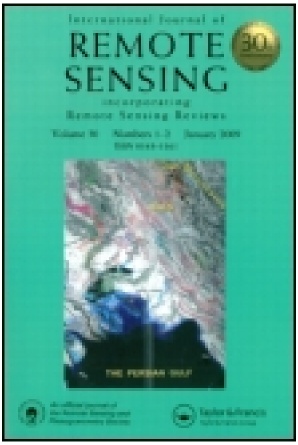

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Water balance study and conjunctive water use planning in an irrigation canal command area: A remote sensing perspective

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Water balance study and conjunctive water use planning in an irrigation canal command area: a remote sensing perspective

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Abstract. Water budgeting of the D-36 and D-36 A distributaries confined between Pedda Vagu, Korutla Vagu and Kakatiya main canal of the Sri RamSagar Project (SRSP) Command area was conducted using remote sensing derived crop areas, land cover information, irrigation tank inventory and source-wise distribution of irrigated areas, together with conventional meteorological, canal flows and well inventory data. A semi-empirical water balance model was developed and validated using remote sensing derived objective information of the command area and the validated model used for predicting the groundwater table under normal rainfall conditions. Recharge and water balance in the study area indicated that the net recharge to the aquifer is negative to the tune of 2.54 Mm^3 resulting in a fall of the groundwater table by 0.79 m during 1992–93. However, normalized groundwater recharge and water balance estimates indicate an impending waterlogging problem with an annual groundwater table rise of 0.35 m. In view of existing water management practices, a conjunctive water use plan of rotational operation of aquifers and canals is suggested.

1. Introduction

Judicious management of the water resources of a groundwater basin needs a comprehensive understanding of the total system and its response to recharge. An adequate estimate of the availability of groundwater storage in a basin requires water budgeting. Water budgeting helps to evaluate the net available water resources, both surface and subsurface, and to assess the impact of existing water utilization pattern and practices. The need for accurate and reliable information on crop inventory, land cover, soils, source-wise distribution of irrigated areas and irrigation tank inventory, has often precluded quantitative description and analysis of various processes that describe the water resources regime in any irrigation command. The emergence of remote sensing as a tool for providing the above-mentioned base-line information not only in a spatial dimension but also to monitor them through time, is cost and time effective. This information, together with the conventional meteorological, canal flows and well inventory data can be used as inputs to the various existing empirical, semi-empirical and conceptual models to understand the various components of water budgeting. This constitutes the scientific basis for development of guidelines for planning sustainable use of groundwater resources in conjunction with surface water resources in the irrigation command area. In recent years there

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has been more emphasis on groundwater development in irrigation projects and on the planned conjunctive use of canal water and groundwater to augment canal supplies and control waterlogging and salinity, thereby increasing the reliability of irrigation system operation. This fact is duly recognized in India and constitutes one of the strategies for sustainable development of irrigated agriculture (Ministry of Irrigation 1984, Government of India 1985).

The groundwater estimation committee (Ministry of Irrigation 1984) recognized the availability of groundwater potential in major irrigation projects and recommended specific empirical constants to estimate the recharge from the conveyance and distribution system of these projects. These constants are now routinely applied by the various government agencies to estimate the groundwater potential of a region. The methodology is based on such specific empirical constants, which are modified based on objective information derived from satellite remote sensing data and field data, for estimating the groundwater recharge and annual water balance of the study area.

2. Study area

The study area for this paper lies between 78° 41′ to 78° 48′ E longitude and 18° 44′ to 18° 53′ N latitude and is confined by two tributaries: Pedda Vagu and Korutla Vagu of the river Godavari and the Kakatiya main canal of the SriRamSagar project (SRSP), with a gross command area of 6800 ha, spread across nine villages of three mandals (administrative units) of Karim Nagar district, Andhra Pradesh (figure 1) . The climate is semi-arid and the average annual rainfall of the study area is 948 mm. Irrigation systems in the study area comprise canals, wells, dug-wells and tanks. D-36 and D-36 A are the two distributaries commanding 1475 and 55.5 ha respectively. The general localization pattern in SRSP is single wet crop in the D-36 distributary and single irrigation dry crops in the D-36A distributary. The major crops grown are paddy, maize, turmeric, sugarcane, ground nut and other crops. Red soils (sandy loam and sandy clay loam) are predominant covering an area of about 65% of the total, while black soils (clay and silty clay) occupy about 35% (SRSP-CADA 1980). The major physiographic units of the area are (i) granite hills and inselbergs, (ii) granite hill foot slopes, and (iii) granite undulating plain. The two generalized land systems of the study area are: (i) denudational (residual hills), and (ii) pediments. Most of the study area is under pediments (lower pediments) with slope range of 3–8%, moderately eroded with good to moderate groundwater potential. The command area is underlain by archean group of rocks consisting of granites and gneisses, metasediments of the purana group. The granites are mostly exposed as sheets, boulders or domes. Groundwater occurs under water table conditions in the weathered and fractured zones of granites. The saturated thickness of the aquifer is 4–8 m. The thickness of the weathered zone varies from about 10 to 16 m. These weathered rock aquifers are developed through large diameter irrigation dug wells, generally rectangular in shape.The depth of water levels vary from 2 to 11 m. The wells sustain continuous pumping of 2–3 h per day and yield varies from 90 to 120 m^3 per day.

