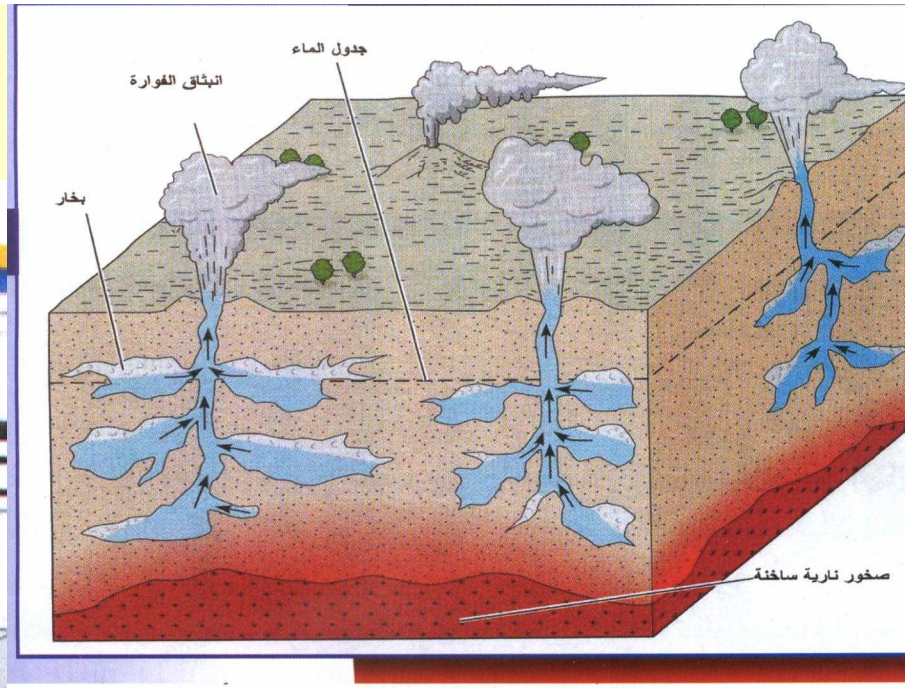
a. Natural Discharge:

The groundwater natural discharge involves:

1. **Discharge by Springs**
2. **Discharge by Outflow into streams**
3. **Discharge by Evaporation and Evapotranspiration**
4. **Discharge by Submarine outflow**

1. Discharge by Springs:

Springs occur in many zones of Yemen:



ل (**4.4**) يوضح كيفية تكوين المياه الحارة في باطن الأرض.

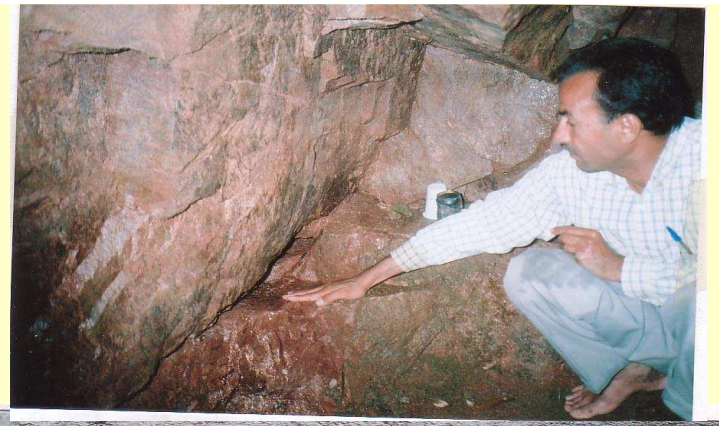
1. Discharge by Springs:

