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Remote Sensing and GIS in Estimating Groundwater Balance in Semi-Arid Regions

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Abstract

Accurate estimation of various flows to and from the groundwater system is essential for groundwater management mainly in the over-exploited and aquifers with very low specific yield. Groundwater balance studies within watersheds require the components to be estimated reasonably accurately and within a specified budget. The components of a groundwater balance include the inflows and outflows. Inflows include the recharge from precipitation, artificial recharge, agricultural return flow etc. Outflows include evapotranspiration, pumping, evaporation from water table, baseflow etc. Conducting ground survey for collecting all the information regarding these parameters is costly as well as time consuming, and thus impractical. Use of Remote sensing and GIS techniques can reduce the cost and efforts of data collection and also assist in further analysis.

In over-exploited aquifers, precise estimation of groundwater withdrawal is of utmost importance and in countries like India where pumps are not fitted with flow meters, indirect methods are employed for this estimation. In a small watershed of about 85 Km2 irrigated crop mapping & delineation was done for two seasons (rabi and kharif) using IRS P6 (Resourcesat I) LISS-4 multispectral imagery. The irrigated crop area is directly proportional to the borewell yield. The relationship between irrigated crop area and borewell yield was established for this watershed using field validation of both parameters for a representative sample of fields during the rabi as well as kharif season. The observed relationship was 0.0144m/day & 0.0103m/day for the rabi and kharif seasons respectively. These values were multiplied by the total irrigated area (obtained from satellite image) to obtain the groundwater abstraction per day. Finally, the daily abstraction was converted into seasonal abstraction by multiplying with the number of irrigation days for that season. In this watershed the seasonal abstraction was calculated to be 7.126 million cubic meters and 9.639 million cu. m. for Rabi and Kharif seasons respectively. These seasonal groundwater abstractions were used as input for a Decision Support Tool prepared for the area. Although, groundwater abstractions derived from this method are not as accurate as those obtained from well inventory method, but taking account the many practical difficulties involved, a trade off between accuracy and time-cost factors has to be made. Remote sensing method is surely cheaper and time saving.

Keywords: Groundwater Balance, Remote Sensing, GIS, Pumping Flows

Introduction

In tropical semi-arid regions with hard rock aquifers the groundwater reserves are the only dependable sources of water for irrigation and human consumption. Large parts of the Indian subcontinent are covered by archean granites that form extensive hard rock aquifers. These aquifers have a semi-confined attitude and are fairly productive. In recent years, there has been a large withdrawal of water from these aquifers mainly for agricultural activities. Annual pumping rates have exceeded the annual recharge rates by monsoon and cyclonic rains. This is rapidly depleting the ground water reserves in the region. The high stress on groundwater due to abstraction of large quantities of water through pumping for irrigation threatens the sustainability of agricultural development. Therefore, it is necessary to adapt the exploitation of groundwater to its availability. For that purpose, it is indispensable to assess the water balance of the aquifer. For the estimation of groundwater balance, percolation flows, return flow, horizontal inflows and outflows, pumping outflows, and evaporation from the ground water table have to be calculated. These calculations require extensive field data that is sometimes difficult and even impossible to obtain. The use of Remote sensing technology can substantially simplify this process. The assessment of water abstraction by pumping (pumping outflows) using satellite imagery is the focus of this paper.

Study Area

The study was conducted in the Gajwel watershed (*figure 1*), located 60 km NE from Hyderabad city. The watershed covers an area of 83 km2. The topography is relatively flat (520 to 620 m above sea level) with the absence of perennial streams. Streams are dry most of the time, except a few days a year after very heavy rainfall events during the Monsoon. The region experiences a semiarid climate controlled by the periodicity of the Monsoon; rainy or "Kharif" season from June to October and dry or ‘Rabi’ season from November to May. Mean annual precipitation is about 720 mm, of which more than 90 % falls during the Monsoon season. The mean annual temperature is about 26 °C; although in summer the maximum temperature can reach 45°C.

The area includes 10 villages with a population of about 36130 inhabitants (about 7300 households). The area has a predominantly agrarian economy, which is typical of South India. The Gajwel area is overexploited due to the large groundwater abstraction for the irrigation of crops (mainly paddy) (APGWD). Depth to Piezometric surface ranges from 16 to 30 meters. There are numerous small dams for artificial recharge and to reduce soil erosion.