3. Agricultural crop land inventory

Geocoded FCC (NIR, red and green bands) imagery at 1:50 000 scale on three dates: 28 October 1992 (path—row 144/ 047, Landsat-5 TM), 17 January and 29 May 1993 (Path-row 026—55, IRS 1B LISS-II) representing Kharif, Rabi and summer

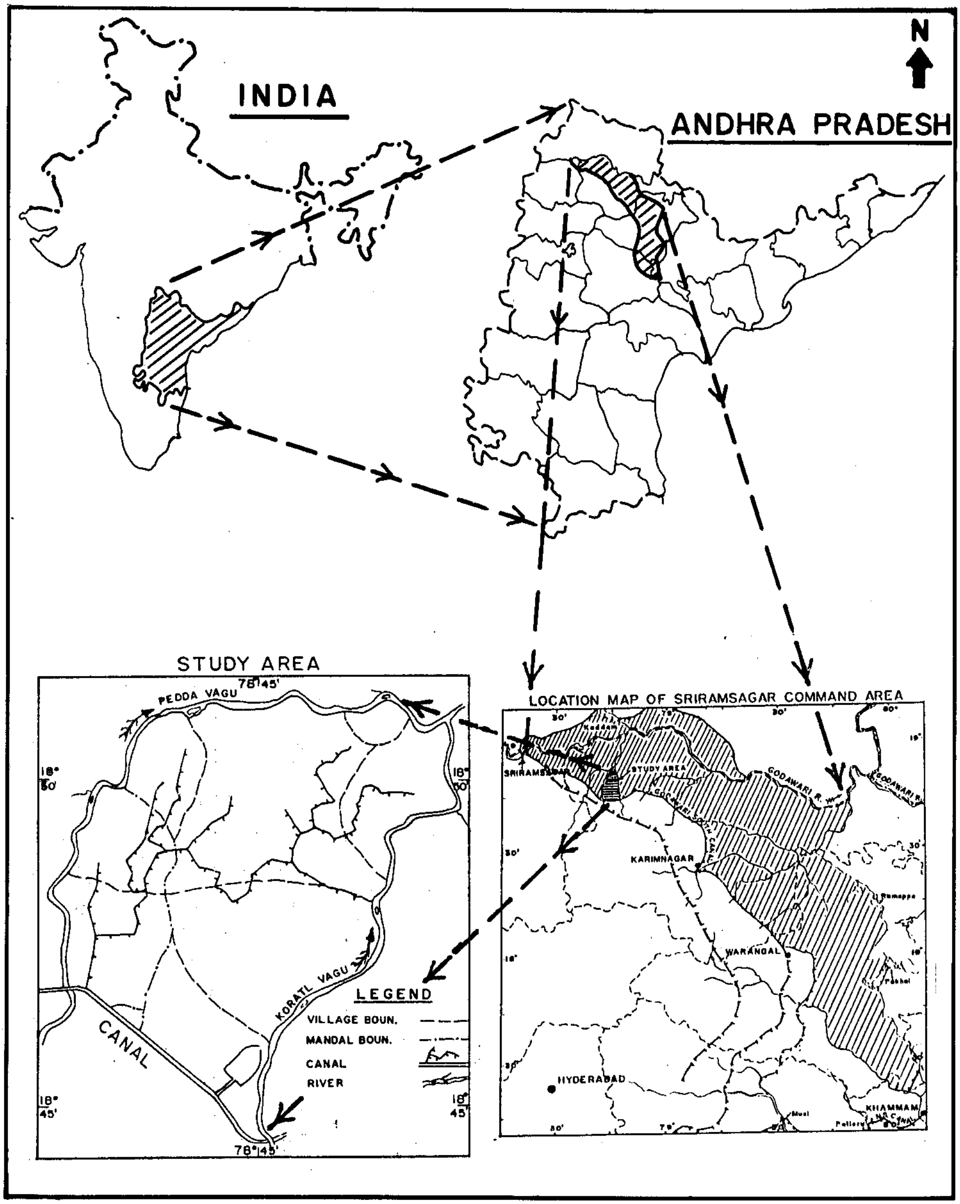

Figure 1. Location map of the study area.

seasons, respectively, were visually interpreted to prepare a land cover map for each season. The agricultural crop land is further divided into paddy land and non-paddy land. Further, a distinction between various ID (irrigated dry) crops and the non-paddy category could not be made from the visual interpretation techniques. The study area is one of the typical command areas in the country and has a diversified cropping pattern (heterogeneously cropped).

