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# Evaluating the Spatio-Temporal Distribution of Irrigation Water Components for Water Resources Management using Geo-Informatics Approach.

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**Abstract:** Irrigation water management components evaluation is mandatory for sustainable irrigated agriculture production in the era of water scarcity. In this research spatio-temporal distribution of irrigation water components were evaluated at canal command area in Indus Basin Irrigation System (IBIS) using remote sensing based geo-informatics approach. Satellite derived MODIS product-based Surface Energy Balance Algorithm for Land (SEBAL) was used for the estimation of the Actual Evapotranspiration (ETa). Satellite derived SEBAL based ETa was calibrated and validated using the ground data-based advection aridity method (AA). Statistical analysis of the SEBAL based ETa and AA shows the mean 87.1 mm and 47.9 mm and, 100 mm and 77 mm, Standard deviation of 27.7 mm and 15.9 mm and, 34.9 mm and 16.1 mm, R of 0.93 and 0.94, NSE of 0.72 and 0.85, PBIASE -12.9 and -4.4, RMSE 34.9 and 5.76 for the Kharif and Rabi season, respectively. Rainfall data was acquired from the Tropical Rainfall Measuring Mission (TRMM). TRMM based rainfall was calibrated with the point observatory data of the Pakistan Metrological Department Stations. Canal water data was collected from the Punjab Irrigation department for the assessment of canal water availability. The water balance approach was applied in the unsaturated zone for the quantification of the gross and net Groundwater irrigation. Monthly variation of ETa with the minimum average value of 63.3 mm in January and the maximum average value of 110.6 mm in August was found. While the average annual of four cropping years (2011-12 to 2014-15) ETa was found 899 mm. Average of the sum of Net Canal Water Use (NCWU) and Rainfall during the study period of four years was only 548 mm (36% of ETa) and this resulted the 739.6 mm of groundwater extraction. While the annual based variation in groundwater extraction of 632 mm and 780 mm was found. Seasonal analysis revealed 39% and 61% of groundwater extraction proportion during Rabi and Kharif season, respectively. The variation in four cropping year's monthly groundwater extraction was found 28.7 mm to 120.3 mm. This variation was high in the 2011-12 to 2012-13 cropping year (0 mm to 148.7 mm), dependent upon the occurrence of rainfall and crop phenology. Net groundwater irrigation, estimated after incorporating the efficiencies was 503 mm year$^{-1}$ on average for the four cropping years.

Keywords: SEBAL; Remote Sensing; GIS; Groundwater Irrigation

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# 1 Introduction

Management of water resources to feed the swift increasing population is the biggest challenge of the 21$^{st}$ century. [1] found an exponential rise in population in South Asian countries, including Pakistan. Pakistan is one of the ten largest populous countries in the world. The agriculture-based economy of Pakistan is dependent on irrigation waters supplied by the Indus River and its tributaries. The largest irrigation system in the world is inefficient and it never meets the crop water requirement. These gaps include its designed of colonial based irrigation system [2] with the designed cropping intensity of 75% [3]. The agriculture sector is the largest 97% and 93% user of water in Pakistan described by [4] and [5], respectively. While the irrigation efficiency of system is very low with an efficiency of 36% [6]. Active use of water resources is at its peak and its further exploitation is constricted [7]. Groundwater contribution in crop production is 40–50 % in the IBIS [8]. Higher rate of groundwater extraction is causing decline in water table at the rate of 1 to 2 m per year in most of the areas [9]. The overexploitation of the water resources puts the irrigation system as one of the mismanaged irrigation systems in the world [10]. The mismanagement causes the land degradation due to salinity and waterlogging, conflicts due to inequity of water distribution and social and institutional conflicts [11]. Ensured food security is coupled with the timely precise application of the irrigation across the Indus basin that directs the implementation of the improved water management practices [12], [13].

Certainly, there is a dire need to provide the deliberated water management solution based on the water resources management components [14]. The remote sensing provides an opportunity to estimate the water resources management components at both the space and time domain. This detailed information of water resources management at the high spatio-temporal scale provides the confined way for the basin scale water resources management [15]. High resolution spatio-temporal information of water resources management can be achieved using the geo-informatics approach that integrates the satellite derived remote sensing hydrological variables, ground data and GIS based geostatistical approach.

