5.2. DIRECTION AND SPEED OF GROUNDWATER MOVEMENT

The hydraulic parameters like speed and direction of groundwater in aquifers have a great significance to determine contamination of water with various components,which tends to percolate down to the saturated zone of aquifers. Filteration coefficient and speed of groundwater movement for a particular layer depict groundwater regime for a specific location. Moreover, flow of groundwater is placed under the substancial influence of pressure, hydarulic gradient, hydraulic conductivity and dynamic porosity. Though, groundwater hydraulic conductivity itself is dependent on surface characterstics like shape, size, interconnectedness and porosity. The ability of a geological material to move water is called *hydraulic gradient*, and generally, expressed in gallons per day per square foot (gal/d/ft2) or in feet per day (ft/d). The height of water level attained over the arbitrary level or datum level is known as *hydraulic head or simply head*. The movement of water follows in direction from a point of higher static groundwater elevation to lower elevation and higher to lower water head or potential, which is generally a virtue of position. Moreover, differential water level facilitate the movement of water, their speed as well a direction. Under the influence of all these parameters, groundwater moves slowly, may be less than one foot to few tens of feet per day (Harter, 2003). Unlike surface water, groundwater is restricted to flow freely and largly dependent on interconnected pores of the material. That’s why, hydraulic conductivity of sand and gravels is much larger in comparision to finely grained material like clay, whose interconnected pores are limited to support the flow of groundwater. The porosity of the material not only controls flow of water underneath but also responsible for contamination of groundwater with pollutants through percolation from land surface to groundwater. Higher percolation rate results in filteration of a significant amount of chemicals and pathogens to groundwater. The intergranular space between the particles of the material, also governs the storage capacity of aquifers. Highly porous medium like sand and gravels accommodate more water due to compartively richer intergranular space in comparsion of granite or clay.

5.2.1 Darcy Law

The flow of groundwater in aquifers from recharge to discharge point is a function of porous medium. For the first time, the flow of groundwater in granular or porous medium is expressed through a generalised mathematical relationship, which is known as Darcy Law, on the name of a French engineer, Henry Darcy. The empirical equation was formulated considering the prilimnary experiments conducted in 1803 to detremine the flow of groundwater through beds of porous materials like sand, rocks etc, which further formulates the basis for modern hydrogeology. He designed a transmission system for supply of safe drinking water through a porous material (sand) packed pipes from a large spring which was distant for more than 10 km from Dijon. The porous material acts as purification substrate for the supply and distribution of safe and relaibale drinking water. In 1856, he published his scientific finding and produce a empirical equation in term of Darcy Law, which indicates the fact that the rate of flow of a fluid (volume of fluid flow per unit time) between two ends is directly related to the pressure difference, distance and permeability of interconnecting pathways between the end points of connecting channel. Here, in this empirical equation (Equation 6), pressure represents the excessive pressure exerted due to gravity, underneth to the ground suface, over the normal hydrostatic fluid pressure. The experimental setup followed for Darcy Law is depicted in Fig. 5.

In modern sense, considering a cylindrical column of length of interest “l” and cross section area “A”, stoppered on both the ends and outfitted with tubes for inflow, outflow tubes and manometer, Darcy Law can be expressed as:

$$Q = -KA\, dh/dl = -Ki$$

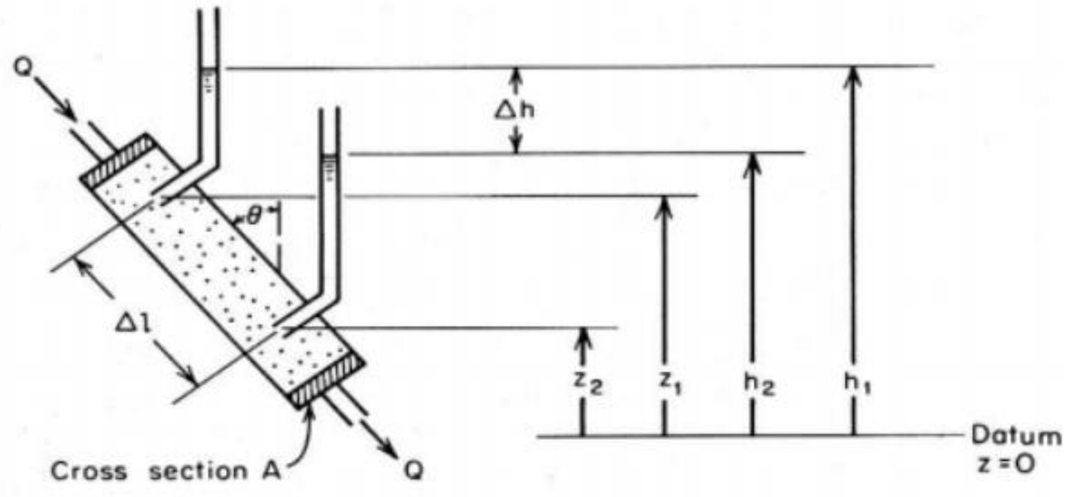
where: Q = Rate of flow of fluid (groundwater) [volume per time or m^3/d]

