TRAINING COURSE

ON

# SOFTWARE FOR GROUNDWATER DATA MANAGEMENT

UNDER

## WORLD BANK FUNDED HYDROLOGY PROJECT

**LECTURE NOTES**
**ON**

# GROUNDWATER BALANCE

(UNIT-1)

**BY**

***C P KUMAR***

***ORGANISED BY***

**NATIONAL INSTITUTE OF HYDROLOGY**
**ROORKEE - 247 667**
**INDIA**

# RECHARGE FROM RAINFALL & IRRIGATION RETURN FLOW

## 1. INTRODUCTION

Water balance techniques have been extensively used to make quantitative estimates of water resources and the impact of man's activities on the hydrologic cycle. The study of water balance is defined as the systematic presentation of data on the supply and use of water within a geographic region for a specified period. With water balance approach, it is possible to evaluate quantitatively individual contribution of sources of water in the system, over different time periods, and to establish the degree of variation in water regime due to changes in components of the system.

The basic concept of water balance is :

Input to the system - outflow from the system = change in storage of the system (over a period of time)

The general methods of computations of water balance include:

(i) identification of significant components,
(ii) evaluating and quantifying individual components, and
(iii) presentation in the form of water balance equation.

### 1.1 Ground Water Balance Equation

Considering the various inflow and outflow components, the terms of the ground water balance equation can be written as:

$$R_i + R_c + R_r + R_t + S_i + I_g = E_t + T_p' + S_e + O_g + \Delta S$$

where,

$R_i$ = recharge from rainfall;
$R_c$ = recharge from canal seepage;
$R_r$ = recharge from field irrigation;
$R_t$ = recharge from tanks;
$S_i$ = influent seepage from rivers;
$I_g$ = inflow from other basins;
$E_t$ = evapotranspiration;
$T_p$ = draft from ground water; .
$S_e$ = effluent seepage to rivers;
$O_g$ = outflow to other basins; and
$\Delta S$ = change in ground water storage.

All elements of the water balance equation are computed using independent methods wherever possible. Computations of water balance elements always involve errors, due to shortcomings in the techniques used. The water balance equation therefore usually does not balance, even if all its components are computed by independent methods. The discrepancy of water balance is given as a residual term of the water balance equation and includes the errors in the determination of the components and the values of components which are not taken into account.

The water balance may be computed for any time interval. The complexity of the computation of the water balance tends to increase with increase in area. This is due to a related increase in the technical difficulty of accurately computing the numerous important water balance components.

## 1.2 Data Requirement

The data required for carrying out the ground water balance study can be enumerated as follows :

Rainfall data

Monthly rainfall data of sufficient number of stations lying within or around the study area should be available. The location of raingauges should be marked on a map.

Land use data and cropping patterns

Land use data are required for estimating the evapotranspiration losses from the water table through forested area. Crop data are necessary for estimating the spatial and temporal distributions of the ground water withdrawals and canal releases, if required. Evapotranspiration data and monthly pan evaporation rates should also be available at few locations for estimation of consumptive use requirements of different crops.

River data

River data are required for estimating the interflows between the aquifer and hydraulically connected rivers. The data required for these computations are the river gauge data, monthly flows and the river cross-sections at a few locations.

Canal data

Monthwise releases into the canal and its distributories along with running days each month will be required. To account for the seepage losses, the seepage loss test data will be required in different canal reaches and distributories.

Tank data

Monthly tank gauges and releases should be available. In addition to this, depth vs area and depth vs capacity curves should also be available. These will be required for computing the evaporation and the seepage losses from tanks. Also field test data will be required for computing final infiltration capacity to be used to evaluate the recharge from depression storage.

Aquifer parameters

The specific yield and transmissivity data should be available at sufficient number of points to account for the variation of these parameters within the area.

Water table data

Monthly water table data or at least pre-monsoon and post-monsoon data of sufficient number of wells should be available. The well locations should be marked on a map. The wells should be adequate in number and well distributed within the area, so as to permit reasonably accurate interpolation for contour plotting. The available data should comprise reduced level (R.L.) of water table and depth to water table.

