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ASSESSMENT OF IRRIGATION RETURN FLOW

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ABSTRACT

Irrigation return flow is one of the most significant components in the water balance of irrigation command areas. A part of the water applied to irrigated fields percolates deep to recharge the ground water which is known as irrigation return flow. In absence of any studies, it is usually taken as 35% of the water applied for irrigation in case of canal irrigation and 30% in case of irrigation from ground water. But this is only an approximate estimate. The irrigation return flow will depend upon soil moisture characteristics, meteorological parameters, crop types, method of irrigation, and depth to water table.

This report presents the various methodologies for correct assessment of irrigation return flow.

1.0 INTRODUCTION

In irrigation practice, certain portion of the applied water, over and above the consumptive use, infiltrates into the ground to reach either an aquifer as deep percolation or to a nearby stream as interflow. This contributory replenishment from irrigation is referred to as 'Irrigation Return Flow' (Jensen, 1983 and Hurley, 1968).

Irrigation return flow may amount to as much as 20% to 40% of the volume of water applied for irrigation. In absence of any studies, it is usually taken as 35% of the water applied for irrigation in case of canal irrigation and 30% in case of irrigation from ground water applied to small segments of irrigation commands.

Seepage loss from canal and field channel is a major component of irrigation return flow. The seepage loss from a canal reach is maximum when the water table lies at large depth (more than 1.5 times the width of the canal at water surface). As irrigation continues, the water table rises and reaches a dynamic equilibrium. If the water table under dynamic equilibrium lies at a shallow depth, the potential difference between the canal water body and ground water in the vicinity of the canal governs the seepage losses from the canal and the seepage loss is reduced. In such situation, the irrigation return flow will be lower than what is being currently assumed.

Estimation of irrigation return flow is a complex problem and its solution requires a detailed study of the water balance in the study area. When irrigation water is supplied from groundwater reservoir, the water is applied without conveying it over long distances and the transmission loss is small. In applying groundwater, crop needs and extractions can be matched evenly. In such cases, the irrigation return flow will depend on local soil characteristics besides the climatological factors. The irrigation return flow should be computed for each soil group and crop type at micro level through soil moisture balance. However, most of the irrigation water is supplied from surface water sources. The conveyance system (i.e. canal system) supplies water to the canal command area and the seepage loss from the canal adds to the irrigation return flow. The conveyance system involves travel through long distances. The transmission losses are governed by the hydraulic conductivity of the canal bed material besides the combined effect of all hydrological stresses in the canal command. The water table position in an aquifer is governed by recharge to aquifer from various sources and withdrawal from ground water reservoir. The position of water table in turn controls the seepage losses from the canal. The computation of irrigation return flow should therefore be made at macro scale considering the entire command area and the prevailing hydrologic boundary conditions.

Irrigation return flow is one of the most significant components in the water balance of irrigation command areas. It depends upon the geological set up of the irrigation command, soil moisture characteristics $[K(\theta), \psi(\theta)]$, meteorological parameters, crop types, method of irrigation and depth to water table etc. Application of fertilizers and leaching requirement of soil salts may result in application of more irrigation water leading to more irrigation return flow.

Process level models i.e. evaluation of seepage from a canal reach, evapotranspiration from the root zone, infiltration-redistribution and field tailwater by themselves have only marginal utility in evaluating irrigation return flow unless they are used in the fabrication of a macro level model study (Walker, 1978). The input data for macro level study can be obtained from process level models. Deep percolation, which represents a major component of irrigation return flow, can be estimated using soil moisture modelling for each soil group and crop type. Using this estimate of deep percolation and other components of recharge and groundwater withdrawal, the water level fluctuation can be simulated using a distributed groundwater flow model for the command area. Considering the saturated flow control volume, the following equation can be used to compute the return flow (Khan, 1980) :

$$\sum_{i=1}^{N} QI_i + (1-\alpha) QI_{ir} + QI_g - \sum_{i=1}^{N} QO_i - QO_g = \frac{\Delta V}{\Delta t}$$

in which (in terms of average flow rates taken over Δt period),

$\sum_{i=1}^{N} QI_i$ = the total inflow into the section through precipitation, seepage from rivers and streams, artificial recharge, etc.;

α = the irrigation efficiency over the section which is unknown ;

QI_{ir} = the total quantity of water used for irrigation;

QI_g = the ground water inflow from adjacent sections;

$\sum_{i=1}^{N} QO_i$ = the total outflow from the section through pumpage ;

QO_g = the ground water outflow to the adjacent sections;

ΔV = the change in volume of water within the control volume during the time Δt which is equal to integration of change in water level multiplied by specific yield. ΔV can be computed either using the distributed groundwater flow model or by direct measurement.