Different approaches are available to estimate the different water resources management components based on data availability and purpose of use. As the groundwater extraction estimation is normally carried out using the tubewell utilization factor technique or water table fluctuation methods [16]. It is almost impossible to apply the utilization factor method in the large irrigation scheme of IBIS where the ownership of 90% land is less than 12.5 acre and every individual small farmer has its own diesel operated tubewell. Spatial mapping of actual evapotranspiration on the large scheme requires the very high resolution data that is only possible with the remote sensing and can be used for the estimation of groundwater component [17]. Geo-informatics approach provides the enough efficiency for the application of water balance approach in the unsaturated zone for the quantification of groundwater component [14], [17]. Surface water supplies are usually considered as the equally distributed depth of water throughout the canal command area [14], [17]–[19]. In case of reliably dense meteorological station, spatial distribution of rainfall is assessed through the interpolation [19]. While in data scare basin, Tropical Rainfall Measuring Mission (TRMM) is mostly adopted source for the assessments of the spatial distribution of rainfall [20]. Further, the calibration and validation of the TRMM with the point sources data increase its reliability in the water balance studies [20], [21].

This study presents the estimation of the critical water management component in the largest irrigation scheme of the Indus basin for the period of (2011-12 to 2014-15). The water resources management components include the actual evapotranspiration, gross and net canal water availability, gross and effective rainfall and gross and net groundwater recharge. The distribution and availability of the water resources management components at fine spatial and temporal resolution will help the policy makers to develop the effective water management strategies to enhance the water productivity.

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# 2 Methodology

## 2.1 Study Area

The lower Chenab canal system is the oldest and largest irrigation system in the Indus Basin Irrigation System. The canal command area is between the two rivers (Ravi and Chenab) of the Pakistan (Figure. 1). The area of the LCC system is about 1.24 million ha (Mha). Climate of the study area is considered as the semiarid with average annual rainfall of 380 to 400 mm. cropping pattern of the irrigation system is wheat as the major winter crop and rice, cotton and maize as the major Kharif crop. Crop water requirement is fulfilled from the surface and groundwater resources. The network of the irrigation system have seven main distributaries. Water from these distributaries is further diverted to the sub-channels to deliver water in the farmer's field channels. Water distribution is fixed based on the water allowance from the Irrigation Department for each hierarchy of channel. The participatory management-based decision, cost recovery and distribution uniformity are the core responsibility of the Farmers Organization (FOs). FOs members are farmers from the representative distributary of the irrigation system. Further these FOs elected the chairman of the rea water board of the whole irrigation system i.e. LCC.