Thorough examination of the digital data of the study area indicated that the spectral signatures of the major ID crops are not separable. Hence, it was proposed

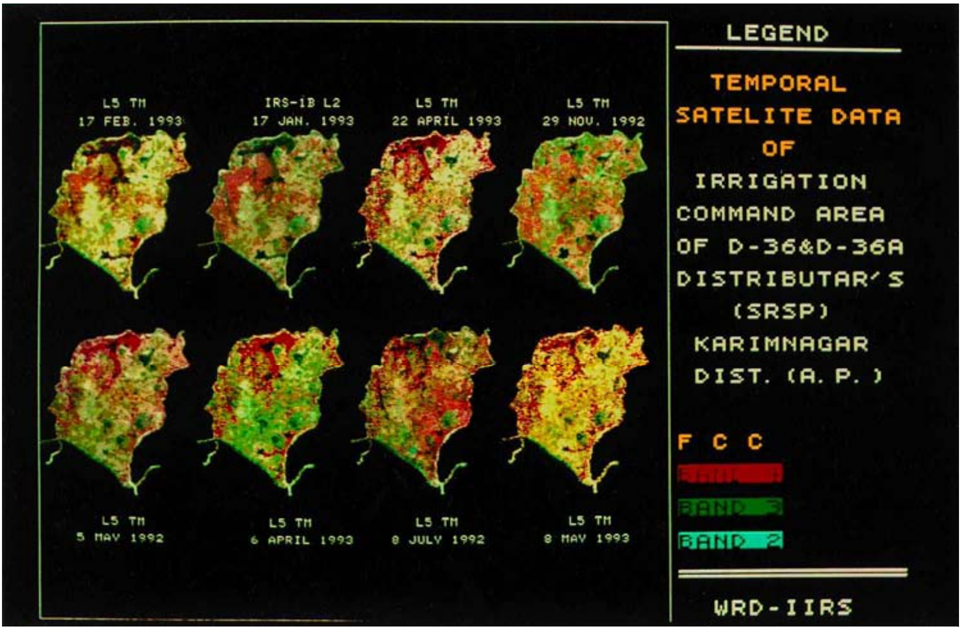

Figure 2. Temporal satellite data of the study area.

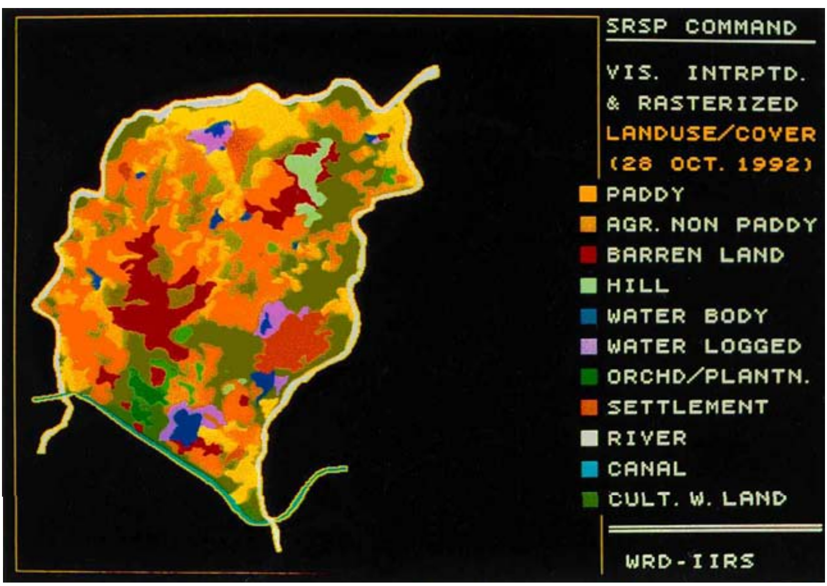

Figure 3. Land cover map (visually interpreted and rasterized image) of the study area during kharif season, 1992.

to use a combination of visual interpretation and digital analysis of multi-temporal satellite data consistent with the crop calendar in the study area to extract major ID crops within non-paddy land cover category. Multi-temporal digital satellite data of 8 July 1992, 28 October 1992, 29 November 1992, 17 February 1993, 6 April 1993, 8 May 1993 (Landsat-5 TM) and 17 January 1993 (IRS-1B, LISS II) were used (figure 2) to generate standard FCCs. Visually interpreted seasonal land cover maps (figure 3) were digitized and made compatible with the above-mentioned temporal satellite digital data in terms of resolution of the picture element. The non-paddy land cover category from the three digitized visually interpreted maps was extracted by masking out other features. Then, these masked images were superimposed on to the multi-temporal digital satellite data based on the season in which it fell. Thus, non-paddy areas were transferred from visually interpreted seasonal maps to the multi-temporal digital data and the rest of the features on FCC were masked.