Draft from wells

A complete inventory of the wells operating in the area, their running hours each month and discharge are required for estimating ground water withdrawals. If draft from wells is not known, this can be obtained by carrying out sample surveys.

The estimation of a few important inflow and outflow components of the ground water balance equation are discussed below.

## 2. RECHARGE FROM RAINFALL

Part of the rain water, that falls on the ground, is infiltrated into the soil. This infiltrated water is utilized partly in filling the soil moisture deficiency and part of it is percolated down reaching the water table. This water reaching the water table is known as the recharge from rainfall to the aquifer. Recharge due to rainfall depends on various hydrometeorological and topographic factors, soil characteristics and depth to water table. The methods for estimation of rainfall recharge involve the empirical relationships established between recharge and rainfall developed for different regions, ground water estimation committee norms, water balance approach, and soil moisture data based methods.

## 2.1 Empirical Methods

(i) Chaturvedi formula

Based on the water level fluctuations and rainfall amounts in Ganga-Yamuna doab, Chaturvedi in 1936, derived an empirical relationship to arrive at the recharge as a function of annual precipitation.

$$R = 2.0\ (P - 15)^{0.4}$$

where,

R = net recharge due to precipitation during the year, in inches;
P = annual precipitation, in inches.

This formula was later modified by further work at the U.P. Irrigation Research Institute, Roorkee and the modified form of the formula is

$$R = 1.35\ (P - 14)^{0.5}$$

The Chaturvedi formula has been widely used for preliminary estimations of ground water recharge due to rainfall. It may be noted that there is a lower limit of the rainfall below which the recharge due to rainfall is zero. The percentage of rainfall recharged commences from zero at P = 14 inches, increases upto 18 % at P = 28 inches, and again decreases. The lower limit of rainfall in the formula may account for the soil moisture deficit, the interception losses and potential evaporation. These factors being site specific, one generalized formula may not be applicable to all the alluvial areas.

Tritium tracer studies on ground water recharge in the alluvial deposits of Indo-Gangetic plains of western U.P., Punjab, Haryana and alluvium in Gujarat state have indicated variations with respect to Chaturvedi formula.

(ii) Amritsar formula

Using regression analysis for certain doabs in Punjab, Sehgal developed a formula in 1973 for Irrigation and Power Research Institute, Punjab.

$$R = 2.5\ (P - 16)^{0.5}$$

where, R and P both are measured in inches.

(iii) Krishna Rao

Krishna Rao gave the following empirical relationship in 1970 to determine the ground water recharge in limited climatological homogeneous areas :

$$R = K\ (P - X)$$

The following relation is stated to hold good for different parts of Karnataka :

$R = 0.20 (P - 400)$ for areas with annual normal rainfall ($P$) between 400 and 600 mm
$R = 0.25 (P - 400)$ for areas with $P$ between 600 and 1000 mm
$R = 0.35 (P - 600)$ for areas with $P$ above 2000 mm

where, R and P are expressed in millimetres.

The relationships indicated above, which were tentatively proposed for specific hydrogeological conditions, have to be examined and established or suitably altered for application to other areas.

## 2.2 Ground Water Estimation Committee Norms

A committee 'Ground Water Estimation Committee' was constituted in 1982 to improve the existing methodologies for estimation of the ground water resource potential. It was recommended that the ground water recharge should be estimated based on ground water level fluctuation method. However, in areas, where ground water level monitoring is not being done regularly, or where adequate data about ground water level fluctuation is not available, adhoc norms of rainfall infiltration may be adopted. As a guideline, following norms for recharge from rainfall may be adopted :

(i) Alluvial areas

In sandy areas - 20 to 25 percent of rainfall
In areas with higher clay content - 10 to 20 percent of rainfall

(ii) Semi-consolidated sandstones

Friable and highly porous - 10 to 15 percent of rainfall

(iii) Hard rock areas

Granitic terrain :
Weathered and fractured - 10 to 15 percent of rainfall
Unweathered - 5 to 10 percent of rainfall

Basaltic terrain :
Vesicular and jointed basalt - 10 to 15 percent of rainfall
Weathered basalt - 4 to 10 percent of rainfall

Phyllites, limestones, sandstones, quartzites, shales etc. - 3 to 10 percent of rainfall.

