Hydrology

This text-book is prepared especially for the introductory course in environmental and resources engineering study within the TEMPUS Joint European Project 2004. The length and depth of coverage is satisfactory in one-semester sequence. Briefly, Hydrology and Hydraulic structures text-book is divided into two parts.
The first module - Hydrology provides a review of hydrological principles and their application, followed by sedimentation dynamic in watershed scale, and some specialized topics in groundwater and urban hydrology. The second part deals with design of hydraulic structures for erosion, sedimentation and flood control.

11. Urban hydrology

Upon completion of this lesson, the students will get familiar with topics covered by urban hydrology. The structures and design principles are dealt with in Module 2.

Urban hydrology is a part of hydrology which investigates water regime in urbanized areas. This part of hydrology deals with problems of ecology, environmental protection, conservation and rational use of water resources. Therefore, urban hydrology is a link between different sciences. The problems of studying the influence of urbanized areas on the hydrological cycle and water regime have become extremely important regarding that by the end of 2000 half of the Earth's population lived in cities.

11.1 Precipitation

The changes in precipitation regime in the cities are related to the presence of the "heat island" above the city, to the change of aerodynamic roughness of the underlying surface due to the structures, and to the atmospheric pollution. The quantity of clouds in large cities is 5-10% greater than in the surrounding area. The fog is greater up to 100% in winter and to 30% in summer. To design the efficient storm water drainage systems in urban areas data on intensity, duration and frequency are used.

11.2 Evaporation

The evaporation in urban areas is also greater due to the input of large amount of heat and increased evaporating area. The evaporability in cities is 5-10% higher than beyond them. The significant by asphalted area, structures and the presence of diversion storm sewer system contributes to a rapid water diversion. However, it should be noted that the temperature, humidity and evaporation regime in the cities, often strongly depend on the location of the water objects and dominating winds.

11.3 Storm water runoff

One of the main problems of urban hydrology is calculation of the floods necessary for the design and implementation of drainage sewer system. The surface drainage in cities is much greater than the runoff from natural landscapes due to the presence of water impermeable covers and structures. The runoff coefficient increase several folds compared with the non-urbanized areas. At the complete urbanization of the watershed, the average flood discharge in small rivers can increase up to 10 fold. The design discharge for stormwater drainage system may be calculated by different methods, such as empirical formulas, rational method, correlation studies, and hydrograph method, which are discussed previously. Storm sewer system analysis occurs in two basic calculation sequences: hydrology and hydraulics. In hydrology the watersheds are analyzed and flows are accumulated from upstream inlets towards the system outlet. In hydraulic part tailwater condition is assumed at the outlet, and the flow values are used to compute hydraulic grades from the outlets towards upstream inlets. The reader is referred to www.haested.com and use the StormCAD. StormCAD is extremely powerful and flexible program and helps civil engineers to design and analyzed storm sewer systems in all phases of the project.

11.4 Research development

The urban hydrology issues raised by the practice of city planning and environmental protection are beyond the development of theory of hydrological calculations and modeling of the processes of anthropogenic interference to the natural hydrological cycle. The hydrological problems of urbanized landscapes are extremely complicated. For further development of theoretical and practical studies in urban hydrology, it is necessary to organize a system of observations and measurements. In respect to this the following can be proposed: a) establishing the systematic observation points in the river upstream and downstream of the city, b) accurate and full assessment of then water intake and discharge by water users separately by the types of sources, c) organization of the experimental polygons at the separate watersheds of stormwater systems with automatic continuous record of the runoff and rainfall. Flood control, storage and diversion of flood, construction and operation of sewerage systems in urban landscapes require constant improvement of methodology and forecast of the hydrological cycle components.

12. Soil physics

In this section the physical properties of soils will be discussed. Also governing principles and relations of water flow through porous media are presented. Upon completion of this lesson, the students will be able to understand the calculate groundwater flow.

The main topics to be discussed are formation and mechanical composition of soil and soil water. Soils are formed from exposed masses of partially weathered rocks of the Earth's crust. The sheetlike deposits of glaciers are called till, which is a heterogeneous, nonstratified mixture of clay, silt, sand, gravel, and boulders. Water erosion has laid down alluvium in flood plains or bottomlands of streams. Alluvium includes clays and silts and occasional gravel deposits. Soil is often considered to be formed by five factors: climate, organisms, topography, parent material, and time. The part of geology that deals with the distribution and movement of water in soil and rocks is called *hydrogeology* (*hydro*- meaning water, and -*geology* meaning the study of the Earth). Hydrogeology, as stated above, is a branch of the earth sciences dealing with the flow of water through aquifers and other shallow porous media (typically less than 450 m below the land surface.) The very shallow flow of water in the subsurface (the upper 3 m) is pertinent to the fields of soil science, agriculture and civil engineering, as well as to hydrogeology. Groundwater is a slow-moving, viscous fluid. Many of the empirically derived laws of groundwater flow can be alternately derived in fluid mechanics.