The term $(1-\alpha)QI_{ir}$, irrigation return flow, can be determined if all other elements of the above hydrologic balance equation are known. Integration of percolation losses from the command area during a particular time period computed using process level model at micro level can be compared with irrigation return flow computed from the above equation which treats the problem at macro level.

Evaluation of water balance components requires a close observation network for measurement of meteorological data, surface water diversions and soil moisture characteristics of the root zone. For evaluation of the irrigation return flow, it is necessary to consider the source of irrigation (ground water or surface water), the type of crops (paddy or non paddy), the type of soil and the depth to water table below ground level. It is necessary to quantify the amount of return flow from specific irrigation command areas as case studies.

As per the report of Ground Water Resource Estimation Committee (1996), the recharge due to return flow from irrigation may be estimated, based on the source of irrigation (groundwater or surface water), the type of crop (paddy, non-paddy) and the depth of water table below ground level, using the norms provided below (recharge given as percentage of application).

Source of irrigation	Type of crop	Water table below ground level		
		<10m	10-25m	>25m
Groundwater	Non-paddy	25	15	5
Surface water	Non-paddy	30	20	10
Groundwater	Paddy	45	35	20
Surface water	Paddy	50	40	25

Ground Water Resource Estimation Committee (1996) has also provided the norms for recharge due to seepage from canals, indicating 1.8 to 2.5 cumecs per million sq. m. of wetted area for unlined canals in normal soil, 3.0 to 3.5 cumecs per million sq. m. of wetted area for unlined canals in sandy soil, and 20% of above values in case of lined canals. However, it may be noted that seepage losses from canals also depend upon width of canal, depth of flow, hydraulic conductivity of the bed material and depth to water table.

In the present study, a research methodology is formulated for assessment of irrigation return flow.

2.0 METHODOLOGIES

The quantification of irrigation return flow should be made both at micro scale (by process level model) and macro scale. The micro scale quantification will be useful in ascertaining the return flow corresponding to soil and crop type and method of irrigation. The treatment of the investigation at macro scale will enable to verify the accuracy of computation made at micro scale. The distributed mathematical model of ground water flow, which simulates the evolution of ground water table in a canal command area, can be used to cross check the computation of irrigation return flow determined at micro scale. If the inputs to the groundwater flow model, which are estimated using process level models, are correct then the simulated water table by groundwater flow model will match with the observed water level fluctuation. The hydraulic gradient across the canal boundary will enable the determination of seepage from canal independently which could be compared with the computation of seepage made from surface water balance of the canal reach. The effluent seepage to a stream computed from the model should match with the base flow in the stream draining the groundwater basin during the lean flow. The studies required to be conducted at micro and macro scale are described below.

2.1 Soil Moisture Modelling

Irrigation return flow can be estimated by modelling the surface and subsurface flow. One-dimensional St. Venant equation can be used to represent the overland surface flow and one-dimensional Richards equation can be used to represent the subsurface flow as the movement of soil moisture in unsaturated zone. The governing equations are given below.

For surface flow, the governing equations are (Chaudhry, 1993):

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = (R-I) .$$

$$\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left[\frac{q^2}{h} + \frac{gh^2}{2}\right] = gh(S_o - S_f)$$

where, h=flow depth (m); q=discharge per unit width (m^2/s); g=acceleration due to gravity (m/s^2); R=volumetric rate of rainfall per unit area (m/s); I=volumetric rate of infiltration per unit area (m/s); S_o=slope of the catchment; S_f=friction slope; x=distance (m); and t=time (s).