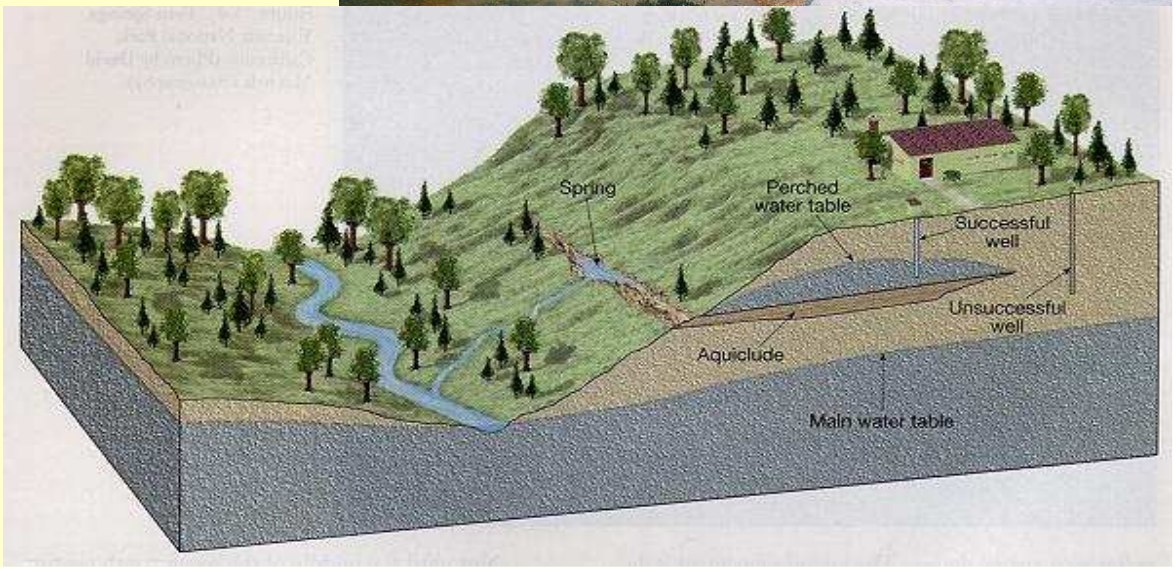
- **Springs in Amran Limestone**

- **Springs in the rocks of Hadramout Group**

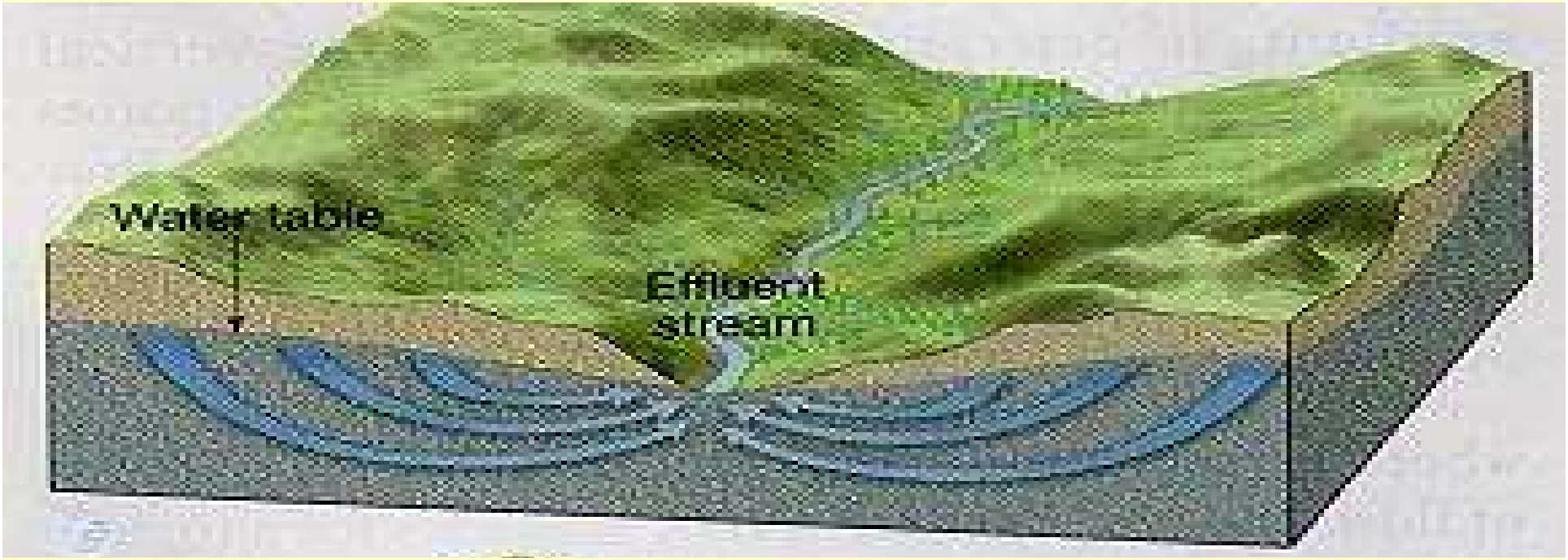
- **Springs in Volcanic rocks**

- **Springs in Tawilah Sandstones (Wadi Al-Ahjur)**



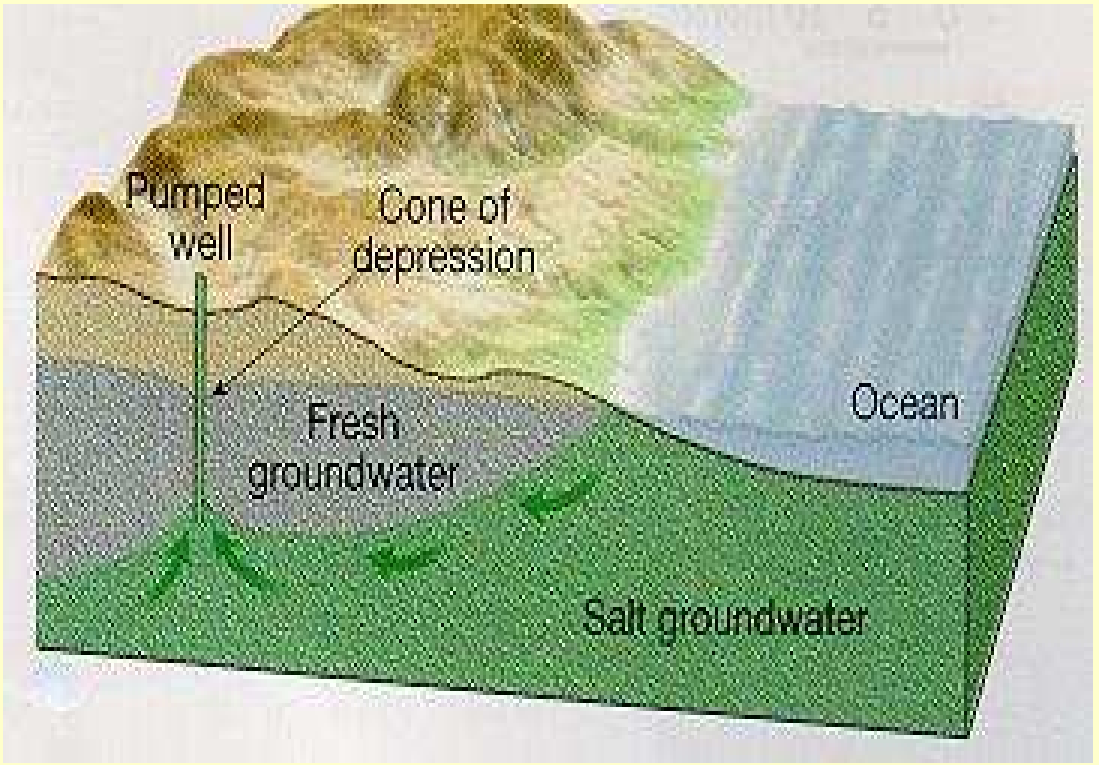


2. Discharge by Outflow into streams



3. Discharge by Evaporation and Evapotranspiration

4. Discharge by Submarine outflow



b. Human Induced Discharge

• Groundwater abstraction has gained enormously in importance over the last 25-30 years.
• Less than one generation ago, it was a minor components of the total discharge of the groundwater systems.
• Nowadays, it is the dominant form of groundwater discharge of most of Yemen's groundwater systems.
This was due to:

- 1ntroduction of modern technology such as drilling rigs and powerful pumps
- Growing water demands of a developing society

Estimates to groundwater abstraction:

Estimates of groundwater abstraction result mainly from well inventories

Table 6.2 Estimates of groundwater abstraction rates

AREA	LATEST WELL INVENTORY/ASSESMENT				1994 ESTIMATES	
	Reference	No.of pumped wells	Total abstraction (Mm^3/yr)	Year	Total abstraction (Mm^3/yr)	
Highland Plains :						*500*
Baqim Plain	DHV,1993n	107	6.1	1991	6	
Sadah Plain	DHV,1993m	2330	80.4	1992	80	
Al Harf, Hamra and Al Ashash Plains	DHV,1993	346	11.9	1991	12	
Attaf Plain	DHV,1993r	112	14.8	1991	15	
Amran Valley	DHV,1993s	800	77.2	1991	77	
Sana'a Basin	TS-HWC,'92i		180.6	1990	185	
Dhamar Plains	Chilton,1980	395	11	1976	40 (?)	
Rada Plain	Ilaco, 1984	556	9.0	1983	25 (?)	
Tihama zones:						*810*
Northern zone	DHV, 1988	676	114	1984	120	
Wadi Mawr	DHV, 1988	1200	156	1984	165	
Wadi Surdud	DHV, 1988	900	117	1984	125	
Wadi Siham	DHV, 1988	960	125	1984	135	
Jahabah	DHV, 1988	1088	141	1984	150	
Wadi Rima/Zabid	DHV, 1988	1983	261	1984	280	
Wadi Rasyan	DHV, 1988	431	30	1984	33	
Wadi Mawza	DHV, 1988	442	30	1984	33	
Other zones	DHV, 1988	516	53	1984	54	
