CHAPTER FOUR

GROUNDWATER POTENTIAL AND DISCHARGE AREAS

4.1 Lithology, Stratigraphy and Structure

The nature and distribution of aquifers and aquitards in a geological system are controlled by lithology, stratigraphy, and structure of the geological deposits and formations. The **lithology** is the physical makeup, including the mineral composition, grain size, and grain packing, of the sediments or rocks that make up the geological system. The **stratigraphy** describes the geometrical and age relations between the various lenses, beds, and formations in geological systems of sedimentary origin. The **structural features**, such as cleavages, fractures, folds, and faults are the geometrical properties of the geologic systems produced by deformation after deposition or crystallization. In unconsolidated deposits, the lithology and stratigraphy constitute the most important controls. In most regions knowledge of the lithology, stratigraphy, and structure leads directly to an understanding of the distribution of aquifers and aquitards (see **Figure 4.1**).
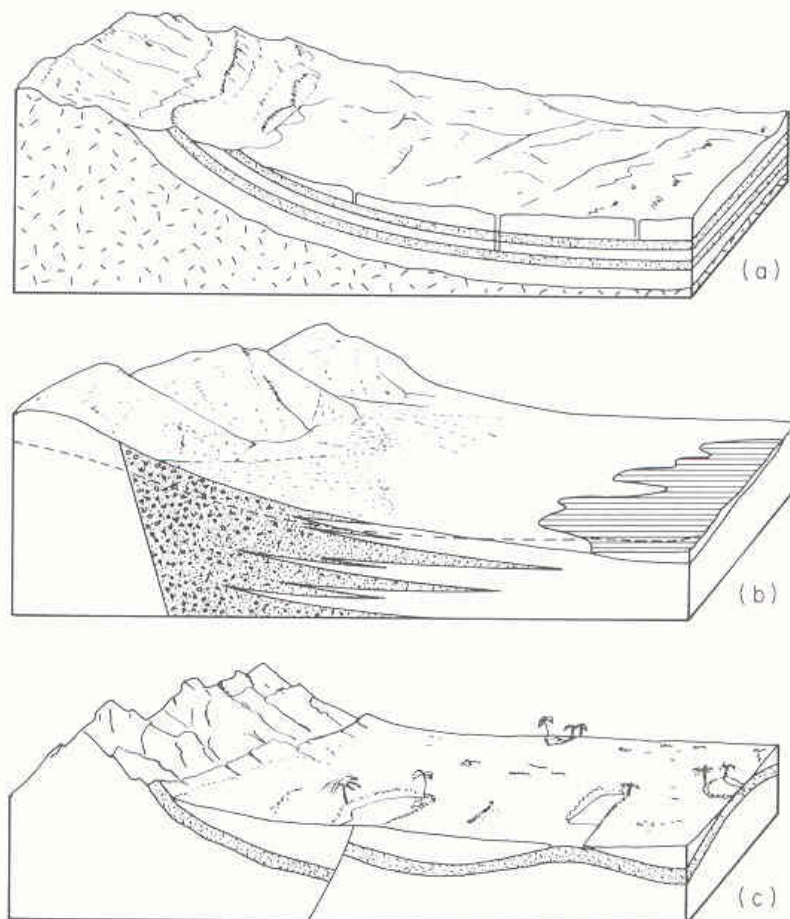

Figure 4.1   Influence of stratigraphy and structure on regional aquifer occurrence. **(a)** Gently dipping sandstone aquifers with outcrop area along mountain front; **(b)** interfingering sand and gravel aquifers extending from uplands in intermountain region; **(c)** faulted and folded aquifers in desert region. Surface water bodies reflect structural features.

In terrain that has been deformed by folding and faulting, aquifers can be difficult to discern because of the geologic complexity. In these situations the main intergradient in groundwater investigation is often large-scale structural analysis of the geologic setting.

Figures 4.2, 4.3 illustrate the stratigraphy and the structure of the West Bank.
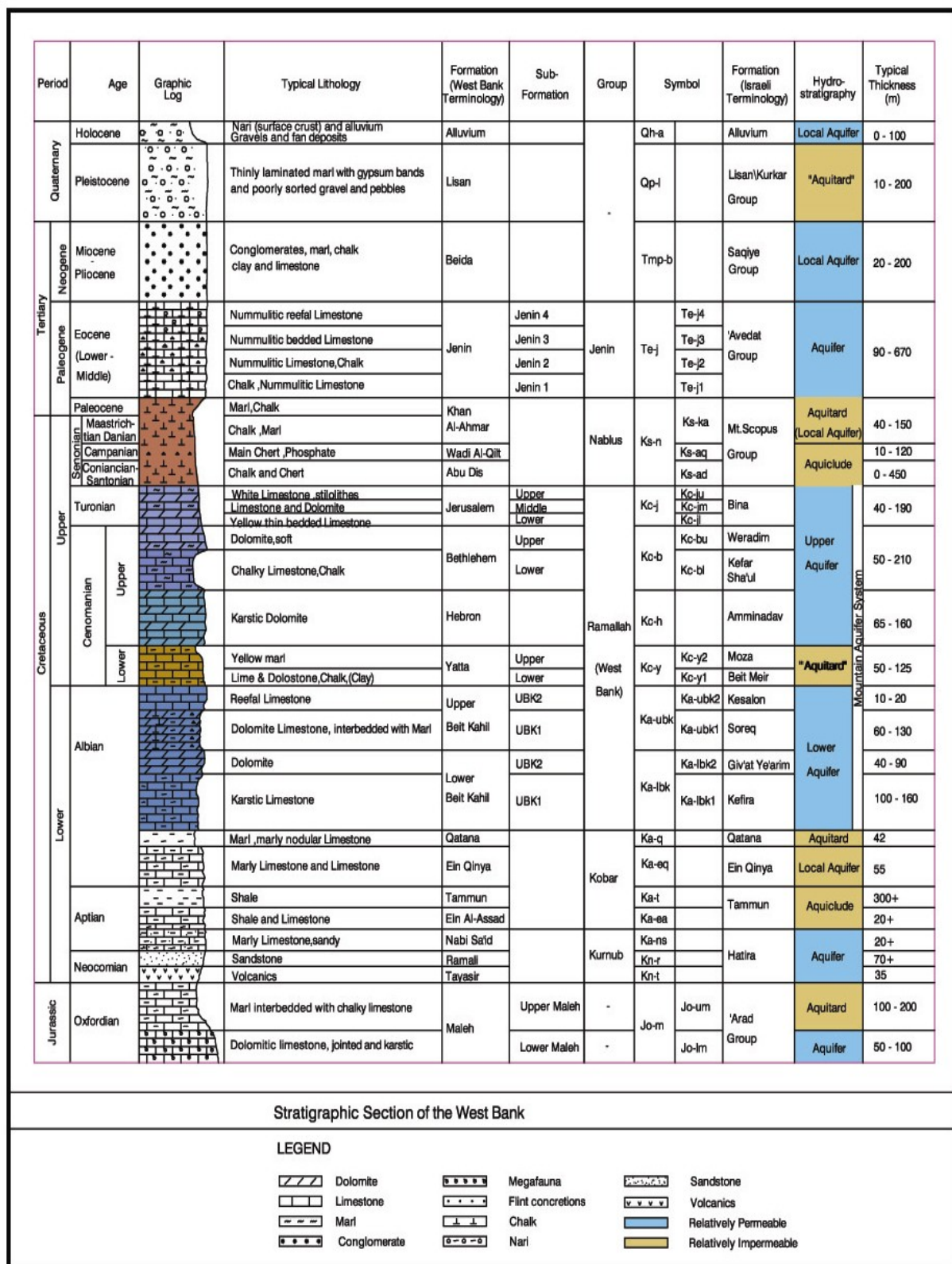
Period	Age	Graphic Log	Typical Lithology	Formation (West Bank Terminology)	Sub-Formation	Group	Symbol		Formation (Israeli Terminology)	Hydro-stratigraphy	Typical Thickness (m)
Quaternary	Holocene		Nari (surface crust) and alluvium Gravels and fan deposits	Alluvium			Qh-a		Alluvium	Local Aquifer	0 - 100
Quaternary	Pleistocene		Thinly laminated marl with gypsum bands and poorly sorted gravel and pebbles	Lisan			Qp-l		Lisan\Kurkar Group	"Aquitard"	10 - 200
Tertiary — Neogene	Miocene - Pliocene		Conglomerates, marl, chalk clay and limestone	Beida			Tmp-b		Saqiye Group	Local Aquifer	20 - 200
Tertiary — Paleogene	Eocene (Lower - Middle)		Nummulitic reefal Limestone	Jenin	Jenin 4	Jenin	Te-j	Te-j4	'Avedat Group	Aquifer	90 - 670
Tertiary — Paleogene	Eocene (Lower - Middle)		Nummulitic bedded Limestone	Jenin	Jenin 3	Jenin	Te-j	Te-j3	'Avedat Group	Aquifer	90 - 670
Tertiary — Paleogene	Eocene (Lower - Middle)		Nummulitic Limestone,Chalk	Jenin	Jenin 2	Jenin	Te-j	Te-j2	'Avedat Group	Aquifer	90 - 670
Tertiary — Paleogene	Eocene (Lower - Middle)		Chalk ,Nummulitic Limestone	Jenin	Jenin 1	Jenin	Te-j	Te-j1	'Avedat Group	Aquifer	90 - 670
Cretaceous — Senonian	Paleocene / Maastrichtian Danian		Marl,Chalk	Khan Al-Ahmar		Nablus	Ks-n	Ks-ka	Mt.Scopus Group	Aquitard (Local Aquifer)	40 - 150
Cretaceous — Senonian	Maastrichtian Danian		Chalk ,Marl	Khan Al-Ahmar		Nablus	Ks-n	Ks-ka	Mt.Scopus Group	Aquitard (Local Aquifer)	40 - 150
Cretaceous — Senonian	Campanian		Main Chert ,Phosphate	Wadi Al-Qilt		Nablus	Ks-n	Ks-aq	Mt.Scopus Group	Aquiclude	10 - 120
Cretaceous — Senonian	Coniancian-Santonian		Chalk and Chert	Abu Dis		Nablus	Ks-n	Ks-ad	Mt.Scopus Group	Aquiclude	0 - 450
Cretaceous — Upper	Turonian		White Limestone ,stilolithes / Limestone and Dolomite / Yellow thin bedded Limestone	Jerusalem	Upper / Middle / Lower	Ramallah (West Bank)	Kc-j	Kc-ju / Kc-jm / Kc-jl	Bina	Upper Aquifer	40 - 190
Cretaceous — Cenomanian Upper			Dolomite,soft	Bethlehem	Upper	Ramallah (West Bank)	Kc-b	Kc-bu	Weradim	Upper Aquifer	50 - 210
Cretaceous — Cenomanian Upper			Chalky Limestone,Chalk	Bethlehem	Lower	Ramallah (West Bank)	Kc-b	Kc-bl	Kefar Sha'ul	Upper Aquifer	50 - 210
Cretaceous — Cenomanian Upper			Karstic Dolomite	Hebron		Ramallah (West Bank)	Kc-h		Amminadav	Upper Aquifer	65 - 160
Cretaceous — Cenomanian Lower			Yellow marl	Yatta	Upper	Ramallah (West Bank)	Kc-y	Kc-y2	Moza	"Aquitard"	50 - 125
Cretaceous — Cenomanian Lower			Lime & Dolostone,Chalk,(Clay)	Yatta	Lower	Ramallah (West Bank)	Kc-y	Kc-y1	Beit Meir	"Aquitard"	50 - 125
Cretaceous — Albian Lower			Reefal Limestone	Upper Beit Kahil	UBK2	Ramallah (West Bank)	Ka-ubk	Ka-ubk2	Kesalon	Lower Aquifer	10 - 20
Cretaceous — Albian Lower			Dolomite Limestone, interbedded with Marl	Upper Beit Kahil	UBK1	Ramallah (West Bank)	Ka-ubk	Ka-ubk1	Soreq	Lower Aquifer	60 - 130
Cretaceous — Albian Lower			Dolomite	Lower Beit Kahil	UBK2	Ramallah (West Bank)	Ka-lbk	Ka-lbk2	Giv'at Ye'arim	Lower Aquifer	40 - 90
Cretaceous — Albian Lower			Karstic Limestone	Lower Beit Kahil	UBK1	Ramallah (West Bank)	Ka-lbk	Ka-lbk1	Kefira	Lower Aquifer	100 - 160
Cretaceous — Albian Lower			Marl ,marly nodular Limestone	Qatana		Kobar	Ka-q		Qatana	Aquitard	42
Cretaceous — Albian Lower			Marly Limestone and Limestone	Ein Qinya		Kobar	Ka-eq		Ein Qinya	Local Aquifer	55
Cretaceous — Aptian			Shale	Tammun		Kobar	Ka-t		Tammun	Aquiclude	300+
Cretaceous — Aptian			Shale and Limestone	Ein Al-Assad		Kobar	Ka-ea		Tammun	Aquiclude	20+
Cretaceous — Aptian			Marly Limestone,sandy	Nabi Sa'id		Kurnub	Ka-ns		Hatira	Aquifer	20+
Cretaceous — Neocomian			Sandstone	Ramali		Kurnub	Kn-r		Hatira	Aquifer	70+
Cretaceous — Neocomian			Volcanics	Tayasir		Kurnub	Kn-t		Hatira		35
Jurassic	Oxfordian		Marl interbedded with chalky limestone	Maleh	Upper Maleh — -		Jo-m	Jo-um	'Arad Group	Aquitard	100 - 200
Jurassic	Oxfordian		Dolomitic limestone, jointed and karstic	Maleh	Lower Maleh — -		Jo-m	Jo-lm	'Arad Group	Aquifer	50 - 100