Each of these digital datasets was classified into cropped and non-cropped (harvested fields) for non-paddy areas using the Gaussian maximum likelihood classification algorithm. Then the results from all the multi-temporal digital data were sequentially analysed consistent with the crop calendar for the major crops grown in the study area to extract the extent of each major crop: maize, turmeric, sugarcane, groundnut and others in each season. In this study, besides agricultural crop information, remote sensing derived source-wise irrigated areas, land cover, irrigation tank water spread, ayacut (area commanded by a tank) information, and water yield estimates from the irrigation tanks (Rao and Chakraborti 1995) were used together with the conventional field data as the inputs to estimate various components of water balance and groundwater recharge.

4. Assessment of net groundwater recharge

The net regional recharge (R_n) to groundwater during any time period is estimated (Sondhi *et al.* 1989) by

$$R_n = R_g + Q_g - Q_p \qquad (1)$$

where R_g = gross recharge to groundwater basin; Q_g = groundwater inflow/outflow; and Q_p = groundwater extraction through wells.

The gross recharge (R_g) to the groundwater basin is given (Rao 1992) by

$$R_g = R_e + R_c + R_d + R_t + R_{ci} + R_{wi} + R_{ti} \qquad (2)$$

where R_e = recharge due to rainfall; R_c = recharge due to seepage from major distributaries; R_d = recharge due to seepage from minor distributaries; R_t = recharge due to percolation from irrigation tanks; R_{ci} = recharge due to percolation losses from canal irrigated areas; R_{wi} = recharge due to percolation from well irrigated areas; R_{ti} = recharge due to percolation losses from tank irrigated areas.

All the components in equation (2) were estimated by following the recommendations of the groundwater estimation committee of the Ministry of Irrigation (1984), with some modifications based on remote sensing derived command area inventory and the field observed data. R_e, recharge due to rainfall, was estimated from the daily rainfall records and the soil types and their extent in the command area. R_c and R_d were estimated from the canal cross-sectional details, length of the canals, number of days the canal operated, etc. R_t, percolation from irrigation tanks, was estimated from the remote sensing derived irrigation tank water spread area and utilizable water yield from irrigation tanks. While R_{ci} and R_{ti} were estimated using the remote sensing derived source-wise irrigated area information as one of the inputs, the R_{ti} could not be estimated using remote sensing data. Since the area estimates of various land covers and the tank irrigated areas compared very well (RD, relative deviation = 4.1%) with the ground observed ACA (agricultural census abstracts) figures, the area irrigated by groundwater wells was estimated using the proportion derived from the percentage contribution of various sources of irrigation to the total irrigated area in ACA estimates. There are no groundwater wells present in the tank irrigated areas in the study area. Details of estimation of each recharge component are given by Rao and Chakraborti (1995). The specific percentage allowances for the various recharge components (table 1) are as follows:

1. Recharge from rainfall (R_e) is estimated as 12.5% of the annual rainfall
2. Recharge due to seepage losses from the major distributary at $3.5\,m^3\,s^{-1}\,10^6\,m^{-2}$, estimated to be 11% of water delivered
3. Recharge due to seepage from distributaries (R_d) at $3.5\,m^3\,s^{-1}\,10^6\,m^{-2}$, estimated to be 9% of water delivered
4. Recharge due to percolation from irrigation tanks (R_t) is 25% of live storage capacity
5. Recharge due to seepage from canal irrigated areas (R_{ci}) of 35% of water delivered at the outlets is 6.39 Mm^3
6. Recharge due to seepage from well irrigated areas (R_{wi}) of 30% is 0.60 Mm^3
7. Recharge due to seepage from tank irrigated areas is 40%; as recommended by the groundwater estimates committee is 2.87 Mm^3
8. In addition to the above, seepage losses from paddy fields contribute 3 mm day^{-1} for 120 days

Q_p is the volume of groundwater extracted in the year 1992–93 in equation (1), estimated from well inventory data of the area, using average annual drafts for each type of well operating in the region. The subsurface inflow or outflow of groundwater across the aquifer boundaries (Q_g) cannot be directly estimated. Hence, it is calculated as the residue from the annual (crop year) water balance equation (Sondhi *et al.* 1989).

$$(P+I)=(ET+E\pm Q_g+Q_s+Q_p\pm\Delta S_s\pm\Delta S_m\pm\Delta S_g) \quad (3)$$

where P = precipitation over the region; I = sum of irrigation water applied over the region by the canal system (Q_c), groundwater (Q_p) and irrigation tank water (Q_t); ET = evapotranspiration; E = soil evaporation from the uncultivated areas; Q_g = groundwater inflow/outflow; Q_s = surface run-off; ΔS_m = change in soil moisture storage; ΔS_s = change in surface water storage; and ΔS_g = change in groundwater storage.