Southern coastal plains:						*250*
Tuban delta	McDonald,'86a		87.2	1984	90	
Wadi Rabwa	Selkhozp.,'90a		5.8	1988	7	
Abyan delta	WRAY, 1995		86.4	1993	87	
Wadi Ahwar	Selkhozp., '90b		5.8	1988	7	
Fuwah-Buweish-Huweira-Arf-Khird	Sogreah, 1980a		9.8	1980	15	
Ramlat as Sabatayn fringe zone:						*375*
Al Jawf Plain	AHT, 1982	800	30	1982	40	
Marib Plain	WRAY, 1992	1869	174	1991	180	
Beihan zone	WBAP	842	75	1986	80	
Wadi Markhah zone	Strojexport, 1984		12.8	1982	20	
Wadi Hadramawt	McDonald,1988		158.9	1985	180	*200*

Estimates to groundwater Recharge:

- **The assessment of groundwater recharge is very difficult.**
- **It has to be estimated by indirect methods**
- **The lake of reliable data is a sever constraint.**

- **Methods used for studies in Yemen include:**
  - **water balance methods through flow estimation**
  - **Tracer techniques,**
  - **Modeling techniques and**
  - **Empirical relations with rainfall**

Aggregating estimates of groundwater abstraction, groundwater recharge and stored volume of groundwater for the major aquifer complexes leads to the provisional picture presented in the following table

Table 6.3 Current abstraction rates, recharge rates and groundwater storage for the main aquifer complexes in Yemen

Aquifer complex	Approximate abstraction (Mm^3/year)	Approximate average recharge (Mm^3/year)	Fresh groundwater stored (Mm^3)	Remarks
Tihama Quaternary aquifer	810	550	250 000	Quaternary aquifer
Southern Coastal Plains (west of Mukalla)	225	375	70 000	several Quaternary aquifer units
Extended Mukalla Complex	575	500	10 000 000	Cretaceous Sandstone with interconnected Quaternary deposits
Highland Plains	500	100	50 000	various isolated units with variable lithology

Notes: (1) Recharge in this table is 'natural recharge' as defined in Section 6.4.1, thus it does not include return flow from abstracted groundwater
(2) Recharge and storage figures are only tentative
(3) Fore definition of the Extended Mukalla Complex, see section 6.3.4.

