Chapter 2

Review of Literature
Chapter-2

REVIEW OF LITERATURE

2.0 Introduction

Groundwater recharge is the downward flow of surface water joining the water table and thereby adding an additional amount of water to groundwater reservoir. Groundwater recharge may be natural or artificial. Natural recharge takes place naturally without any intervention and human effort. Artificial recharge systems are the engineered systems where surface water is put on or in the ground for infiltration and subsequent movement to aquifers to augment groundwater resources (Bouwer, 2002).

According to UNEP artificial recharge of groundwater is the planned human activity of augmenting the amount of groundwater available through the works designed to increase the natural replenishment or percolation of surface waters into the groundwater aquifers, resulting in a corresponding increase in the amount of groundwater available for abstraction (UNEP, 2000). Central Groundwater Board of India defines artificial recharge as the process by which the groundwater reservoir is augmented at a rate exceeding that under natural conditions of replenishment (CGWB, 1994).

The main source of groundwater recharge is the rainfall. The other sources of groundwater recharge are

i. Recharge due to seepage from the canals
ii. Return seepage from the irrigation fields
iii. Seepage from the tanks

At a given locality, recharge is largely governed by number of processes. Infiltration is the first and foremost process that regulates the flow of water to underlying formations. Infiltration is largely dependent on the surface soil conditions and vegetative cover. The infiltrated water may or may not reach the groundwater table because of limitations posed by the processes occurring in the unsaturated zone. There may be considerable reduction in the recharge, even under favorable infiltration rate, due to presence of low conductivity horizons and low transmissivity of the aquifer. In such cases infiltrated water may disappear as interflow to nearby location where it runs off or evaporates instead of joining
water table. It may also happen that surface soil may possess limited infiltration rate, but the aquifer material bears good transmissivity and high percolation rate. If this situation prevails in areas of good rainfall it gives rise to production of high runoff volumes.

Natural recharge is how natural (meteoric) groundwater is formed as the difference between the water inputs into the soil (precipitation and infiltration from the streams, lakes, or other natural bodies) and outputs (evapotranspiration and runoff) (Bouwer, 2002). Natural recharge is typically about 30-50% of precipitation in temperate humid climates, 10-20% of precipitation in dry climates (Bouwer, 1989, 2000c; Tyler et al., 1996).

Based on several field studies, CGWB of India has also estimated the natural groundwater recharge for various zones of India. For alluvial plains covering Indo-Gangetic and inland areas, east coast and west coast recharge varies between 8-22% of precipitation. In hard rock areas of Indian peninsula, recharge was estimated as 5-14% of the precipitation.

Estimation of groundwater recharge and its availability around the year is very important activity for efficient and sustainable groundwater resource management in a given area. Several field methods and groundwater models are available for the estimation of groundwater recharge.

In this chapter a thorough review on groundwater recharge processes, factors affecting groundwater recharge, various methods for the estimation of groundwater recharge and assessment of rechargeable runoff have been presented.

2.1 Recharge Process

Number of processes occurring at the soil surface, in the vadose zone and in the aquifer itself affects the rate of recharge directly or indirectly.

Lerner (1997) put forth three processes by which recharge occurs. These are,

i. Diffuse percolation, as unsaturated flux or a saturated front (Piston-type flow),

ii. Macro-pore flow through root channels, desiccation cracks and fissures, and

iii. Preferential flow caused by unsaturated wetting fronts and different soil physical characteristics within the soil.
Rainfall supplies the land surface with water, soil allows the water to infiltrate to the water table, and a deeper geologic framework provides the permeability necessary for the deeper flow.

The other processes that govern the recharge are summarized below.

### 2.1.1 Infiltration Rate

Infiltration is the first and the foremost process that has its great influence on quantity and rate of recharge, particularly in the situations when surface methods of groundwater recharge are followed. Infiltration is associated largely with the land surface. A natural depression with good infiltrating soils underlain by transmissive aquifers constitutes good sites for the percolation ponds.

### 2.1.2 Vegetation Evapotranspiration

Due to the high evapotranspiration rates, vegetation bears good powers of controlling the groundwater recharge; this fact makes vegetation as an important parameter in assessing the recharge potential at a site. Recharge is generally much greater in the non-vegetated than vegetated regions (Gee et al., 1994) and greater in the areas of annual crops and grasses than in areas of trees and shrubs (Prych, 1998). Enhanced recharge consists mainly of vegetation management to replace the deep-rooted vegetation by shallow rooted vegetation or bare soil, or by changing to plants that intercepts less precipitation with their foliage, thus increasing the amount of water that reaches the soil. In wooded areas, this is achieved, for example, by replacing the conifers with deciduous trees (Querner, 2000). Studies conducted by Gee et al., (1994) at Hanford have shown that when desert plants are present on sandy or gravelly surface soils, deep drainage was reduced but not eliminated.

### 2.1.3 Clogging Ability of Aquifer Material

Water sources for in- and off-channel recharge systems should be of adequate quality to prevent clogging of infiltrating surface by the undue accumulation of suspended solids, by formation of bio-films and biomass on and in the soil; by precipitation of calcium carbonate or other salts on and in the soil; or by formation of gases that remain entrapped in the soil, where they block the pores and reduce hydraulic conductivity. Clogging of the
infiltrating surface and reduction in the infiltration rate are the bane of all artificial recharge schemes (Baveye et al., 1998; Bouwer et al., 2001; Bouwer and Rice 2001). Pretreatment of water to reduce suspended solids and regular drying of the system to enable drying and cracking of clogging layer might be necessary to minimize the clogging effect.