Stratigraphic Section of the West Bank

LEGEND

Dolomite	Megafauna	Sandstone
Limestone	Flint concretions	Volcanics
Marl	Chalk	Relatively Permeable
Conglomerate	Nari	Relatively Impermeable

Figure 4.2 Lithological and Stratigraphical Section of the West Bank, Palestine
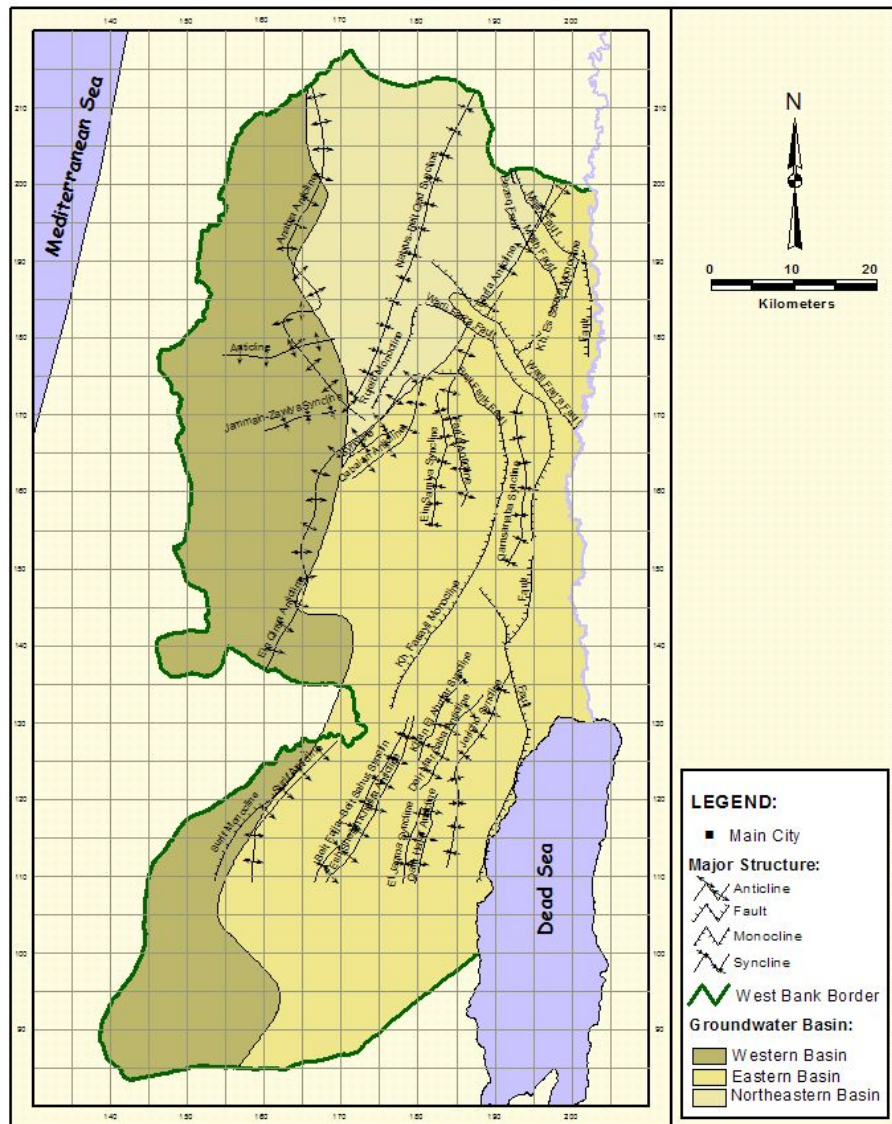
Figure 4.3   Major structure in the West Bank Aquifers, Palestine

4.2   Which Rocks Make the Best Aquifer?

Whenever an experienced hydrogeologist approaches an area which is new to them, they inevitably bring to bear a store of knowledge based on other projects elsewhere in the world. Experiences gained in various geological settings invariably predispose the hydrogeologist to expect certain kinds of rocks to behave largely as aquifers, and other kinds of rocks to behave largely as aquitards. For better or for worse, when a hydrogeologist travels to a new destination and begin to examine the local rock sequence for the presence or absence of aquifers, he/she instinctively turns attention first to any of the following four rock types in the area: 1. unconsolidated sands and gravels; 2. sandstones; 3. limestones; and 4. basaltic lava flows. Of course it is possible to quote examples of sandstone, limestone, and basalt aquitards, yet more than 80% of all the aquifers encountered have corresponded to one or other of these four rock types. Similarly, normally you expect any mudstone, siltstones, metamorphic rocks, and plutonic rocks to behave as aquitards, and rarely proved wrong. Again exceptions exist, but they are still greatly outnumbered by the many aquitards of these lithologies.

4.2.1 Alluvial Deposits

Probably 90 percent of all developed aquifers consist of unconsolidated rocks, chiefly gravel and sand. These aquifers may be divided into four categories, based on manner of occurrence: water courses, abandoned or buried valleys, plains, and intermontane valleys. *Water courses* consists of all alluvium that forms and underlies stream channels, as well as forming the adjacent floodplains. Wells located in highly permeable strata bordering streams produce large quantities of water, as infiltration from the streams augments groundwater supplies. *Abandoned or buried valleys* are valleys no longer occupied by streams that formed them. Although such valleys may resemble water courses in permeability and quantity of groundwater storage, their recharge and perennial yield (that is the rate at which water can be withdrawn perennially under specified operating conditions without producing an undesired result) are usually less. In some places gravel and sand beds form important aquifers under these plains; in other places they are relatively thin and have limited productivity.

4.2.2 Sandstone

About 25% of the sedimentary rock of the world is sandstone. In many countries sandstone strata form regional aquifers that have vast quantities of potable water. Sandstone bodies of major hydrologic significance owe their origin to various depositional environments, including floodplain, marine shoreline, deltaic, and turbidity-current environments. Knowledge of the distribution of permeability in sandstones can be best acquired within an interpretive framework that is based on an understanding of depositional environments in which the sand bodies were formed.

Nonindurated sands have porosities in the range 30-50%. Sandstones, however, commonly have lower properties because of compaction and because of cementing material between the grain. In extreme cases porosities are less than 1% and hydraulic conductivities approach those of unfractured siltstone and shale (i.e. less than about 10^{-10} m/s). The most common cementing material are quartz, calcite, and clay minerals. These minerals form as a result of precipitation or mineral alteration during groundwater circulation through the sand. Compaction is important at great depth, where temperature and pressures are high. It should be known that an increase in porosity of several percent corresponds to a large increase in permeability.

As sands become more cemented and compacted the contribution of fractures to the bulk permeability of the material increases. The ten-decay of large permeability values to occur in the horizontal direction is replaced by a preference for higher fracture permeability in the vertical direction. The nature of the anisotropy in the fractured medium can reflect a complex geological history involving many stress cycles.

4.2.3 Carbonate Rock

Carbonate rocks, in the form of limestone and dolomite, consists mostly of the minerals calcite and dolomite, with very minor amounts of clay. Nearly all dolomite is secondary in origin, formed by geochemical alteration of calcite. This mineralogical transformation causes an increase in porosity and permeability because the crystal lattice of dolomite occupies about 13% less space than that of calcite. Geologically young carbonate rocks commonly have porosities that range from 20% for coarse, blocky limestone to more than 50% for poorly indurate minerals is normally compressed and recrystallized into a more dense, less porous rock mass. The primary permeability of old unfractured limestone and dolomite is commonly less than 10^{-7} m/s at near-surface temperature.

Many carbonate strata have appreciable secondary permeability as a result of fractures or openings along bedding planes. Secondary openings in carbonate rock caused by changes in the stress conditions may enlarged as a result of calcite or dolomite dissolution by circulating groundwater. For the water to cause enlargement of the permeability network, it must be undersaturated with respect to these minerals.