The study area is underlain by Archean granites very similar to the ones commonly found in the Hyderabad region. The geology of the watershed is relatively homogeneous and composed of the orthogneissic Archean granite. The weathering profile is few tens meters thick and very similar to the one known in the Hyderabad region. There are numerous dugwells and outcrops for geological observations. The weathering profile is also the one commonly found in the Hyderabad region. It is characterized by remains of ancient and more recent weathering profiles (multi-phase weathering profile). From top to bottom, the typical weathering profile comprised of the following

- 0-1 m black or red soil
- 1-3 m of sandy regolith
- 10-15 m of laminated layer
- 20-30 meters of fissured layer

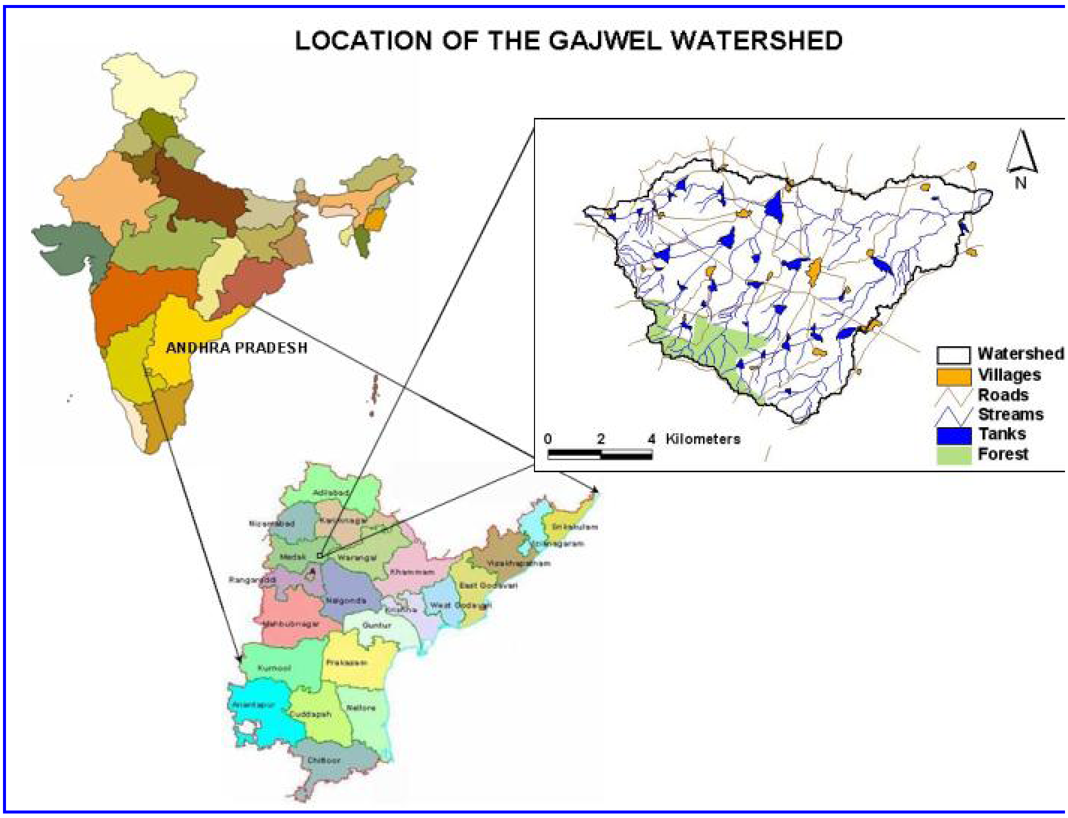

Figure 1 - Location of the study area

Methodology

In the study area, the dominant use of pumped water is for paddy cultivation. Paddy covers the largest area in the watershed followed by vegetables, maize and cotton. Other groundwater uses like domestic use and poultries are also identified.

Several methods can be employed for the assessment of pumping outflows. These methods can be broadly grouped into direct and indirect methods. The direct method for assessment of the groundwater pumping is by the use of volume meters attached to the borewells. But this method is very costly and impractical in countries like India. The indirect methods include the borewell inventory method & the Land use method. In the borewell inventory method groundwater use can be estimated indirectly using hours of pump operation (from energy consumption) multiplied by average pumping rate. This method is difficult to sustain in regions where electricity is free and there is no exact record of duration of pumping hours. In many cases the borewells are pumped to extreme limits so that there is no discharge even when the pump is on. Pumps are thus consuming electricity during both abstraction and non-abstraction phases, which introduces errors in the calculations. Borewell inventory method, although giving very good results has not been chosen because of being too much time consuming: in Gajwel watershed about 1000 borewells are used for crop irrigation.