2.1.4 Capillary Rise

Water that has passed the root zone can be assumed to have escaped the evapotranspiration and could recharge the groundwater reservoir. However, mechanisms exist that can cause soil water to ascend from considerable depths, notably under arid and semi arid conditions. Coudrain-Ribstein et al., (1998), for example, report on isotope studies that suggest fluxes of about 1mm/year by capillary rise from the water table at a depth of about 20m.

2.1.5 Vapour Transport

This is another mechanism that produces considerable flux in situations with a temperature gradient. De Vries et al., (2000) measured an average temperature difference of 4°C in the Botswana Kalahari sand beds between the root zone causing upward vapour transport during the winter and downward vapour transport during summer of about 0.2-0.3 mm per season.

2.1.6 Preferential Flow

Percolation of rainwater through cracks, fissures and worm and root channels in the soil (preferential flow paths) is receiving increasing attention from scientists all over the world. De Vries, (2000) reported that preferential flow contributes on average -50% of the estimated recharge, though values as high as 70-90% are known.

De Vries and Simmers (2002) have presented comprehensive studies on various processes, which govern the recharge. They reported that interaction of climate, geology, morphology, soil condition and vegetation determines the recharge process. In addition to infiltration, permeability, rainfall and aquifer parameters, transpiration by vegetation, vapor transport, fluxes of capillary rise and hydraulic gradient from paleoclimatic
conditions remains as an important processes that regulates recharge. Vegetation transpires considerable amounts of water from water table and it’s significant effect was found in the range of 20 to 30 m below ground level. Loss of water by vapor transport and capillary rise was reported as 0.2 to 0.3 mm/season and 1 mm/year respectively.

2.2 Factors affecting groundwater recharge

The mechanism by which water reaches to the saturated zone greatly depends on various aquifer and unsaturated zone properties. Various recharge parameters that have influence on the quantity and rate at which water is recharged are discussed here.

2.2.1 Specific yield

Specific yield is the volume of water that can be drained from the unit volume of aquifer formation under the influence of gravity. Specific yield of aquifer becomes a vital parameter when water table fluctuation method is employed for the estimation of groundwater recharge and also in the estimation of static and dynamic groundwater resource of the area.

Singh, (2002) distinguished between static and dynamic groundwater component. The dynamic groundwater resource is amount of groundwater available in zone of water level fluctuation. Whereas static groundwater component is groundwater contained within the permanently saturated zone of the groundwater reservoir, and represents total groundwater reserve minus the dynamic component.

Static component of groundwater is estimated as :

\[ Q_s = b \times A \times S_y \]  
\[ (2.1) \]

Where: \( Q_s \) = static groundwater reserve (m³)  
\( b \) = thickness of aquifer below the zone of groundwater level fluctuation down to exploitable limit (m)  
\( A \) = areal extent of the aquifer (m²)  
\( S_y \) = specific yield of the aquifer (dimensionless)

Specific yield concept gives clear idea of how much water the aquifer can store and it is a good indicator of storage potential of the aquifer. But how good it is as a reservoir is dependent on how quickly you can get the water out of it. Specific yield increases as
sediment size decreases down to medium sands, but then begins to decrease, as sediments get smaller than medium sand. This is largely due to surface tension of water, which causes more and more of the water to adhere to individual particles, as they get smaller. Small particles have much larger surface area per unit volume and it is this surface area that water spreads over. The water released in the rock to surface tension is called pendular water (Fetter, 2001). Norms for the specific yields provided in the report of Groundwater Resource Estimation committee of CGWB (1997) are presented in Table2.1

### 2.2.2 Hydraulic conductivity

Hydraulic conductivity is the rate at which volume of water is moving through a given area of aquifer when subject to a hydraulic gradient. Hydraulic conductivity is measured in volume per unit time per unit area i.e. m³/m² day or simply as m/day. Some typical values of hydraulic conductivity of aquifer material are presented in Table 2.2.

Permeability is the ability of a rock or a rock or earth material to transmit water, while hydraulic conductivity is a measure of this ability determined by the size and shape of the pore spaces in the medium and their degree of interconnection and also by the viscosity of the fluid.

#### Table 2.1 Norms for selection of Specific yield (%) value for different types of aquifer

<table>
<thead>
<tr>
<th>Aquifer / Area Type</th>
<th>Recommended</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A) Alluvial areas</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandy alluvium</td>
<td>16</td>
<td>12</td>
<td>20</td>
</tr>
<tr>
<td>Silty alluvium</td>
<td>10</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Clayey alluvium</td>
<td>6</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td><strong>B) Hard rock areas</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weathered granite, gneiss and schist,</td>
<td>3</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>with low clay content</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weathered granite, gneiss and schist,</td>
<td>1.5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>with significant clay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weathered or vesicular jointed</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>basalt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laterite</td>
<td>2.5</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Sand stone</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>Quartzite</td>
<td>1.5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Limestone</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Karstified limestone</td>
<td>8</td>
<td>5</td>
<td>15</td>
</tr>
<tr>
<td>Phyllites, shales</td>
<td>1.5</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Massive poorly fractured rock</td>
<td>0.3</td>
<td>0.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

(Source: CGWB, 1997)
Hydraulic conductivity of aquifer formation is a function of under listed parameters of aquifer material:

i.  *Median grain size*. Hydraulic conductivity and grain size has direct relationship. As grain size increases, pore spaces are larger and permeability increases because surface tension effects are reduced.

ii. *Sorting*. In case of poorly sorted material there are more chances of the large pores to get filled by the smaller sized particles because of their movement with the flowing water. This situation gives rise to reduced hydraulic conductivity. However, if the percentage of clay particles is comparatively less they stick to the other larger size particles by the adhesive force and hydraulic conductivity may be of considerable magnitude.

