CONJUNCTIVE USE OF SURFACE WATER AND GROUNDWATER RESOURCES-I

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Training Course on
HYDROLOGICAL INVESTIGATION TECHNIQUES FOR WATER RESOURCES DEVELOPMENT & MANAGEMENT
(26-28 August 2012)

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INTRODUCTION

Nature seldom provides adequate amount of water to meet crop requirements at the desired place and time. Therefore, availability of irrigation water continues to be the first and foremost requirement for promoting agriculture. It is rightly said, "Agriculture sustains life whereas irrigation sustains agriculture". Development of water resources for irrigation is as old as the history of mankind. From just 8 million hectares (M ha) in the year 1800, irrigated area across the world increased five-fold to 40 M ha in the year 1900, to 100 M ha in the year 1950 and to just over 255 M ha by the year 1995. With almost one-fifth of that area (50.1 M ha net irrigated area), India has the highest irrigated land in the world. Irrigation is the largest consumer of freshwater. It has been estimated that around 70% of the water used worldwide every year produces 30 to 40% of the world's food crops on 17% of the arable land.

As in the reviews on India's irrigation sector (World Bank, 1998; Govt. of India, 1999): "India's irrigated agriculture sector has been fundamental to India's economic development and poverty alleviation. Some 28% of India's Gross Domestic Product and 67% of employment is based on agriculture. Agriculture is the primary source of livelihood in rural areas, which account for 75% of India's population and 80% of its poor. And in turn, irrigation is the base for about 56%, possibly more, of total agricultural output. The rapid expansion of irrigation and drainage infrastructure has been one of India's major achievements. From 1951 to 1997, gross irrigated area (GIA) (including double cropping) expanded four-fold from 23 MHa to 90 MHa. Increase in irrigation intensity has contributed to the growth in the overall cropping intensity, which increased from 111.07% in 1950-51 to 131.19% in 1993-94. As a result, India has moved from the specter and actuality of food imports and periodic famines to self-sufficiency since the early 1970s, food exports and progressively more diversified production".

Environment is in dynamic balance with its elements. If changes are introduced in some of the elements, a new order develops which, in course of time, stabilizes in an altered environment. Planning of irrigation projects should be accomplished in a manner such that the changed environment is healthy and there are no adverse impacts. Introduction of canal irrigation in a command area sets in new hydrological regime with revised conditions of surface water and groundwater use. If water is not utilized sustainably or if there is significant difference in the actual and design values of demands and supply, an imbalance is created in the command area that can lead to gradual deterioration of the system. For example, over-utilization of surface water, especially in the upper and middle reaches of canal commands, can give rise to harmful effects like waterlogging and salinization. Thus, after development of new infrastructure, it is important to conjunctively manage the water resources.

At a place, water descends in the form of rainfall or precipitation. In the course of time, it gets partitioned into surface water or groundwater resource. Since ancient times, both surface water and groundwater have been used for agricultural, industrial and domestic purposes. Surface water and groundwater, though two distinguished resources, tend to be inter-related in the sense that groundwater may feed surface water bodies and vice-versa. However, the two sub-systems of hydrological cycle have different properties with regard to flow availability, storage, speed of travel, quality parameters, cost of exploitation and vulnerability to pollution. Under conjunctive plan, available surface and groundwater resources are used such that one supplements the other to compensate for the inadequacies (in terms of quantity and quality in time and space) for getting the increased productivity while mitigating environmental hazards like high water table, salinity, aquifer mining etc.

CONCEPT OF CONJUNCTIVE USE

Conjunctive use is the coordinated management of surface and groundwater resources, taking advantage of their complementary properties. The objectives of such coordination may be higher agricultural production, improved sustainability of the system and/or more acceptable socio-economic equity. Both, surface and groundwater resources are used to redistribute the water in time and space so as to match supply with the demands. The conjunctive use concept recognizes the unified nature of the surface water and ground water resources and takes advantage of the interactions between them in planning their use. Some of the interactions between surface water and groundwater resources include contribution to base flow from groundwater, recharge to groundwater from fields irrigated with surface water, artificial recharge of surface water to groundwater, indirect use of ground water through augmentation tube wells into canals, and recharge from irrigation conveyance system to ground water. Figure1 shows the conceptual framework of conjunctive use.