In the Land use approach, the groundwater abstraction is calculated by multiplying the average water requirement for a particular crop with the total coverage of that crop. The average water requirement for a crop is calculated by establishing empirical relationship between crop area and borewell yield using a sample data set. The water requirement of crops changes with the season; hence the crop area survey was conducted on randomly distributed crop fields within the watershed, during both Kharif (2006) and Rabi (2007) seasons. The field survey comprised the measurement of the irrigated field area (using a handheld Garmin GPS), measurement of the instantaneous pumping flow rate of the borewells supplying the field (use of a 25 liters bucket & a stopwatch), and information from the farmer about the cropping calendar, duration of pumping, etc. During this survey, 32 paddy fields (380 to 38900 m2 in area), 4 vegetables fields (450 to 3600 m2) and 2 maize fields (3200 and 5200 m2) were investigated. Investigations on paddy fields have been carried out during both seasons (November 2006 and April 2007) because paddy field size may vary up to a factor of two. Survey on vegetables and maize fields has only been carried out in Rabi season (April 2007), since most vegetables and maize do not require irrigation during the Kharif season.

In this area (and in most of the places of South India), the duration of pumping depends on electrical power availability. The information on the average daily duration of pumping has been collected from the Gajwel electrical station during the two seasons. Duration of pumping is on an average 9 h per day in Kharif 2006 and 7 h per day in Rabi 2007; this information has been found consistent with the farmer's information.

The second factor in the land use approach, the total area for different irrigated crops within the watershed was obtained by using satellite imagery. Indian Remote Sensing Satellite - IRS-P6 (Resourcesat-I) multispectral imagery (purchased from the National Remote Sensing Agency, Hyderabad) was used for this purpose. The image includes the Green (0.5-0.6), Red (0.6-0.7), & Near-Infrared (0.7-0.9) bands from the LISS IV sensor: (LISS - Linear Imaging Self Scanning Sensor). The spatial resolution of the satellite image is 5.8 meters. An FCC (False Color Composite) was prepared using the free software MultiSpec v3.1. Supervised image classification was attempted after procuring training sets from the field. The training sets were carefully selected to include all possible irrigated crops in the classification scheme. The training sets were obtained during field campaigns using a handheld Garmin GPS. Landuse maps were prepared using supervised classification algorithms (maximum likelihood) using the MultiSpec image processing software:

(*http://cobweb.ecn.purdue.edu/~biehl/MultiSpec/*).

The landuse map was refined by taking inputs from the high resolution imagery available in Google Earth (*http://earth.google.com/*). Landuse maps were prepared for the Kharif 2006 (*figure 5*) and Rabi 2007 (*figure 4*) seasons. Subsequently, the area for different crops was calculated using the software. It should be clarified here that in this watershed almost all crop existing in the Rabi (dry) season is irrigated, while during the Kharif (rainy) season the dominant share of irrigation is consumed by paddy.

Results and Discussion

The mean daily water requirement for the different crops has been evaluated at the seasonal scale while taking into account the pumping duration for the corresponding seasons. For paddy, results (*figure 2*) show that the amount of water used for the irrigation is proportional to the cultivated area (linear relationship); this depicts the fact that farmers are adjusting the size of paddy fields according to the yield of their borewells and to the electrical supply availability (i.e., quantity of water extracted). In the Rabi season the paddy fields are sustained solely on the basis of ground water irrigation, hence the amount of pumped water required for paddy in the Rabi season is greater per m^2 than in the Kharif season, when additional water in the form of rains is provided by the monsoons. The paddy field size is thus larger in the Kharif. On average, it can be deduced from Figure 2 that the mean daily water input for paddy is 14.4 mm/d in Rabi and 10.3 mm/d in Kharif. For other crops too, the results (*figure 3*) show a linear relationship, i.e. an increase in the crop field area with increasing pumping rates of borewell. Since crops other than paddy are all rain-fed during Kharif, hence there is no need to conduct the survey for other crops during Kharif. However, during the Rabi season, the mean daily water input for all other crops combined was calculated to be around 11.5 mm/d.

The mean daily water requirement for different crops for different seasons was derived from purely ground based surveys as shown above. However, the determination of the acreage of different crops for the Rabi and the Kharif seasons was possible only by the use of satellite imagery. Landuse maps were prepared for the two seasons. F*igure 4 & 5* shows the landuse maps for the Rabi 2007 and Kharif 2006 seasons respectively. Total area for Paddy during the Rabi 2007 and Kharif 2006 seasons was estimated to be around 4.124 km^2 & 6.932 km^2 respectively, while the total area for other crops for the Rabi 2007 season was estimated to be around 1.127 km^2.