<table>
<thead>
<tr>
<th>Type of formation</th>
<th>cm / hr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unconsolidated deposits</strong></td>
<td></td>
</tr>
<tr>
<td>Gravel</td>
<td>5764.84</td>
</tr>
<tr>
<td>Clean sand</td>
<td>571.347</td>
</tr>
<tr>
<td>Silty sand</td>
<td>57.705</td>
</tr>
<tr>
<td>Silt, loess</td>
<td>0.57083</td>
</tr>
<tr>
<td>Glacial till</td>
<td>0.05707</td>
</tr>
<tr>
<td>Un-weathered marine clay</td>
<td>0.00005</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type of formation</th>
<th>cm / hr</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rocks</strong></td>
<td></td>
</tr>
<tr>
<td>Shales</td>
<td>0.000057</td>
</tr>
<tr>
<td>Un-fractured metamorphic and igneous rocks</td>
<td>0.0000057</td>
</tr>
<tr>
<td>Sandstone</td>
<td>0.057083</td>
</tr>
<tr>
<td>Limestone and dolomite</td>
<td>0.0571347</td>
</tr>
<tr>
<td>Fractured metamorphic and igneous rocks</td>
<td>5.7083</td>
</tr>
<tr>
<td>Permeable basalt</td>
<td>570.83</td>
</tr>
<tr>
<td>Karst limestone</td>
<td>570.83</td>
</tr>
</tbody>
</table>

(Source: Freeze and Cherry, 1979)
iii. *Weathering*, which creates secondary pores

iv. *Degree of fracturing*: a highly fractured zone creates more pathways for the movement of water and the consequence is increased permeability.

v. *Characteristics of fluid (viscosity, density)*

vi. *Anisotropy* gives information about the velocity at which water move in different directions.

In general, unconsolidated sands have high porosity and permeability, which is an indication of better aquifer. A basalt aquifer may also have high hydraulic conductivity if it contains sufficient amount of fractures, and can act as a good aquifer with good water yields.

Another important consideration is layering of the aquifer. Layering determines the method to be adopted for the recharge of the aquifer. If a relatively impervious layer at shallow depth overlies aquifer, the surface spreading methods of recharge will be of no use, as water will start encroaching root zone, and the consequence will be the problem of water logging. Therefore, for having the insight of layering of aquifer strata, it is important to evaluate hydraulic conductivities at different depths.

### 2.2.3 Physiography

An understanding of physiography provinces is useful in developing conceptual model of recharge in a system (Scanlon *et al.*, 2002). This will help in identifying the recharge sources, flow mechanisms and spatial variability in the recharge.

### 2.2.4 Soil texture

Fine textured soils, like clay series, though they are having higher porosities, they are less permeable owing to small size of pores, which imparts high resistance to flow. In contrast, coarse textured soils, like sandy soils, bears good permeability values and has greater recharge rates in general. Cook *et al.*, (1992) have found out an apparent negative correlation between clay content in the upper 2m depths and recharge rate. Therefore, knowledge of the soil texture and their permeability values is highly important in the
recharge schemes where surface spreading techniques are used for the artificial recharge of aquifers.

### 2.2.5 Effective porosity

Effective porosity is the interconnected pore volume or void space in aquifer material that contributes to fluid flow in a reservoir. Effective porosity does not include isolated pores and pore volume occupied by water adsorbed on clay minerals or other grains. Total porosity is the total void space in the rock whether or not it contributes to fluid flow. Effective porosity is typically less than total porosity. Porosity determines the maximum volume of water that can be held in the pores of formation. Porosity of the formation depends on the type of packing of particles (cubical, rhombic or rhombohedral) constituting an aquifer and it practically independent of the diameter of the particles forming an aquifer. Other factors that affect the porosity are,

- Sorting
- Grain shape
- The size and abundance of fractures
- The extent of cementing between particles

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Geologic materials</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Un compacted mud</td>
<td>40 – 70 %</td>
</tr>
<tr>
<td>2.</td>
<td>Unconsolidated sand</td>
<td>25 – 50 %</td>
</tr>
<tr>
<td>3.</td>
<td>Sandstone</td>
<td>5 – 30 %</td>
</tr>
<tr>
<td>4.</td>
<td>Shale</td>
<td>&lt; 10 %</td>
</tr>
<tr>
<td>5.</td>
<td>Unfractured igneous rock</td>
<td>&lt; 5 %</td>
</tr>
<tr>
<td>6.</td>
<td>Unfractured marble</td>
<td>&lt; 3 %</td>
</tr>
</tbody>
</table>

*(Catherine, 2004)*
Taneja and Khepar (1996), carried out investigations on effect of artificial recharge on the various parameters of the aquifer using a sand tank model simulating the confined aquifer. A cavity well was constructed, and analytical solution of the well hydraulics was developed. By discharging and recharging the well, data on the rise and fall of the water table were collected. Aquifer parameters were estimated by substituting these data in the analytical solution. It was observed that during the recharge through the well, the hydraulic conductivity and the specific storage coefficient of the aquifer decreased by 15% and 13% respectively in relation to those of discharge. Also, the aquifer parameters found to be least affected with the change in the rate of recharge or discharge.

