**Lecture 21 Management of Groundwater**

21.1 Introduction

The assessment and development of groundwater resources are essential for ensuring sustainable water supplies to domestic, agricultural and industrial sectors along with the ecosystems. There are overriding advantages of storing surplus water in subsurface reservoirs compared to surface reservoirs, which are as follows:

1. Large storage volume which can be developed in stages according to the water demand;
2. Little land-area requirement;
3. Resilience to droughts;
4. Relatively low environmental impact of well-field developments;
5. More or less uniform water temperature;
6. Relatively high purity and less vulnerability to contamination;
7. Slight to no evaporation loss;
8. No requirement of conveyance systems; and
9. Slight to no danger of catastrophic structural failure.

With the ever increasing use of groundwater throughout the world along with the mismanagement or lack of management of groundwater basins, there is a continuing need to manage this vital resource effectively so as to ensure sustainable groundwater development. The modern concept of water management states that surface water and groundwater are integrated resources, and hence they should be managed together. This concept must be followed in practice for efficient water resources management at a local, regional or national scale.

Groundwater management involves planning, implementation, and operation necessary to provide safe and reliable groundwater supplies. This necessitates groundwater management at a basin scale. Groundwater management objectives typically focus on aquifer yield, recharge, and water quality (i.e., groundwater quantity and quality) as well as on socio-economic, legal, and political factors. After the proper evaluation of available water resources in a basin and the preparation of alternative management plans, action decisions can be made by suitable government or public agencies. The formal groundwater management approach, though generally more important for large-scale development, can also be applied to smaller-scale projects or even individual well projects (Roscoe Moss Company, 1990).

In this lesson, basic concepts of groundwater management are briefly discussed, together with salient methods of groundwater management. An overview of groundwater modeling, which plays a significant role in managing groundwater resources of large and complex basins, is presented in next lesson (Lesson 22).

21.2 Basic Concepts of Groundwater Management

To manage a groundwater basin, a proper knowledge of the quantity of water that can be developed is a prerequisite. Determination of available water within a basin requires the evaluation of the elements constituting the water cycle. Therefore, the most fundamental approach to groundwater management is based on water balances within a groundwater basin. The water balance equation (or hydrologic budget) for a groundwater basin can be written as:

                            (21.1)

Where, R = recharge to groundwater [L/T], Qi = surface-water inflow into groundwater storage in the basin [L3/T], A = area of the basin [L2], ET = loss of groundwater due to evapotranspiration [L/T], Qo = groundwater outflow from the basin (groundwater outflow into surface water) [L3/T], Qp = total groundwater pumping from the basin [L3/T], and ΔS = change of groundwater storage in the basin [L/T]. The values of these parameters are considered over a specific period of time for which the groundwater balance is sought.

Eqn. (21.1) indicates that for a given amount of recharge (R+Qi) in a groundwater basin, the increase of pumping rate (Qp) will eventually decrease the groundwater outflow into surface water (Qo), evapotranspiration (ET), and groundwater storage (S). The decrease in the groundwater outflow into surface water may reduce flow in streams, creeks, lakes and springs, whereas the decrease in groundwater storage will lower the groundwater level in aquifers. Exactly how, when, and where these changes will be manifested depends on several factors such as the basin size, hydrogeologic setting, and the times involved. Complexity often arises in real-world basins because an increase in pumping also increases recharge to some extent; it is known as induced recharge.

Proper management of groundwater basin is concerned with renewability of the groundwater resource and its practical exploitation. Historically, one of the earliest approaches to analyzing groundwater yields was built on the concept of safe yield, which is associated with the amount of groundwater supply that a water user can depend upon (Todd, 1980; Fetter, 1994; Schwartz and Zhang, 2003). Safe yield is defined as the ratio of groundwater extraction from a basin for consumptive use over an indefinite period of time that can be maintained without producing negative effects on groundwater quantity, quality or environment. The goal of the safe yield is to achieve a ‘long-term balance’ (e.g., annual) between groundwater use and groundwater recharge in a basin so as to avoid groundwater depletion. Note that the purpose of the safe-yield goal is not to prevent pumping and use of groundwater, rather to limit pumping to the amount of groundwater that can be safely withdrawn each year. A few rules of thumb concerning safe yield are (Schwartz and Zhang, 2003): (i) the annual withdrawal of groundwater should not exceed the average annual recharge, (ii) the withdrawal of groundwater should not lower the groundwater level so that the permissible cost of pumping is exceeded (i.e., pumping becomes uneconomical), (iii) groundwater pumping should not lead to an undesirable deterioration in the quality of groundwater due to influx of contaminants, and (iv) groundwater pumping should not lead to land subsidence.

