Water Mass Balance Approach and Available Technology

Dr. Anupma Sharma
Scientist-F
Groundwater Hydrology Division
National Institute of Hydrology, Roorkee
anupma.nihr@gov.in

Outline

- What is water balance?
- Groundwater balance equation
- Data requirements for GW balance
- GEC norms for estimation of GW balance
- Employing remote sensing techniques
- Estimation of GW balance components

Water Balance

Water Balance

What is Water Balance?

Systematic presentation of data on water supply and its use within a study area for a specific period.

Defined by hydrologic equation - law of conservation of mass as applied to hydrologic cycle.

Water balance: During a time period, various inflows balance the various outflows, any difference accounted for by aggregate changes in surface water, soil water and GW storage.

Water Balance

Why do we need a water balance study?

- Freshwater shortages due to rapid industrial development, urbanization and increase in agricultural production.

- To make a quantitative estimation of available water resources of a region and plan a sustainable development of water resources.

GW Balance

Groundwater balance:

Special component of water balance

Over a time period, the GW balance of a region is

Inflow to GW system - Outflow from GW system

= Change in storage of GW system

GW Potential Estimation

Computation of GW balance:

(a) identification of significant inflow/outflow components in a region,

(b) quantification of individual components, and

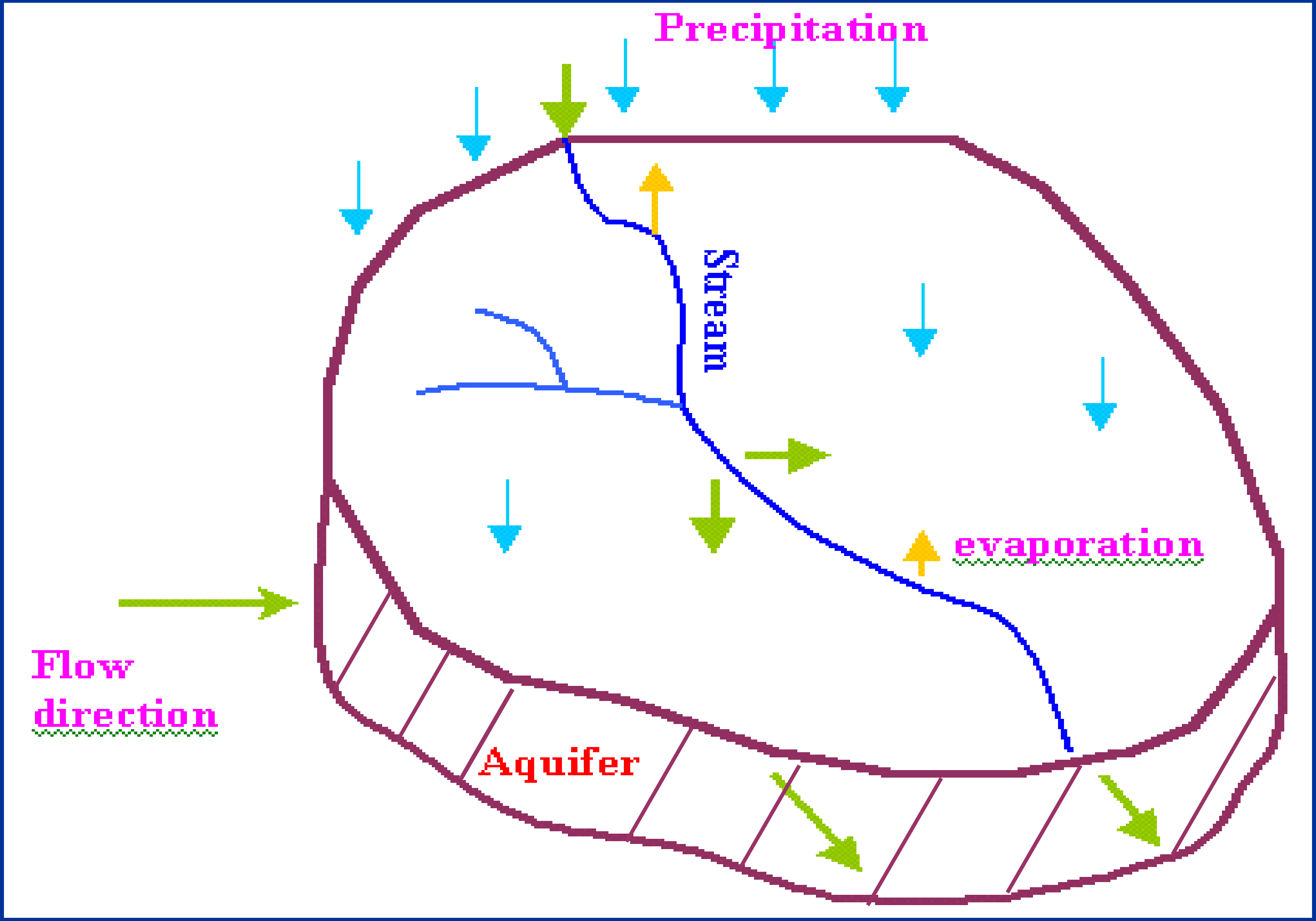
(c) analysis using GW balance equation.