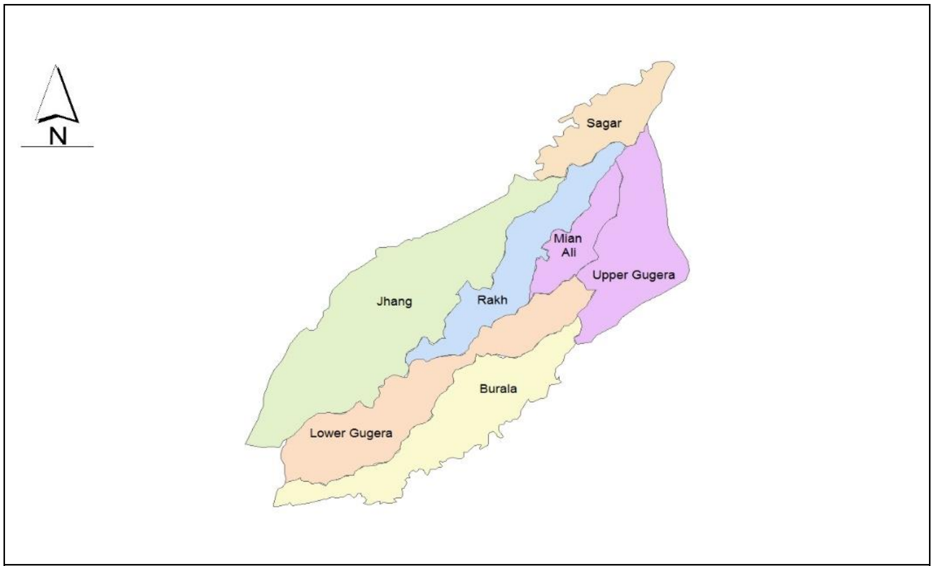


Figure 1: Lower Chenab Canal Command Area

## 2.2 Canal Water Irrigation

Canal water is the main source of the irrigation in the LCC system along with the significant proportion of groundwater. Lower Chenab canal system is distributed into 7 main distributaries. All these distributaries are monitored by the Program Monitoring and Implementation Unit (PMIU) of the Punjab Irrigation Department. Discharge from the distributary is measured with depth (stage) at the inlet of the system. This inlet based collected data of discharge was converted into monthly, seasonal and annual scale gross canal water depth of irrigation. For the estimation of the net canal water depth of irrigation, gross irrigation water depth was multiplied with irrigation efficiency of the system. Irrigation efficiency is product of field and irrigation network efficiency. Irrigation efficiency was incorporated from the study of [6] that define the field efficiency of 75% and the irrigation network efficiency of the 48%. According to the aforementioned definition of the irrigation efficiency, 36% irrigation efficiency of the system was obtained.

## 2.2 SEBAL for the Estimation of Actual Evapotranspiration

Surface Energy Balance Algorithm for Land (SEBAL) is widely used for the estimation of the actual evapotranspiration in the hydrological studies. Input used in this energy balance is the satellite derived remote sensing imagery. SEBAL was successfully used in the water balance studies at different temporal and spatial scale [17], [21]–[24] conducted a research in Pakistan and provide the theory of SEBAL algorithm. The methodology was successfully applied in the IBIS by [25]. The residual of the energy budget is actual evapotranspiration which is demonstrated below [equation 1].

$$R_n = G_o + H + \lambda E \quad (1)$$

Where, $R_n$, $G_o$, H and $\lambda$E represents net radiation (W $m^{-2}$), soil heat flux (W $m^{-2}$), sensible heat flux (W $m^{-2}$) and latent heat flux (W $m^{-2}$) respectively.

The concept of evaporative fraction was introduced by [17] and on the basis of this concept latent heat flux can be represented [equation 2] by considering net available energy (Rn - G0) and evaporative fraction:

$$\lambda E = \Delta(R_n - G_o) \quad (2)$$

Where, Δ = evaporative fraction and was formulated as:

$$\Delta = \frac{\lambda E}{R_n - G_o} = \frac{\lambda E}{\lambda E + H} \quad (3)$$

Net available energy can be calculated from instant, daily or monthly timescale. For the calculation of the daily ET, Soil heat flux can be ignored at the time scale of one day and net radiation (Rn) will be considered as the net available energy. Daily ET can be calculated as equation [4]:

$$ET_{24} = \frac{86400 \times 10^3}{\lambda \times \rho_w} \times \Delta \times R_{n24} \quad (4)$$

Where, $R_{n24}$, $\lambda$ and $\rho_w$ described the 24-hour averaged net radiation, latent heat of vaporization and water density respectively.

[26] described the important variable for the ET estimation includes land cover, land surface albedo and land surface temperature. Remote sensing makes the estimation of the variable possible using different satellite sensors [24]. MODIS product was used due to its best spatiotemporal resolution and spectral bands. The MODIS standard products can be downloaded free from the USGS websitehttps://lpdaac.usgs.gov/get_data/data_pool. Table 1 described the detail of the product used in this study.

Table 1: MODIS products used in this study

| Product name | Dataset used | Spatial Resolution (m) | Sensor |
|---|---|---|---|
| MOD09Q1 | Land surface reflectance (band 1 and band 2) | 250 | TERRA |
| MOD11A2 | Land surface temperature and emissivity | 1000 | TERRA |
| MOD13A2 | NDVI | 1000 | TERRA |

## 2.3 Advection Aridity

The advection aridity (AA) model was successfully used by many researchers under different climatic condition and found reasonable with the water balance and eddy covariance method [27]–[29] applied the advection aridity method at basin scale and found good agreement with surface energy balance system (SEBS). [30] applied the AA model at regional scale and found good agreement between SEBAL and AA model. [28] applied three different methods for the mapping the ETa in China and found the AA model most accurate. Firstly, [31] proposed the AA model using [32] for the wet surface ET as formulated in equation 5 and for the potential evapotranspiration, [33] equation was used as given below [equation 6] and an empirical wind function was used as given below in equation [7]