Although the concept of ‘safe yield’ is widely used as a groundwater management tool, it has been criticized by some groundwater experts for not taking surface water into consideration. As indicated by Eqn. (21.1), excessive pumping not only lowers the groundwater level but also decreases the groundwater outflow into surface water bodies. Many perennial streams across the world dried up as groundwater levels significantly declined due to excessive pumping. Also, plants and animals thrive in fragile ecosystems developed along the perennial streams. These ecosystems are particularly at risk when the overdevelopment of groundwater resources lowers water tables in the riparian zones or results in significant water-table fluctuations. Thus, groundwater plays an important role in sustaining life as well as in sustaining some aquatic and terrestrial ecosystems (Humphreys, 2009; Steube et al., 2009). Further discussion on the concepts of ‘safe yield’ and ‘sustainable yield’ can be found in Alley et al. (1999), Alley and Leak (2004), and Jha (2013). A thorough discussion on the constraints and challenges of sustainable development and management of groundwater resources in developing nations can be found in Jha (2013).

21.3 Salient Techniques for Groundwater Management

A well-organized plan is essential to any groundwater management program, because it relates all necessary tasks, resources and time. During the preparation of a groundwater management plan, the knowledge of possible management techniques plays an important role, among other information. In this section, some useful groundwater management techniques such as ‘conjunctive use of surface water and groundwater’, ‘artificial recharge of groundwater and seawater barriers’, ‘interbasin transfer of water’, ‘intrabasin transfer of water’, ‘indirect recharge through avoidance of pumping’, and ‘control well fields’ are briefly discussed, while Fig. 21.1 illustrates these management techniques. Further details of groundwater management, with salient case studies can be found in Todd (1980), Fetter (2000), Schwartz and Zhang (2003) and Sarma (2009).



   Fig. 21.1. Illustration of salient groundwater management techniques.

(Source: Roscoe Moss Company, 1990)

21.3.1Conjunctive Use of Surface Water and Groundwater

Conjunctive use of surface water and groundwater is a management technique designed to maximize the use of available water resources. The major objectives of conjunctive use technique are: (i) to maximize net benefits, (ii) to increase reliability of supply, (iii) to enhance overall efficiency of a water system, and (iv) to minimize the degradation of ecosystems/environment. It requires a coordinated operation plan for both surface water and groundwater designed to meet demands while ensuring maximum water conservation (Roscoe Moss Company, 1990). Conjunctive use plans vary from percolation of natural streamflows to complex programs involving inter and intrabasin water transfers, with facilities for recharge, extraction, and distribution. Some important benefits of conjunctive use are (Roscoe Moss Company, 1990): (i) reduced surface-water storage facilities, (ii) water conservation, (iii) smaller surface-water networks, and (iv) less evaporation loss.

An excellent discussion on the concept, advantages and constraints of conjunctive use, together with some case studies can be found in Coe (1990), Todd (1980), and Sarma (2009).

21.3.2 Artificial Recharge of Groundwater and Seawater Barriers

Storing surface water into underground formations as groundwater for future use is an established practice in a conjunctive-use program. Groundwater recharge is accomplished by inducing percolation of surface water, thereby replenishing underlying aquifers. Further details of artificial groundwater recharge are given in Section 21.4.

When pumping near coastal areas creates depressions in groundwater levels, seawater migrates into the inland and contaminates underlying freshwater aquifers.  Protection of coastal aquifers against seawater intrusion requires some kind of seawater barriers such as a ridge of ‘protective groundwater elevations’ constructed through the use of a line of injection wells (recharge wells) along the seashore or a ‘pumping trough’ to intercept intruding seawater. These methods, together with other methods of controlling seawater intrusion into freshwater aquifers are discussed in ASCE (1987).