12.1 Physical properties

In order to describe the water movement and water quantity in soils some primary and derived physical properties are introduced below.
Aquifers are broadly classified as being either confined or unconfined, and either saturated or unsaturated. *Hydraulic head* φ or h is the driving force which causes water to move from one place to another. It is composed of pressure head $p/\rho g$ and elevation head z, $\varphi = p/\rho g + z$. The head gradient is the change in hydraulic head per length of flow path, and appears in *Darcy's* law as being proportional to the discharge. The record of hydraulic head through time at a well is a hydrograph. The changes in hydraulic head recorded during the pumping of a well in a test are called drawdown. *Porosity* n is a directly measurable aquifer property which indicates the amount of pores per unit total volume. For sandy soils the porosity is about 0,35-0,45. For clays and peat the porosity is usually in the range 0,40-0,60, but it may sometimes be as large as 0,85 or even more. The porosity of a porous medium (such as rock or sediment) describes the fraction of void space in the material, where the void may contain, for example, air or water. It is defined by the ratio:

$$n = \frac{V_v}{V_T} \qquad (12.1)$$

where V_V is the volume of void-space (such as fluids) and V_T is the total bulk volume of the material, including the solid and void components.

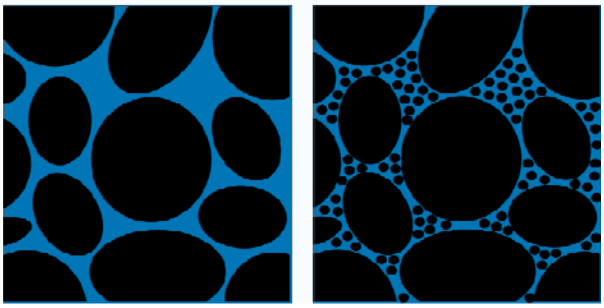

Figure 12.1 Effects of sorting on alluvial porosity

The porosity value can alternatively be calculated from bulk density (*BD*) and particle density (*PD*):

$$n = 1 - \frac{BD}{PD} \qquad (12.2)$$

Normal particle density is assumed to be approximately 2.65 g/cm³, although a better estimation can be obtained by examining the lithology of the particles. *Permeability* is an expression of the connectedness of the pores. For instance, an unfractured rock unit may have a high *porosity* (it has lots of *holes* between its constituent grains), but a low *permeability* (none of the pores are connected). An example of this phenomenon is pumice, which, when in its unfractured state, can make a poor aquifer. *Hydraulic conductivity k* and *transmissivity T* are indirect aquifer properties (they cannot be measured directly). *T* is the *k* integrated over the vertical thickness (*b*) of the aquifer (*T=kB* when *k* is constant over the entire thickness). These properties are measures of an aquifer's ability to transmit water. *Saturation S* or the degree of saturation is the volume of water in the pores per unit total pore volume. It essentially varies between 0, for completely dry soil, and 1, for completely saturated soil.

12.2 Governing equations

Darcy's Law

Darcy's law is the equation empirically derived by *Henri Darcy* (1856) that describes the flow of a fluid through a porous medium. It states that the amount of groundwater discharging through a given portion of aquifer is proportional to the cross-sectional area to flow, the hydraulic head gradient and the hydraulic conductivity.

$$Q = kA\frac{\varphi_1 - \varphi_2}{\Delta s} \qquad (12.3)$$

where Q is total discharge (m³/s), A is the cross-sectional area to flow (m^2), (φ_1-φ_2) is the pressure drop or water table drop in unit height (m), Δs is the length where the pressure drop is taking place, and k is a proportionality constant. This constant is called the coefficient of permeability (some others use the expression hydraulic conductivity) and its measure is that of velocity (m/s). The definitions are shown in Figure 12.2.