$$ET_w = \propto_e \frac{\Delta}{\Delta + \gamma}(R_n - G) \quad (5)$$

$$ET_p = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma} \times E_r \quad (6)$$

$$E_r = f(U_2) \times (e_s - e_a) \quad (7)$$

$$f(U_2) = 0.26(1 + 0.54U_2) \quad (8)$$

Where, $\propto_e$= 1.26 is the Priestly and Taylor coefficient, and variables $(R_n - G)$, $\Delta$, $\gamma$, $U_2$, $e_s$ and $e_a$ represents the available energy at the surface, slope of saturated water vapor pressure curve at the current time (kP°C-1), psychometric constant (kP°C-1), mean wind speed above the 2 m of the ground surface, saturated vapor pressure and actual vapor pressure respectively. [31] combines the potential ET [equation 5] and the wet surface ET [equation 6] following the relationship given by [34] as shown below [equation 9]:

$$AET = (2 \propto_e - 1)\frac{\Delta}{\Delta + \gamma}(R_n - G) - \frac{\Delta}{\Delta + \gamma} \times 0.26(1 + 0.54U_2)(e_s - e_a) \quad (9)$$

In this study, due to the unavailability of the directly measured ET, AA model was used for the evaluation of SEBAL estimated ETa. The climatic data used for the AA model was collected from the University of Agriculture, Faisalabad and Pakistan Meteorological Department.

### 2.4 Satellite Derived Rainfall

Pakistan Meteorological Department (PMD) is responsible for the measurement of meteorological data at regional scale. Total observatory in the Pakistan are 97 (PMD online source). However, there only two observatory stations in the study area. GIS based interpolation was not found appropriate for the low-resolution dataset. Therefore, satellite-based raster data was acquired with spatial resolution of 25 km along with monthly temporal resolution using Tropical Rainfall Measurement Mission (TRMM). Low resolution rain gauge availability creates the limitation for the calibration of TRMM data. [35] provides the solution under this limited environment by averaging the measurement over time. Therefore, 3B43 product was accumulated into seasonal basis using the cropping pattern. The Kharif season include mid of April to the mid of November. Following the experience of [30], local calibration and validation of this data is performed with point observatory data. Monthly rainfall data were summed up to obtain seasonal rainfall for all Kharif and Rabi seasons. Further, GIS was used to extract the data from each pixel and the detailed data was interpolated using kriging to create the high-resolution map.

### 2.5 Groundwater Irrigation

Net groundwater Irrigation at the spatial scale of distributaries and two temporal scale of LCC was estimated using Geo-informatics techniques. This approach provides the advances above the conservative and indirect approaches [36]. Satellite derived actual evapotranspiration was used as a key component for establishment of water balance approach in the unsaturated zone. This approach was successfully applied by [17] [equation 10].

$$NGWI = ET_a - P_e - NCWI \quad (10)$$

Where, NCWI, Pe and NGWi described the net canal water irrigation, effective rainfall and net groundwater irrigation respectively.

This approach provides the net groundwater irrigation that is the water used by the plants or evaporated from the under consideration. While the pumping from the aquifer is more than the net groundwater irrigation due to the inefficient delivery system of irrigation. Therefore, groundwater abstraction was estimated using the field application efficiency. In this study, the results of [6] were used that showed the field application efficiency of 75% and network efficiency of 90%. This resulted the 68% irrigation efficiency of the system. Framework of the study is shown in figure 2.