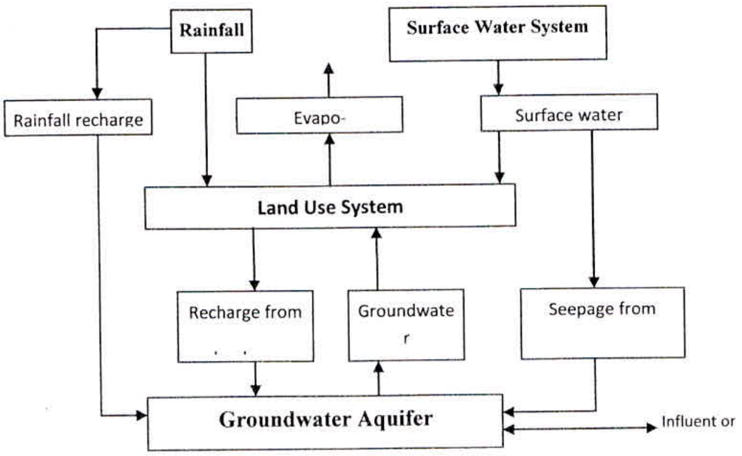

Figure1.Conceptual representation of conjunctive use of surface water and groundwater

Conjunctive use of surface water and groundwater resources in a canal command provides best solution for beneficial use of water. Joint operation of all manageable water resources can increase the yield, efficiency, supply reliability and cost-effectiveness for the command. This requires integration of the policies of water use from the two sources at various levels and in various ways, resulting in conjunction over space, over time, and by augmentation. Under conjunction over space, some parts of the irrigation command are supplied with surface water and other parts with groundwater. This is preferred in those areas which cannot be physically, adequately, or reliably supplied with surface water such as upland patches. Under conjunction over time, some parts of the command are supplied with surface water at one time and groundwater at another time period. In the Indian hydro-meteorological and agro- climatic conditions, an example of a typical conjunctive use over time is the use of surface water in monsoon season (June – October) when there is abundant water in the rivers and with groundwater in the non-monsoon season (November – May) when rivers usually carry lean flows. Under conjunction by augmentation, supplies from one source are augmented by those from the other source to meet the demands adequately. This is particularly useful when surface/groundwater resources in some parts of the command are deficient in meeting water demands due to quantity or quality constraints.

OBJECTIVES OF CONJUNCTIVE USE

The main objective of conjunctive use of surface water and groundwater in a canal command is to achieve optimal utilization of water resources for maximizing the agricultural production per unit of water used without adversely affecting the environment. Different objectives of the conjunctive use of water resources in an irrigation command have been enumerated by the National Commission for Integrated Water Resources Development Plan (NCIWRDP, 1999) in the report of its sub-group no. VIII on Groundwater including Conjunctive Use. These are summarized below:

- A higher total amount of supply.
- Better regulation of the combined system using the storage space of aquifers. Use of ground water storage has many advantages such as no construction cost, no siltation, no evaporation loss, uniform temperature and no requirement of additional space except that required for recharge fields.
- Higher flexibility in supply according to the demand by moderating peaks in stream flow and pumping groundwater as and when needed.
- Alleviating the problems of high water table and salinity resulting from the introduction of canal system without proper provision of drainage and/or adequate ground water development.
- Facilitating the use of high salinity groundwater which cannot otherwise be used without appropriate dilution.
- Arresting depletion of groundwater table in areas where no surface irrigation exists and excessive ground water extraction is done by introducing surface irrigation from

small rivers. Conjunctive use not only provides increased recharge but also relieves the demand on the groundwater resource.