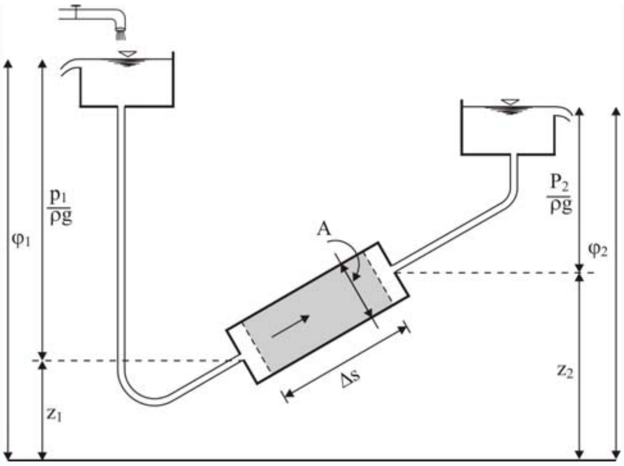

Figure12.2 Darcy's law experiment

The quantity *Q/A* (discharge per unit of cross-sectional area) is called specific discharge *u*, and by writing $(\varphi_2-\varphi_1)=\Delta\varphi$ the last equation becomes:

$$u = -k\frac{\Delta\varphi}{\Delta s} \qquad (12.4)$$

Darcy's law is a simple mathematical statement which neatly summarizes several familiar properties that groundwater flowing in aquifers exhibits, including the following assumptions:

- if there is no pressure gradient over a distance, no flow occurs (this is hydrostatic conditions);
- if there is a pressure gradient, flow will occur from high pressure towards low pressure (opposite the direction of increasing gradient - hence the negative sign in *Darcy's* law);
- the greater the pressure gradient (through the same formation material), the greater the discharge rate, and
- the discharge rate of fluid will often be different through different formation materials (or even through the same material, in a different direction) even if the same pressure gradient exists in both cases.

Darcy's law is only valid for slow, viscous flow. Fortunately, most groundwater flow cases fall in this category. Typically any flow with a *Reynolds* number R_e less than one is clearly laminar, and it would be valid to apply *Darcy's law*. Experimental tests have shown that for flow regimes with values of *Reynolds* number up to 10 may still be Darcian. *Reynolds* number (a dimensionless parameter) for porous media flow is typically expressed as:

$$R_e = \frac{ud}{\nu} \qquad (12.5)$$

where ν is the kinematic viscosity of the fluid (m^2/s), *u* is the specific discharge (m/s), *d* is the effective pore diameter for the porous medium. The *Reynolds* number must be smaller than some critical value. Various others give different values, all in the range from 1 to 10.

Laplace's equation

For a rectangular system of coordinates *x*, *y* and *z*, to be established in a homogeneous porous medium of constant hydraulic conductivity *k*, from the equation of continuity (known from fluid mechanics) and Darcy's low, may be derived the following expression:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \qquad (12.6)$$

which is governing the groundwater flow. Many solutions of this equation, especially when the groundwater surface is horizontal, are available. Since this equation is difficult to solve when there is curved groundwater surface, the *Dupuit-Forchheimer* theory was developed:

$$kh\left(\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}\right)+k\left[\left(\frac{\partial h}{\partial x}\right)^2+\left(\frac{\partial h}{\partial y}\right)^2\right]+N=0 \tag{12.7}$$

where N represents the volume of water entering a unit (horizontal) area of the aquifer per unit time, due to precipitation. The dimension of N is that of velocity (m/s). Negative values of N represent evaporation. This equation is the basic differential equation for the flow in unconfined aquifers. *Dupuit* pointed out the advantage of introducing h^2 as variable instead of h itself. By replacing the second order partial derivatives of h^2 the last expression can be rewritten as linear partial differential equation:

$$\frac{k}{2}\left[\frac{\partial^2(h^2)}{\partial x^2}+\frac{\partial^2(h^2)}{\partial y^2}\right]+N=0 \tag{12.8}$$

In case of one-dimensional problem of unconfined flow, such as the flow through a dam with vertical faces, and no rain will be taken into account N=0, the basis differential equation becomes:

$$\frac{d^2(h^2)}{dx^2}=0 \tag{12.9}$$

which general solution is written:

$$h^2=C_1x+C_2 \tag{12.10}$$

where the constants C_1 and C_2 can be determined from the boundary conditions ($x=0$: $h=H_1$ and $x=L$: $h=H_2$). Substitution of the evaluated constants into the last equation leads to the following expression:

$$h^2=H_1^2-\frac{H_1^2-H_2^2}{L}x \tag{12.11}$$

This equation expresses that the water table is parabola, the so called *Dupuit* parabola. The total discharge through a dam of length B can be now obtained:

$$Q=kB\frac{H_1^2-H_2^2}{2L} \tag{12.12}$$

In case of radial flow (pumping from a well) the fundamental differential equation takes a form:

$$\frac{k}{2}\left[\frac{d^2(h^2)}{dr^2}+\frac{1}{r}\frac{d(h^2)}{dr}\right]+N=0 \tag{12.13}$$