Observations in quarries and other excavations in flat-lying carbonate rocks indicated that solution openings along vertical joints generally are widely spaced. Openings along bedding planes are more important from the point of view of water yield from wells. It nearly horizontal carbonate rocks with regular vertical fractures and horizontal bedding planes, there is usually a much higher probability of wells encountering horizontal openings than vertical fractures. This is illustrated in **Figure 4.4.** In fractured carbonate rocks, successful and unsuccessful wells can exist in close proximity, depending on the frequency of encounter of fractures by the well bore. Seasonally, the water levels in shallow wells can vary greatly because the bulk fracture porosity is generally a few percent or less.
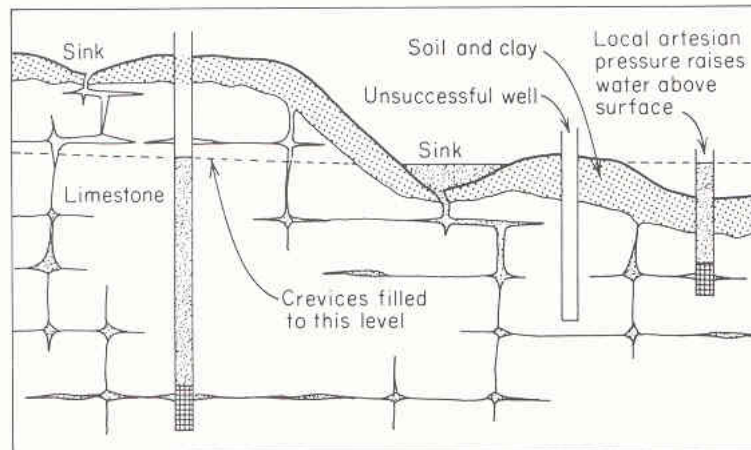
Figure 4.4   Schematic illustration of the occurrence of groundwater in carbonate rock in which secondary permeability occur along enlarged fractures and bedding plane openings.

In some carbonate rocks lineations of concentrated vertical fractures provide zones of high permeability. **Figure 4.5** illustrates a situation where the fracture intersections and lineaments are reflected in the morophology of the land surface. Zones in which fractures are concentrated are the zones of most rapid groundwater flow. Dissolution may cause the permeability of such zones to increase. In some areas, however, excessive thickness of overburden prevent recognition of bedrock lineaments, and the search for favorable drill sites in this manner is not feasible.
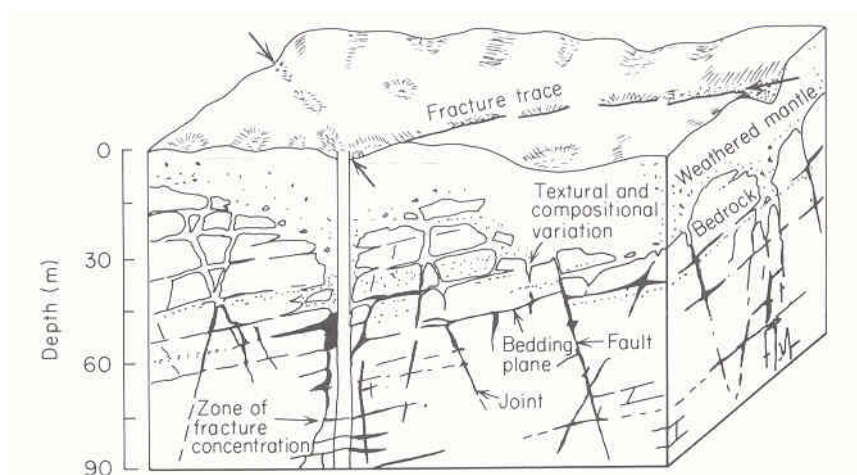
Figure 4.5   Occurrence of permeability zones in fractured carbonate rock. Highest well yields occur in fracture intersection zones.

In areas of folded carbonate rocks, the zones of fracture concentration and solution enlargement are commonly associated with the crest of anticlines and to a lesser extent with synclinal troughs (**Figure 4.6**). In situations where rapid direct recharge can occur, fracture enlargement by dissolution has great influence. In the situation illustrated in Figure 4.6, water that infiltrates into the fractured carbonate rock beneath the alluvium will cause solution enlargement if the alluvium is devoid of

carbonate minerals. If the alluvium has a significant carbonate-mineral content, groundwater would normally become saturated with respect to calcite and dolomite prior to entry into the fracture zones in carbonate rock. In fractured carbonate rock in which solution channeling has been active in the geologic past, caverns or large tunnels can form, causing local permeability to be almost infinite compared to other parts of the same formation.
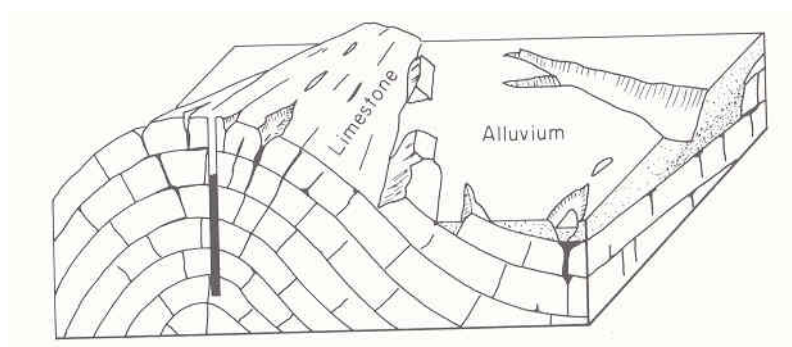
Figure 4.6   Occurrence of high-permeability zone in solution-enlarged fractures along the exposed crest of an anticline in carbonate rock.

In general, limestone varies widely in density, porosity, and permeability depending on degree of consolidation and development of permeable zones after deposition. Those most important as aquifers contain sizable proportions of the original rock that have been dissolved and removed. Openings in limestone may ranges from microscopic original pores to large solution caverns forming subterranean channels sufficiently large to carry the entire flow of a stream. The term *lost river* has been applied to a stream that disappears completely underground in a limestone terrane. *Large springs are frequently found in limestone areas.*

The solution of calcium carbonate by water causes prevailingly hard groundwater to be found in limestone aquifers; also, by dissolving the rock, water tends to increase the pore space and permeability with time. Solution development of limestone forms a **karst terrane**, characterized by solution channels, closed depressions, subterranean drainage through sinkholes, and caves. Major limestone aquifers occur in the Mediterranean area **(including Palestine)**.

Table 4.1 shows the geologic origin of (sedimentary rocks) aquifers based on type of porosity.

Table 4.1   Geologic Origin of Aquifer (Sedimentary Rocks) Based on Type of Porosity (after Todd, 1980)

Type of Porosity	Sedimentary rocks		
	Consolidated	**Unconsolidated**	**Carbonates**
Intergranular		Gravelly sand Clayey sand Sandy clay	
Intergranular and fracture	Breccia Conglomerate Sandstone Slate		Zoogenic limestone Oolitic limestone Calcareous grit
Fracture			Limestone Dolomite Dolomitic limestone

4.2.4 Volcanic Rocks

Because volcanic rocks crystallize at the surface, they can retain porosity associated with lava-flow features and pyroclastic deposition. Volcanic rock can form highly permeable aquifers; basalt flows in particular often display such characteristics. The types of openings contributing to the permeability of basalt aquifers include, in order of importance: interstitial spaces in clinkery lava at the tops of flows, cavities between adjacent lava beds, shrinkage cracks, lava tubes, gas vesicles, fissures resulting from faulting and cracking after rocks have cooled, and holes left by the burning of trees overwhelmed by lava.

4.2.5 Igneous and Metamorphic Rocks

In solid forms igneous and metamorphic rocks are relatively impermeable and hence serve as poor aquifers. In order for groundwater to occur, there must be openings developed through fracturing, faulting, or weathering. Fractures can be developed by tectonic movements, pressure relief due to erosion of overburden rock, loading and unloading of glaciation, shrinking during cooling of the rock mass, and the compression and tensional forces caused by regional tectonic stresses. In general, the amount of fracturing in crystalline rocks decreases with depth. Chemical weathering of crystalline rock can produce a weathering product called **Saprolite**. This minerals has porosities of 40% to 50% and a specific yield of 15% to 30%. It acts as a reservoir, storing infiltrated water and releasing it to wells intersecting fractures in the underlying crystalline rock.

The probability of obtaining a high-yield well in crystalline rock areas can be maximized if drilling takes place in an area where fractures are localized. It has been observed that zones of high conductivity in crystalline rock areas underlie linear sags in the surface topography. Such sages are the surface feature that overlies major zones of fracture concentration. These show as fracture traces and lineaments on areal and satellite photographs. If, in drilling a water-supply well in crystalline rock area, sufficient water is not encountered in the first 100 m of drilling, in most situations other than where deep tectonic fracturing is suspected a new location should be sought rather than drilling any deeper. Because most fractures are vertical, or nearly so, an angled borehole will be more likely to intersect fractures and create a successful well. Well yields in some areas of crystalline rock are greater when the wells are located on valley bottoms. Many of the valley bottoms probably developed along fracture traces. Limitations on the use of angled boreholes in fractured rock include stability problems, especially blocks of rock breaking off and lodging in the borehole, and lower potential drawdown than in a vertical borehole of the same length.

4.2.6 Shale

Shale beds constitute the thickest and most extensive aquitards in most sedimentary basins. Shale originates as mud laid down on ocean bottoms, in the gentle-water areas of deltas, or in the backswamp environments of broad floodplains. Digenetic processes related to compaction and tectonic activity convert the clay to shale. Mud, from which shale is formed, can have porosities as high as 70-80% prior to burial. After compaction, however, shale generally has a primary porosity of less than 20% and in some cases less that 5%. In outcrop areas, shale is generally softer, fractures are much less frequent, and permeability is generally very low. Some shale beds are quite plastic and fractures are insignificant.

4.3 Structural Factors: Faults, Fracture, and Folds

4.3.1 Introduction

Folding and faulting of sedimentary rocks can create very complex hydrogeologic systems, in which determination of the locations of recharge and discharge zones and flow systems is confined. Not only

must the hydrogeologist determine the hydraulic characteristics of rock units and measure groundwater levels in wells to determine flow systems, but detailed geology must also be evaluated. In most cases, the basic geologic structure will have already been determined; however, logs of test wells and borings must be reconciled with the pre-existing geologic knowledge.