2.3 Methods for estimation of groundwater recharge

Number of methods is available in the literature for the estimation of natural and artificial recharge to the aquifer, selection of which depends on available data, local geographic and topographic conditions, spatial and temporal scale required and reliability of results obtained by different methods. According to Scanlon et al. (2002) techniques based on the surface water and unsaturated-zone data provide estimates of potential recharge, whereas those based on groundwater data provides estimate of actual recharge. Owing to uncertainties involved in each approach, he suggested to use multiple techniques to increase the reliability of the results.

2.3.1 Water table fluctuation (WTF) method

In the application of WTF method the basic assumption is that, the rise in the groundwater level in unconfined aquifer is only due to recharge water arriving at the water table. Recharge is calculated as

\[ R = S_y \frac{dh}{dt} = S_y \frac{\Delta h}{\Delta t} \]  \hspace{2cm} (2.2)

Where,

\[ R = \text{rate of recharge (LT}^{-1}) \]
\[ S_y = \text{specific yield, (M}^0\text{L}^{-1}\text{T}^0) \]
\[ Dh = \Delta h = \text{water table rise, (L)} \]
\[ Dt = \Delta t = \text{time within which rise dh takes place, (T)} \]
The value of \( R \) obtained above can be multiplied by areal extent of aquifer to get recharge in terms of volume per unit time.

A time lag occurs between the arrival of water and its redistribution to the other components like base flow, groundwater evaporation and net sub-surface flow from an area. WTF method can be applied over longer time intervals (seasonal or annual) to estimate the change in subsurface storage. Healy et al. (2002) reported that the WTF method for estimation of groundwater recharge was applied as early as the 1920s (Meinzer, 1923; Meinzer and Stearns, 1929) and since then has been used in numerous studies.

The method is quite simple as no assumptions are made on the mechanism by which water reaches to groundwater. The method has some disadvantages also. Water table fluctuation method is applicable to only unconfined aquifers and the method cannot account for steady rate of recharge. This means, if the rate of recharge from an area is equal to rate of drainage, water levels will not change and WTF method will predict no recharge. Other difficulties arise in calculation of specific yield values.

Many researchers have tried this method for the estimation of groundwater recharge. Allison et al., (1990) employed water table fluctuation method for estimation of artificial recharge in southern Australia. They observed groundwater levels that were steadily increasing at 0.1 m/year following clearing of native vegetation. Assuming a specific yield of 0.2 this corresponds to an increase in recharge of 20 mm/year. This value was found consistent with the recharge estimated by other independent methods.

Comprehensive reviews on the groundwater recharge estimation methods that are based on groundwater level data were presented by Healy and Cook (2001). They concluded that WTF method that uses specific yield and variations in water table level over time might be the most widely used method for the estimation of groundwater recharge.

### 2.3.2 Water budget method

The water budget methods are those that are based on water budget equation. The water budget of a basin can be stated as

\[
P + Q_{on} = ET + Q_{off} + \Delta S \quad \text{.................................(2.3)}
\]
Where,

\( P \) = precipitation (and may also include irrigation) (mm/day)

\( Q_{on} \) and \( Q_{off} \) = water flow onto and off the site (surface flow, interflow and groundwater flow) (mm/day)

\( ET \) = evapotranspiration (mm/day) and

\( \Delta S \) = change in storage (mm/day).

Based on the above water balance equation, Schict and Walton (1961) formulated the budget equation for recharge estimation as:

\[
R = \Delta S_{gw} + ET_{gw} + (Q_{off}^{gw} - Q_{on}^{gw}) + Q^{bf} \tag{2.4}
\]

Where,

\( R \) = recharge

\( \Delta S_{gw} \) = change in subsurface storage

\( Q^{bf} \) = base flow

\( ET_{gw} \) = evaporation from groundwater and

\( Q_{off}^{gw} - Q_{on}^{gw} \) = net surface flow from the basin

In above model all other parameters, except \( R \), can be measured or estimated. This method can be adopted for wide range of spatial and temporal scales. However, major limitation of this approach is that the accuracy of the recharge estimates depends on the accuracy with which other components of the water balance equation are measured (Scanlon et al., 2002).

2.3.3 Darcy’s law

Darcy’s law states that fluid flux; such as recharge in an aquifer system can be calculated if both the head gradients and hydraulic conductivities are known. Darcy’s law is used to calculated recharge (\( R \)) in the saturated zone according to the following equation:

\[
R = -K(\theta) \frac{dH}{dz} = -K(\theta) \frac{dh}{dz} (h + z) = -K(\theta) \left( \frac{dh}{dz} + 1 \right) \tag{2.5}
\]

Where,

\( K(\theta) \) = hydraulic conductivity at the ambient water content,

\( H \) = total head, and
h = metric potential head
z = horizontal distance between the two points where hydraulic head is measured

Application of Darcy’s law requires measurements or estimates of the vertical total head gradient and the unsaturated hydraulic conductivity at the ambient soil-water content. The method has been applied in many studies under arid and semiarid conditions (Enfield et al., 1973; Sammis et al., 1982; Stephens and Knowlton 1986) and also under humid conditions (Ahuja and El-Swaify 1979; Steenhuis et al., 1985; Kengni et al., 1994; Normand et al., 1997).

In the areas where thick unsaturated zone exists in uniform porous media the value of metric potential head can be assumed to be 1. (unit-gradient assumption)(Gardner, 1964; Childs, 1969; Chong et al., 1981 and Sisson, 1987). The unit-gradient assumption removes the need to measures the metric pressure gradient and sets recharge equal to the hydraulic conductivity at the ambient water content.