The friction slope can be calculated by using Manning formula i.e. $q = (h^{5/3} \sqrt{S_f})/n$ where, n=Manning coefficient; and R=hydraulic radius. If the kinematic flow number $K_f \geq 20$, one can go for kinematic wave approximations, i.e. by assuming friction slope equal to the bed slope. The kinematic flow number is defined as (Chaudhry 1993):

$$K_f = \frac{S_o L_o}{y_n F_r}$$

where, K_f=kinematic flow number; S_o=slope of the catchment; L_o=length of the overland flow plane; y_n=normal flow depth; and F_r=Froude number;

For subsurface flow, the governing equation is (Freeze and Cherry, 1979) :

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial \psi}{\partial z} - 1\right)\right] - Si(z,t)$$

where, θ is the moisture content; $K(\psi)$ is the unsaturated hydraulic conductivity (cm/s), ψ is the soil suction head (relative to the atmosphere) expressed in cm of water, z is the gravitational head (cm) considered positive in downward direction, Si is the sink term representing the rate of withdrawal of water per unit volume of the soil.

Both surface and subsurface flow equations can be solved simultaneously using the numerical methods. The surface and subsurface flow are linked through the process of infiltration into the ground. Explicit finite-difference scheme may be used for the solution of surface flow whereas implicit finite-difference scheme may be used for the solution of subsurface flow. Flow depth at surface will be calculated by solving the surface flow equations. The upstream boundary condition will be the discharge supplied at the inlet point. The rate of infiltration into the ground will be computed by solving the Richards equation. The downward flux at root zone depth will be computed by solving the Richards equation with the surface flow as the top boundary condition. The return flow is the cumulative downward flux at root zone depth. The study should be carried out at each unit of soil and crop types. It can give idea about return flow versus culturable command. This method will compute the losses from irrigation application at micro level.

2.2 Water Balance Approach

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

The water balance of unsaturated zone is (ILRI, No. 16, Vol III, 1980):

$$(Pr + Irr - Ro) - Evpt - (Per-Cap) = \Delta Sm$$

where, Pr=precipitation; Irr=irrigation supply; Ro=surface runoff; Evpt=evapotranspiration; Per=percolation; Cap=capillary rise; and ΔSm=Change in soil moisture storage.

Potential evapotranspiration may be computed using Hargreave's (vide Garg. 1996) average value of coefficient, which accounts for percentage of crop growing season, and class-A Pan evaporation. Class A pan evaporation can be measured in the field. Actual evaporation, which would also depend on available soil moisture, may be computed using Fleming's table (Fleming, 1964). Soil moisture in the root zone can be ascertained using tensiometer and pre-determined soil moisture characteristics. Surface runoff from the irrigation plot can be measured using a V-Notch. Surface runoff may also be estimated by using the SCS method and soil saturation concept i.e. by assuming that runoff is contributed only from saturated part of the plot (Manely, 1977).

All quantities in the equation are directly measurable, except for percolation and capillary rise, which is nothing but irrigation return flow. This method will compute the losses from irrigation application at micro level. Accuracy of the method would largely depend upon accuracy of the computation of evapotranspiration. There are other methods also for computation of reference crop evapotranspiration namely Blaney Criddle, Radiation and Penman method etc. Pan evaporation method is the simplest one and more accurate than Blaney Criddle and Radiation method (Doorenbos and Pruitt, 1977). The proposed method would require continuous record of all the parameters involved.

2.3 Experimental Determination of Irrigation Return Flow

2.3.1 Theory

The component of irrigation return flow, due to percolation from water applied for irrigation in the field, can be ascertained from soil moisture balance in the root zone.

The flow through any section of soil is given by the Darcy's law

$$q_z = -K(\psi)\left(\frac{\partial\psi}{\partial Z} - 1\right)$$

where, q_z=Darcy's flux in Z-direction (positive downward); $K(\psi)$=hydraulic conductivity; ψ=suction head; and Z=Depth.

Suction head can be measured at various depths in the soil, from which the hydraulic gradient $\left(\frac{\partial\psi}{\partial Z} - 1\right)$ can be calculated. After knowing the hydraulic gradient and hydraulic conductivity of particular section of soil, one can calculate the flux through that section using above equation. Irrigation return flow can be calculated by continuously monitoring the pressure head in the field and is given by the following equation

$$I_R = \int_{t_1}^{t_2}\left[-K(\psi)\left(\frac{\partial\psi}{\partial Z} - 1\right)\right]_{z_0} dt$$

where, I_R=irrigation return flow; t_1=starting time of irrigation prior to sowing; t_2=time at the end of harvesting and Z_o=root depth.

The cumulative values of return flow are calculated at root depth up to the required time level. This will be carried out in each unit of soil type and crop type. This method will compute the losses from irrigation application at micro level.