The Response of the groundwater systems to increasing abstraction

The drop of water table level in the highland areas ranges between 2 to 6 m/year

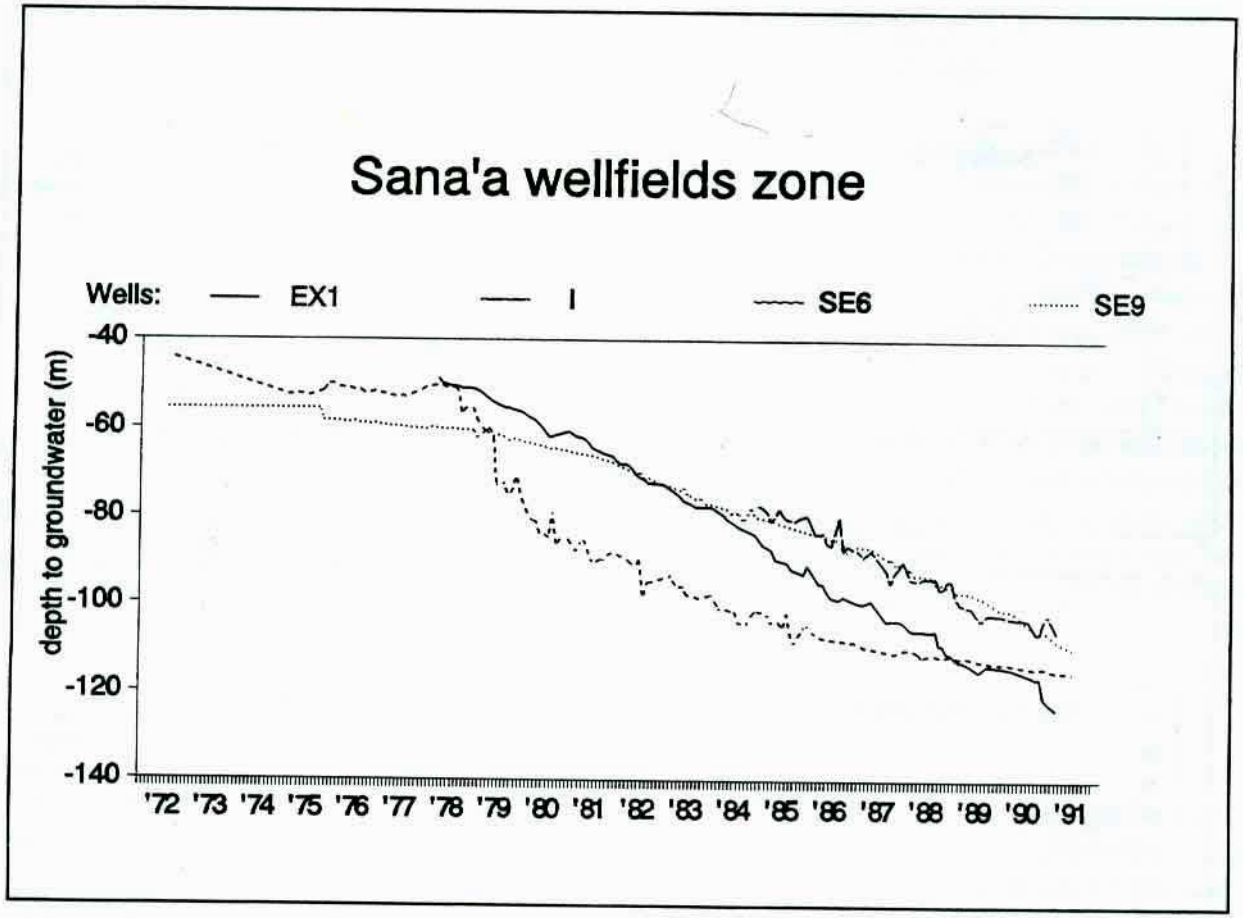