GW Balance

GW balance study serves following purposes:

- as a check on whether all flow components have been quantitatively accounted for, and what components have the greatest bearing on the problem under study.
- to calculate one unknown component of GW balance eq., provided all other components are quantitatively known.
- as a model of hydrological processes, which can be used to predict effect of changes in one component on other components of GW system.

Stream-aquifer system



Inflow & Outflow to GW system

Inflow :

natural recharge, artificial recharge, streamflow, irrigation return flow etc.

Outflow:

pumping, artificial drainage, springs, subsurface outflow, phreatophyte transpiration etc.

Data requirements for GW balance

GW Balance Equation

$$R_p + R_c + R_{ir} + R_t + S_{in} + I_g = E_t + W_g + S_{ef} + O_g + \Delta S$$

where R_p = recharge from rainfall, R_c = recharge from canal seepage, R_{ir} = recharge from field irrigation, R_t = recharge from tanks, S_{in} = influent seepage from rivers, I_g = inflow from other basins, E_t = evapotranspiration, W_g = GW draft, S_{ef} = effluent seepage to rivers, O_g = outflow to other basins, and ΔS = change in GW storage.

GW Balance Equation

Inflow – Outflow = Change in Storage (of an aquifer)

$$\Delta S = R_{RF} + R_{STR} + R_{C} + R_{SWI} + R_{GWI} + R_{TP} + R_{WCS} \pm VF \pm LF - GE - T - E - B$$

Where, ΔS – Change is storage, R_{RF} – Rainfall recharge, R_{STR}- Recharge from stream channels, Rc – Recharge from canals, R_{SWI} – Recharge from surface water irrigation, R_{GWI}- Recharge from ground water irrigation, R_{TP}- Recharge from Tanks& Ponds, R_{WCS}– Recharge from water conservation structures, VF – Vertical inter aquifer flow, LF- Lateral flow along the aquifer system (throughflow), GE-Ground Water Extraction, T- Transpiration, E- Evaporation, B-Base flow

At present, water budget may be restricted to major components only taking into consideration certain reasonable assumptions.

GW Balance Equation

In GW balance eq., all quantities are expressed in same dimensions/units, e.g., in units of discharge: m^3/day, mm^3/day, litres/sec, etc., or in units of discharge/area: m/day, mm/day.

Preferably, all elements of GW balance eq. should be computed using independent methods. Sometimes, depending on the problem, some components can be lumped, and account only for their net value in eq.

Data requirements for GW balance

Rainfall data: Monthly rainfall data of raingauge stations & locations.

Landuse data and cropping patterns: area under cultivation, forests or barren conditions; forested area for estimating evapotranspiration losses from WT; cropping pattern data for estimating spatial & temporal distributions of GW withdrawals.

Data requirements for GW balance

River data: Monthly river stage & discharge data with river cross-sections at specific locations.

Canal data: Monthwise water releases into canal and distributaries with running days.

Tank data: Monthly tank gauges & water releases.

Data requirements for GW balance

WT data: Monthly WT data (or at least pre-monsoon and post-monsoon data) from sufficient number of obs. wells, with their locations.

GW draft: Number of wells operating in area, running hours & discharge. Otherwise data from sample surveys.

Aquifer parameters: Data regarding S and T at sufficient number of locations.

Estimation of GW balance

GEC norms

Estimation of GW balance

Estimation of various inflow/outflow components

- Appropriate empirical relationships suitable for a region,
- Groundwater Estimation Committee norms, or
- Field experiments.

Groundwater Estimation Committee (GEC) Norms

GEC was constituted by Gov. of India in 1982 to recommend methodologies for estimation of GW potential in India. To review the recommended methodology, GEC was reconstituted in 1995, which released its report in 1997. Recent report released in 2015.

Estimation of GW balance

GEC norms

- Balance eq. holds good for any period and can be applied to a year as a whole or to different seasons in a year separately (monsoon & non-monsoon or kharif, rabi and summer seasons).