All the above components are expressed in depth units (mm) for the area of 6800 ha. The methodology and data used are presented in the flow chart (figure 4). Weighted rainfall estimated using the Thiessen polygon method assessing the daily rainfall records of five rain gauge stations located in and around the area were used

Table 1. Gross recharge components to groundwater in the study area in 1992–93.

Sl. no.	Sources of recharge	Recharge in Mm^3
1	Recharge from rainfall (R_e)	5.18
2	Recharge from D-36 and D-36A major distributaries (R_c)	1.73
3	Recharge from minors (R_d)	1.25
4	Recharge from irrigation tanks (R_t)	1.91
5	Recharge from canal irrigated areas (R_{ci})	6.39
6	Recharge from tank irrigated areas (R_{ti})	2.87
7	Recharge from areas irrigated by wells (R_{wi})	6.01
Total		25.36

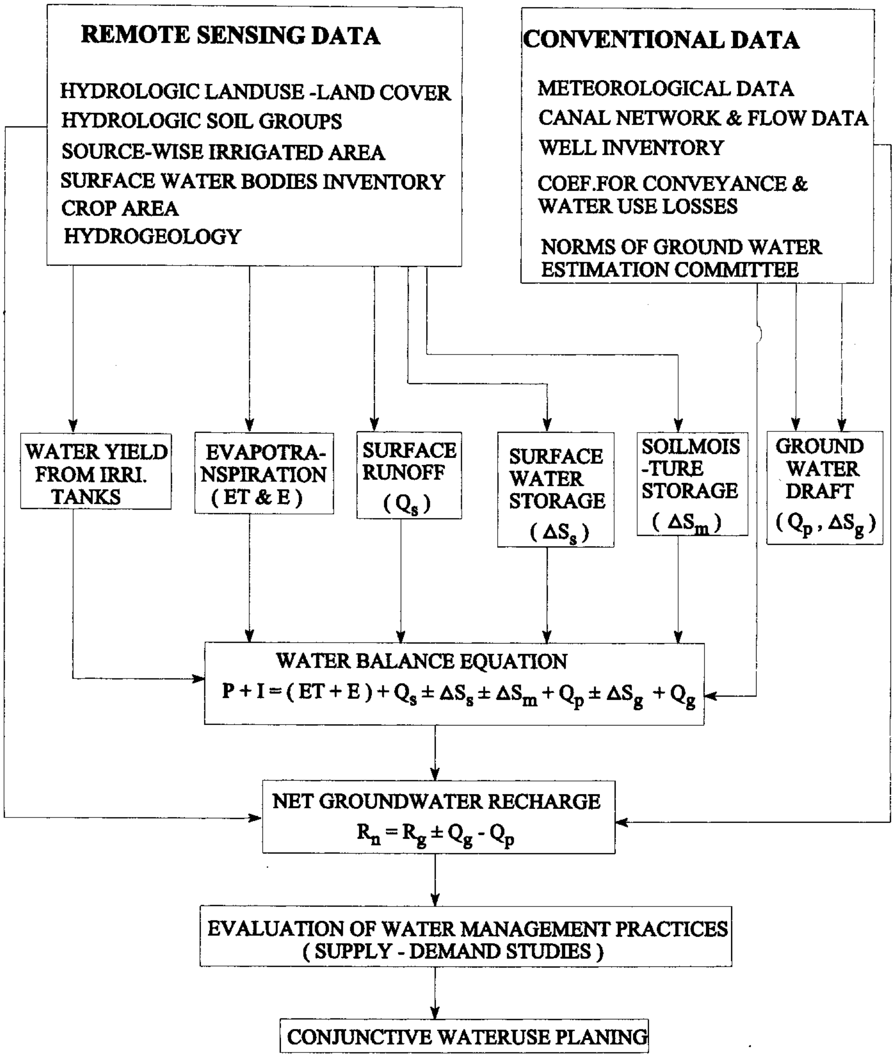

Figure 4. Methodology to estimate net groundwater recharge from the water balance study using satellite data and ancillary data for conjunctive water use planning.