Figure 6.9 Changing groundwater levels in the Sana'a basin

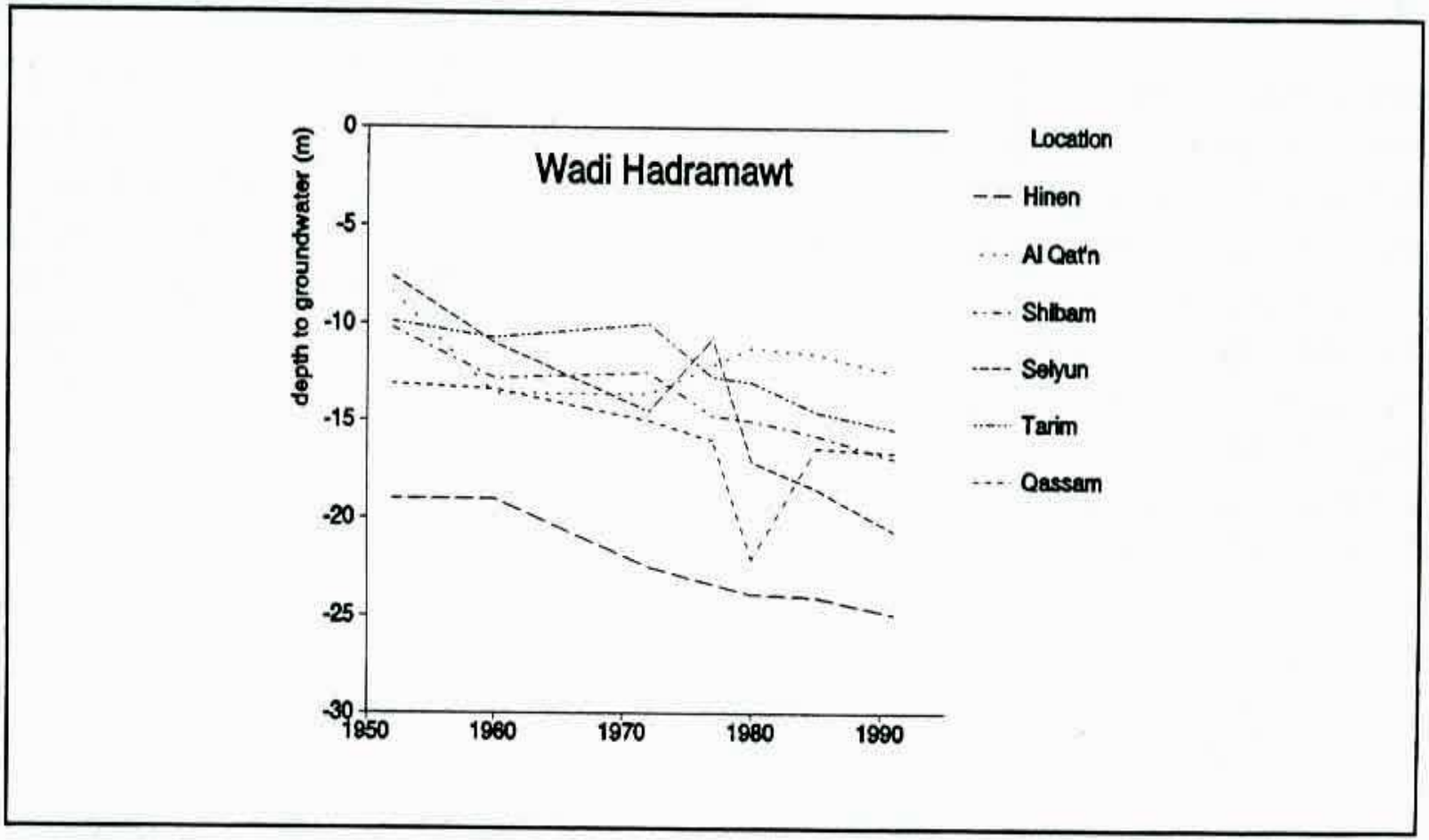
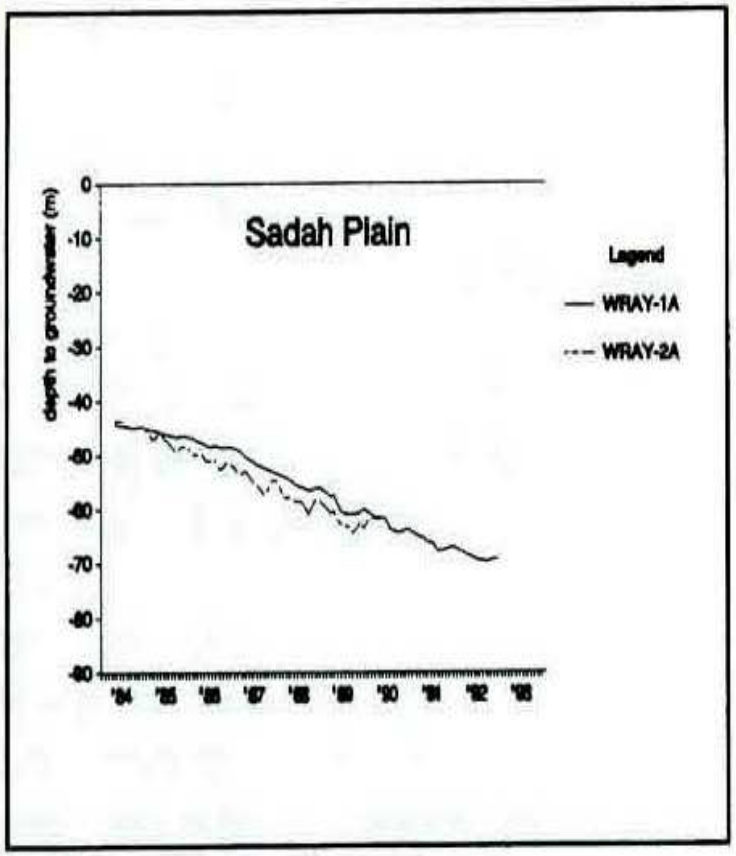
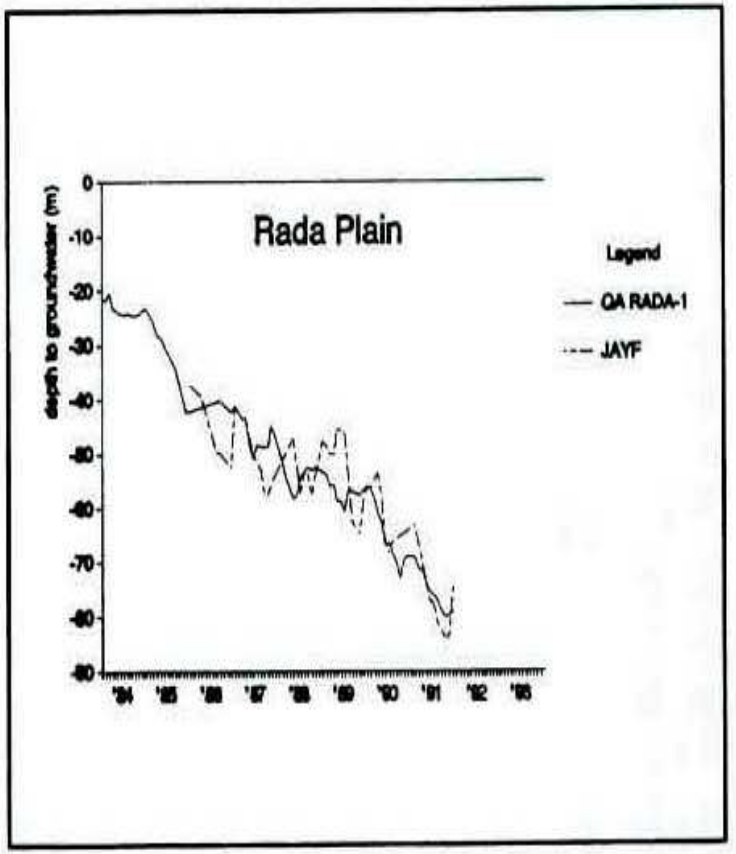