- GW level measurements at beginning and end of seasons are necessary.

- Unit for GW assessment: basin/sub-basin/watershed, so that subsurface inflow/outflow across boundaries may be taken as negligible.

Estimation of GW balance
GEC norms

- Unit for assessment in hard rock areas: watershed. In alluvial areas : assessment may be made on block/taluka/mandal-wise basis.

- Due to spatial and seasonal variability of GW resource, total geographical area of a unit may be delineated into subareas such as hilly areas, saline GW areas, non-command areas and command areas of major/medium surface water irrigation schemes.

Estimation of GW balance
GEC norms

- Estimation of GW recharge in non-command areas: water level fluctuation method.

- If pre- and post-monsoon data are not available, use rainfall infiltration factor method.

- In command areas, two additional components of recharge are considered:
  - recharge due to seepage from canals, &
  - recharge due to return flow from surface water irrigation.

Estimation of GW balance components

GEC norms

GEC 2015 recommends aquifer wise groundwater resource assessment to which demarcation of lateral as well as vertical extent and disposition of different aquifers is pre-requisite.

GW resources may be assessed to a depth of 100 m in hard rock areas and 300 m in soft rock areas till the aquifer geometry is completely established throughout the country through aquifer mapping.

Estimation of GW balance

GEC norms

GEC 2015 also recommends estimation of replenishable and in-storage GW resources for both unconfined and confined aquifers.

Keeping in view of the rapid change in GW extraction, GEC-2015 recommends resources estimation once in every three years.

Methodology recommends that after assessment is done, a quality flag may be added to assessment unit for parameters salinity, fluoride and arsenic.

Estimation of GW balance

GEC norms

In inhabited hilly areas, where surface and sub-surface runoff is high and generally water level data is missing, it is difficult to compute the various components of water balance equation.

GEC 2015 recommends that wherever spring discharge data is available, the same may be assessed as a proxy for ‘ground water resources’ in hilly areas.

Employing Remote Sensing Techniques

Employing Remote Sensing Techniques

- DEM data can be utilized for delineating hilly areas where slope is more than 20%.
- Delineating the water spread area of tanks & ponds and the number of days water is available in such structures.
- Assessing cropped area and mode of irrigation (either groundwater or surface water) predominantly employed.

Estimation of GW Balance Components

Estimation of GW recharge (R_p)

What is rainfall recharge?

Rainfall is a major source of recharge to GW.

Only a part of total rainfall received infiltrates the soil. Large part lost through evaporation, transpiration, runoff, etc.

Part of infiltrated water fills soil moisture deficiency; remaining portion percolates down to reach WT, termed as rainfall recharge to aquifer.

Amount of rainfall recharge depends on various hydrometerological & topographic factors, soil characteristics & depth to WT.

Estimation of GW recharge (R_p)

Methods

- Empirical methods
- GEC norms
- GW level fluctuation method
- Soil water balance method
- Nuclear methods

Estimation of GW recharge (R_p)

Empirical methods

Chaturvedi formula: For Ganga-Yamuna doab. R = net recharge (in inches), P = annual precipitation (in inches)	$R = 2(P-15)^{0.4}$
UP Irrigation Research Institute, Roorkee, modified the formula.	$R = 1.35(P-14)^{0.5}$
Amritsar formula: Irrigation and Power Research Institute, Amritsar, developed following formula for Punjab	$R = 2.5(P-16)^{0.5}$

Estimation of GW recharge (R_p)
GEC Norms

Rainfall infiltration method: Recharge due to non-monsoon rainfall taken as zero, if it is less than 10% of normal annual rainfall.

GEC (1997) infiltration factors:

(a) Alluvial areas

Indo-Gangetic and inland areas	-	22%
East coast	-	16%
West coast	-	10%

Estimation of GW recharge (R_p)
GEC Norms

(b) Hard rock areas

Vesicular and jointed basalt	-	13%
Weathered basalt	-	7%
Semi-consolidated sandstone	-	12%
Consolidated sandstone, quartzite, limestone (except cavernous limestone)	-	6%
Phyllites, shales	-	4%
Massive poorly fractured rock	-	1%

Estimation of GW recharge (R_p)

GW level Fluctuation method

- All components of balance eq. (except rainfall recharge) are estimated individually.
- Algebraic sum of all input and output components is equated to the change in storage as reflected by WT fluctuation
- Solve for the single unknown in the eq., i.e., rainfall recharge.