4.3.2   Faults

Faults are planar features across which the elevations of specific rock horizons are displaced (see **Figure 4.7**). In order to concisely describe the geometry of faults it is helpful to introduce a little jargon. Given that most fault planes are not absolutely vertical, it is normally possible to identify a block of which lies above a given fault plane and another which lies below it. The overlying block is called the **hanging wall,** whereas the underlying block is called the **foot wall**. Two principal types of faults are distinguished on the basis of the relative displacements of the hanging wall and foot wall rocks (see **Figure 4.7**):

1   **Extensional faults** (referred to in the older literature as **normal faults**) are defined as those in which the hanging wall rocks appear to have been displaced downwards relative to the foot wall rocks. Extensional faults in a given area will be extensional in the absence of direct evidence.

2   **Compressional faults** (referred to as **reverse faults** in the older literature) are those in which the hanging wall rocks appear to have been displace upwards relative to the foot wall rocks. Where the plane of a compressional fault lies at a low angle (i.e. has a dip of 45 degrees or less), the fault might be referred to as a "thrust" or "over-thrust". Compressional faults are especially common in the central districts of most no volcanic mountain ranges, and in lowland areas containing rocks which were formerly located in such districts at an earlier stage in geological history.
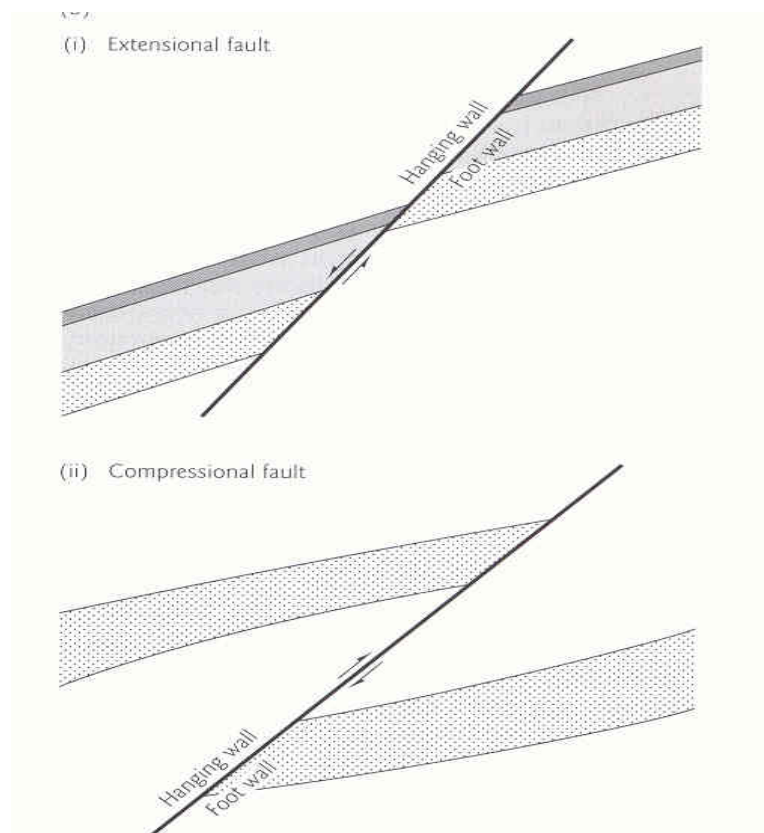
Figure 4.7   The two main types of fault which are commonly found to disrupt the lateral continuity in aquifer horizons: i) extensional fault; ii) compressional fault

Fault zones can act either as barriers to ground-water flow or as groundwater conduits, depending upon the nature of the material in the fault zone. If the fault zone consists of finely ground rock and clay (gouge), the material may have a very low hydraulic conductivity. Significant differences in groundwater levels can occur across such faults. Impounding faults can occur in unconsolidated materials with clay present, as well as in sedimentary rocks where interbedded shales, which normally would not hinder lateral groundwater flow, can be smeared along the fault by drag folds. **Clastic dikes** are intrusions of sediment that are forced into rock fractures. If they are clay-rich, they can act as groundwater barriers in either sediments or in a lithified sedimentary rock. Clastic dikes are known to occur in alluvial sediments, glacial outwash, and lithified sedimentary rock.

Faults in consolidated rock units can act either as pathways for water movement or as flow barriers. If there has been little displacement along the fault, then the fault is more likely to develop fracture permeability because there is less opportunity for the formation of soft, ground-up rock, called **gouge**, to form between the moving surfaces. Fault gouge can have a matrix of rock breccia encased in clay and can have a wider range of permeability.

If the fault zone has a high porosity and hydraulic conductivity, it can serve as a conduit for groundwater movement. Springs discharging into the Colorado River are controlled by a vertical fault zone, the Fence Fault. The springs discharge where the faults intersect the river. The fault zones provide for vertical movement of recharging groundwater from the land surface as well as lateral movement toward the river. The geochemistry of the spring water indicates that some of the water discharging on one side of the river originated in the groundwater basin on the opposite side of the river, indicating the fault zone was conducting some groundwater flow beneath the river even though it is a regional discharge zone.

Faults may contain groundwater at great pressures at depths where tunnels or mines may be constructed. One of the dangers of hard-rock tunneling is the possibility of breaching an unexpected fault zone. Damaging and dangerous flooding can occur if the fault contains groundwater wit hydraulic head.

4.3.3   Folds

Folding can affect the hydrogeology of sedimentary rocks in several ways. The most obvious is the creation of confined aquifers at the centers of **synclines**. The nature of the fold will affect the availability of water. A tight, deeply plunging fold might carry the aquifer too deep beneath the surface to be economically developed. Deeply circulating groundwater is also typically warmed by the geothermal gradient and may be highly mineralized. A broad, gentle fold can create a relatively shallow, confined aquifer that extends over a large area. This might be a good source of water if sufficient recharge can occur through the confining layer or if the aquifer can transmit enough water from areas where the confining layer is absent.

Another effect of folding is to create a serious of outcrops of soluble rock, such as limestone, alternating with rock units that are not as permeable. Smaller streams flowing across the limestone might sink at the upper end, only to reappear at the lower outcrop. They type of trellis drainage that can develop on folded rocks is shown in **Figure 4.8.** Surface streams follow the strike of rock outcrops, usually along fault or fracture traces. In folded sedimentary rocks with solutional conduits in carbonate units, groundwater flow may be along the conduits that parallel the strike of the fold and not down the dip.

In areas of homoclinal folds, the outcrop areas usually have bands of sedimentary rocks, with resistant rocks forming ridges and more easily erodable rocks forming valleys. The ridges may create groundwater divides, with aquifers outcropping in the valleys. The outcrop area of an aquifer will have local water table flow systems with relatively large amounts of water circulating. These areas also serve as the recharge zones for the more distal parts of the aquifer, which are downdip in the basin and are confined. There is a limited amount of natural discharge from the confined portions of the aquifer; this is typically upward leakage into overlying beds with lower hydraulic head. Because of

poor groundwater circulation, the confined portions of the aquifer may have low hydraulic conductivity and poor water quality.
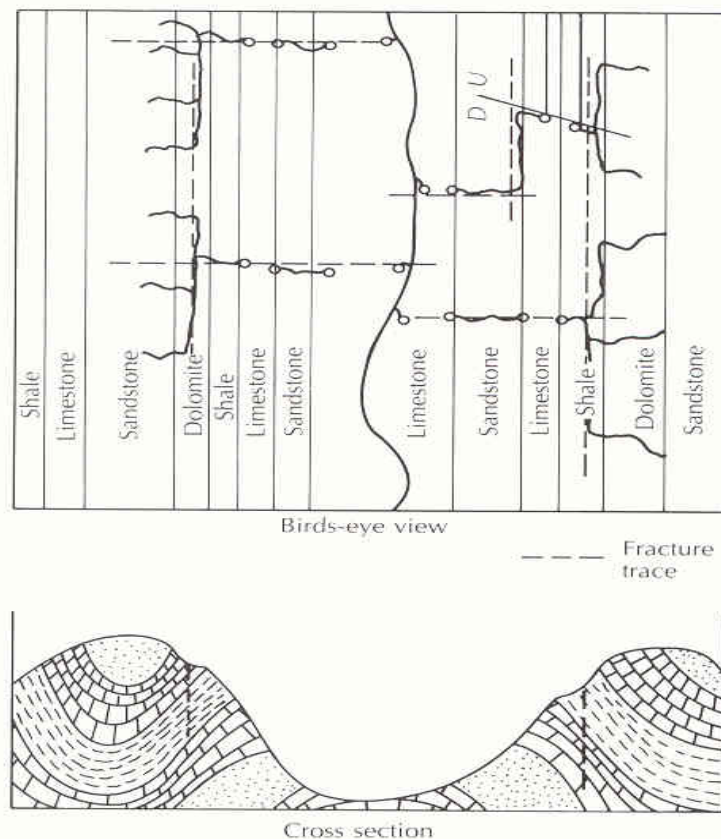

Birds-eye view

- - - Fracture trace

Cross section

Figure 4.8 Drainage pattern developed in an area of longitudinally folded rock strata: **A.** Top view. **B.** Cross section.

The two major folds are discernible in **Figure 4.9,** an **antiform or anticline** (i.e. an up-fold shaped thus: ∩) and a synform or syncline (i.e. a down-fold shaped thus: ∪). These folds obviously have a profound effect on the depths below groundwater surface at which the various aquifers (i.e. Aquifers 2, 3, and 4) would be encountered when drilling from the surface.
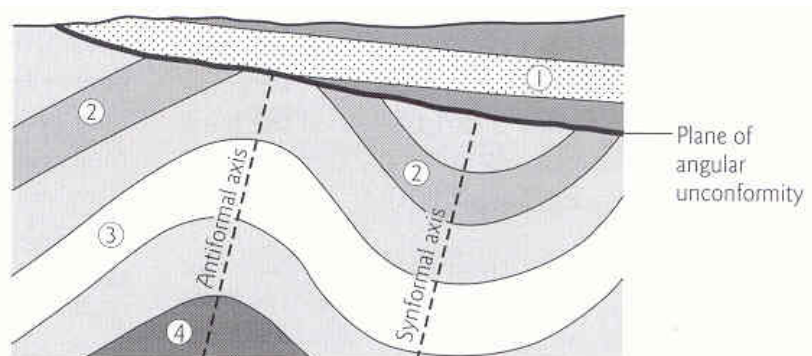
Figure 4.9 Common structural features which affect the spatial distribution and interconnectivity of aquifers. The horizons numbered 1 through 4 are all aquifers, the unnumbered horizons are aquitards. The two principal types of fold are antiforms (upfolds) and synforms (downfold); the centre lines (axes) of examples of both types are shown to affect aquifers 2 through 4 and their enclosing aquitards. A period of erosion must have followed the episode of folding that affected these aquifers, for angular uncomformity separates them from the overlying (and evidently youner) aquifer 1, which is unaffected by the folding.