- Reduction of capital investments and operational expenditures by shortening conveyance route for surface water.
- Control of salt-water intrusion in coastal areas by maintaining the fresh water aquifer at a higher level compared to saline water aquifer through increased application of surface water under conjunctive use plan.

STRATEGIES OF CONJUNCTIVE USE

Different strategies of conjunctive use can be employed in an irrigation command (CWC Guidelines, 1995) depending on the spatial and/or temporal availability and utilization of surface water and groundwater. Strategies also differ for the use of good quality water or the saline water. General strategies of conjunctive use in an irrigation command are as follows:

Strategy-1: Allocating parcels of land permanently to particular use

Under this strategy, separate areas of the command are permanently allocated for surface water or groundwater use. The areas at higher elevation where it is difficult to take the canal water could be some such areas where ground water might be the sole source of irrigation. It is envisaged in this strategy that recharge from the surface water application will supplement the groundwater and this will be utilized in an adjacent area allocated for groundwater use.

This form of conjunctive use is effective in those conditions where distance of the wells from the recharge area (surface irrigation) is so small that the groundwater flow is sustained by the available gradient. Application of such strategy is feasible in alluvial areas because of the appreciable movement of groundwater. In hard rock areas and in clay soils, this strategy may not be feasible.

Strategy-2: Allocating surface water and groundwater in time

Under this strategy, surface water and groundwater resources are allocated in time such that in a particular season (wet season or monsoon season), only surface water is used and in the other season (dry or non-monsoon season), only groundwater is used. Since the same area is irrigated with surface water at one point of time and groundwater at another point of time, groundwater is allowed to use the same field channels that carry the surface water. If private sources of groundwater extraction are not available in the command, then augmentation tube wells are planned and operated in such a way that groundwater carriage over long distances is avoided.

Combination of Strategy 1 and 2: Space & time integration

Under this strategy, some parcels of land are permanently allocated for surface water use, some parcels are permanently allocated for groundwater use, and some parcels are supplied with surface water in one season and groundwater in another. For parcels of land in which both groundwater and surface water are used, the intra-annual regime of uses can vary from year to year to take advantage of the stable regime of groundwater.

Strategies of Conjunctive Use for Salinity Control

When the groundwater is saline and unfit for direct use as a single source, then either the water from the surface and groundwater resources are physically mixed in the water courses/minors/distributary canals to have resultant water of acceptable quality (mixing mode) or rotations are distributed amongst the two sources (cyclic mode) depending upon the availability of canal/groundwater or depending upon the salinity build-up.

Mixing of saline water and fresh water

Mixing of high-salinity groundwater with canal water can dilute the saline water to an acceptable quality, which can then be used for irrigation. In India, Haryana has taken a lead in experimenting with mixing mechanism in a canal network. Good crop yield was obtained when tube well water of EC 3 dS/m and SAR 16 was blended in 1: 1 ratio with good quality water. Very little data are available in India on the mixing strategy for large-scale systems under field conditions. Doubts have been raised on the advisability of mixing of saline and fresh waters at the system level where canal water is often supplied for drinking purposes. Some of the problems related to mixing in the irrigation system could be overcome by selecting suitable sites for mixing. For example, mixing in the canal/distributaries/minors could be avoided and preference could be given to mixing at the water course level.

Cyclic or rotational application

In those cases where canal water supplies have infrequent delivery schedules, rotational application of fresh and saline waters is resorted to. The rotation schedule depends essentially upon the sensitivity of a crop at a particular growth stage, soil texture, rainfall and its distribution and the salinity of ground water. Most crops are sensitive at germination stage. Irrigation with fresh water at the initial stage and saline water subsequently can stretch the water supply. Rhoades (1984), Minhas et al (1986) and ICAR, New Delhi (1989) have reported applicability of this strategy for a number of crops. Abrol et al. (1988) has reported that under the agro-climatic conditions prevailing at Agra, alternate application of water from canal and tube well (EC 6 dS/m) resulted in 77 to 95% of yield obtained with application of only canal water.