The figures indicated above are given as a guideline and it does not automatically imply that upper limit can invariably be applied. Based upon the status of knowledge available, a value in between can be chosen. If the recharge calculated on the basis of the water table fluctuation approach widely exceeds (more than 10 %) the value estimated on the basis of the penetration norms, the matter should be reviewed.

## 2.3 Water Balance Approach

In this approach, all the components of water balance equation other than the rainfall recharge, are estimated using the relevant hydrological and meteorological information. The rainfall recharge is calculated by substituting these estimates in the water balance equation. A pre-requisite for successful application of this technique is very extensive and accurate hydrological and meteorological data. The water balance approach is valid for the areas where the year can be divided into monsoon and non-monsoon seasons with the bulk of rainfall occurring in former.

Water balance study for monsoon and non-monsoon periods is carried out separately. The former yields an estimate of recharge coefficient and the later determines the degree of accuracy with which the components of water balance equation have been estimated. Alternatively, the average specific yield in the zone of fluctuation can be determined from a water balance study for the non-monsoon period and using this specific yield, the recharge due to rainfall can be determined using the water balance components for the monsoon period.

## 2.4 Soil Moisture Data Based Methods

Soil moisture data based methods are the lumped and distributed model and the nuclear methods. In the lumped model, the variation of soil moisture content in the vertical direction is ignored and any effective input into the soil is assumed to increase the soil moisture content uniformly. Recharge is calculated as the remainder when losses, identified in the form of runoff and evapotranspiration, have been deducted from the precipitation with proper accounting of soil moisture deficit. In the latter model, the variation of soil moisture content in the vertical direction is accounted for and the method involves the numerical solution of partial differential equation (Richards equation) governing one-dimensional flow through unsaturated medium, with appropriate initial and boundary conditions.

Nuclear techniques have been extensively used for the determination of recharge by measuring the travel of moisture through the soil column. The technique is based upon the existence of a linear relation between neutron count rate and moisture content (% by volume) for the range of moisture contents generally occurring in the unsaturated soil zone. The mixture of Beryllium (Be) and Radium (Ra) provide a convenient source of neutrons. Another method is the gamma ray transmission method based upon the attenuation of gamma rays in a medium through which it passes. The extent of attenuation or absorption is closely linked with moisture content of the soil medium. The method can be used without causing health hazards.

## 2.5 Establishment of Recharge Coefficient

Ground water balance study is a convenient way of establishing the rainfall recharge coefficient, as well as to cross check the accuracy of the various prevalent methods for the estimation of ground water losses and recharge from other sources. The steps to be followed are :

1. Divide the year into monsoon and non-monsoon periods.

2. Estimate all the components of the water balance equation other than rainfall recharge for monsoon period using the available hydrological and meteorological information and employing the prevalent methods for estimation.

3. Substitute these estimates in the water balance equation and thus calculate the rainfall recharge and hence recharge coefficient (recharge/rainfall ratio). Compare this estimate with those given by various empirical relations valid for the area of study.

4. For non-monsoon season, estimate all the components of water balance equation including the rainfall recharge which is calculated using recharge coefficient value obtained through the water balance of monsoon period. The rainfall recharge ($R_i$) will be of very small order in this case. A close balance between the left and right sides of the equation will indicate that the net recharge from all the sources of recharge and discharge has been quantified with a good degree of accuracy.