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8.1 GROUND-WATER RECHARGE AND DISCHARGE

The function of a ground-water system is to store and transmit water. Storage occurs within the voids of sediment or rock. Transmission occurs from areas of intake or recharge to areas of discharge or outflow. Change in ground-water storage (ΔS_{gw}) in a ground-water system can be stated as

$$\Delta S_{gw} = \text{recharge} - \text{discharge} = \text{inflow} - \text{outflow} \tag{8.1}$$

Under natural conditions $\Delta S_{gw} = 0$ or inflow = outflow. $\tag{8.2}$

Ground-water recharge occurs where the supply of water enters the aquifer. Natural recharge into an aquifer includes deep percolation from precipitation, seepage from streams, wetlands or lakes, or a transfer of ground water from one aquifer unit into another. Many natural recharge areas are located at topographic highs and are characterized by deep water tables and water dilute of dissolved minerals (Fig 8.1-A). Table 8.1 shows chemical analysis for a nest of ground-water wells constructed in an area of recharge. Notice that most of the chemical parameters increase with sample depth, which is typical of a recharge area. **Artificial recharge**, which may or may not be intentional, is supplied by anthropogenic canals, reservoirs, drainage ditches, ponds, lakes, wetlands, septic systems, irrigation, and recharge or injection wells (Table 8.2).

Ground-water discharge occurs where ground water leaves the system. Natural outflow from the aquifer occurs as seepage into streams, lakes or wetlands, flow from springs, transpiration and evaporation. Natural discharge often occurs at topographic lows and is characterized by shallow or exposed water tables and mineralized water (Fig. 8.1). **Artificial discharge** results from wells and drains (Table 8.3).

A recharge area for an unconfined aquifer is often broad in areal extent (Fig. 8.2). It is dependent on the rate and duration of precipitation, vegetation cover, percolation rate of surficial deposits, and the transmissive properties of the aquifer. The properties of the aquifer are important because they determine how fast the new supply of water can move away from the recharge area. Seasonal temperature of recharge water is also a controlling factor. At winter temperatures ground water flows at a relatively high viscosity. Manning (1992) reports that the difference between summer and winter recharge, through the gravel bed of a riverine system located in the state of Washington, amounted to about 1.3 million gallons per day --- due exclusively to the change in water temperature.
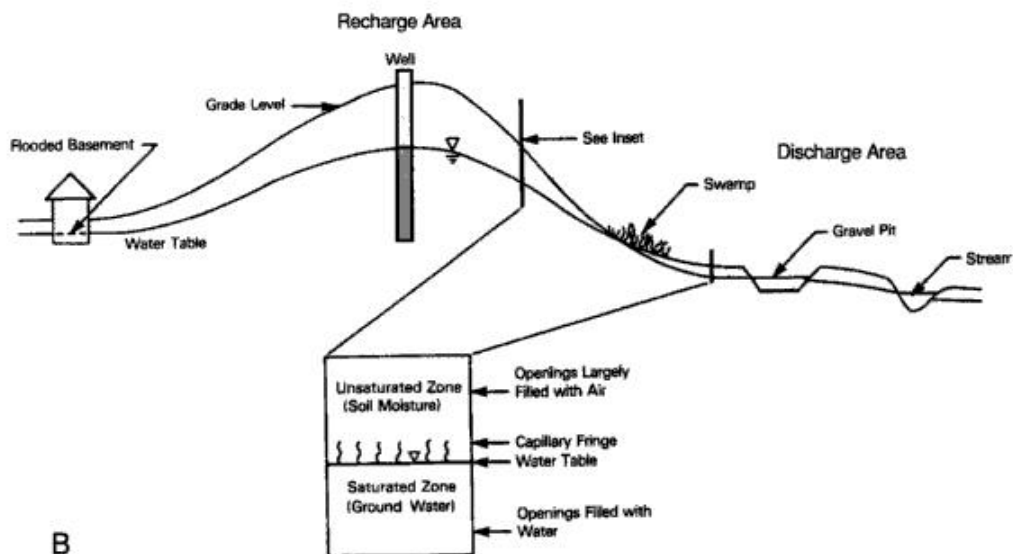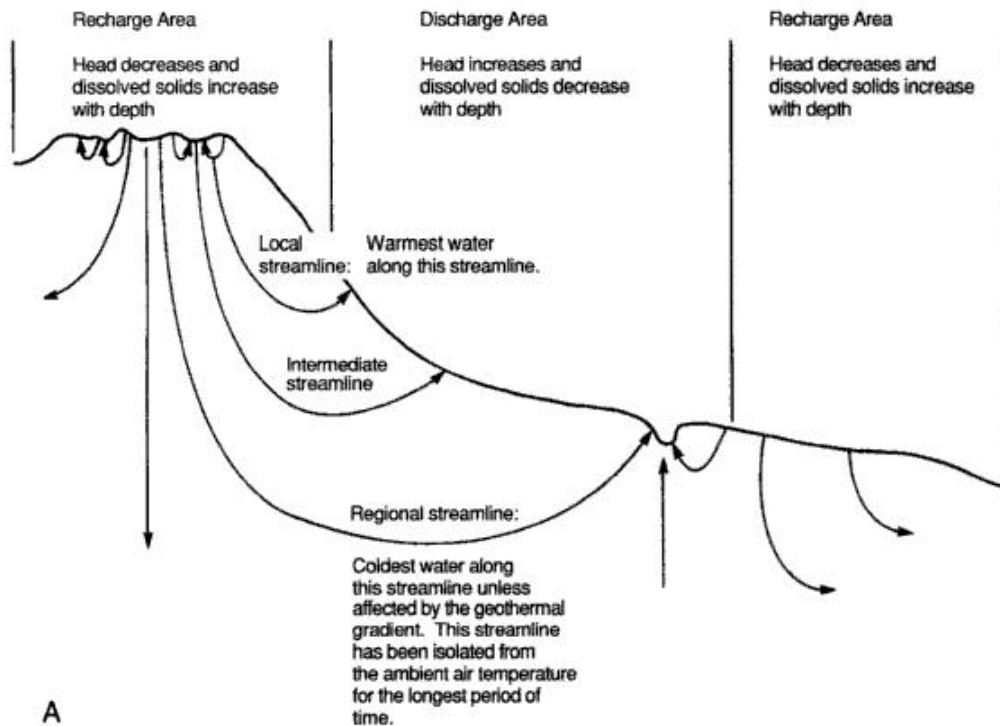
Recharge Area

Head decreases and dissolved solids increase with depth

Discharge Area

Head increases and dissolved solids decrease with depth

Recharge Area

Head decreases and dissolved solids increase with depth

Local streamline:

Warmest water along this streamline.

Intermediate streamline

Regional streamline:

Coldest water along this streamline unless affected by the geothermal gradient. This streamline has been isolated from the ambient air temperature for the longest period of time.

A

Recharge Area

Well

Grade Level

Flooded Basement

Discharge Area

See Inset

Swamp

Gravel Pit

Stream

Water Table

Unsaturated Zone (Soil Moisture)

Openings Largely Filled with Air

Capillary Fringe

Water Table

Saturated Zone (Ground Water)

Openings Filled with Water

B

Figure 8.1.   "A": dissolved minerals in ground water will often increase with residence time as flow moves from areas of recharge to discharge. Ground-water recharge."B": the water table generally conforms to the surface topography (source: US EPA).

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Table 8.1. Chemical analysis for a nest of ground-water wells constructed in an area of ground-water recharge (Kasenow[a]). The reverse pattern, with some exceptions, would be typical of a ground-water discharge area.

Well #	Depth of Sample	Temp $^{\circ}$C	pH	Conduc. (μS)	Ca^{+2}	[1]Total Hardness
	Rain Gauge	21.3	3.93	27.9	1.6	4.4
	Surface Water	19.0	3.99	45.3	3.0	11.6
1	Shallow	17.2	4.40	64.3	4.8	17.1
2	Intermediate	14.2	5.73	253.8	28.9	102.0
3	Deep	13.1	6.55	592.0	106.9	317.0

Well #	Depth of Sample	Ba^{+2}	Fe^{+2}	K^+	Mg^{+2}	Na^+
	Rain Gauge	0.02	0.06	0.31	0.29	1.35
	Surface Water	0.01	1.29	1.21	1.01	1.43
1	Shallow	0.03	1.68	1.40	1.20	1.03
2	Intermediate	0.13	5.13	2.43	7.15	1.48
3	Deep	0.10	12.55	2.68	13.50	1.43

Well #	Depth of Sample	Cl^-	[2]HCO_3^-	SiO_2	SO_4^{-2}	NH_4^+ / N
	Rain Gauge	0.82	0.00	0.31	6.49	0.20
	Surface Water	4.28	1.90	3.32	1.94	0.44
1	Shallow	2.11	9.53	4.34	2.98	1.77
2	Intermediate	2.05	107.90	8.03	0.76	16.18
3	Deep	2.00	292.00	14.08	0.69	26.80

[1]as $CaCO_3$; [2]alkalinity as $CaCO_3$

Table 8.2. Sources of ground-water recharge (source USDI, 1995).

Source	Explanation
Deep percolation from precipitation.	Deep percolation of precipitation is one of the most important sources of ground-water recharge. The amount of recharge in a particular area is influenced by vegetation cover, topography, nature of soils, as well as the type, intensity, and frequency of precipitation.
Seepage from streams and lakes.	Seepage from streams, lakes and other water bodies is another important source of ground-water recharge. In humid and sub-humid areas where ground-water levels may be high, the influence of seepage may be limited in extent and may be seasonal. However, in regions where the entire flow of streams may be lost to an aquifer, seepage may be of major influence.
Underflow from another aquifer.	An aquifer may be recharged by underflow from a nearby, hydraulically connected aquifer. The amount of the recharge depends on the head differential, the nature of the connection, and the hydraulic properties of aquifers.
Artificial recharge.	Artificial recharge to the ground water may be achieved through planned systems, or may be unforeseen or unintentional. Planned major contributions to the ground-water reservoir may be made through spreading grounds, infiltration ponds, and recharge wells. Irrigation applications, sewage effluent spreading grounds, septic take seepage fields, and other activities have a similar, but usually unintentional effect. Seepage from reservoirs, canals, drainage ditches, ponds, and similar water impounding and conveyance structures may serve as local sources of major ground-water recharge. Recharge from such sources can completely change the ground-water regimen over a considerable area.

Table 8.3. Sources of ground-water discharge (source USDI, 1995).