to estimate rainfall for the year 1992–93. Satellite remote sensing derived water yield estimates (Rao and Chakraborti 1995) from irrigation tanks together with the monthly canal releases at the off-take point and groundwater extraction during 1992–93 were used to obtain I. For the annual water balance (for the crop year May–June) both ΔS_s and ΔS_m may reasonably be assumed to be zero. However, satellite imageries of 5 May 1992 and 8 May 1993 were digitally analysed to examine the change in surface water body (irrigation tanks) spread areas. The areas were found to be 27.4 ha in May 1992 and 27.1 ha in May 1993. The change in surface storage ($\Delta S_s = 0.3$ ha) during 1992–93 is insignificant and, hence, assumed to be zero. The ΔS_m under the semi-arid conditions that exist in the soils (predominantly sandy loam) of the command area over prolonged dry spell conditions (during summer months), is insignificant and can be assumed to be zero. The ΔS_g was calculated from data of pre-monsoon (April/June) water levels recorded at nine observation wells distributed over the study area. A value of 0.04 was used as specific yield (Ministry of Irrigation 1984) for the granitic hard rock unconfined aquifer of the area.

Evapotranspiration (ET) was estimated from monthly data of potential evapotranspiration, and the area under various crops was estimated from the analysis of temporal digital satellite data of the area consistent with the local crop calendar. A distinction was made between evapotranspiration from irrigated and unirrigated areas for each crop. It is presumed that the ET from the irrigated crop areas both in monsoon and non-monsoon season occurs at potential rate. For the unirrigated crops, ET is limited by the maximum available soil moisture at the beginning of the season in the effective root zone of crops. Normally it is taken to be 80% of ET (PET or ET_{crop}) from irrigated areas in the Kharif season and 60% of ET from irrigated areas in the Rabi season. Evaporation from uncultivated areas (E) was calculated using Ritchie's equation (Ritchie 1972).

$$E = ET_0 t^{-1/2} \tag{4}$$

where ET_0 = the reference evapotranspiration; and t = the time after the last rain in days.

In the monsoon season, when the soil is frequently wetted, E is estimated to be about 50% of ET_0 by this formula. In other seasons it is about 25% (October–February) and 10% (March–June) of ET_0. Since the stream flow data is not available, the surface run-off (Q) in the study area was estimated using the USDA soil conservation service (SCS) model, which is a popular model to estimate surface run-off from an ungauged agricultural watershed. Remote sensing derived land cover information together with the basic soil information of the study area were used in IDRISI GIS environment for estimating the area of each land cover in each one of the hydrologic soils.

Since all the terms of the annual water balance equation except Q_g are known, this quantity is determined as a residual of equation (3), as shown in table 2. The net annual recharge and the corresponding water table rise (0.79 m) can therefore be estimated using equations (1) and (2), as given in table 3. Comparison of the model-estimated groundwater table rise with the observed water table rise (0.93 m) during the year 1992–93 indicated in table 3 shows that the estimates of the water

Table 2. Estimates of water balance components during 1992–93 in the study area.

Sl. no.	Water balance component	Quantity (mm)
1	Rainfall (P)	622
2	Canal supplies (Q_c)	229
3	Groundwater draft (Q_w)	233
4	Irrigation tank supplies (Q_t)	133
5	Total input	1216
6	Evapotranspiration (ET)	363
7	Evaporation (E)	299
8	Pumpage (Q_w)	233
9	Change in groundwater storage (ΔS_g)*	− 32
10	Surface run-off (Q_s)	175
11	Total output	1038
12	Groundwater outflow (Q_g)	178

*'− ' sign indicates falling groundwater table.

Table 3. Comparison of computed and observed water table in the study area.

Gross groundwater recharge (R_g) in Mm^3	Groundwater outflow (Q_p) in Mm^3	Groundwater draft (Q_g) in Mm^3	Net groundwater recharge (R_n) in Mm^3	Eqivalent fall in water table (m)	Observed water table fall (m)
25.36	12.10	15.80	2.54	0.93	0.79

balance and net regional groundwater recharge are realistic. The validated model is then used for predicting the groundwater table level under normal rainfall conditions.

5. Results and discussion

A systematic analysis of irrigation water demand in relation to available canal supplies, groundwater and irrigation tank water was undertaken in the present study. The overriding objective was to provide quantitative information on the current operating practices and to suggest guidelines for improved water management in the study area. This was done by comparing monthly and seasonal canal water availability with the corresponding demand for water from CCA (Culturable Command Area) of D-36 and D-36A distributaries and from the total cropped area, given in figure 5. The balancing role of groundwater as an additional resource and for increasing the reliability of system operation was also examined. The analysis of groundwater recharge and the water balance study were examined in this context to investigate the scope for possible conjunctive water use in the study area.