K =Hydraulic conductivity (m/d), which depends on the size and arrangement of the water-transmitting openings (pores and fractures) and on the dynamic characteristics of the fluid (water) such as kinematic viscosity, density, and the strength of the gravitational field;

A = Cross sectional area of cylindrical column (m^2)

dh/dl = Loss of hydraulic head over the length of interest of cylindrical column (m/m)

i = Hydraulic gradient.



When water is introduced to the inlet channels of cylinderical pipe and allowed to flow through the porous medium, then it will take some time to get all pores filled with water and to attain flow rate equilibrium at inlet and outlet point.

In this sense, Darcy Law may be defined as rate of flow of fluid in porous medium or specific discharge (as shown in Equation 7) or Darcy velocity is proportional to the loss of hydraulic head and inversaly proportional to the length of path followed for the flow of liquid, or

$$v = K \frac{\Delta h}{\Delta l} = -Ki$$

Under the set of assumptions, the permeability of a medium is considered as 1 darcy, when it allows a fluid flows with a speed of 1cm3/s with viscosity 1 cP (1 mPa•s) under a pressure gradient of 1 atm/cm acting across a cross sectional area of 1 cm².

Limitations with applicability of Darcy Law

The application of Darcy Law are limited for specific circumstances and conditions, governing the flow of fluids from one zone to another and finally to assess the scope of hydraulic fracturing fluids towards fresh water zone. The extent of the law includes laminar flow of fluids in saturated granular medium under steady state conditions, assuming homogeneous, incompressible and isotherm fluids with negligible kinetic energy. In such an assumptions fluid movement is governed through viscous forces, when fluids are moving slowly along the parallel streamlines. Moreover, the speed of fluid increases on rapid extraction at the discharge point. At this point, the movement become chaotically and turbulent under the inertial forces rather than viscous forces. In such a situation, flow is computed with Reynolds number, which is the ratio between the inertial forces and viscous forces governing the flow. Specifically, Reynolds numbers are used to distinguish between the laminar flow, transition zone and the turbulent flow.

The validity of the law deviated when flow is turbulent, which may be identified in cavernous limestone or fractured basalt. However, averaging character considering negligible influences of factors and representative range, Darcy Law can be applicable for several circumstances in-spite of basic assumptions (Freeze and Cherry, 1979).

The cogency of Darcy Law is considered with few of the conditions or circumstances which are enlisted as under:

- Saturated and unsaturated flow of fluids in aquifers and aquitards
- Steady-state and transient flow;
- Flow in granular media and in fractured rocks;
- Flow in homogeneous systems and heterogeneous systems.

5.2.2 Steady State groundwater flow equation

When groundwater is stationary in a saturated porous medium under steady-state conditions, state variables became independent of time. The steady-state conditions define constant flow rate, piezometeric head and volume of stored fluid with respect to time. Moreover, the law of conservation of mass for such steady- state flow indicates the equilibrium condition of fluid flow at recharge and discharge point of any elementary control volume. In such constant conditions, flow equation for a homogenous, isotropic medium may get reduced to *Laplace's equation or potential equation*.

$$\nabla(K\nabla h)=0$$

Moreover, the equation may also follow the condition in shallow parts, where pore space deformation is negligible. However, in certain conditions, when flow may be incompressibleand deviate from steady-state condition, the boundary layer become time dependent with continuously rising and falling of water table. In such a generalized assumption of homogeneous hydraulic conductivity, the equation may be expressed as given below:

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=0$$

Or $\nabla^2 h=0$

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