The general solution of this equation is:

$$h^2=-\frac{N}{2k}r^2+C_1\ln r+C_2 \tag{12.14}$$

where the constants C_1 and C_2 can be determined from the boundary conditions ($r=r_0$: $h=H_0$, and $r=R$: $h=H$). Considering that the discharge from the well Q_0 and the radius of the aquifer R are known, the last equation may be written:

$$h^2 = H^2 + \frac{N}{2k}\left(R^2 - r^2\right) + \frac{Q_0}{\pi k} ln\left(\frac{r}{R}\right) \quad (12.15)$$

13. Groundwater hydrology

Groundwater occurrence and major features are discussed in this lesson. Also interactions of ground and surface water is presented. Groundwater budgets and influence of groundwater exploitation to other water bodies in a catchment is presented.

13.1 Introduction

Groundwater is water located beneath the ground surface in soil pore spaces and in the fractures of lithologic formations. The study of the distribution and movement of groundwater is hydrogeology, also called groundwater hydrology.

13.2 Groundwater in the water cycle

Groundwater can be a long-term 'reservoir' of the natural water cycle (with residence times from days to millennia), as opposed to short-term water reservoirs like the atmosphere and fresh surface water (which have residence times from minutes to years). Figure 13.1 shows how deep groundwater (which is quite distant from the surface recharge) can take a very long time to complete its natural cycle. Groundwater is naturally replenished by surface water from precipitation, streams, and rivers when this recharge reaches the water table. It is estimated that the volume of groundwater comprises 30.1% of all freshwater resource on earth compared to 0.3% in surface freshwater; the icecaps and glaciers are the only larger sources of fresh water on earth at 68.7%.

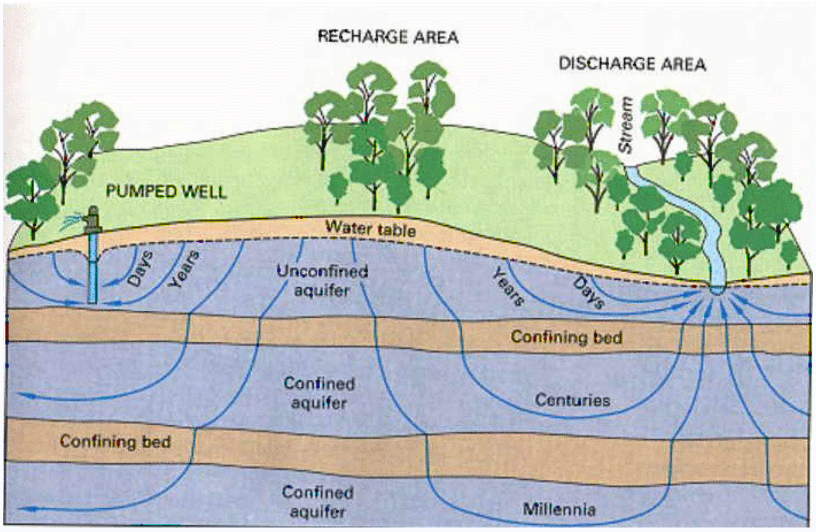

Figure 13.1 Relative groundwater travel times

Groundwater makes up about twenty percent of the world's fresh water supply, which is about 0.61 percent of the entire world's water, including oceans and permanent ice.

13.3 Basic terms

Ground water occurs almost everywhere beneath the land surface. Natural sources of freshwater that become ground water are: (1) areal recharge from precipitation that percolates through the unsaturated zone to the water table and (2) losses of water from streams and other bodies of surface water such as lakes and wetlands. The top of the subsurface ground-water body, the water table, is a surface, generally below the land surface, that fluctuates seasonally and from year to year in response to changes in recharge from precipitation and surface water bodies. On a regional scale, the configuration of the water table commonly is a subdued replica of the land-surface topography. The depth to the water table varies.