Choice of the strategy for conjunctive use in saline environment depends upon the quality of groundwater, soil type, crop to be grown and the agro-climatic condition of the area. It is commonly believed that cyclic use strategy has an advantage over the mixing strategy as soil salinity can be lowered at critical times, use of water supplies can be maximized and waters of relative higher salinity could be used. On the other hand, from agronomic point of view, it is always easier to handle a single supply than the two supplies. Mixing strategy is useful in cases where fresh water supplies are limited and quality of ground water is highly saline. One may go in for mixing of water, if the salinity of the mix water is below the threshold salinity of the most sensitive crop grown in the area. If the salinity of mix water exceeds this limit, one may need to evaluate pros & cons of two strategies and go in for most practical solution.

METHODOLOGY FOR CONJUNCTIVE USE PLANNING

Planning a conjunctive irrigation system essentially consists in establishing a match between the demands and supplies of irrigation water on a seasonal as well as critical period basis. The demands are based on seasonal and critical period crop water requirements for various crops under different cropping patterns, at maximum feasible cropping intensity, as determined by the given soil, agronomic and agro-climatic conditions. Conjunctive use planning requires detailed investigation of sub-soil conditions of the basin and its interaction with surface water.

The first requirement in planning conjunctive use of surface water and groundwater is the knowledge of their availability and distribution. It is also essential to work out a water budget for all sources of water for each area/sub-basin/basin/region. Water resources availability of surface water is determined from the hydrology of the surface water sources, typically a river at its point of diversion. Availability of groundwater resource is mainly determined from the horizontal and vertical recharges of various aquifers in confined, semi-confined and unconfirmed conditions. In addition to water availability, the knowledge of land resources, rainfall pattern, soil types, cropping pattern, etc. is also essential to properly evaluate the potentials of conjunctive use.

Estimation of surface water resources

Total available surface water resource in a basin is represented by the total mean annual stream flow at the downstream end of the basin plus the withdrawal and the influent recharge of ground water (ignoring evaporation from the stream channel). Dependable assessment of the surface water resources can be made when records of stream flow and withdrawals are available for a sufficiently long period. Flow duration curves at different gauging sites in a basin can be prepared using the past historical records and the water availability at different dependability levels can be estimated.

In a typical situation in a developing country, rainfall records of long durations are generally available while the records of stream flow observations are either not available at all, particularly for the small streams/rivers, or are available only for a limited period. The methods used for estimation of runoff under such situations are:

- Rainfall-runoff relationship may be established on the basis of actually observed data in some typical representative basins. These may be applied to other basins with similar characteristics and rainfall data for these basins are converted to stream flow.
- Rainfall-runoff relationship may be evolved on the basis of data collected from a gauged site in the basin and then applied to other ungauged sites in the same basin to obtain stream flows from observed rainfall values.
- At the same discharge site in the basin, short-term rainfall and discharge data may be used to establish rainfall-runoff relationship, which may then be utilized in building up runoff data for longer period on the basis of available rainfall data.

Estimation of groundwater resources

Groundwater is concealed under the Earth and its availability and distribution is controlled by complex hydro-geological and hydrological factors like sub-surface lithology, nature and properties of aquifers, sources of recharge, quantity and pattern of rainfall, nature of infiltrating medium etc. For this reason, the quantification of ground water potential is mostly based on empirical norms. Moreover, there exist two types of storage in ground water reservoir: static storage and dynamic storage. Static storage is a sort of dead storage which is not annually replenished and is difficult to exploit either because of geometric or quality considerations. Dynamic storage, on the other hand, is annually replenishable and used on a continuous basis from year to year.

For utilization of groundwater for irrigation, it has to be ensured that the safe yield of the groundwater basin is not exceeded. The safe yield is determined by natural recharge for both unconfined top aquifers as well as for confined or semi-confined deeper aquifers. The actual utilisation of total available ground water resources would depend on the extent to which the lowering of water table is permissible. Since it is difficult to make precise calculations in this regard, certain percentage factors are usually adopted for different regions to compute usable ground water resources. To quantify the usable groundwater resource of a region, the groundwater balance of that region is studied over a given time period.