2.3.4 Empirical relationships

Empirical relationships can also be developed between groundwater recharge and rainfall based on seasonal groundwater balance studies. Kumar and Seethapathi (2000) made one such attempt for Upper Ganga Canal command area. An empirical relationship was suggested for estimation of the ground water recharge by fitting the estimated values of rainfall recharge and the corresponding values of rainfall in the monsoon season through the non-linear regression techniques. The relation between rainfall and recharge is shown by the equation as

\[ R = 0.63 (P - 15.28)^{0.76} \]  

Where,

- \( R \) = recharge (m)
- \( P \) = precipitation (m)

The above equation is based on Chaturvedi (1973) formula for Ganga-Yamuna doab.
2.3.5 Groundwater models

Recharge measurements in the field still contain an appreciable amount of uncertainty and much study on the subject is ongoing (Sanford, 2002). Along with the variety of approaches used to make measurements in the field, investigators have used groundwater models in estimating recharge. Models can also be used to predict distribution of recharge in temporal and spatial scales based on the geologic properties and rate of recharge.

Groundwater flow and contaminant transport models are being extensively used in the studies related to groundwater systems. Groundwater flow models are used to calculate the rate and direction of movement of groundwater through aquifers and confining units in the subsurface. These calculations are referred to as simulations. The simulation of groundwater flow requires a thorough understanding of the hydro-geologic characteristics of the site (DEQ, 2001-2004).

The accuracy of model predictions depends upon successful calibration and verification of the model in determining groundwater flow directions, and transport of contaminants. In relation with groundwater models, Sanford (2002) has highlighted two important issues. As recharge is a fundamental component of the groundwater models, while reviewing one must assess how recharge is represented in the groundwater models and how recharge is estimated using groundwater models. Use of groundwater models is very fruitful. The analysis proposed by artificial recharge scheme has been improved by groundwater modeling exercises (Peters, 1998; Latinopoulos, 1981).

2.3.6 Tracer techniques

Recently, the techniques based on the heat or chemical isotopic tracers are gaining much importance in the estimation of groundwater recharge. Measuring the concentration of the environment tracers that indicate groundwater age has been increasingly popular approach in this field. Number of articles and research papers about application and theories of isotopic methods for characterizing groundwater and recharge are available. In the field of groundwater, isotopic tracers provide a powerful investigative tool. Coplen (993) reported that another major technological growth area has been in the application of isotopic analysis to groundwater hydrology, wherein isotopic measurements are being
used to help interpret and define groundwater flow paths, ages, recharge areas, leakage, and interactions with surface water.

Datta (1999) used the signatures of $^{18}$O isotopes to investigate groundwater occurrence and recharge in the National Capital Territory (NCT) of Delhi. These signatures revealed that groundwater in well of Delhi area are a mixture of varying proportions of different water sources and the aquifer in the area does not constitute a homogeneous system in lateral extent.

Due to large uncertainties involved in the measurement of individual parameters of each method, many researchers (Healy and Cook, 2002, Scanlon et al., 2002) have suggested that it is highly beneficial to apply multiple methods of estimation to arrive at somewhat reliable results.

McCartney and Houghton (1998) used three independent methods for the computation of groundwater recharge on the Channel Island of Jersey. These are (a) chloride balance, (b) stream base flow analysis, and (c) rainfall-recharge-runoff simulation. All three methods produced reasonably consistent results, indicating that long-term recharge is 16-19% of average annual rainfall, and results of modeling indicate that groundwater abstraction may have exceeded recharge in 5 out of 28 years.

### 2.4 Estimation of groundwater recharge rate and potential

Groundwater recharge rate, which is the rate at which the water table is replenished (during rainfall, irrigation or from seepage from surface water bodies), is the single most important parameter one needs to know in developing the groundwater resource. It is also important as one of the important inputs into groundwater management models and in the studies of contamination and pollution of groundwater resources and determination of safe dumping sites for wastes.

In order to represent recharge effectively in a groundwater model, one must consider both the processes that control the rate of recharge and objectives of the modeling study (Sanford, 2002). The factors that control the rate of recharge are related to hydrologic landscape of the aquifer system. The three main factors in the hydrologic landscape that
control water flow are classified by winter (2002) as climate, topology and geologic framework.

Proper assessments of groundwater recharge and potential are the two factors of paramount importance in the management of groundwater resources in optimal manner. Gee et al., (1994) studied the recharge potential under three distinct and different climatic and soil conditions. All three sites showed increased water storage with time when soils are coarse textured and plants are removed from the surface, the rate of increase was found to be influenced by climatic variables such as precipitation, radiation, temperature and wind. Recharge from bare sandy soil was estimated as of the order of 10 to >50% of the annual precipitation.

Brand (2003) assessed the potential for artificial recharge in the upper black squirrel creek basin, Colorado, using chloride mass balance techniques for the quantification of natural recharge. He investigated other aquifer properties like lithology by drilling test holes; percolation rates by conducting constant head bore hole percolation testing. Infiltration rates (analogous to vertical hydraulic conductivities) were calculated using the methodology developed by Bouwer et al., (1998). The chloride mass balance analysis revealed that natural recharge rate to the aquifer was approximately 5.2 cm per year.

Ali and Turner (1997) put forth an innovative idea for the recharge of groundwater in Eastern Goldfields of Western Australia. They proposed to investigate the feasibility of harvesting the periodically available surface water resources in the region that accumulate in natural impoundments such as salt lakes, and artificially recharging them into shallow aquifers for later recovery and use, provided the aquifer used for the recharge was having sufficient storage potential.