## 3. IRRIGATION RETURN FLOW

Water requirements of crops is met, in parts, by rainfall, contribution of moisture from the soil profile, and applied irrigation water. A part of the water applied to irrigated fields for growing crops is lost in consumptive use and the balance infiltrates to recharge the ground water. The process of re-entry of a part of the water used for irrigation is called return seepage. Percolation from applied irrigation water, derived both from surface water and ground water sources, constitutes one of the major components of ground water recharge in areas under wet crops like paddy, in view of the continuous submergence of the soil for long durations. For irrigation of dry crops, the water applied is much less as the soil is required to be saturated for short periods, with the result that the greater part of the water applied is abstracted from the soil and lost to the atmosphere through evapotranspiration, leaving only a small fraction, if any, to recharge the ground water.

### 3.1 Factors Affecting Irrigation Return Flow

Irrigation return flow may amount to as much as 20 % to 40 % of the volume of water used for irrigation. This amount reaching the aquifer as return flow depends on the following factors :

(i) Season during which the return flow is determined :

It is observed that maximum rates of return flow occur during the summer and fall months following the periods of irrigation and minimum rates during the winter and spring months preceding the periods of irrigation.

(ii) Conveyance and irrigation efficiencies :

The rates of return flow are observed to decrease with increase in the conveyance and irrigation efficiencies as higher efficiencies lead to lesser water losses consequently lesser quantities of return flows.

(iii) Amounts of water diverted for irrigation :

It is observed that as the amounts of water diverted for irrigation (over and above the required) is increased, there is a corresponding increase in the rates of return flow.

(iv) Period of years the lands have been irrigated :

Irrigation return flow also depends on the history of irrigation practices.

(v) Hydrological properties of the soil :

The hydraulic properties of the soil and the structure of soil strata influence the rates of return flow significantly. The antecedent soil moisture conditions in the irrigated lands and the existing conditions of salts in the soil also have a characteristic influence on the rates of return flow. The first irrigation during the cropping season leads to less quantity of return flow (as the soil is dry). However, this increases with the number of applications of irrigated water.

## 3.2 Assessment of Irrigation Return Flow

### 3.2.1 Ground Water Estimation Committee Norms

Ground Water Estimation Committee (1984) recommended the following norms for return seepage from irrigation fields :

(a) Irrigation by surface water sources

(i) 35 percent of water delivered at the outlet for application in the field.
(ii) 40 percent of water delivered at outlets for paddy irrigation only.

(b) Irrigation by ground water sources

30 percent of the water delivered at outlet. For paddy irrigation 35 percent as return seepage of the water delivered may be taken.

In all the above cases, return seepage figures include losses in field channels and these should not be accounted for separately.

### 3.2.2 Typical studies

The efficiency of irrigation with the system of application of water is usually about 0.60 for canal irrigation and 0.65 for well irrigation. The results of a few studies are indicated below.

(a) In case of a World Bank project in Haryana, following figures were adopted for losses in water courses and field combined [Chandra (1983)].

| | |
|---|---|
| Canal irrigation with unlined water courses | = 37 % |
| Canal irrigation with lined water courses | = 20 % |
| Tubewell irrigation | = 20 % |

(b) The deep percolation losses in canal irrigation in U.P. are assessed as below [Gupta (1962)].

| | |
|---|---|
| Sandy soils | = 25 % to 50 % |
| Sandy loams | = 15 % to 25 % |
| Fine sandy loams | = 10 % to 20 % |
| Heavy clay loams | = 5 % to 15 % |

(c) In command areas of Rajasthan canal, nearly 40 % of applied water in surface irrigation methods goes as deep percolation beyond the effective root zone during application [Sikka and Seth (1984)].

### 3.2.3 Water balance approach

For a correct assessment of the quantum of recharge by applied irrigation, studies are required to be carried out on experimental plots under different crops in different seasonal conditions. The method of estimation comprise application of the water balance equation involving input and output of water in experimental fields, or by adopting the drum culture technique.

The water balance equation, as applied to a closed paddy field under continuous submergence conditions, is :

$$P + W = CU + I$$

where,

$P$ = precipitation accumulated during the period of observation, in mm
$W$ = water applied, in mm
$CU$ = consumptive use (which can be equated with evapotranspiration), in mm
$I$ = infiltration, in mm

Care should be taken to ensure that there is no inflow or outflow of water into or out of the experimental field. Change in soil moisture prior to and at the end of the period of application of water can be ignored if it forms only a small part of the total water applied.