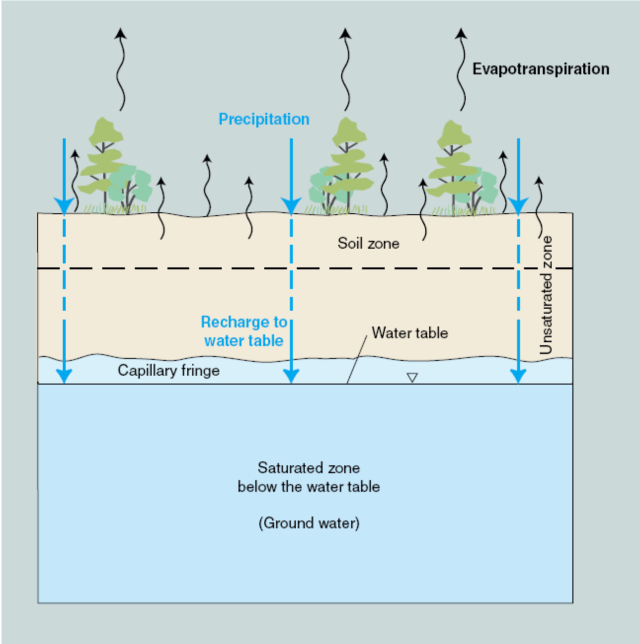

Figure 13.2 Unsaturated zone, capillary fringe, water table, and saturated zone

Water beneath the land surface occurs in two principal zones, the *unsaturated zone* and the *saturated zone*. In the unsaturated zone, the spaces between particle grains and the cracks in rocks contain both air and water. In contrast to the unsaturated zone, the voids in the saturated zone are completely filled with water. The approximate upper surface of the saturated zone is referred to as the *water table*. Water in the saturated zone below the water table is referred to as *ground water*.

The *water table fluctuates* seasonally and from year to year in response to changes in recharge from precipitation and surface-water bodies. On a regional scale, the configuration of the water table commonly is a subdued replica of the land-surface topography. The depth to the water table varies.

Ground water commonly is an important *source of surface water*. The contribution of ground water to total streamflow varies widely among streams, but hydrologists estimate the average contribution is somewhere between 40 and 50 percent in small and medium-sized streams. Hydrologically speaking the groundwater supplies the so-called base flow of the discharge hydrograph of surface water streams.

Velocities of ground-water flow generally are low and are orders of magnitude less than velocities of streamflow. The movement of ground water normally occurs as slow seepage through the pore spaces between particles of unconsolidated earth materials or through networks of fractures and solution openings in consolidated rocks. A velocity of 1 m/day or greater is a high rate of movement for ground water, and ground-water velocities can be as low as 1 m/year or 1 m/decade. In contrast, velocities of streamflow generally are measured in meters per second. A velocity of 1 m/s equals about 86,4 km/day. The low velocities of ground-water flow can have important implications, particularly in relation to the movement of contaminants.

Under natural conditions, ground water moves along flow paths from areas of *recharge* to areas of *discharge* at springs or along streams, lakes, and wetlands. Discharge also occurs as seepage to bays or the ocean in coastal areas and as transpiration by plants whose roots extend to near the water table. The three-dimensional body of earth material saturated with moving ground water that extends from areas of recharge to areas of discharge is referred to as a *ground-water-flow system*.

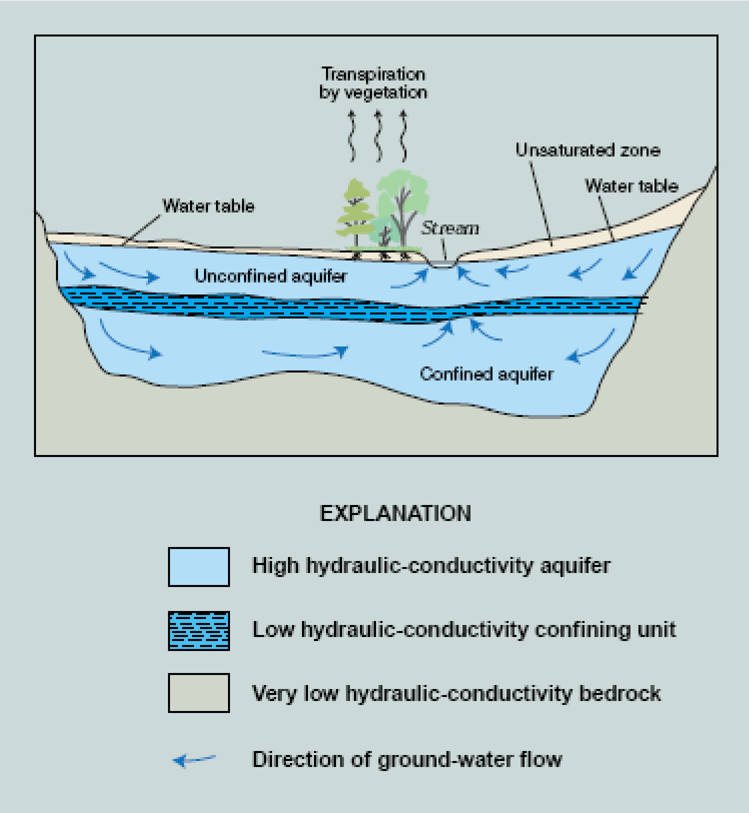

Figure 13.3 Local scale ground-water-flow system

In ground-water-flow system shown in Figure 13.3, inflow of water from areal recharge occurs at the water table. Outflow of water occurs as: (1) discharge to the atmosphere as ground-water evapotranspiration (transpiration by vegetation rooted at or near the water table or direct evaporation from the water table when it is at or close to the land surface) and (2) discharge of ground water directly through the streambed. Short, shallow flow paths originate at the water table near the stream. As distance from the stream increases, flow paths to the stream are longer and deeper. For long-term average conditions, inflow to this natural ground-water system must equal outflow.
The *areal extent* of ground-water-flow systems varies from a few square kilometers or less to tens of thousands of square kilometres
The *age* (time since recharge) of ground water varies in different parts of ground-water-flow systems.