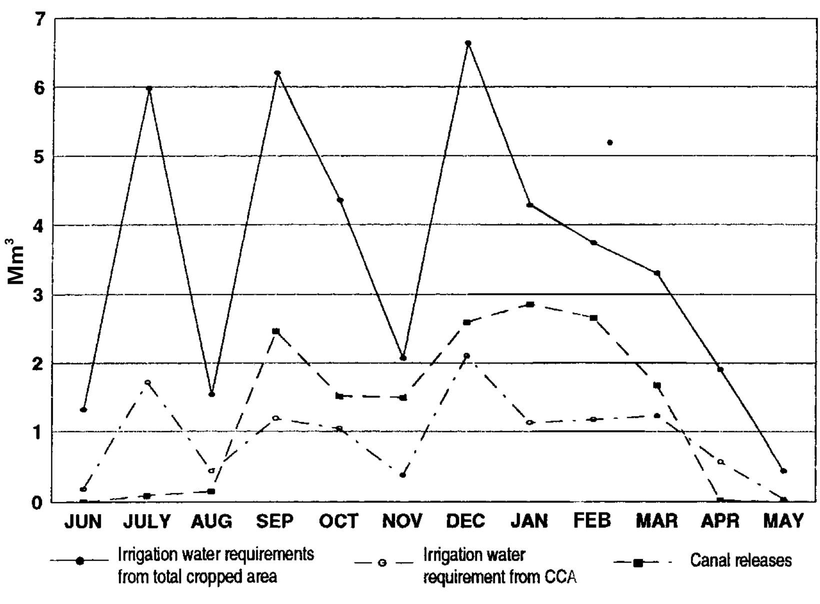

Figure 5. Comparison of monthly irrigation water supply and demand in the study area during 1992–93.

5.1. *Status of water management and implications for conjunctive water use*

The following are the observations from the supply–demand study (Rao and Chakraborti 1995) conducted using satellite-derived command area inventory.

1. It was observed that the contribution to the total irrigated area from various sources of irrigation, i.e. canals, wells and tanks was 40, 41 and 19%, respectively, during the year 1992–93.
2. From the supply–demand study, it was observed that for the net sown area, the total available irrigation water from all the sources was 39.04 Mm^3, whereas the requirement was 41.74 Mm^3, resulting in a deficit of 2.7 Mm^3 in 1992–93 (figure 6). This emphasizes the need for the balancing role of groundwater in conjunction with the proper regulation of canal flows, so as to avoid surplus/deficit situations during various time periods (months) during the crop year (1992–93).
3. The study revealed that the cropping pattern in the canal command area showed a large deviation from the designed cropping pattern, eventually leading to mismanagement of canal waters. This was reflected in the reduction of the total area commanded by canals which was 820 ha in 1992–93, where the designed command was 1512 ha. The impact of this deviation from the designed cropping pattern was seen from the deficits in the months of July (1.73 Mm^3) and April (0.54 Mm^3), due to the large area under paddy crop, although there was a surplus of 4.34 Mm^3 in canal supplies as shown in figure 5.