Smith (1968) established a criterion for the estimation of the recharge potential of the aquifer based on the parameters like thickness and areal extent of the aquifer, minimum economical withdrawal rate; as well as the limits of the turbidity, temperature, and mineral and bacteriological quality of the recharge water. These recharge criteria were applied to areas of Illinois where aquifers were known to exist. Estimates show large potential for artificial recharge in to the surface sands and gravel aquifers of the state.
Kaledhonkar et al., (2003) carried out a case study on artificial groundwater recharge through recharge tube wells constructed in the bed of old Sirsa canal bed in the North-Eastern region of the state of Haryana. Location for the tube wells were selected based on the electrical resistivity surveys. Performance of the recharge wells was evaluated based on the water level observations in the grid of observation wells installed on one side of the canal. The recharge tube wells performed well with an average recharge rate of 10.5 lps for individual well, which was reasonably good.

2.5 Assessment of rechargeable runoff

In order to augment the depleting ground water resources, it is essential that the surplus monsoon runoff that flows into the sea is conserved and recharged to augment ground water resources. Ground water storage that could be feasible has been estimated as 214 Billion Cubic Meters (BCM) of which 160 Billion Cubic Meters is considered retrievable. The Central Ground Water Board (CGWB) has prepared the master plan for artificial recharge to ground water for all states in the country. Out of total geographical area of 3287263 sq. km. of the country, an area of 448760 sq. km. has been identified feasible for artificial recharge. The total quantity of surplus monsoon runoff that can be recharged, works out to be 36.4 BCM. The master plan envisages number of artificial recharge and water conservation structures around 39 lakh in the country at an estimated cost of Rs. 24500 crores.

Runoff is an important parameter in the watershed management and in flood prone areas necessitating flood control measures. Reliable prediction of runoff from an un-gauged watershed is tedious and time consuming. However, this problem can be well circumvented by Soil Conservation Service Curve Number method of runoff prediction. Curve Number (CN) is a quantitative descriptor of the land use/land cover and soil characteristics of a watershed and is commonly assigned values based on information acquired from field surveys and/or interpretation of aerial photographs. Remote Sensing and Geographic Information System technique can be used effectively to generate the land use/land cover and change detection map for evaluating the changes in an area.

Tiwari et al. (1991) reported that, the observed volume of runoff and that estimated using remote sensing and GIS technique have close correlation and the coefficient of correlation
was found to be 0.80. Many researchers (Slack and Welch, 1980, Pandey and Sahu, 2002) have utilized the satellite data to estimate the USDA Soil Conservation Service Runoff Curve Number. To arrive at any optimal artificial recharge scheme for a basin, assessment of rechargeable runoff stays as a factor of prime importance. Surface runoff, which is highly variable and of short duration, does not occur during peak demand periods. Because there are no reservoirs, the runoff is lost by evaporation from shallow playas.

Biwalkar and Taneja (2003) analyzed the rainfall data and estimated the volume of non-committed surplus runoff for the ‘kandi’ area of Punjab. After studying well logs at two different locations, recharge well was suggested as the best suitable means of recharging available surface water into aquifers owing to the presence of three clay layers above water table which obstructed the percolation of surface water. The least hydraulic conductivity among various layers was found to be the controlling factor for groundwater recharge rate.

Bouwer and Rice (2001) proposed that some form of storage is needed where streams with varying flows are used for artificial recharge and the major runoff events occur in short “bursts”, and where recharge system do not have enough capacity to absorb all the high flows at once. Water so stored can later be released slowly to the recharging structure. Turbid floodwaters for artificial recharge of groundwater may best be captured and stored in deep reservoirs where solids can settle to the bottom before water is diverted to the recharge system. The optimum combination of reservoir capacity for capturing the flood flows and of recharge capacity for storing them underground depends on the magnitude of flood flows to be captured, availability of land for storage and recharge, water needs, eco-environmental aspects, economics, and other local conditions.

2.6 Delineation of potential groundwater recharge zones

Identifying aquifer recharge area is important, as any pollution in these areas could affect the cleanliness of the aquifers and the purity of the water that comes from them (Ravella et al., 1996). In an effort to develop a better understanding of ground water recharge processes and to identify aquifer recharge areas in the Keene region, Ravella et al., (1996) determined soil infiltration rates and soil moisture contents, and monitored soil tension, water table and piezometric head levels over time at selected sites. Sites having high
infiltration rate followed by high percolation and good aquifer hydraulic conductivity was selected as potential area for groundwater recharge.

The CGWB has prepared a Manual and subsequently a Guide on Artificial Recharge to Ground Water which provides guidelines on investigation techniques for selection of feasible sites, planning & design of artificial recharge structures, economic evaluation & monitoring of recharge facility. These are of immense use to States/U.T.s in planning and implementation of artificial recharge and rain water harvesting schemes for augmentation of ground water in various parts of the country.

During the Ninth Five Year Plan, a Central Sector Scheme “Studies on Recharge of Ground Water” was undertaken by the CGWB, in which 165 artificial recharge pilot projects were implemented in 27 States/UTs in coordination with organizations of State governments & NGO / VOs, etc. with 100% central funding. Civil works were done by state implementing agencies under technical guidance of the CGWB. State wise details of pilot artificial recharge and rainwater harvesting projects along with their cost is indicated in Annexure I. Efficacy of the recharge structures constructed in different hydrogeological conditions of the country was assessed through impact assessment studies taken after completion of recharge facility and has indicated rise in water levels and sustainability of dug wells/ tube wells locally including other benefits like decrease in soil erosion and improvement in socio-economic status of farmers of benefited zone due with increase in crop production.