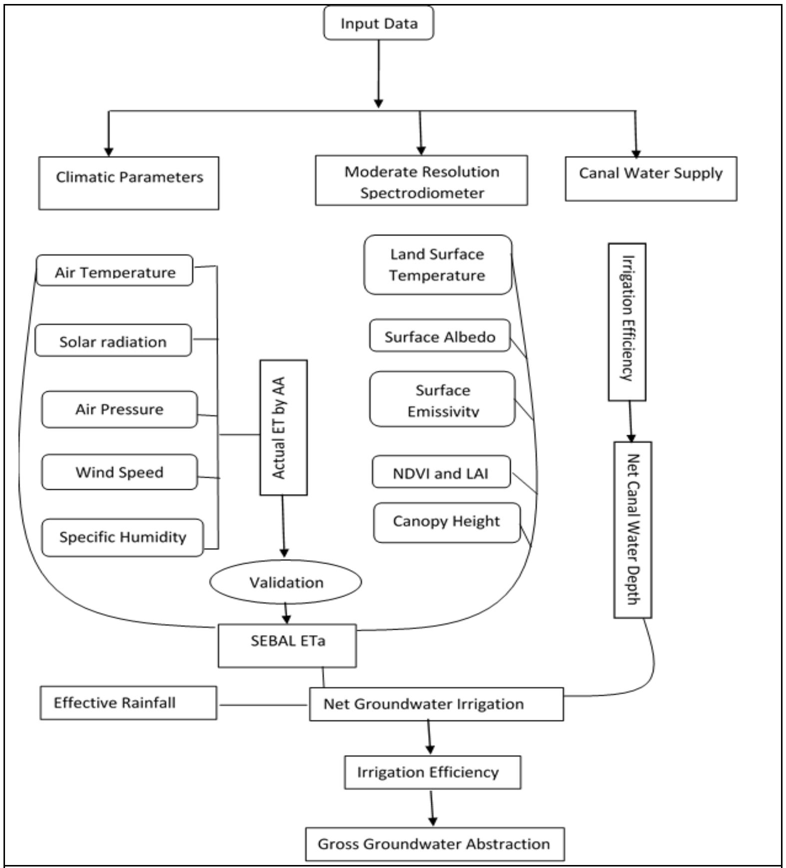


Figure 2: Methodological FrameWork for the quantification of groundwater Irrigation

# 3 Result and discussion

## 3.1 Canal water availability

Estimation of canal water availability, maximum gross canal water irrigation depth (GCW) depth of 343 mm was found during the 2014–15 cropping year, while in cropping year of 2011-12 the GCW was found minimum with the value of 305 mm for the LCC (Table 2). Water supply during Kharif season was 32% more than Rabi season due to canal closure during the Rabi. Every year for the revival of accumulated silt in the irrigation system, canal remains closed during December and January [37] and sometimes for the months of February. During the spatial analysis, the gross canal water distribution was found maximum at the Upper Gugera, while the minimum was the Sagar Distributaries (figure 3). Distribution of gross canal water from the LCC system was minimum during the Month of February and maximum was during the months of July and Augusts. This less canal water availability in the month of February is due the closure of the canal for the annual removal of silts from the Irrigation system. While the maximum in the July and August is due the maximum surface water availability in the Indus basin due to heavy snow melting and occurring of monsoon rainfall.

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Table 2: Gross canal water distribution (mm) in LCC from 2011-12 to 2014-15

| **Annual** | Rabi Season | | | | | | | | Kharif Season | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nov | Dec | Jun | Feb | March | 1-15 Apr | Total Rabi | | 16-30 Apr | May | Jun | Jul | Aug | Sep | Oct | Total Kharif | Total Annual |
| **2011-12** | 27.3 | 26.2 | 13.7 | 0 | 24.4 | 11.4 | 103.1 | | 11.5 | 19.1 | 26.9 | 39.6 | 40.1 | 35.4 | 29.2 | 201.9 | 305.8 |
| **2012-13** | 23.8 | 25.0 | 12.5 | 8.5 | 28.9 | 14.7 | 113.5 | | 14.3 | 31.8 | 36.7 | 39.6 | 40.2 | 35.5 | 29.3 | 227.3 | 340.8 |
| **2013-14** | 29.50 | 26.25 | 12.47 | 15.27 | 25.87 | 13.21 | 122.57 | | 13.26 | 30.83 | 37.20 | 40.02 | 41.04 | 17.06 | 34.82 | 214.23 | 336.8 |
| **2014-15** | 29.57 | 29.44 | 9.10 | 8.15 | 21.09 | 12.99 | 110.34 | | 15.37 | 36.11 | 33.15 | 39.41 | 40.93 | 37.32 | 30.67 | 232.96 | 343.3 |
| **Average** | 27.55 | 26.73 | 11.94 | 7.96 | 25.08 | 13.10 | 112.38 | | 13.59 | 29.46 | 33.50 | 39.67 | 40.56 | 31.32 | 30.99 | 219.12 | 331.7 |