Groundwater balance

The groundwater balance of a region requires quantification of all individual inflows to or outflows from a groundwater system and the changes in storage therein over a given time period. Considering the various inflow and outflow components in a given study area, the groundwater balance equation can be written as

$$R_p + R_c + R_{ir} + R_t + S_{in} + I_g = E_t + W_g + S_{ef} + O_g + \Delta S \qquad \ldots(1)$$

whereR_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 = evapo-transpiration, W_g= groundwater draft, S_{ef} = effluent seepage to rivers, O_g= outflow to other basins, and ΔS = change in groundwater storage. All the components of the equation are expressed in volume units. Various inflow/outflow components of the groundwater balance equation may be estimated through appropriate empirical relationships suitable for a region, field experiments, or Groundwater Estimation Committee (GEC) norms which are briefly presented below.

CWC guidelines for planning conjunctive use

Recognizing the urgent need of conjunctive use concept, Central Water Commission (CWC) is now ensuring that new projects, which do not take into account conjunctive use, are not recommended for Planning Commission's clearance. CWC in March 1995, issued general guidelines for planning conjunctive use. According to these guidelines, the quantification of water available for conjunctive use may have to be decided using appropriate methodologies developed in this regard. The steps include:i) establishing a general ground water balance of the command area for "without conjunctive use project" conditions, ii) delineating the area where ground water development is to be taken up based on the depth to water table and resource potential of aquifers, iii) deciding the additional recharge that would become available in the command area in "with conjunctive use project condition", iv) deciding the planned quantity of groundwater use so as not to lead to progressive lowering or rising of water table, and v) deciding the quantum of groundwater use available for irrigation after considering the other (non-irrigation) uses of the planned groundwater use, taking into account quality limitations such as the presence of brackish water. However, detailed action plans to implement the guidelines have to be drawn by respective states considering local conditions.

The guidelines recognize the importance of working out accurate groundwater balance: with the joint efforts of geo-hydrologists, surface water hydrologists, hydro-meteorologists, and planners of the projects. However, to begin with, it suggests the use of NABARD guidelines for establishing preliminary ground water balance based on some rules of thumb for estimating recharge in command areas arising from seepage from canals, field channels and tanks and return flow from irrigation fields. In addition to estimating net annual ground water recharge, the report also stresses on taking into account: i) minimum necessary withdrawal in order to avoid large imbalance leading to large rise in groundwater table, and ii) maximum permissible withdrawals with a view to maintain ecology and not allowing ground water to deplete, unless such depletion is likely to be beneficial due to the very high ground water table or rising tendency in the "without conjunctive use project" condition itself. The guidelines for extraction in command areas as percentage of additional recharge caused by the project are given in Table-1.

Table 1. CWC Guidelines for ground water extraction

Present Groundwater Status		**Minimum necessary additional withdrawal (%)**	**Maximum permissible withdrawal (%)**
Depth of Groundwater	**Trend**		
Less than 2 m	Rising	70	100
Less than 2 m	Generally steady	50	80
Less than 2 m	Falling	30	60
2 m to 6 m	Rising	60	90
2 m to 6 m	Steady	40	70
2 m to 6 m	Falling	20	60
More than 6 m	Rising	50	80
More than 6m	Steady	30	60
More than 6 m	Falling	0	40

For the purpose of this table, a general long-term rise or fall of more than 0.2m/year in case of alluvial condition and of more than 0.5m/year in case of hard rock areas would qualify for classifying the trend as "rising" or "falling". In case an accurate ground water regime worked out by the specialists and tested and verified through modeling and field verification in both conditions is available, the maximum/minimum withdrawal can be worked out on the basis of the water balance studies instead of using the percentage given above. Such detailed studies are desirable in specialized areas having salinity problems. Further, economic considerations would finally decide the quantum of use of surface and ground water in space and time. These guidelines may have to be modified in special situations such as coastal areas and areas with saline ground water etc.