The decline in water levels indicates that much of the water has been withdrawn from storage and will continue to decline unless groundwater withdrawals are decreased and recharge areas are maintained. Location of groundwater recharge areas is important in developing groundwater management strategies to protect these areas from the negative impacts of land-use (Braun, et al., 2001).

Jyothiprakash et al. (2003), delineated the potential artificial recharge zones in Agniar-Ambuliar-Southvellar river basin in Tamilnadu through integration of various thematic maps using Arc View GIS. Thematic maps pertaining to geology, permeability, effective soil depth, drainage density, soil texture, water holding capacity and physiography were prepared. Each theme was assigned a weightage depending on its influence on the
groundwater recharge. Ranking method was followed for the delineation of the potential recharge areas and final map was prepared showing four different categories of the potential zones for artificial recharge. The study showed that the areas having rapid permeability with higher water holding capacity in alluvium soil are excellent zones for constructing artificial recharge structures.

2.7 Application of models in groundwater studies

The earlier generation of irrigation performance indicators was based on canal flow data. Commonly, they quantify performance in a command area downstream of a discharge measurement device. Remote sensing determinants, such as actual evapo-transpiration, soil water content and crop growth reflect the overall water utilization at a range of scales, up to field level. Crop evapo-transpiration includes water originating from irrigation supply, water from precipitation, groundwater and water withdrawn from the unsaturated zone. Hence, this is a refinement in spatial scale as compared to the classically collected flow measurements, and describes moreover depletion from all water resources. If these possibilities are well implemented, we expect that a new generation of irrigation performance indicators can be quantified in a cost-effective manner. Especially, because satellite measurements pave a way to standardize data collection between different irrigation schemes among different countries at costs which are currently decreasing. These challenges can only turn into a success if irrigation managers are involved in pilot projects and demonstration studies exploring satellite data. W.G.M. Bastiaanssen (2007).

James et al., (1980) reported that use of numerical models requires an understanding of the physical problem and field data. To use these models, the hydrologist must assess the merits of alternative numerical methods, evaluate available data, estimate data where missing or absent, and interpret computed results. The review of previous model application can provide valuable insight on how these tasks may be approached. They stated that it may be necessary to modify some of the input data until all observed and predicted ground water table values compare sufficiently well. Parameter estimation techniques are used to modify the initial estimates of input data. They also warned about the misuse of models, like assuming 3D flow and inappropriate grid size, which results in additional work and expense.
James *et al.*, (1981) stated that Ground-water modeling is a tool that can help analyze many ground-water problems. Models are useful for reconnaissance studies preceding field investigations, for interpretive studies following the field program and also to estimate future field behavior. In addition to these applications, models are useful for studying various types of flow behavior by examining hypothetical aquifer problems. Before attempting such studies, however, one must be familiar with ground water modeling concepts, model usage and modeling limitations.

Rao and Sharma (1981) derived an equation for the formation of groundwater mounds on recharge from a rectangular area to a finite aquifer. This numerical solution described the actual field response of water table to recharge better than the equations derived for infinite aquifers. They assumed that the aquifer is resting on a horizontal and impermeable base.

Huston (1993) studied the well field, Kabwe, Zambia and reported that the response of water level fluctuations were dependent upon pumping rates and prior rainfall and can be simulated by a simple linear regression model. The rate of dewatering of mine was shown to be dependent upon mine size and antecedent rainfall, and could also be simulated by a multiple linear regression model. Such models can be used for forecasting and control of groundwater systems, where more costly and complex methods cannot be used. He also cautioned about the principal limitation of multiple linear regression models that it needs data collected over a reasonable time span for producing meaningful results.

Viswanathan (1983) used the recursive least squares method to develop linear model, which estimates the daily water level in the borehole, given the rainfall on the same day and up to eight days before. He concluded that soil parameters that determine the infiltration rates are time dependant and their variation can be tracked by introducing “forgetting factor”. This factor cutback the memory of the algorithm, hence the parameter values depend on the current values of levels and rainfall than on past values.

Prihar *et al.*, (1993) used the water table rise and fall along with the agro-climatic zones to divide the Punjab into agro-climatic irrigation zones. They mentioned that the difference in water supply and water requirement to meet the ET of the crops grown in
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each irrigation zone and the utilizable water supply exclusive of marginally fit and unfit (for irrigation) ground water supplies, changes in groundwater level would depend upon the balance between water supply and water requirement. The Directorate of Water Resources, Punjab has used the average water table rise and fall in blocks values and the weighted average rise and fall for each irrigation zone. They also reported that the rising water table does not mean that the supply exceeds the demand. Due to brackish groundwater, in certain zones the utilizable supply is less than the total supply that affects the changes in ground water level.

El-Kadi et al., (1994) reported that the groundwater modeling is generally hindered by the lack of information about the groundwater system for data preparation and result analysis. Such a lack of information usually demands for use of a tedious iterative methodology within a sensitivity analysis scheme. These kinds of situations were managed by using GIS. They integrated the modeling environment with the GIS as an item in the main menu. The formulation of the groundwater-modeling environment necessitated creation of a spatial mesh with parameter values that were assigned to each element or node of the mesh. They also reported that the aquifer parameters were usually known at a limited number of sampling points. The values assigned to the elements were estimated by interpolation. They also stated that the integrated system that they used was suitable for extracting and interpolating from the point measurements from the maps. Through this, the data can be imported and exported to or from the cells.