Figure 6.10 Groundwater level trends in Wadi Hadramawt


Sadah Plain
depth to groundwater (m)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
'84
'85
'86
'87
'88
'89
'90
'91
'92
'93
Legend
WRAY-1A
WRAY-2A


Rada Plain
depth to groundwater (m)
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
'84
'85
'86
'87
'88
'89
'90
'91
'92
'93
Legend
QA RADA-1
JAYF

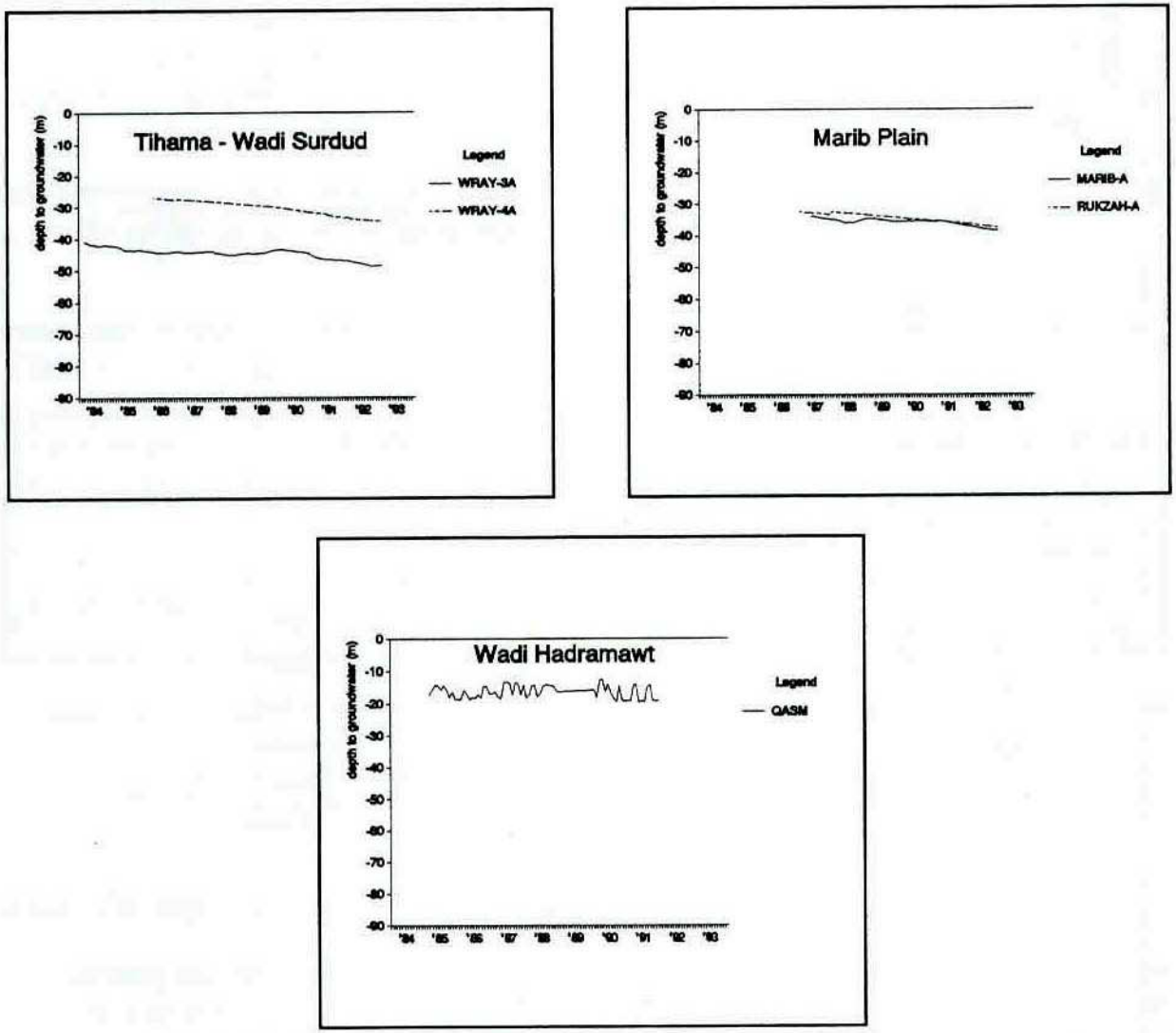
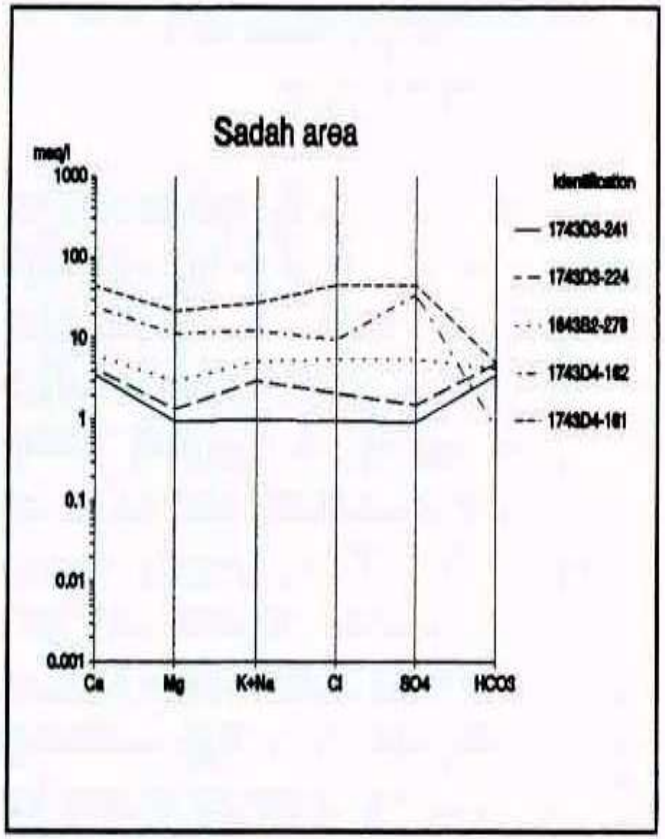