13.4 Aquifer characteristics

With respect to hydraulic properties, the sub-surface formations may be classified in:

- *Aquifers:* water bearing layers for which the porosity and pore size are sufficiently large to allow transport of water in appreciable quantities;
- *Aquitards:* less permeable layers, not capable of transmitting water in horizontal direction, but allowing vertical flow;
- *Aquicludes:* impermeable layers that may contain water, but are incapable of transmitting significant quantities;
- *Aquifuges:* impermeable rocks neither containing nor transmitting water.

With respect to position the following aquifer types are distinguished:

- *Unconfined aquifer:* (also called phreatic or water-table aquifer) which consist of a pervious layer underlain by a (semi-) impervious layer. The upper boundary is formed by a free water table (phreatic surface);
- *Confined aquifer:* consisting of a pervious layer bounded by impervious layers. The water level in wells tapping those aquifers rises above the top of the pervious layer and sometimes even above the soil surface (artesian wells).

- *Semi-confined aquifer*: consist of a completely saturated pervious layer, but the upper and/or lower boundaries are semi-pervious.

13.5 Specific storage and specific yield

Specific storage (S_s) and its depth-integrated equivalent, storativity ($S=S_sb$), are indirect aquifer properties; they indicate the amount of groundwater released from storage due to a unit depressurization of a confined aquifer. They are fractions between 0 and 1.
Specific yield (S_y) is also a ratio between 0 and 1 ($S_y \leq$ porosity) which indicates the amount of water released due to drainage, from lowering the water table in an unconfined aquifer. Typically S_y is orders of magnitude larger than S_s. Often the porosity (see Chapter 12.) or effective porosity is used as an upper bound to the specific yield.
Sustainable yield is a safe yield of water extraction per unit time, beyond which the aquifer risks the state of overdrafting or even depletion.

13.6 Ground-water budgets

In nature, the ground-water system is in long-term equilibrium. That is, averaged over some period of time, the amount of water entering or recharging the system is approximately equal to the amount of water leaving or discharging from the system. Because the system is in equilibrium, the quantity of water stored in the system is constant or varies about some average condition in response to annual or longer-term climatic variations. This predevelopment water budget is shown schematically in Figure 13.3A.
We also can write an equation that describes the water budget of the predevelopment system as: $R=D$, *w*here: R - Recharge (water entering) and D - Discharge (water leaving).

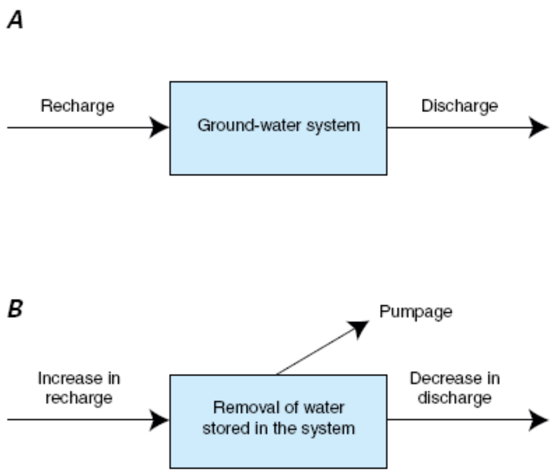

Figure 13.3 Water budgets for a ground-water system for predevelopment and development conditions.

The water leaving often is discharged to streams and rivers and is called base flow. The possible inflows (recharge) and outflows (discharge) of a ground-water system under natural (equilibrium) conditions are:

Inflow/recharge
- Areal recharge from precipitation that percolates through the unsaturated zone to the water table.
- Recharge from losing streams, lakes, and wetlands.

Outflow/discharge
- Discharge to streams, lakes, wetlands, saltwater bodies (bays, estuaries, or oceans), and springs.
- Ground-water evapotranspiration.