21.3.3 Interbasin Transfer of Water

In many areas of the world, low precipitation rates, coupled with limited natural surface-water supplies necessitate the import of water from far distances. For example, the California aqueducts bring water hundreds of miles from the areas where surface water is abundant to the southern semi-arid region (Roscoe Moss Company, 1990). This water is either consumed directly or stored in groundwater reservoirs for later recovery. This transfer of water can be done on a seasonal basis, and if sufficient surface-water supplies are available, it can change the dynamics of water utilization. Generally, the water management technique, ‘interbasin transfer of water’ involves huge expenses and raises serious environmental issues. Therefore, proper planning and analysis are essential prior to the adoption of this water management technique.

21.3.4 Intrabasin Transfer of Water

Complex geologic conditions exist in most groundwater development areas. For example, it may be possible to overdraft one area while excessively recharging another, and still not exceed the safe-yield values predicted by regional groundwater budget calculations (Roscoe Moss Company, 1990). Therefore, a detailed basin investigation and analysis is necessary to delineate the areas of excess or deficiency and effectively design optimum pumping, distribution, and recharge programs. This management technique is usually less expensive and more environment friendly (i.e., reduced environmental impact) than the ‘interbasin transfer of water’.

21.3.5 Indirect Recharge through Avoidance of Pumping

This is one of the innovative groundwater management techniques, which makes use of an indirect method of recharge. This technique encourages or requires groundwater users to purchase imported water instead of pumping groundwater (Roscoe Moss Company, 1990). In fact, this is equivalent to recharging the basin by the quantity of water not pumped. Such water management programs are made effective by keeping the costs of imported water supplies equal to or less than the pumping costs. They are implemented periodically by groundwater basin managers to regulate groundwater levels (Roscoe Moss Company, 1990).

21.3.6 Control Well Fields

Another technique used to conserve groundwater is through the use of ‘control well fields’. Control well fields are strategically placed to produce interference effects for the control of hydraulic gradients and induce desirable groundwater-flow directions (Roscoe Moss Company, 1990). Control well fields typically control outflow from basins or restrain contaminant plumes. Well head protection (WHP) strategy used in many developed countries is one example of groundwater management by using the technique of control well fields.

Besides the above-mentioned groundwater management techniques, the specialized techniques like Soil-Aquifer Treatment (SAT) and River Bank Filtration (RBF) are also promising techniques, among others, for managing water-quality problems at a basin or sub-basin scale.

21.4 Artificial Recharge of Groundwater

21.4.1 Concept and Significance

In order to augment the natural supply of groundwater, people artificially recharge groundwater basins. Artificial recharge can be defined as “augmenting the natural movement of surface water into underground formations by some method of construction, by spreading of water, or by artificially changing natural conditions” (Todd, 1980). Various methods have been developed for artificial recharge, including water spreading, recharging through pits and wells, and pumping to induce recharge from surface water bodies such as rivers and lakes (Asano, 1985; Huisman and Olsthoorn, 1983; Johnson and Finlayson, 1988). The choice of a particular recharge method depends on several factors such as local topography, geologic and soil conditions, amount of water to be recharged, and the ultimate use of water. Under special circumstances, the value of land, water quality, or climate can be important factors in the selection of recharge methods (Todd, 1980).

Artificial recharge projects are designed to serve one or more of the following purposes (Todd, 1980):

(1)    Maintain or augment the natural groundwater as an economic resource.

(2)    Coordinate operation of surface and groundwater reservoirs.

(3)    Combat adverse conditions such as progressive lowering of groundwater levels, unfavourable salt balance, or saline water intrusion.

(4)    Provide subsurface storage for locally available surplus surface water or imported surface water.

(5)    Minimize or prevent land subsidence.

(6)    Provide a localized subsurface distribution system for established wells.

(7)    Provide on-site treatment and storage for the reclaimed wastewater for subsequent reuse.

(8)    Conserve or extract energy in the form of hot or cold water.