Source	Explanation
Seepage to streams.	In certain reaches of streams and in certain seasons of the year, ground water may discharge into streams and maintain their flows. This condition is more prevalent in humid areas than in semi-arid areas.
Flow from springs and seeps.	Springs and seeps exist where the water table intersects the land surface or a confined aquifer outlets to the surface.
Evaporation and transpiration.	Ground water may be lost by evaporation if the water table is near enough to the land surface to maintain flow by capillary rise. Also, plants may transpire ground water from the capillary fringe or the saturated zone.
Artificial discharge.	Wells and drains are imposed artificial withdrawals on ground-water storage and in some areas are responsible for the major depletion of water supply.
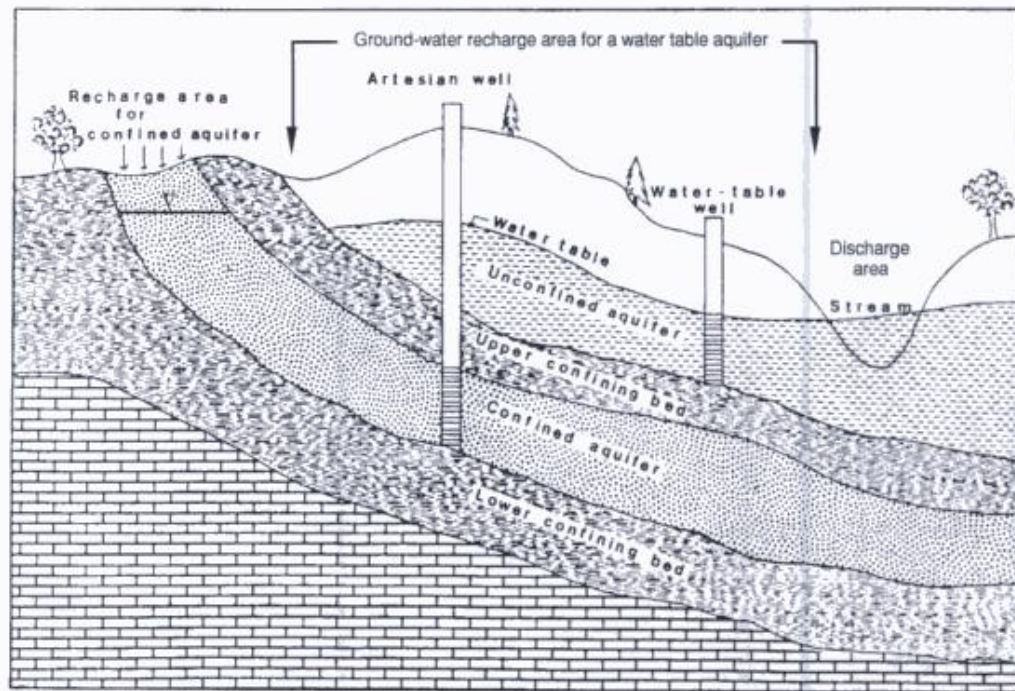
Figure 8.2. Ground-water recharge and discharge areas (modified from Michigan Department of Natural Resources).

The potentiometric surface or water table at a recharge area is elevated topographically; therefore, it is an area of high potential energy and low hydraulic pressure. Potential energy in a recharge area decreases with depth. Flow is down and away from the area; as this occurs hydraulic pressure increases.

The surficial area of recharge in regard to a confined aquifer is relatively small and is unconfined (Fig. 8.2); therefore, factors controlling unconfined aquifer recharge determine supply. Recharge to a confined aquifer can also occur from hydraulically connected leaky-confined systems. Ground water can flow upwards from a leaky system that is situated below the confined aquifer or downward from a leaky system situated above the aquifer. **Where leakage occurs, the thickness and vertical hydraulic conductivity of the confining material are two important controlling factors.**

The potentiometric surface or water table at a discharge area is located at a topographic low, but potential energy in a discharge area increases with depth. Here, the flow of ground water is upward or into the discharge environment. The outflow is under high hydraulic pressure. The period of time for equilibrium between recharge and discharge to occur is often less than a year or at the most a few years in humid regions. However, natural recharge can range from several years up to centuries in areas that receive less than 500 mm (20 inches) of precipitation per year (Heath, 1983).

8.11 EQUIPOTENTIALS AS INDICATORS

As discussed in Chapter Five, head fluctuations in ground water determine the static water table. A nest of wells can be used to determine the direction of ground-water flow. A well nest is more than one well, usually three, constructed adjacent to each other, but screened at different depths. Each screen set at a selected depth measures the hydraulic head at that screened interval. Assuming three wells screened at three successive depths: when the static water table in the deepest well is situated below the static water table in the shallow and intermediate wells, it can be concluded that ground water is recharging the flow field (ground water is flowing into the system). Conversely, when the static water table in the deepest well is situated above the static water table in the intermediate and shallow wells, it can be concluded that ground water is discharging from the flow field (ground water is flowing upwards) (Fig. 8.38). The nest of wells should be screened within the same material. The hydraulic head may appear to be exaggerated in a well screened in material with a hydraulic conductivity much greater or less than the K values in which the other wells are screened. This is because clays and silts have a much greater resistance to flow when compared to sands and gravels. The greater the resistance to flow the greater the head loss per unit distance along a streamline (Fig. 8.39).

8.12 SPRINGS

One of the most obvious discharge areas are fresh water springs. Springs are the historic landmarks of ancient settlements. Cities are named after springs. Springs are the symbolism of art and literature --- of religion. The Fountain of Youth is said to be a spring. Corporate soothsayers brag about its medicinal magic. Call it "Artesian" and the world will buy it. It is a new beginning after winter and the end of the line for ground water.

Springs are classified in many ways. By discharge, lithology, rock structure, water temperature, chemical characteristics, and relation to topography. Some springs are permanent, because they flow annually, others are intermittent or even ephemeral. Some have diurnal fluctuations, flowing only at night, as plants use and transpire the needed ground water in the day-light hours. The discharge of ground water from some springs is greater than 30 m^3/ s (1000 ft^3/ s), while others discharge at less than a few milliliters per second. Much of the water that springs from the subsurface is "pure" enough to drink. Some of it is not --- it may by highly mineralized and contain noxious gases with water temperatures near 100°C.
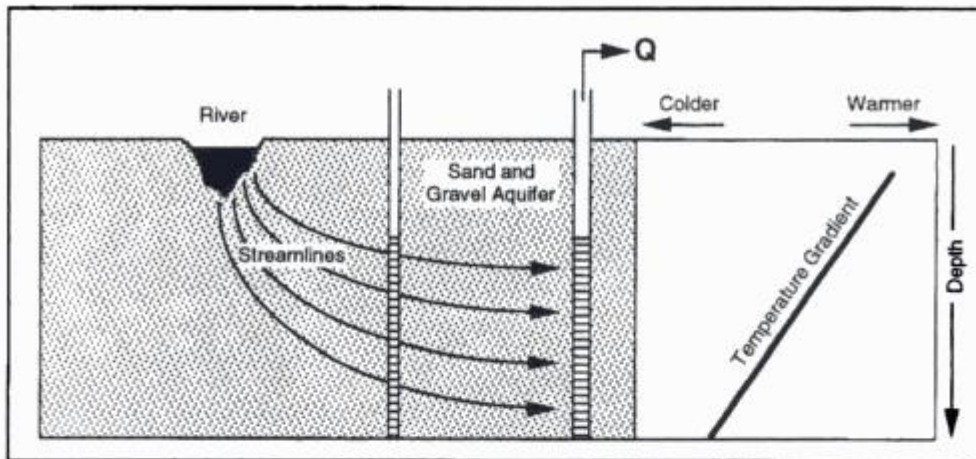
Figure 8.35. Ground-water temperature gradient in a homogeneous system (After Norris and Spieker, 1966 and Smith, et al., 1982).
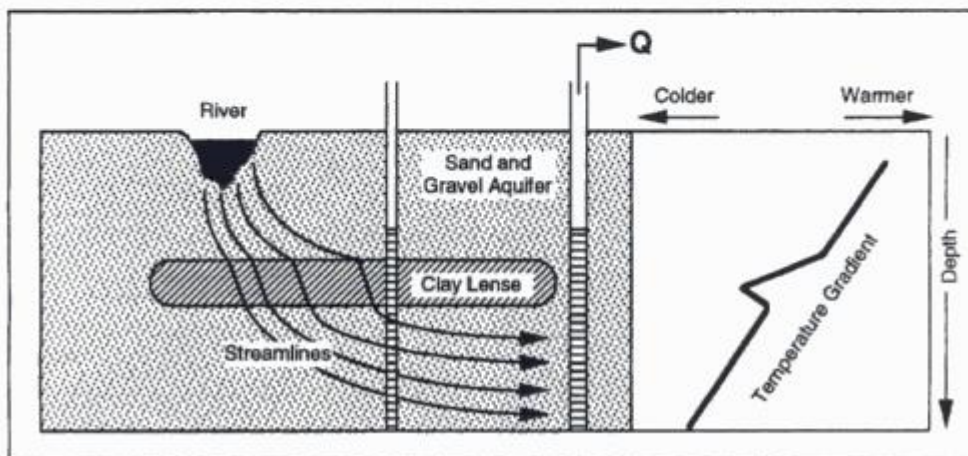

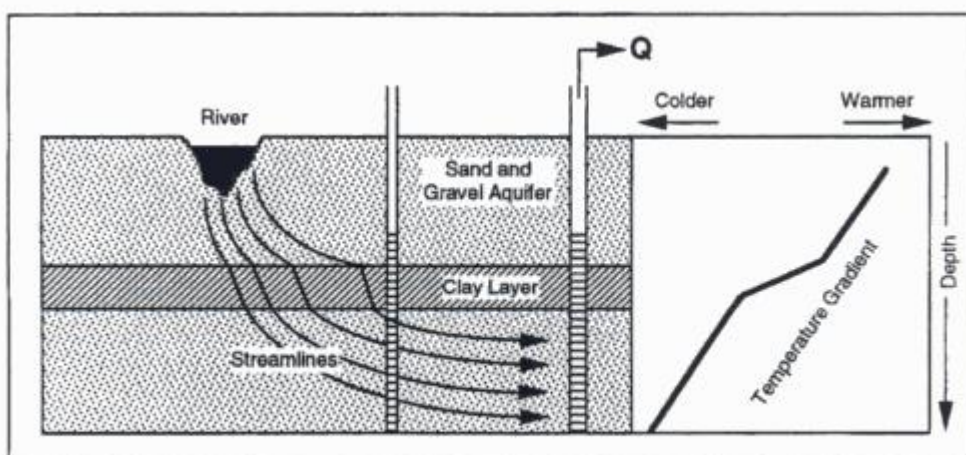**Figure 8.36. Ground-water gradient through a discontinuous clay lens.**