In Figure 13.3, the predevelopment water-budget diagram is illustrating that inflow equals outflow. Water-budget diagram (B) showing changes in flow for a ground-water system being pumped. The sources of water for the pumpage are changes in recharge, discharge, and the amount of water stored. The initial predevelopment values do not directly enter the budget calculation. This statement, illustrated in Figure 13.3 *B*, can be written in terms of rates (or volumes over a specified period of time) as:

Pumpage = Increased recharge + Water removed from storage + Decreased discharge.

It is the changes in the system that allow water to be withdrawn. That is, the water pumped must come from some change of flows and from removal of water stored in the predevelopment system.
Regardless of the amount of water withdrawn, the system will undergo some drawdown in water levels in pumping wells to induce the flow of water to these wells, which means that some water initially is removed from storage.
The relative contributions of changes in storage, changes in recharge, and changes in discharge evolve with time. The initial response to withdrawal of water is changes in storage. If the system can come to a new equilibrium, the changes in storage will stop and inflows will again balance outflows:

Pumpage = Increased recharge + Decreased discharge

Thus, the long-term source of water to discharging wells is typically a change in the amount of water entering or leaving the system. How much ground water is available for use depends upon how these changes in inflow and outflow affect the surrounding environment and what the public defines as undesirable effects on the environment.
In determining the effects of pumping and the amount of water available for use, it is critical to recognize that not all the water pumped is necessarily consumed. For example, not all the water pumped for irrigation is consumed by evapotranspiration. Some of the water returns to the ground-water system as infiltration (irrigation return flow).

13.7 Effects of ground-water development

As development of land and water resources intensifies, it is increasingly apparent that development of either ground water or surface water affects the other.
Streams either gain water from inflow of ground water (gaining stream; Figure 13.4. *A*) or lose water by outflow to ground water (losing stream; Figure 13.4. *B*). Many streams do both, gaining in some reaches and losing in other reaches. Furthermore, the flow directions between ground water and surface water can change seasonally as the altitude of the ground-water table changes with respect to the stream-surface altitude or can change over shorter timeframes when rises in stream surfaces during storms cause recharge to the streambank. Under natural conditions, ground water makes some contribution to streamflow in most physiographic and climatic settings. Thus, even in settings where streams are primarily losing water to ground water, certain reaches may receive ground-water inflow during some seasons.

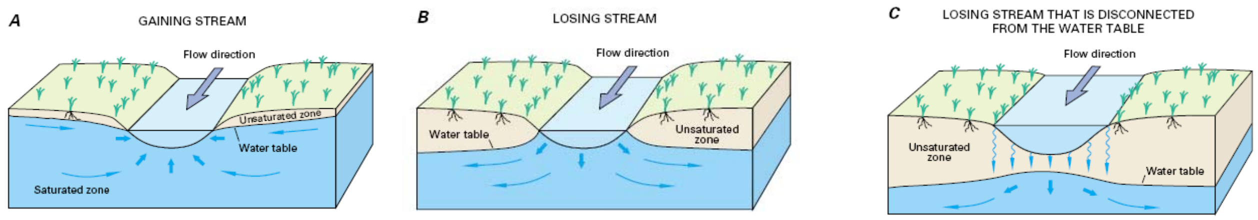

Figure 13.4. Interaction of streams and ground water

A pumping well can change the quantity and direction of flow between an aquifer and stream in response to different rates of pumping. Figure 13.5 illustrates a simple case in which equilibrium is attained for a hypothetical stream-aquifer system and a single pumping well. Reductions of streamflow as a result of ground-water pumping are likely to be of greatest concern during periods of low flow.

Lakes, both natural and human made, are present in many different parts of the landscape and can have complex ground-water-flow systems associated with them. Lakes interact with ground water in one of three basic ways: some receive ground-water inflow throughout their entire bed; some have seepage loss to ground water throughout their entire bed; and others, perhaps most lakes, receive ground-water inflow through part of their bed and have seepage loss to ground water through other parts. Lowering of lake levels as a result of ground-water pumping can affect the ecosystems supported by the lake, diminish lakefront esthetics, and have negative effects on shoreline structures such as docks.

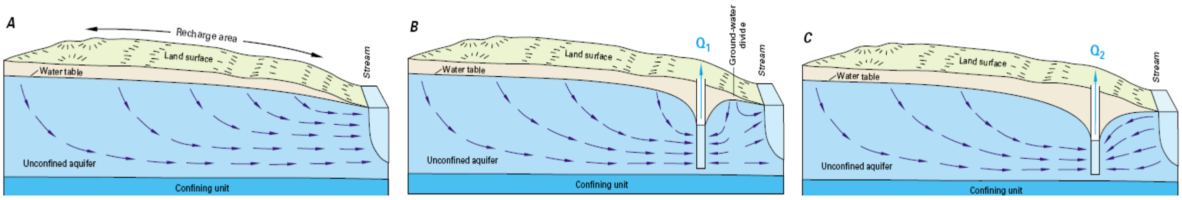

Figure 13.5 Effects of pumping from a hypothetical ground-water system that discharges to a stream.