Estimation of GW recharge (R_p)

Technique Based on Saturated-Zone Studies

Physical Techniques - Water-table fluctuation method

The water-table fluctuation (WTF) method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. Recharge is calculated as

$$R = S_y dh/dt = S_y \Delta h/\Delta t$$

where Sy is specific yield, h is water-table height, and t is time.

The method is best applied over short time periods in regions having shallow water tables that display sharp rises and declines in water levels. Analysis of water-level fluctuations also useful for determining the magnitude of long-term changes in recharge caused by climate or land-use change. **Difficulties in applying the method**: determining a representative value for Sy and ensuring that fluctuations in water levels are due to recharge and not due to other phenomena, such as pumping.

Recharge by Seepage from Canals (R_c)

Seepage losses from irrigation canals -

significant part of total recharge to GW system.

Losses depend upon

- size and cross section of canal,
- depth of flow,
- characteristics of soils in the bed and sides,
- location and level of drains on either side of canal.

Recharge by Seepage from Canals (R_c)

Empirical formulae

unlined channels in UP

$$Losses\ in\ cumecs/km = \frac{C}{200}(B+D)^{2/3}$$

where B and D are channel bed width & depth (in m); C is constant (= 1.0 for intermittent running channels, & 0.75 for continuous running channels).

lined channels in Punjab

$$S = 1.25\,Q^{0.56}$$

where S is seepage loss in cusecs per million sq. foot of wetted perimeter; Q, in cusecs, is discharge carried by channel.

Recharge by Seepage from Canals (R_c)

GEC norms

- Unlined canals in normal soil with some clay content - 1.8 to 2.5 cumec per million sq. m. of wetted area,
- Unlined canals in sandy soil with some silt content - 3.0 to 3.5 cumec per million sq. m. of wetted area
- Lined canals and canals in hard rock areas - 20% of above values for unlined canals.

Values are valid if WT is relatively deep. In shallow WT/water logged areas, recharge from canal seepage is reduced.

Recharge by Seepage from Canals (R_c)

Field tests

(a) Inflow-Outflow method (b) Ponding method

Inflow-Outflow method:

Water flowing into & out of canal section is measured using current meter or Parshall flume method.

Difference between quantities of water flowing into & out of canal reach is computed as seepage.

Recharge by Seepage from Canals (R_c)
Field tests

Ponding method:

- Bunds are constructed in canal at upstream end & at downstream end of canal reach with water filled in it.
- Total storage change in reach over a time period = rate of drop of water surface elevation.

Alternatively, water is added to maintain a constant water surface elevation. Volume of water added is measured along with elapsed time to compute the rate of seepage loss.

Recharge due to Irrig. Return Flow (R_{ir})

Part of water applied to irrigate field crops is lost in consumptive use. The balance infiltrates to recharge GW. Process of re-entry of a part of water used for irrigation is called return flow.

Estimation using GEC norms

Recharge due to return flow based on

- source of irrigation (GW or SW)
- type of crop (paddy, non-paddy)
- depth of WT below ground surface

Recharge due to Irrig. Return Flow (R_{ir})

GEC norms

Recharge given as percentage of water application:

DTW m bgl	Ground Water		Surface Water	
	Paddy	Non Paddy	Paddy	Non Paddy
<=10	45	25	50	30
11	43.3	23.7	48.3	28.7
12	41.7	22.3	46.7	27.3
13	40	21	45	26
14	38.3	19.7	43.3	24.7
15	36.7	18.3	41.7	23.3
16	35	17	40	22
17	33.3	15.7	38.3	20.7
18	31.7	14.3	36.7	19.3
19	30	13	35	18
20	28.3	11.7	33.3	16.7
21	26.7	10.3	31.7	15.3
22	25	9	30	14
23	23.3	7.7	28.3	12.7
24	21.7	6.3	26.7	11.3
>=25	20	5	25	10

Recharge from Tanks (R_t)
GEC norms

Based on average area of water spread, recharge from storage tanks and ponds is 1.4 mm/day for period in which tank has water.

If data on average area of water spread is not available, 60% of maximum water spread area may be used.

For percolation tanks, recharge is 50% of gross storage, considering the number of fillings, with half of recharge occurring in monsoon season and the balance in non-monsoon season.

Influent and Effluent Seepage (S_{in} & S_{ef})

River-aquifer interaction depends on transmissivity and gradient of WT w.r.t. river stage.

Depending on water level in river and in aquifer (in vicinity of river), river may recharge the aquifer (influent) or the aquifer may contribute to river flow (effluent).

Seepage from/to river determined by dividing river reach into small sub-reaches and observing discharges at two ends of sub-reach along with discharges of its tributaries and diversions.