From the groundwater recharge study, it can be seen that the return irrigation

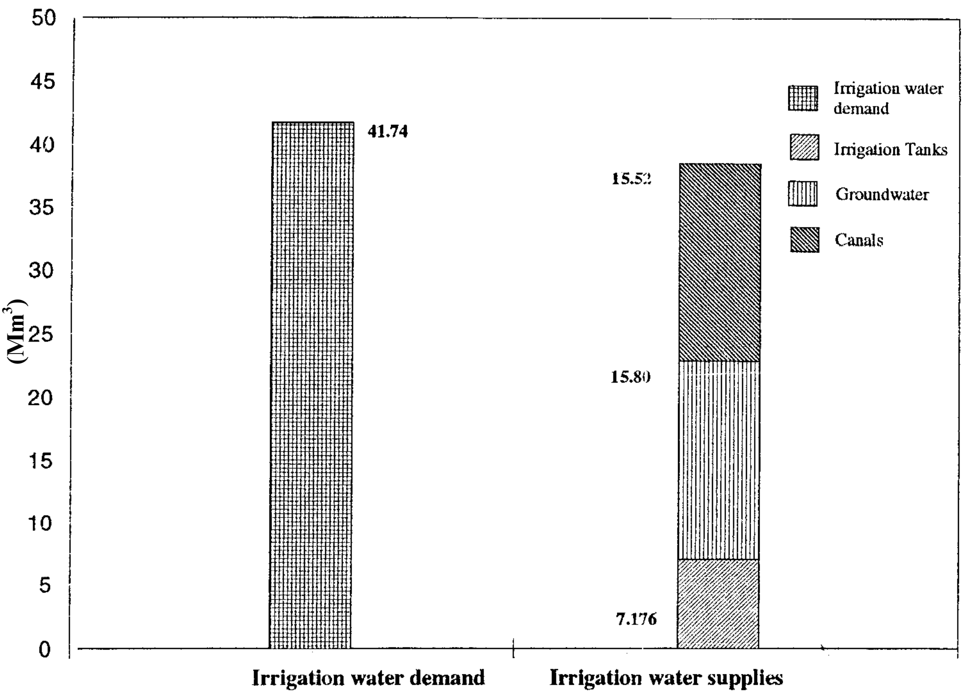

Figure 6. Comparison of total demand for irrigation water and available supplies during 1992–93.

from canal irrigated areas contributes 25% of gross recharge. Well and tank irrigated areas contribute 24% and 11%, respectively. The contribution from rainfall is around 20%. The annual net groundwater recharge was found to be negative by 2.54 Mcm resulting in a fall of the groundwater table by 0.79 m. In the event of normal rainfall (rainfall during 1992–93 was 622 mm, which is 34% less than the average annual rainfall), R_e at the rate 12.5% of annual rainfall will result in higher contribution from it to gross recharge. Normalized values of the recharge estimates, obtained from the water balance model, indicate that there will be around 1.0 Mcm net recharge available as additional potential, which could cause the water table to rise by 0.35 m.

Seepage losses from distributaries and minors are not only a function of canal length and cross-section, but also of initial depth of the water table when seepage begins. Lowering of water tables induces more seepage losses from canals, the canal supplies are reduced and become less reliable as a result. Thus, it appears that the twin objectives of conjunctive water use, namely, lowering the water table to control waterlogging and augmenting the canal supplies, while increasing their reliability, are incompatible. This is so unless at least two additional factors are included. The first is the operating depth of the water table, which is the primary design variable. This value depends on the irrigation system, soils, subsurface conditions, crops grown and other related parameters. The second significant factor is that canals and aquifers must be operated rotationally in different time periods. The rotational periods will be unequal and will vary with irrigation system and aquifer conditions. The operation of surface and groundwater systems in successive periods leads to increased storage (increased flows in canals) in both surface and subsurface reservoirs and to improvements in overall water use efficiency.

From the groundwater budgeting and supply–demand study, the following rotational cycle of conjunctive water use is suggested in the study area. Figure 5 shows that there is a large deficit in the month of July, which is due to non-adherence to the design cropping pattern. Hence, the original cropping pattern envisaged in the design is to be restored so that a large area can be brought under irrigation (under ID crops) and to meet the overall deficit of 2.7 Mm^3 in 1992–93. The aquifers are to be pumped to a pre-defined limit (between 3 and 6 m is suggested based on historical well inventory data of the study area), at this stage to lower the water table and to meet the transplanting requirement of paddy in the month before operating the canals. A large part of the water requirement in this month can be met by the monsoon rainfall besides groundwater. Then, the canals should be run for 40–50 days, to once again raise the water levels, which will be lowered in the next cycle by abstraction from the aquifer. This also meets the high requirement during the months of September–October in the study area. This cycle can be repeated to meet excess demand in December during Rabi paddy transplantation. Since the study area readily responds from return irrigation, this rotational cycle of conjunctive water use will not only eliminate intra-seasonal imbalances in supply–demand in the study area, but also lead to additional development of groundwater potential which will ensure improved water management and bring more area under assured irrigation.

6. Conclusions

In this study an attempt is made to use the remote sensing derived command area inventory, i.e. various land cover categories, paddy and non-paddy crop land, major irrigated dry crops under the non-paddy crop category, irrigation tank water spread information along with their irrigated areas, used in conjunction with the field observed ancillary data in developing a semi-empirical water balance model for the study area. The model was successfully validated in a typical heterogeneously cropped irrigation command area. Water budgeting of the study area during 1992–93 indicated that the net recharge to the aquifer is negative by 2.54 Mcm resulting in a fall of the groundwater table by 0.79 m. The validated water balance model was used to predict the groundwater levels under normal rainfall conditions. It was found that the groundwater table would rise by 0.35 m per year indicating impending waterlogging conditions in the study area. Since the design of conjunctive water use schemes in irrigation projects needs to be based on an understanding of the complex interactions between the surface water and groundwater systems of the area, a further similar study is to be conducted in at least 3–4 years to draw up more realistic conjunctive water use strategies in the study area. The present study also provides scope for better representation of various components that are involved in recharge and water balance studies. Though the study requires further refinement, it holds promise for better parametrization of various variables that are involved in groundwater targeting.

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