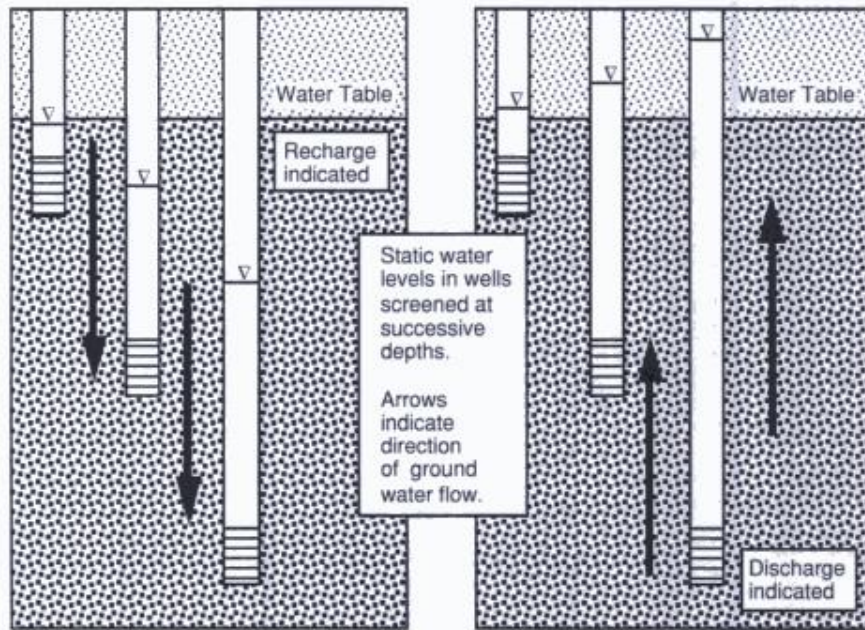**Figure 8.37. Ground-water gradient through a continuous clay layer.**

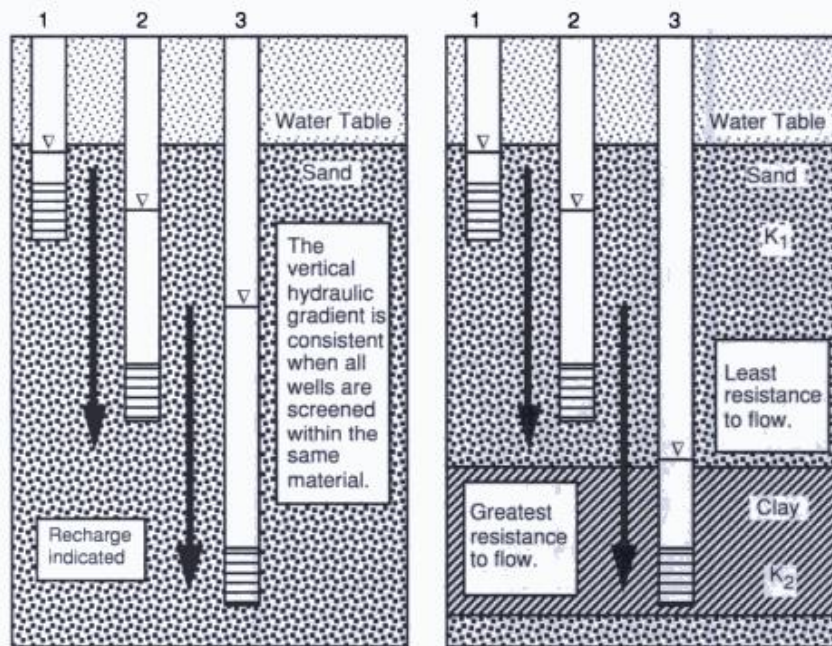**Figure 8.38.** The direction of ground-water flow as indicated by the heads in a nest of wells.

Figure 8.39. The vertical K is not consistent when wells are screened in different material. This is the case when measuring the gradient using head values in wells 2 and 3 (right frame). $K_1 >> K_2$.

A **spring** is ground water that flows naturally from the subsurface to the surface in a concentrated discharge. Fresh water springs also discharge into lakes, rivers and the ocean. If the flow is diffuse it is called a **seep**. Seeps are not as easy to recognize as springs. The brownish color of iron oxidizing or the white precipitant of $CaCO_3$ may help to identify the location of seeps. Springs and seeps are responsible for the formation of many **wetlands** and the waters they contain, especially during dry periods.

The four variables that determine discharge from a spring are 1) the area of recharge contributing ground water to the aquifer, 2) the amount of recharge, 3) the permeability of the aquifer, and 4) the amount and type of vegetation in the area. Spring discharge is often minimal, and may only exist in winter, because summer transpiration by plants is of a great extent.

Meinzer (1923) classified springs based on the **magnitude of discharge (q)** (Table 8.4). Springs of a first magnitude generally occur in volcanic and karst terranes, or flow from coarse gravel aquifers.

Table 8.4. Meinzer's Classification of Springs Based On Discharge (q).

Magnitude	English Units	Metric Units
First	$q > 100 \text{ ft}^3/\text{s}$	$q > 2.83 \text{ m}^3/\text{s}$
Second	$10 < q < 100 \text{ ft}^3/\text{sec}$	$0.283 < q < 2.83 \text{ m}^3/\text{s}$
Third	$1 < q < 10 \text{ ft}^3/\text{sec}$	$28.3 < q < 283 \text{ liters}/\text{s}$
Fourth	$100 \text{ gpm} < q < 1.0 \text{ ft}^3/\text{sec}$	$6.31 < q < 28.3 \text{ liters}/\text{s}$
Fifth	$10 < q < 100 \text{ gpm}$	$0.631 < q < 6.31 \text{ liters}/\text{s}$
Sixth	$1.0 < q < 10 \text{ gpm}$	$63.1 < q < 631 \text{ ml}/\text{s}$
Seventh	$1.0 \text{ pt}/\text{min} < q < 1.0 \text{ gpm}$	$7.9 < q < 63.1 \text{ ml}/\text{s}$
Eighth	$< 1.0 \text{ pt}/\text{min}$	$< 7.9 \text{ ml}/\text{sec}$

Hot springs or **thermal springs** occur where the temperature of the water is greater than the normal ground-water temperature. This water may even be boiling. A **gyser** is an opening at the surface through which steam and water erupt. A **fumarole** is an opening at the surface through which steam and other gases escape. A **mudpot** is an opening at the surface through which a mixture of hot water and clay bubble upward. **Mineral springs** contain dissolved solids that may be 3 to 4 times higher in concentration when compared to local public water-supplies.

Cold water springs are common in areas of ground-water discharge. A **depression spring** occurs where the water table reaches the surface at a low spot or valley in the local topography (Fig. 8.40-A). This type of spring can emerge from sloping terrain or discharge can occur into a surface water body. **Springs flowing from saturated soil** occur where a thin water-bearing soil overlies impervious material that reaches the surface to form a boundary against ground-water flow (Fig. 8.40-B). A **contact spring** occurs where a permeable water-bearing unit intersects the ground surface (Fig. 8.40-C). **Barrier springs** result when the water table comes in contact with igneous or metamorphic rock and ground-water flow is deflected to the surface (Fig. 8.40-D). **Perched aquifers** can also produce springs, especially when the buried lens of clay or lake bed
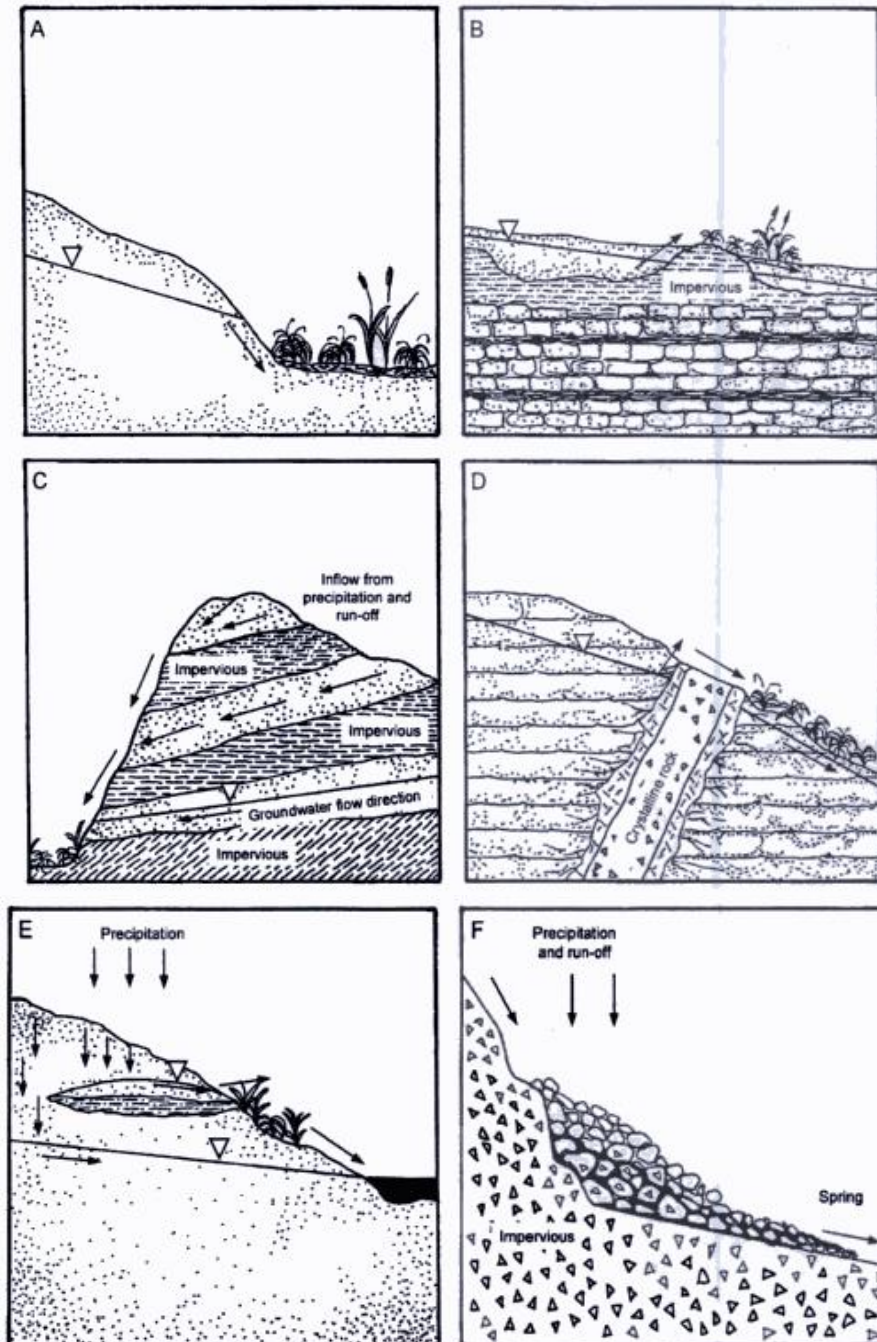
Figure 8.40. "A" depression spring. "B" Spring resulting from saturated soil. "C" are contact springs. "D" igneous intrusion and a barrier spring. "E" is a spring resulting from a perched aquifer. "F" is a landslide spring.