Fields selected for experimental studies are watered, manured, and protected with pesticides, in accordance with local agricultural practices. They should also be free of burrow holes etc. and should not be bordered by unirrigated areas or under different crops. All particulars such as variety of crop, stage of growth, daily inflows and outflows (if any) of water, are recorded. A rain gauge and pan evaporimeter should be installed within the field, or as close to it as possible. Inflows and outflows are measured by V-notch or Parshal flumes. All quantities in the equation are directly measurable, except for infiltration.

### 3.2.4 Drum-culture method

In the drum-culture method, the paddy crop is raised under controlled conditions in drums of standard size, in representative paddy plots. Drums (or tubs) of size 0.9 X 0.9 X 1.0 m dimension have been widely used. Two drums, one with the bottom open and the other with the bottom closed are sunk into the plot to a depth of 75 cm. Both are filled with the same soil to field level. Within the open-ended drum, all agricultural operations are carried out as in the surrounding plot. The heights of the water columns in the drums are maintained equal to that outside. Water levels in the drums are observed twice a day, with the help of gauges, to determine the water consumed. Rainfall and evaporation data are recorded in the hydrometeorological station.

The water loss from the drum with the closed bottom gives the consumptive use, while that from the drum with open bottom gives the consumptive use plus infiltration. The difference in values of the water applied in the two drums gives the infiltration.

### 3.2.5 Soil moisture modelling

Irrigation return flow can also be estimated by modelling the soil moisture movement. Most of the processes involving soil-water interactions in the field, and particularly the flow of water in the rooting zone of most crop plants, occur while the soil is in an unsaturated condition. Unsaturated flow processes are in general complicated and difficult to describe quantitatively, since they often entail changes in the state and content of soil water during flow. Such changes involve complex relations among the variable soil wetness, suction, and conductivity, whose inter-relations may be further complicated by hysteresis. The formulation and solution of unsaturated flow problems very often require the use of indirect methods of analysis, based on approximations or numerical techniques. For this reason, the development of rigorous theoretical and experimental methods for treating these problems was rather late in coming. In recent decades, however, unsaturated flow has become one of the most important and active topics of research and this research has resulted in significant theoretical and practical advances.

Application of the principle of mass conservation and Darcy's law in unsaturated soil profile yields the following one-dimensional Richards equation :

$$C(h)\,\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[\,K(h)\left(\frac{\partial h}{\partial z} - 1\right)\right] - S(z\,,t)$$

where K is the hydraulic conductivity (cm/h), h is the soil water pressure head (relative to the atmosphere) expressed in cm of water, z is the gravitational head (cm) considered positive in downward direction, S is the rate of withdrawal of water per unit volume of the soil and C is the specific water capacity defined as

$$C = \frac{d\,\theta}{d\,h} \qquad \text{(/cm)}$$

Richards equation is used as the basic mathematical expression that underlies unsaturated flow phenomena. Soil water flow, however, is highly non-linear, as both the hydraulic conductivity and the soil water pressure head depend on the soil water content. Exact analytical solutions are only possible for simplified flow cases under a number of restrictive assumptions. Numerical solution of the flow equation on the other hand offers a powerful tool in approximating the real nature of the unsaturated zone for a wide variety of soil systems and external conditions.

The partial differential flow equation can be interpreted numerically by a finite difference, a finite element or a boundary element technique. Then a discretization scheme is applied for a system of nodal points that is superimposed on the soil depth-time region under consideration. Implementing the appropriate initial and boundary conditions then leads to a set of (linear) algebraic equations that can be solved by different methods. The operation by means of such a mathematical model is termed simulation, while the model is called simulation model.

The output of a simulation model can include such variables as pressure head, moisture content and flux as a function of soil depth and time. However, most frequently one calculates the terms of the water balance, i.e. infiltration, actual evaporation, actual transpiration, change in soil water storage and the net flux through the region boundary.

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