2.3.2 Step by step procedure

1. Find irrigation depth at the surface.

2. Find the pressure head at various points below the ground surface up to the root depth at different levels by tensiometer.

3. Calculate the moisture content for the corresponding values of pressure head from the relation θ-ψ.

4. Calculate the unsaturated hydraulic conductivity for the corresponding value of pressure head from the relation K-ψ.

5. Calculate the pressure gradients along the depth for all points.

6. Calculate the Darcy's flux at different depths.

7. Compute the irrigation return flow at the root zone by the equation :

$$I_R = \int_{t_1}^{t_2} \left[-K(\psi)\left(\frac{\partial\psi}{\partial Z} - 1\right)\right]_{z_0} dt$$

8. Steps 1 to 7 can be repeated for a number of points in the command area.

9. Compute seepage losses from different reaches of the canal using potential theory and considering canal cross-section, hydraulic conductivity and depth to water table.

10. Add the canal seepage to return flow computed in step 8 (canal seepage establishes a saturated phreatic zone and ultimately seepage from this zone into the drainage will contribute to return flow).

2.4 Estimation of Irrigation Return Flow through Ground Water Modelling

The canal command area may be considered for ground water modelling. The transmissivity and specific yield can be determined from pump test data. The water table fluctuation may be measured at adequate number of observation wells. The ground water draft can be ascertained from field survey. The seepage losses from canal can be computed by measuring the canal discharge at various points considering the cross-drainage discharge entering into the canal water and water diverted for irrigation. The discharge at inlet to the command area and at the outlet of the command area can be measured through the gauge-discharge measurements. After estimating all the input components (including irrigation return flow) to the aquifer, simulation of ground water fluctuation may be carried out using mathematical modelling. The governing differential equation for two-dimensional ground water flow in an isotropic unconfined aquifer can be written as (Freeze and Cherry, 1979)

$$\frac{\partial}{\partial x}\left[Kh\,\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial y}\left[Kh\,\frac{\partial h}{\partial y}\right] = S_y\,\frac{\partial h}{\partial t} - Q_R + Q_I$$

where, h=hydraulic head; S_y=specific yield; K=saturated hydraulic conductivity; Q_R = recharge to the ground water; and Q_P =ground water withdrawal.

The above nonlinear parabolic partial differential equation can be solved by finite-difference scheme using the Newton-Raphson method. The simulated water table fluctuation may be compared with the observed fluctuation. If all input data including irrigation return flow estimated using process level model are correct, the simulated water table will match the observed water table height. Alternatively, the estimation of recharge component can be treated as an inverse problem. The estimated recharge, obtained by solving the ground water flow equation, may then be compared with return flow obtained through soil moisture modelling. This method will compute the irrigation return flow at macro level.

The response of the aquifer (exchange of flow between the water bodies such as a river and hydraulically connected canal reaches relevant to the hydrogeologic setup, and water level fluctuations in the aquifer) may be computed by considering the various inputs (recharge from rainfall, seepage from different reaches of the canal which are not hydraulically connected with the aquifer, and irrigation return flow from different plots) and hydrogeological parameters (transmissivity, specific yield in the zone of water level fluctuation and storage coefficient of the confined aquifer obtained through field tests) with the aid of the groundwater flow model. If the model parameters and the inputs are correct, the response of the aquifer should tally with the observed water level fluctuation and measured base flow of the river. The influent seepage from canal reaches hydraulically connected with the aquifer, computed through the groundwater flow model, could be checked from water balance applied to canal reaches and also considering observed water table position near the canal.

The recharge from rainfall may be computed from moisture balance in the non-irrigated area which can be further checked from the continuous measurement of water level rise in observation wells located in the same non-irrigated area. The subsurface outflow from the canal command area can be ascertained from the water level contours predicted through the groundwater flow model.

2.5 Regime Channel

A channel flowing in unlimited incoherent alluvium of the same grade as the material transported, if continued uninterrupted (i.e. the condition of discharge and silt remaining constant) would attain final stability or final regime conditions.

A channel is said to have attained a regime condition when a balance between silting and scouring and a dynamic equilibrium in the forces generating and maintaining the channel cross-section and gradient has been obtained. The ideal conditions of regime defined above may be called 'true regime conditions'. In nature, these ideal conditions are seldom achieved.