The persistence, size, and function of *wetlands* are controlled by hydrologic processes. For example, the persistence of wetness for many wetlands is dependent on a relatively stable influx of ground water throughout changing seasonal and annual climatic cycles. Characterizing ground-water discharge to wetlands and its relation to environmental factors such as moisture content and chemistry in the root zone of wetland plants is a critical but difficult to characterize aspect of wetlands hydrology. Wetlands can be quite sensitive to the effects of ground-water pumping. Ground-water pumping can affect wetlands not only as a result of progressive lowering of the water table, but also by increased seasonal changes in the altitude of the water table.

In summary, we have seen that changes to surface-water bodies in response to ground-water pumping commonly are subtle and may occur over long periods of time. The cumulative effects of pumping can cause significant and unanticipated consequences when not properly considered in water-management plans. The types of water bodies that can be affected are highly varied, as are the potential effects.

13.7.1 Possible problems with groundwater use

When calculating the ‘sustainable yield’ of aquifer and river water, often the same water is counted twice, once in the aquifer, and once in its connected river.

The time lags inherent in the dynamic response of groundwater to development have generally been ignored. In brief, the effects of groundwater overdraft may take decades or centuries to manifest themselves.

As water moves through the landscape it collects soluble salts, mainly sodium chloride. Where such water enters the atmosphere through evapotranspiration, these salts are left behind. In irrigation districts, poor drainage of soils and surface aquifers can result in water tables coming to the surface in low-lying areas. Major land degradation problems of salinity and waterlogging result, combined with increasing levels of salt in surface waters. As a consequence, major damage can occur to local economies and environments.

Four important effects are worthy of brief mention. First, flood mitigation schemes, intended to protect infrastructure built on floodplains, have had the unintended consequence of reducing aquifer recharge associated with natural flooding. Second, prolonged depletion of groundwater in extensive aquifers can result in land subsidence, with associated infrastructure damage – as well as (thirdly) saline intrusion . Fourth, draining acid sulphate soils, often found in low-lying coastal plains, can result in acidification and pollution of formerly freshwater and estuarine streams.

Another cause for concern is that groundwater drawdown from over-allocated aquifers has the potential to cause severe damage to both terrestrial and aquatic ecosystems – in some cases very conspicuously but in others quite imperceptibly due to the extended period over which the damage occur.

Sometimes the water movement from the recharge zone to the place where it is withdrawn may take centuries. When the usage of water is greater than the recharge, it is referred to as *mining* water (the water is often called fossil water because of its geologic age). Under those circumstances it is not a renewable resource.

13.7.2 Pollution of Groundwater

Not all groundwater problems are caused by over-extraction. Pollutants released to the ground can work their way down into groundwater. Movement of water and dispersion within the aquifer spreads the pollutant over a wider area, which can then intersect with groundwater wells or find their way back into surface water. As well as the effects of groundwater overdraft may take decades or centuries to recover, the same is valid for the pollution.

References

1. Chow, V. T. (ed.) (1964). Handbook of Applied Hydrology. McGraw-Hill Book Company, New York, US
2. Popovska, C., Gesovska, V., Donevska, K. (2004). Hydrology. Faculty of Civil Engineering, Skopje, Macedonia (in Macedonian)
3. Raudkivi A. J. (1992). Hydrology. Pergamon Press, Oxford, UK
4. Robin, D. (1986). Variation of Ocean Level. In: The Greenhouse Effect, Climatic Change, and Ecosystems. HTML Publication.
5. Skoklevski Z., Todorovski B. (1993). Heavy rainfalls in Republic of Macedonia. Faculty of Civil Engineering, Skopje, Macedonia (in Macedonian)
6. Sutclife, J.V. (2004). Hydrology: A Question of Balance. IAHS Press, Oxfordshire, UK
7. Verruijt A. (1970). Theory of Groundwater Flow. MACMILLAN and Co. Ltd., London, UK
8. Bonacci, O., 1987, *Karst Hydrology: With Special Reference to the Dinaric Karst* (translated from the Yugoslavian) (Springer Series in Physical Environment 2): Springer-Verlag, New York, 184 p
9. USACE 1999. Engineering and Design - Groundwater Hydrology. EM 1110-2-1421. CECW-EH. 28 February 1999
10. Popovska, C., 2003. Fluid mechanics. Gradezen Fakultet, Skopje, Macedonia (in Macedonian)