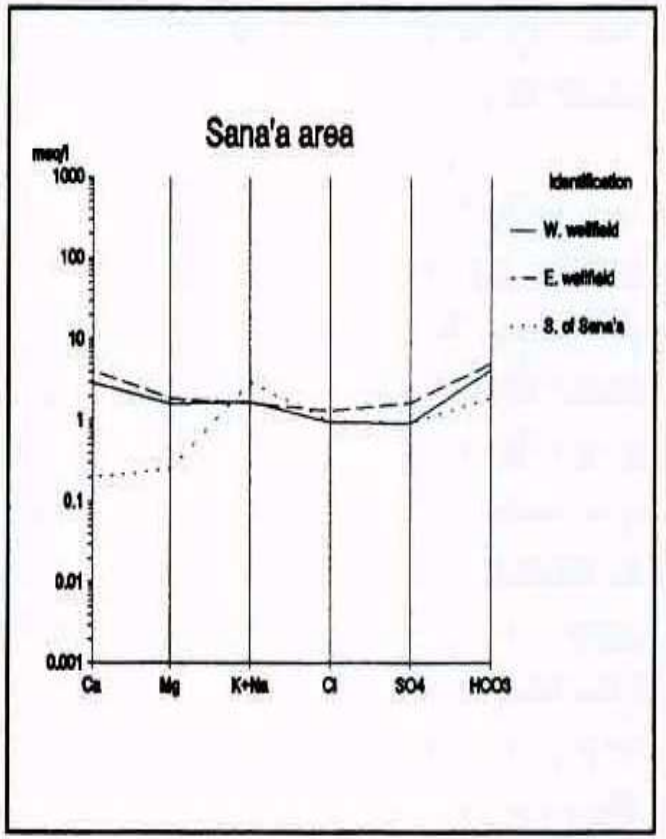
Figure 6.11 Selected groundwater level hydrographs

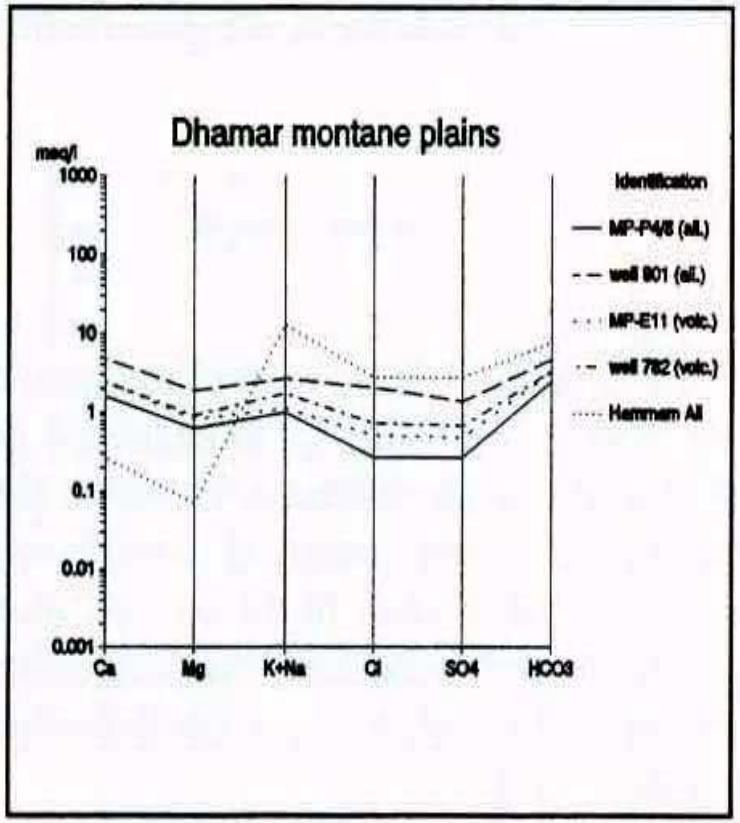
Groundwater Quality:

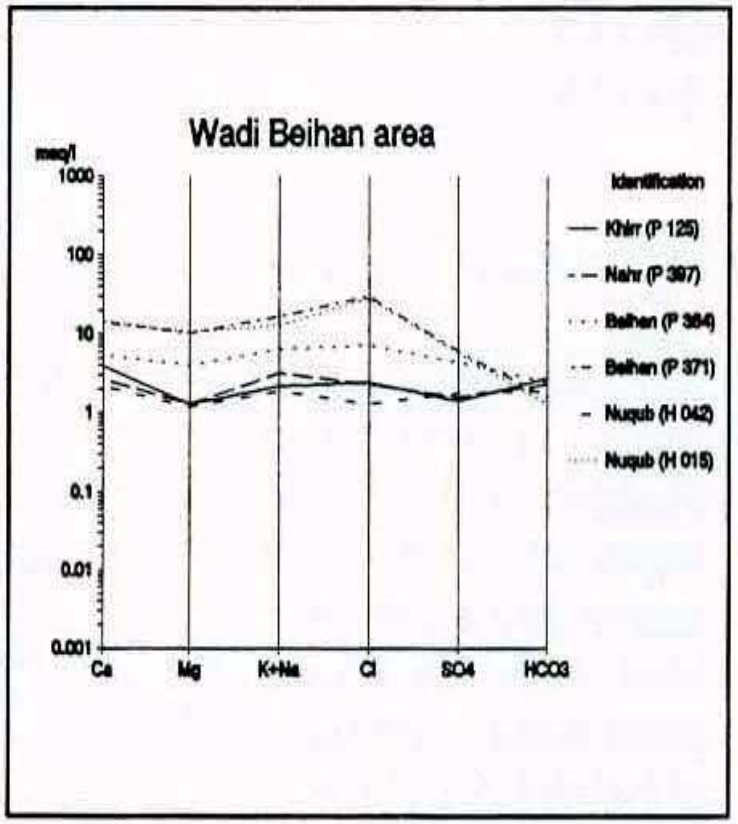
- **Groundwater quality has not been studied in great detail in Yemen.**
- **In most studies the quality of groundwater has been assessed for:**
    - **its suitability for irrigation use and**
    - **its suitability for domestic use**

- **In most studies only Electrical conductivity measurements have been done.**
- **As a result there is a reasonable picture of the occurrence of fresh and brackish/saline groundwater in Yemen.**


Sadah area
meq/l
1000
100
10
1
0.1
0.01
0.001
Ca
Mg
K+Na
Cl
SO4
HCO3
Identification
1743D3-241
1743D3-224
1743D2-278
1743D4-162
1743D4-161


Sana'a area
meq/l
1000
100
10
1
0.1
0.01
0.001
Ca
Mg
K+Na
Cl
SO4
HCO3
Identification
W. wellfield
E. wellfield
S. of Sana'a


Dhamar montane plains
meq/l
1000
100
10
1
0.1
0.01
0.001
Ca
Mg
K+Na
Cl
SO4
HCO3
Identification
MP-P4/6 (all.)
well 901 (all.)
MP-E11 (volc.)
well 782 (volc.)
Hammam Ali


Wadi Beihan area
meq/l
1000
100
10
1
0.1
0.01
0.001
Ca
Mg
K+Na
Cl
SO4
HCO3
Identification
Khirr (P 125)
Nahr (P 397)
Beihan (P 364)
Beihan (P 371)
Nuqub (H 042)
Nuqub (H 015)

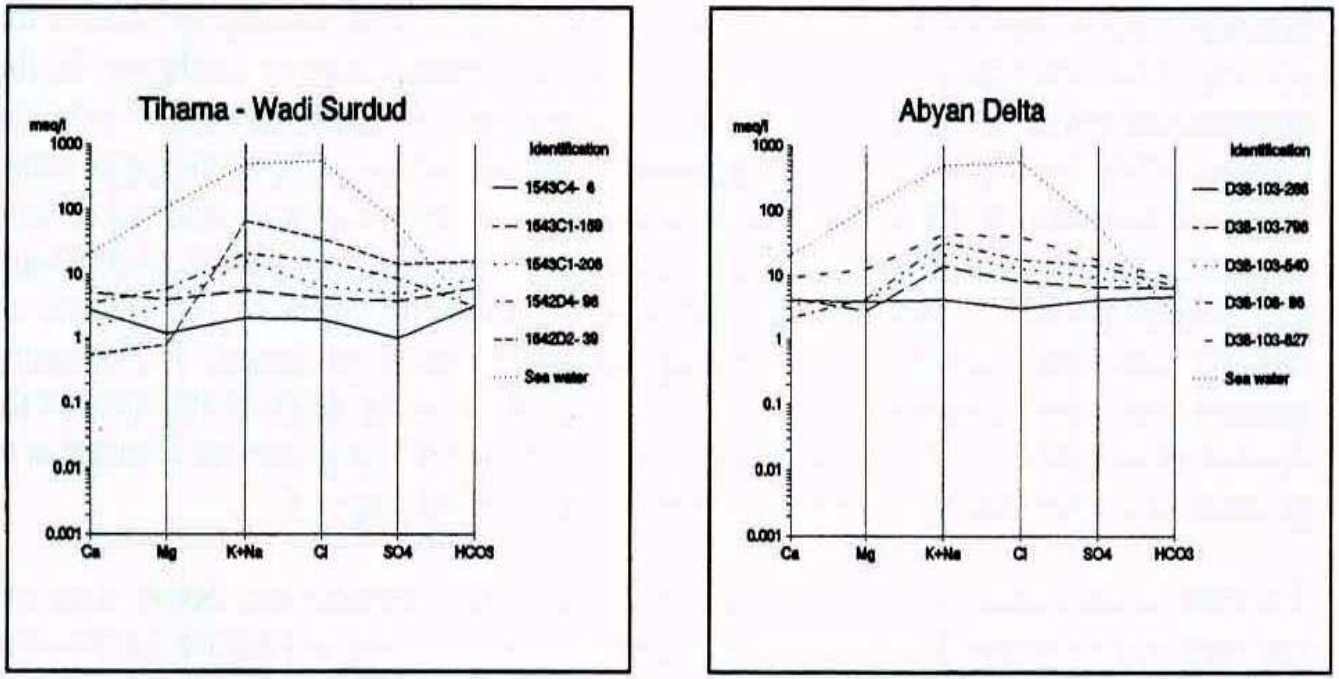


Figure 6.12 Groundwater chemistry of selected groundwater samples