intersects the slope of a hill (Fig. 8.40-E). **Landslide springs** occur at the toe of talus deposits. Up slope, precipitation and run-off are collected by the coarse material. Under the influence of gravity, water moves through the connected voids and emerges down slope (Fig. 8.40-F). Secondary porosity creates **fault springs, joint** or **fracture springs, and karst springs. Fault springs** occur where faults act like conduits for ground water, which is often under **artesian pressure** (Fig. 8.41-A and B). **Joint** or **fracture springs** occur where fractures or joints in rock are connected in such a way that water is transmitted through a conduit-like system (Fig. 8.41-C). **Karst springs** in limestone terrane transmit ground water through the conduit of connected caves and caverns (Fig. 8.41-D).
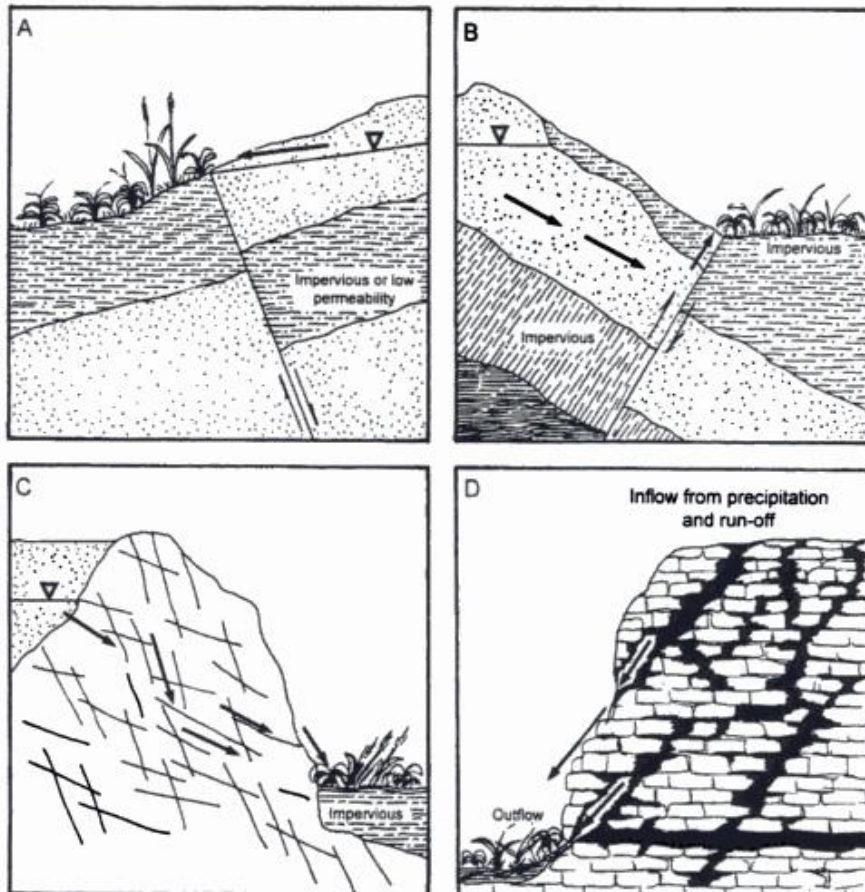

Figure 8.41. "A" is a fault acting as a conduit against a barrier. "B" is a fault acting as a conduit for ground water under artesian pressure. "C" is a spring created through the conduit of joints. "D" are karst springs.

Example 4.1: Circle the letter of the proverbial "best" answer. All of these terms were used in the class lectures, in the readings or both.

1   The difference between anticlines and synclines in geology is:

    a.   Anticlines occur in sedimentary rocks while synclines occur in igneous rocks.
    b.   Anticlines are likely to be encountered in relatively older rocks while synclines are encountered in relatively younger rocks.
    c.   Synclines are a result of faulting while anticlines are a result of folding.
    d.   Synclines are found in thin rocks while anticlines are found in thick rocks.
    e.   Anticlines and synclines are identical terms.

2   One of the following statements is wrong about sandstone rocks:

    a.   About 25% of sedimentary rock of the world is sandstone.
    b.   Normal sandstone aquifers have porosities of 30-50 %.
    c.   It is generally noticed that the porosity of sandstone aquifers decreases systematically with depth.
    d.   Sandstone aquifers can be highly anisotropic.
    e.   It is always in sandstone aquifers that a small increase in porosity corresponds to a large increase in permeability.
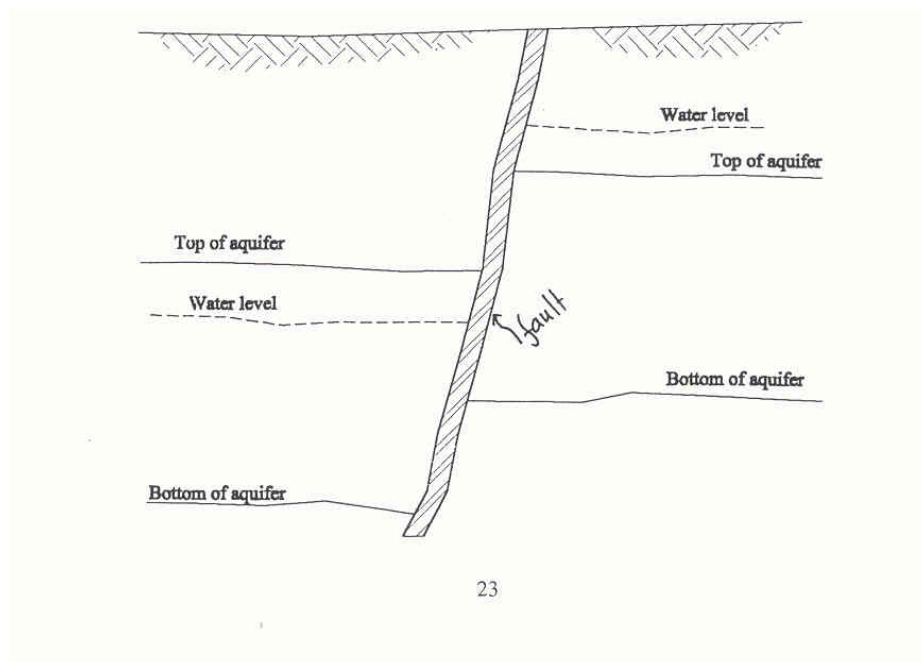
Study **Figure 4.10**, and then answer **questions 3 and 4.**
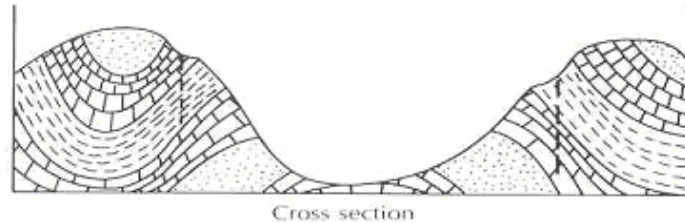

Figure 4.10

3   Faults can act as hydraulic barriers or conducts. What do you think the fault shown in Figure 4.10 act as:

    a.   Barrier.
    b.   Conduit.

5   **Is the groundwater in the aquifer moving from:**

a. Left to right
b. Right to left

5   **The following figure is a cross section in an area undergone longitudinal folding. The effect of folding is as follows:**

Cross section

a. The folding has increased the number of outcropping rocks and hence increasing the chance for recharge.
b. The outcrop of the rocks will create only regional groundwater flow as a result of spreading the rocks widely in the valley.
c. The folding will always cause water to move between aquifers in the locality of folding.
d. The folding creates discharge areas
e. Folding acts exactly as faulting.

6   **Cementation in geology means:**

a. Parts of the voids are filled with precipitated materials such as silica, calcite, iron oxide, etc.
b. Solution of the original materials of rocks.
c. Is am expression of highly porosity values,
d. Is an expression of fracturing,
e. Is an expression of secondary permeability or porosity,

7   **Secondary permeability:**

a. Always take place near the surface
b. Is normally greater near the surface but can take place at substantial depth.
c. Means vertical fracturing.
d. Means lateral dissolution.
e. Is equivalent to primary porosity

8   **Karst in hydrogeology means:**

a. Fractures.
b. Faults.
c. Folds.
d. Sedimentation
e. High dissolution of rocks.

9   Water levels in Karst regions are normally:

a. Steep
b. Flat
c. Shallow
d. Deep
e. Not continuous

10   Saprolite in geology belongs to:

a. Sedimentary rocks.
b. Carbonate rocks.
c. Metamorphic rocks.
d. Volcanic rocks.
e. Coastal Aquifers.

11   In the following figure, the permeability of system B is greater than of system C:

a. Because system B is likely to be more soluble than system C.
b. Because the dolomite of B is more soluble than that of C.
c. Because the limestone of B is more soluble than that of C.
d. Because the water table of C is flatter than that of B.
e. The two systems have the same degree of solubility.
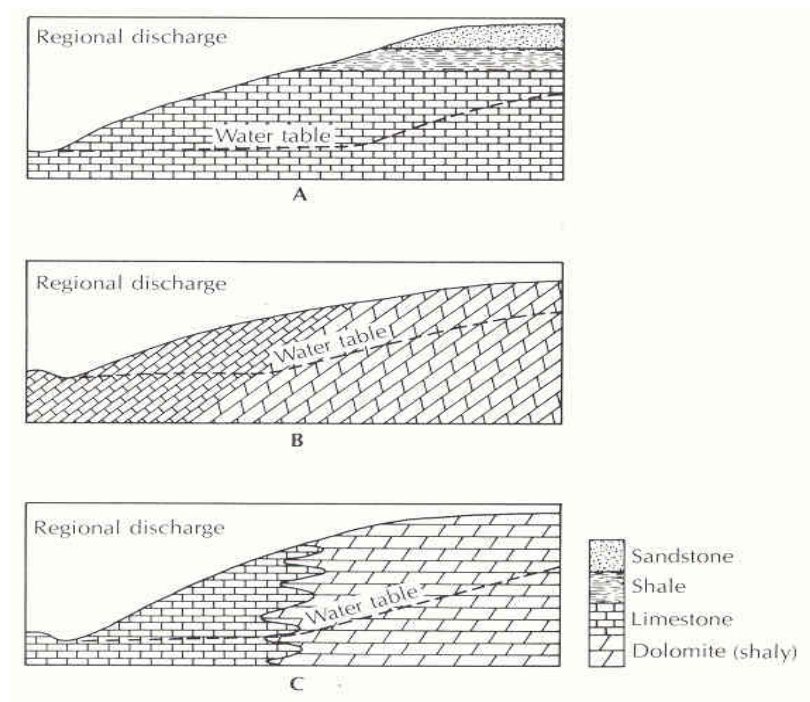
Answers: 1 (b), 2 (d), 3 (a), 4 (b), 5 (a), 6 (a), 7 (b), 8 (e), 9 (b), 10 (c), 11 (a)