Thus, in most situations, artificial recharge projects not only serve as water-conservation mechanisms but also help in overcoming problems associated with groundwater overdrafts (Brown and Signor, 1974). To place water underground for future use requires that adequate amounts of water should be present or obtained for this purpose. Sources of recharge water can be storm runoff collected in ditches, basins, or surface/subsurface reservoirs through rainwater harvesting (RWH). Also, in some places, water is imported into a region by a pipeline or aqueduct from a far-off surface water source, which can be used for recharge. A third possibility involves the utilization of treated wastewater, though it often raises environmental concerns.

As to the history of artificial recharge, the artificial recharging of groundwater began in Europe early in the nineteenth century and in the United States of America (USA) near the end of the century; since then artificial recharge schemes have gradually increased throughout the world (Todd, 1980). Recharge basins form integral parts of many Swedish municipal water supply systems. Artificial recharge is widely practiced in Germany to meet industrial and municipal water demands. In the Netherlands, water supply systems for Amsterdam, Leiden, and The Hague include basins for recharging surface water into coastal sand dunes (Todd, 1980). Today, the need for artificial recharge is being felt throughout the world, including developing nations due to already extensive exploitation of groundwater or gradually increasing groundwater withdrawal for different uses. In fact, artificial recharge and rainwater harvesting have emerged as promising and indispensable tools for the efficient management of vital water resources in the face of changing climate and socio-economic conditions.

21.4.2 Methods of Artificial Recharge

A variety of methods have been developed for recharging groundwater artificially (Huisman and Olsthoorn, 1983; Asano, 1985; ASCE, 2001). However, the most widely used methods of artificial recharge are different types of water spreading (Todd, 1980), which involve application of water to the soil/ground surface for enhanced infiltration and then its downward movement through the unsaturated/vadose zone to the aquifer (groundwater). Spreading methods include basin method, stream-channel method, ditch-and-furrow method, flooding method, and irrigation method. Field studies on water spreading methods have shown that many factors govern the rate at which water will enter the soil. However, from a quantitative viewpoint, area of recharge and length of time that water is in contact with soil are most important. The economy of water spreading methods hinges on the maintenance of a high infiltration rate.

Although artificial recharge methods are classified in different ways by different authors, the classification suggested by Bouwer (1999) is discussed in this lesson. Bouwer (1999) classified artificial recharge systems into five types according to permeable materials in which they can be placed (Fig. 21.2): (i) surface basin, (ii) excavated basin, (iii) trench, (iv) shaft or vadose zone well, and (v) recharge well. The surface basin recharge system (Fig. 21.2a) is suitable for soils that are sufficiently permeable, vadose zones that have no clay or other restricting layers, and aquifers that are unconfined. Artificial recharge can be accomplished by excavated basins (Fig. 21.2b) where permeable soils are not available at relatively small depths (e.g., 1 m). Excavated basins are constructed sufficiently deep to reach permeable material available at the recharge site. Trenches (Fig. 21.2c) are used if the permeable material is too deep to remove overlying material, but is within trenchable depth (e.g., less than about 7 m). Trenches are also suitable in soils that are highly stratified with alternating layers of fine and coarse materials (Bouwer, 1999). Large-diameter wells, pits, or shafts (Fig. 21.2d) in the vadose zone can be used when permeable subsurface formation is too deep to use trenches. These shafts can be drilled by bucket augers to a depth of about 50 m with a diameter of about 1 m (Bouwer, 1999). Furthermore, recharge wells (gravity-flow recharge wells or injection wells) penetrating the aquifer (Fig. 21.2e) can be used in situations where permeable surface soils are not available, vadose zones are not sufficiently permeable to transmit water, or aquifers are confined.



 Fig. 21.2. Artificial recharge systems for increasingly deep permeable subsurface formations: (a) Surface basin; (b) Excavated basin; (c) Trench; (d) Shaft or Vadose zone well; (e) Recharge well. (Source: Bouwer, 1999)

For more detailed information on the theory and practice of artificial recharge, the readers are referred to Asano (1985), Pyne (1995), Huisman and Olsthoorn (1983), and ASCE (2001). Some cost-effective methods of artificial recharge are discussed in Jha et al. (2009), whereas the standard guidelines for artificial recharge of groundwater are given in ASCE (2001).

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Suggested Readings

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