Influent and Effluent Seepage (S_{in} & S_{ef})

The discharge at d/s end is

$$Q_d \Delta t = Q_u \Delta t + Q_t \Delta t - Q_o \Delta t - E \Delta t + Q_g \Delta t \pm S_b$$

Q_d = discharge at d/s, Q_u = discharge at u/s, Q_t = discharge of tributaries, Q_o = discharge diverted from river, E = rate of evaporation from river surface and flood plain, Q_g = GW contribution (unknown; -ve value: influent), Δt = time period, S_b = bank storage change (+ve: decrease)

Change in bank storage is determined by monitoring WT along the cross-section normal to river. Thus, seepage from/to the river over a certain period of time Δt can be computed. However, this is the contribution from aquifers on both sides of stream.

Influent and Effluent Seepage (S_{in} & S_{ef})

The contribution from each side of the stream can be separated by following method:

$$Contribution\ from\ left\ bank = \frac{I_L T_L}{I_L T_L + I_R T_R} . Q_g$$

$$Contribution\ from\ right\ bank = \frac{I_R T_R}{I_L T_L + I_R T_R} . Q_g$$

where, I_L and T_L are gradient and transmissivity, respectively, on the left side and I_R and T_R on right side.

GW Inflow from & Outflow to Other Basins (I_g & O_g)

Regional WT maps are drawn based on observed data from wells.

Gradient (I) is determined by taking slope of WT normal to WT contour.

Length (ΔL) of the section, across which GW inflow/outflow occurs, is determined from contour maps, the length being measured parallel to contour.

GW Inflow from & Outflow to Other Basins (I_g & O_g)

The inflow/outflow is determined as:

$$Q = \sum T \, I \, \Delta L$$

Here T = transmissivity; I = hydraulic gradient averaged over a length ΔL of contour line.

Evapotranspiration from GW Reservoir (E_t)

Evapotranspiration: Combined process of transpiration from vegetation and evaporation from both soil and free water surfaces.

Potential Evapotranspiration: Maximum loss of water through E_t. Occurs in water logged areas or in forested areas with roots extending to WT.

From landuse data, area under forests is available. Water logged areas are demarcated from depth to WT maps. Potential E_t from such areas computed using standard methods (Penman Monteith, Thornwaite, Blaney-Criddle, Hargreaves etc.).

Groundwater Draft (W_g)

Inventory of wells and sample survey of GW draft from various types of wells (state tubewells, private tubewells and open wells).

For state tubewells, information about their number, running hours per day, discharge, and number of days of operation in a season is available in concerned departments.

Unit Draft= Discharge in m^3/hr x No. of pumping hrs in a day x No. of days

For private tubewells, pumping sets and rahats etc., sample surveys are conducted regarding their number/discharge/withdrawals over a season.

Groundwater Draft (W_g)

For energized wells:
draft computed using power consumption data.

By conducting tests on wells, average draft per unit of electricity consumed is determined for different ranges in depth to water levels. By noting depth to water level at each distribution point and multiplying the average draft value with number of units of electricity consumed, the draft at each point is computed for every month.

Change in Groundwater Storage (ΔS)

Change in GW storage between start & end of monsoon season → total volume of water added to GW reservoir.

WT contours are drawn at start & end of season and average change in WT elevation is computed. Change in storage (ΔS) is:

$$\Delta S = S_y \, A \, \Delta h$$

here Δh = average change in WT elevation during a period, A = area, S_y = specific yield.

Change in Groundwater Storage (ΔS)

S_y may be computed from pumping tests.

GEC recommendations

- Alluvial areas

Sandy alluvium	-	16%
Silty alluvium	-	10%
Clayey alluvium	-	6%

- Hard rock areas

Sandstone	-	3%
Quartzite	-	1.5%
Limestone	-	2%
Karstified limestone	-	8.0 %
Phyllites, Shales	-	1.5 %
Massive poorly fractured rock	-	0.3 %

Returning to GW balance eq...

$$R_p + R_c + R_{ir} + R_t + S_{in} + I_g = E_t + W_g + S_{ef} + O_g + \Delta S$$

To conclude, a GW balance study permits...

- Quantification of all inflow/outflow components of a GW system,
- Determination of component having the most significant effect on GW flow regime.
- Computation of one unknown component (e.g. rainfall recharge) of GW balance eq., when all other components are known.
- Lumped modelling of the study area, whereby effect of change in one component can be used to predict changes in other components.

Thus, study of GW balance has a significant role in planning rational GW development of a region.

Thanks for your attention!