Various alternatives are to be considered and the one that gives maximum benefit-cost ratio subject to various constraints, including the social and political ones, is to be selected for actual execution. However, the alternatives available for conjunctive use cannot be evaluated in terms of economics and hydrologic impact without proper representation of the system through models. For determining the optimal solution, recourse has to be taken to the modern methods of digital modeling and optimisation/simulation procedures. With this in view, a variety of models have been proposed by researchers for the study of conjunctive use of surface water and groundwater in different contexts such as for optimum scale of development, evaluation of alternative plans, integrated operation of facilities, stream-aquifer interaction and water quality management. A brief review of conjunctive use management models is presented below.

General form of an economic optimization conjunctive use model

Conjunctive management models have been formulated in different context, such as optimum scale of development for dams and groundwater recharge facilities, evaluation of alternative plans for surface and groundwater use, operation of reservoir and groundwater pumping facilities, temporal and spatial relationship of stream-aquifer system, water quality management, and so forth. For illustration, an economic optimization conjunctive use model is presented below.

Let us assume that a command area is divided into a number of units (called agricultural zones) based on some administrative, technical, or feasibility considerations. The conjunctive use model related to the allocation of resources consists of a number of decision variables such as surface water and groundwater supplies in each time period to each agricultural zone and optimal irrigated area in different agricultural zones. The model requires a number of parameters such as irrigation efficiencies, unit costs of development and operation of surface water and groundwater resources, recharge etc. Different variables and parameters used for i (agricultural zone), j (crop type), and t (time period) are:

Z - Net benefit from irrigated crops
BI - Annual net return from total irrigated area excluding farm cost
BR - Annual net return from unirrigated area
CSW - Annual equivalent cost of surface water development
CGW - Annual equivalent cost of groundwater development
SWC_i - Annual canal capacity in i^{th} area
GWC_i - Annual available pumping capacity in i^{th} area
OCS - Annual operation and maintenance cost of surface water
OCG - Annual operation and maintenance cost of groundwater
Y_j - Yield of j^{th} crop at full irrigation level per unit area
P_j - Selling price of j^{th} crop
C_j - Cost of cultivation of j^{th} crop excluding cost of irrigation per unit area
CC_i - Equivalent unit annual cost of canal, drainage and leveling works for i^{th} zone per unit volume of water used
CG_i - Equivalent unit annual cost of GW pumping system in i^{th} area per unit volume of water used
CP_i - Annual operation and maintenance (O&M) cost of GW pumping system in i^{th} zone per unit volume of water used
CO_i - Annual O&M cost of canal works in i^{th} area per unit volume of water used
SW_{it} - Surface water allocation to i^{th} area during t^{th} period
GW_{it} - Groundwater to be pumped in i^{th} area during t^{th} period
H_i - Average depth to water table in i^{th} area
DD_{it} - Drawdown due to pumping in i^{th} area during t^{th} period
DDL_{it} - Permissible drawdown in i^{th} area during t^{th} period
A_i - Irrigated area in i^{th} agricultural area
AM_i - Available area for irrigation in i^{th} agricultural area
a_{ij} - Area of j^{th} crop in i^{th} agricultural area as fraction of total cultivated area
b_j - Irrigation level expressed as fraction, b_j is 1 when jth crop is fully irrigated
q_{bj} - Yield of j^{th} crop per unit area when irrigated at b_j irrigation level
s - Fraction of irrigation water delivered that becomes surface runoff
r - Fraction of irrigation water delivered that becomes recharge to aquifer

n - Total number of agricultural areas
k - Total number of crops
T - Total number of time periods
P_t - Total precipitation averaged over the area during tth period
ψ_t - Average deep percolation loss from rice fields during tth period
β_{ip} - Drawdown at ith area due to unit pumpage at pth area
δ_{ijt} - Crop water demands per unit area of jth crop in ith area during tth period
θ_{1i} - Conveyance efficiency above outlet in ith area
θ_{2i} - Field channel efficiency in ith area
θ_{3i} - Water application efficiency in ith area