Table 3: net canal water distribution (mm) in LCC from 2011-12 to 2014-15

| **Annual** | Rabi Season | | | | | | | | Kharif Season | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nov | Dec | Jun | Feb | March | 1-15 Apr | Total Rabi | | 16-30 Apr | May | Jun | Jul | Aug | Sep | Oct | Total Kharif | Total Annual |
| **2011-12** | 9.8 | 9.4 | 4.9 | 0.0 | 8.8 | 4.1 | 37.1 | | 4.1 | 6.9 | 9.7 | 14.3 | 14.4 | 12.8 | 10.5 | 72.7 | 110.1 |
| **2012-13** | 8.6 | 9.0 | 4.5 | 3.0 | 10.4 | 5.3 | 40.9 | | 5.1 | 11.4 | 13.2 | 14.3 | 14.5 | 12.8 | 10.5 | 81.8 | 122.7 |
| **2013-14** | 10.6 | 9.5 | 4.5 | 5.5 | 9.3 | 4.7 | 44.1 | | 4.7 | 11.1 | 13.3 | 14.4 | 14.7 | 6.1 | 12.5 | 77.1 | 110.1 |
| **2014-15** | 10.6 | 10.5 | 3.2 | 2.9 | 7.5 | 4.6 | 39.7 | | 5.5 | 12.9 | 11.9 | 14.1 | 14.7 | 13.4 | 11.0 | 83.8 | 123.5 |
| **Avg.** | 9.9 | 9.6 | 4.3 | 2.9 | 9.0 | 4.7 | 40.5 | | 4.9 | 10.6 | 12.1 | 14.3 | 14.6 | 11.3 | 11.2 | 78.9 | 119.4 |