Once the mean daily water input is assessed, it is possible to compute Pumping abstraction *PG* for a particular crop or for all crops (ΣPGi) at the watershed scale. It can be written as follows:

$$PGi = Pgi \,.\, Si \,.\, tK,R$$

PGi: groundwater abstraction for the crop '*i*' [m3], *Pgi*: mean daily water input for the crop '*i*' for a particular season (i.e., Rabi or Kharif) [m/day], *Si*: area of cultivated crop '*i*', and *tK,R*: number of days in the season (Kharif or Rabi) [day].

Using the above equation the Pumping abstraction for the Rabi and Kharif seasons was calculated to be 7.126 million cubic meters & 9.639 m. cu. meters respectively. These seasonal groundwater abstractions were used as input for calculation of the Ground water budget in the study area. The Ground water budget was later used as an input in a Decision Support Tool prepared by the Indo-French Centre for Ground water Research, for effective groundwater management in semi-arid hard rock aquifers.

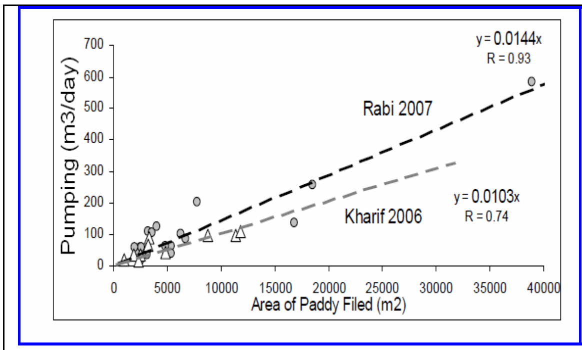

Figure 2 - Relationship between the Pumping rates and the corresponding Paddy field area for the Kharif & Rabi seasons.

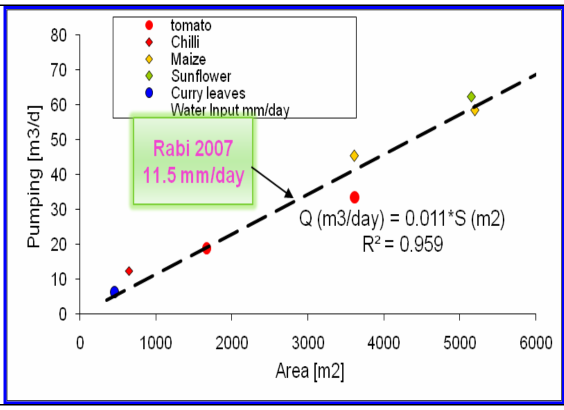

Figure 3 - Relationship between the Pumping rates and the area of irrigated fields of crops other than Paddy for the Rabi 2006 season