Watkins et al., (1996) reported that the Geographic Information Systems (GISs) offer data management and spatial analysis capabilities that can be useful in ground-water modeling. They also reported that GIS was used for automatic data collection, systematic model parameter assignment, spatial statistics generation, and the visual display of model results. To utilize these abilities, however, GIS and Ground-water models must be able to communicate with each other. They used the finite difference method that employs rectangular discretization in which the parameter values are entered and the hydraulic heads are computed for each cell. The MODFLOW (3-D Groundwater Model) was linked with the Arc/Info and named as MODFLOWARC, which needs no data transfer programs to be written separately. They assumed that the flow in the aquifer was horizontal. Stacking grid layers was done to specify the interaction between them, which often represent the three dimensional finite difference models.
Harrington (1998) developed a multiple linear regression model of water table response to pumping. Their multiple regression models uses the relationship between the measured water table fluctuations at monitoring wells, records of pumping and runoff to predict the response of the water table for a given amount of pumping and recharge.

Johnson et al., (1998), stated that the Numerical models such as MODFLOW, provide an excellent tools to assist in the water resource decision process. A simplified representation of the system may in some cases, be obtained by the development of response functions from numerical models. These functions express temporal relationships between causes and effect at specific points within the aquifer and are developed through simulation. It is also reported that the Numerical models such as MODFLOW can produce predictive simulations of cause and effect when properly calibrated and applied to an area. This process normally, involves comparing results of a series of predictive scenarios with the observations, possibly projecting the current conditions into future. The process is valid and useful; however, it requires at least one simulation and comparison for each problem. They also emphasized about the response function of the aquifer system under different stress conditions. The response functions are analytical expressions, graphs or coefficients that describe the relative response of the aquifer system at a given location to a unit stress.

Manglik and Rai (1998) stated that an accurate estimation of water table fluctuations helps in controlling the changes in groundwater regime by selecting an appropriate scheme of recharging and pumping. Since most of the existing solutions on this subject are based on the assumption of constant rate of recharge, they made an attempt by considering the recharge as a time dependant parameter. The rate of recharge follows approximately a similar pattern of variation with less intensity and little time lag. When recharge rate decreases to a minimum prescribed level, the recharge operation is discontinued for some time and after drying, if necessary, scraping and cleaning of the bottom of the basin. They also demonstrated that the solutions based on the assumption of constant recharge rate failed to predict the declining trend of water table, which is due to the decrease in the recharge rate. Therefore, it would be more appropriate to consider the rate of recharge as time varying. Based on these, they developed an analytical solution to simulate water table variations in response to recharge and withdrawal of groundwater from multiple basins and wells, respectively.
Tain-Shing et al., (2001) reported that the interest in restoring the habitat along riparian corridors has necessitated quantifying the interaction between the surface and groundwater conditions, particularly in the lower flow conditions, understanding the transient nature of the river seepage losses and groundwater accretions / depletions is critical in assessing the surface and subsurface riparian environment. They described the application of MODFLOW for simulating the effects of changes in surface water flow on groundwater elevations. They reported that the calibration is initiated with the available data, but the rigorous calibration demands for large data. They also reported that the model is calibrated for steady state and transient state conditions. Since data for the most of the areas are unavailable to conduct rigorous calibration, steady state groundwater elevation is assumed and compared with the existing conditions. Though they are not serving the full calibration purposes, the simulations showed that the model representations were not unreasonable. The sensitivity analysis was conducted for different river flow conditions like flows at 5%, 20%-30% and 60% exceedance levels.

Sakthivadivel and Chawla (2002) studied the behavior of water table and its slope in space and time in Lakhaoti branch command area, a part of Madhya Ganga Canal Project of Uttar Pradesh. A program was developed to take irregularly spaced data and convert it to regularly spaced form to create a surface representation. Using Kriging interpolation method, and using data from 102 irregularly located observation wells, a regularly spaced grid at 2km spacing was created and groundwater elevations were computed and smoothened using a smoothing option. The deeper water table depth was mostly confined to a limited area farther away from the branch canal. Water table along the boundaries of the study area was higher than the middle portion of the area in the initial years. However, in the subsequent years, the gradient from the drains towards the central portion of the study area was either negligible or negative. Canal water supply had not only arrested the lowering of water table but also helped to raise the water table in an incremental fashion over the years. They also reported that the tail reach area has taken longer time than head reach area in responding to canal water recharge. This was primarily because much of the canal water is used in the upstream reach due to inadequate infrastructure for water distribution in the tail reach.

Review of literature presented in the preceding section reveals that, for sustainable utilization of groundwater resource, there is need to estimate the recharge potential of a
given area. This necessitates the selection of proper groundwater recharge estimation method based on available data and the conditions prevailing in the study area. Recharge estimation requires careful study and thorough understanding of the recharge processes. Review also suggests that delineation of the potential groundwater recharge zone is one of the most important inputs in the planning process of the groundwater recharge project. Review of literature also suggests that rainfall is the major source of recharge, and to recommend artificial recharge scheme for a basin, assessment of runoff available for the groundwater recharge is an important activity. In the absence of other sources for recharge, volume of runoff is a deciding factor for the type and number of recharge structures required for the artificial groundwater recharge. Review on ‘groundwater models for simulation studies’ showed that, there are several models available for estimation of groundwater recharge. However, selection of appropriate model depends on the available data and soil and aquifer properties. Based on the review, it can be also said that MODFLOW can be used for the prediction of water table fluctuation resulting from groundwater recharge and pumping.