There is only one section of a channel and only one slope at which the channel carrying a given discharge will carry a particular grade of silt. Natural silt transporting channels have a tendency to assume a semi-elliptical section. The coarser the silt, the flatter is the semi-ellipse, that is, greater the width of water surface. The finer the silt, the more nearly does the section approximate to a semi-circle.

If a channel is designed with a section too small for a given discharge and its slope is kept steeper than required, scour will occur till final regime is obtained. On the other hand, if the section is too large for the discharge and the slope is kept flatter than required, silting will occur till final regime is obtained.

Lacey has given the following regime equations :

$$P = 4.75 \sqrt{Q} \qquad \ldots (2.5.1)$$

$$R = 0.47 \ (Q/f)^{1/3} \qquad \ldots (2.5.2)$$

$$f = 1.76 \sqrt{d} \qquad \ldots (2.5.3)$$

where, P is the wetted perimeter, Q discharge, R hydraulic radius (=A/P, A being the cross-sectional area), f silt factor, and d average particle size in mm.

Let 'a' be the command area in ha and δ be the yearly delta in meters. The required flow rate in the canal,

$$Q = (a*100*100*\delta)/(365*24*60*60) = 3.17*10^{-4}\ a\delta \text{ (cumec)}$$

Approximating the shape of regime channel as triangular with width B and depth D,

$$A = 0.5*B*D$$
$$P = \sqrt{(4D^2 + B^2)}$$
$$R = (0.5*B*D)/\sqrt{(4D^2 + B^2)}$$

Using the Lacey regime equations,

$$P = 4.75 \sqrt{Q}$$
$$\sqrt{(4D^2 + B^2)} = 4.75 \sqrt{Q}$$
$$B = (22.562\ Q - 4\ D^2)^{1/2} \qquad \ldots (2.5.4)$$

$$R = 0.47\ (Q/f)^{1/3} = 0.47[Q/(1.76 \sqrt{d})]^{1/3}$$
$$(0.5*B*D)/\sqrt{(4D^2 + B^2)} = 0.389\ Q^{1/3}\ d^{-1/6} \qquad \ldots (2.5.5)$$

Solving equations (2.5.4) and (2.5.5) for B and D, we get

$$B = [11.28\ Q - 0.5\ (509.044\ Q^2 - 218.448\ Q^{5/3}\ d^{-1/3})^{1/2}]^{1/2}$$

and $$D = [2.82\ Q + 0.125\ (509.044\ Q^2 - 218.448\ Q^{5/3}\ d^{-1/3})^{1/2}]^{1/2}$$

Knowing the values of B and D, the range of seepage losses (S_{max} and S_{min}) from the canal may be obtained as

$S_{max} = K\ (B + 2D)$, in case of deeper water table

$S_{min} = K\ (B - 2D)$, in case of water table at the level of channel bed

where, K is the hydraulic conductivity of channel bed material.

3.0 DATA REQUIREMENT

To estimate the irrigation return flow by the methodologies described, the following data will be needed :

1. Topographical map of the study area (Scale 1:50,000)
2. Soil map
3. Map showing layout of main, branch and distributary canals
4. The cross-sections of the canals in different reaches
5. Longitudinal section of the canal showing the location of water diversions and cross drainage
6. Monthwise number of running days and discharges of the canals
7. Cropping pattern, sowing and harvesting time of different crops grown in the study area
8. Irrigation water applied during the crop growing season for various crops
9. Method of irrigation
10. Outflow from tanks
11. Meteorological data (precipitation, relative humidity, air temperature, wind velocity)
12. Pan evaporation data
13. Lithologs at different points
14. Water table data
15. Specific yield and transmissivity (minimum at three places from pumping test data)
16. Ground water draft
17. Hydraulic conductivity values
18. Soil moisture characteristics ($K(\theta)$, $\psi(\theta)$)

4.0 CONCLUSION

Irrigation return flow is one of the most significant components in the water balance of irrigation command areas. The quantification of irrigation return flow should be made both at micro scale (by process level model) and macro scale. The micro scale quantification will be useful in ascertaining the return flow corresponding to soil and crop type and method of irrigation. The treatment of the investigation at macro scale will enable to verify the accuracy of computation made at micro scale.

Methodologies have been presented for assessment of irrigation return flow through soil moisture modelling; water balance approach; experimental determination; and ground water modelling.

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