The model maximizes the net annual economic return from irrigation water use in year of average water supply. It considers the benefits from growing given crops and development and operation costs of surface and groundwater facilities subject to a variety of constraints. The objective function can be described as:

$$\text{Max. } Z = (BI + BR) - (CSW + OCS + CGW + OCG) \qquad \ldots(2)$$

where,

$BI = f_1 \{A_i, a_{ij}, q_{bj}, b_j, P_j, s, Y_j, P_j, C_j, \text{land capability}\}$
$BR = f_2 \{A_i, a_{ij}, P_t, C_j, \text{land capability}\}$
$CSW = f_3 \{\text{life of system, discount rate, development cost of } SWC_i\}$
$OCS = f_4 (\text{operation year, component life, discount rate, } SW_{it}\}$
$CGW = f_5 \{\text{life of system, discount rate, development cost of } GWC_i\}$
$OCG = f_6 \{GW_{it}, H_i (GW_{it}, \beta_{ip}), CP_i (H_i)\}$

All the above terms are expressed either as present worth value or in terms of annual equivalent cost over the assumed planning period. The optimization of the objective function is subject to the following constraints:

i) Crop water balance constraint

Crop water balance depends on the crop water requirement, desired level of irrigation for jth crop during the tth period, irrigation efficiencies, and surface and groundwater allocations as follows:

$$\sum[\, SW_{it} + GW_{it}\,] = f_7 \{\delta_{ijt}, a_{ij}, A_i, b_j, \theta_{1i}, \theta_{2i}, \theta_{3i}\} \qquad \ldots(3)$$

ii) Recharge balance constraint

Recharge balance depends on the groundwater pumpage, canal seepage, field application losses, rainfall, evapo-transpiration, subsurface inflow and outflow etc. It is required to be maintained through proper surface and groundwater supplies for attaining stabilization of the groundwater system.

iii) Drawdown constraint

Drawdown (DD_{it}) depends on the influence coefficient (β) and the groundwater pumpage. It may be considered to be linear or non-linear. Using this constraint, drawdown is restricted in a particular area as represented below:

$$DD_{it} = f_8 \{GW_{it}, \beta_{ip}\} \quad \ldots(4)$$

$$DD_{it} \leq DDL_{it} \quad \ldots(5)$$

iv) Capacity constraints

Conveyance capacity constraints for existing facilities are to be imposed. Canal water supply to each agricultural area is limited by the existing conveyance capacity. Similarly, groundwater pumpage from the tubewells in each area is limited by the existing pumping capacity. These are represented as below:

$$SW_{it} \leq SWC_{it} \quad \ldots(6)$$

$$GW_{it} \leq GWC_{it} \quad \ldots(7)$$

v) Land constraint

Area irrigated in each agricultural area is limited by the available land under cultivation as follows:

$$A_i \leq AM_I \quad \ldots(8)$$

vi) Other constraints

Miscellaneous other constraints representing policy decisions based on socio-economic considerations may include:

- Irrigation levels for some crops so as to have equitable distribution of water.
- Cropping pattern restrictions based on socio-economic requirements.
- Limits on groundwater pumpage in some time periods.
- Limits on surface water supply in some time periods.

The conjunctive use model, described above, is a non-linear representation of the physical phenomenon. The groundwater dynamics is incorporated in the form of influence coefficients that need to be derived separately for each agricultural area by calibrating a groundwater model for the study area. The objective function and the constraints of the model are specified in the form of equations in a linear programming formulation and the model is solved to provide the irrigated area in different agricultural zones and the surface and groundwater allocation in each zone for obtaining maximum benefits.

A GIS based model application for conjunctive management of surface water and ground water in an irrigation command area will be demonstrated in the next lecture.