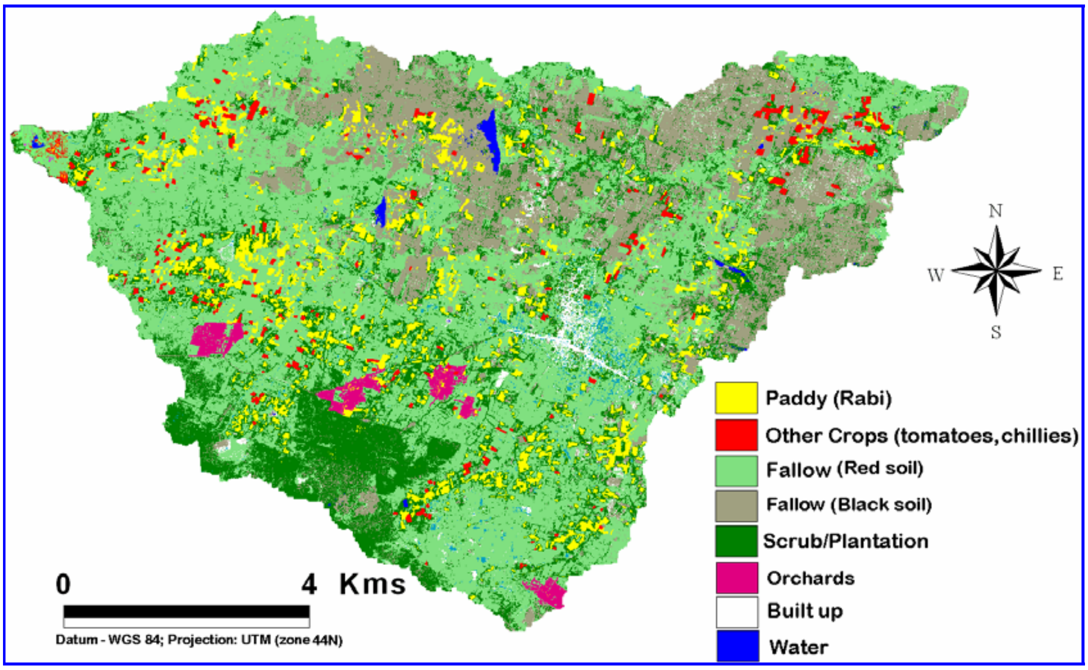

Figure 4 – Landuse map for the Rabi Season

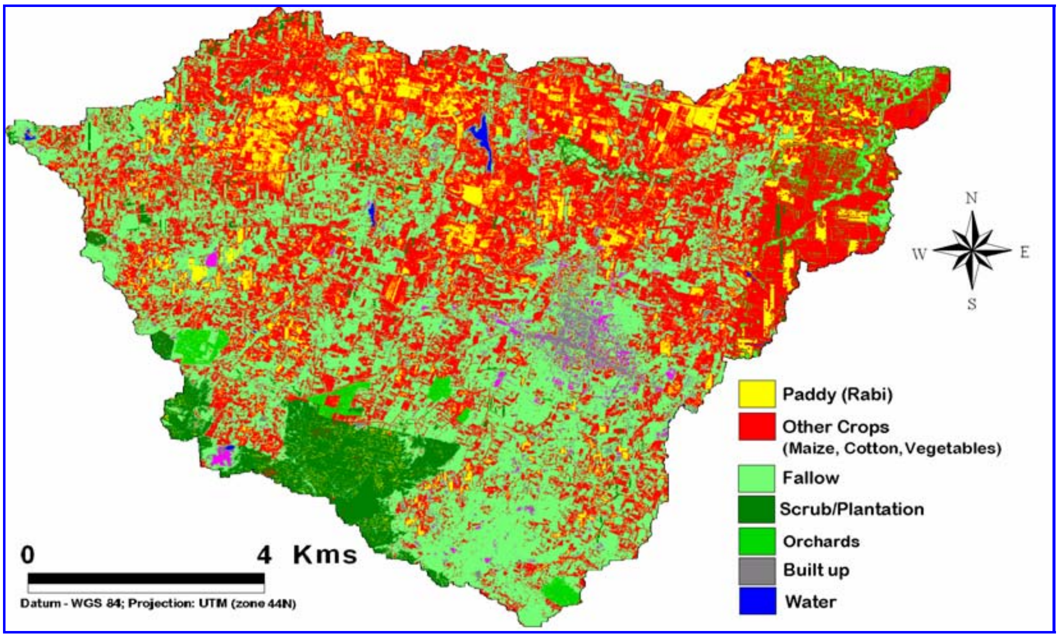

Figure 5 - Landuse map for the Kharif season.

Conclusions

In the present study, the effectiveness of the Remote Sensing techniques have been demonstrated for the calculation of Ground water balance components, especially Pumping flows in semi-arid hard rock areas. Although the borewell inventory method for the estimation of Groundwater withdrawal by Pumping is very accurate, but it involves a lot of input in the form of labor and money, because of which the Remote sensing method was adopted. The landuse approach for estimation of pumping withdrawals is a unique method that is applicable to areas with similar agro-climatic conditions as found in the study area. The limitation of the technique, however, lies in the fact that it becomes difficult to map the irrigated crops during the post monsoon or Kharif season, due to the similar reflectance from non-irrigated areas. For better estimates, better satellite data is needed for monitoring the crop status. Satellite imagery from multispectral sensors with higher resolutions will definitely improve the crop area calculations. For better demarcation of different crop types, high resolution time series of satellite images can be employed, but that will increase the costs depending upon the number of images.

Remote sensing is thus an indispensable tool for collecting data that cannot be otherwise collected based on ground survey methods. With the use of satellite images, not only overall costs are reduced, but there is a drastic decrease in the time required to finish the groundwater balance estimations.

The accuracy of the results is clearly acceptable, and it is expected that with the availability of better satellite data, this method will become practical and easier in future.

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