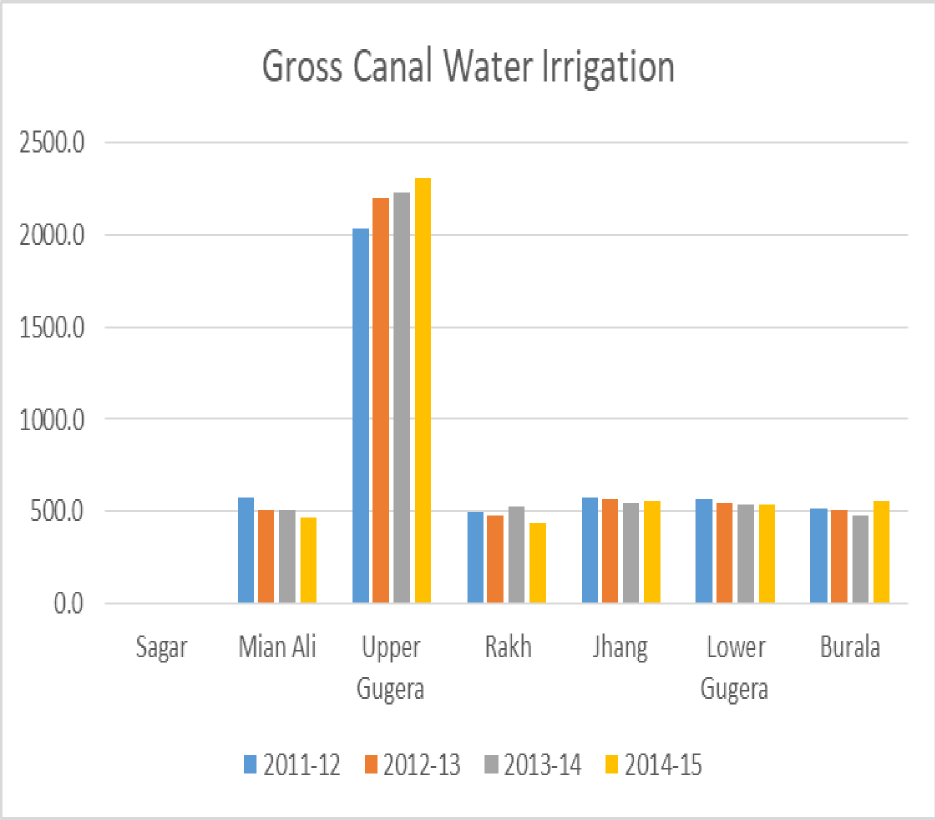
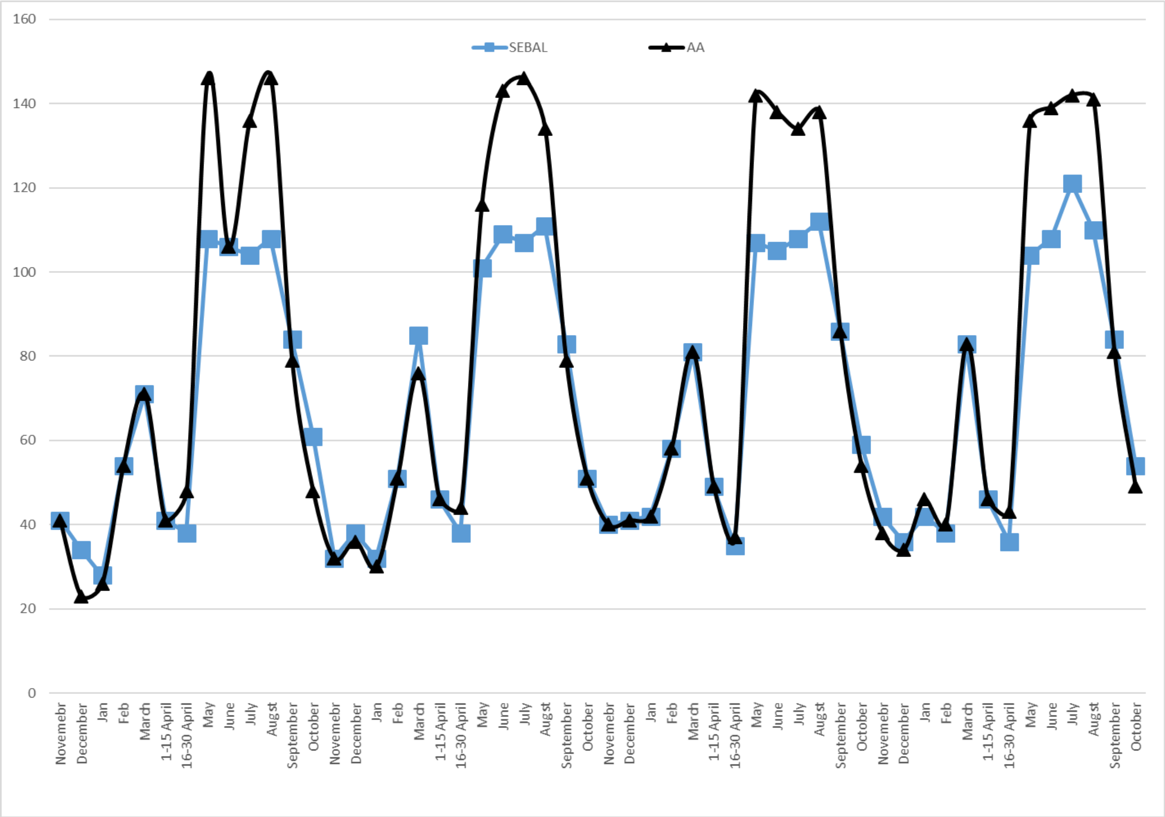



Figure 3: Gross Canal water Distribution at the CCAs of LCC system

### 3.2 Advection aridity method

None of the previous researcher deny the validation of SEBAL model. Validation was done with available data source of ET measurement such as Bowen ration energy balance [38], meteorological data [39], advection aridity method [30] and the eddy covariance [40]. [28] found the AA most accurate method after applying three different techniques for mapping the ETa at regional scale in China. Validation of SEBAL is important for further use in the hydrological studies. SEBAL was successfully validated with AA model by the [30] at the regional scale studies in the Indus basin irrigation system. The results obtained are satisfactory for the Rabi and Kharif season. Nash suit cliff efficiency was found higher in Rabi season as compared to the Kharif season. Similarly, the low bias values were found in the Rabi season relative to the Kharif season. The results are supported with the outcomes of [21]. Similarly, [41] and [28] argued that AA models works well under cold season. Significant difference in the ET was found for both seasons. [30] argued that this difference was due to the difference in climatic condition, change in cop type and water availability. The variation in the ET was found from the upper reaches to the lower reaches of LCC system with same crop type. For the Kharif season the difference was higher than the Rabi season. This variation was 9.63 mm for the rice crop, 9.71 mm for cotton, 10.2 mm for sugarcane. For Rabi crop, wheat shows 1.03, 1.05 % sugarcane. Usman et al, (2014) argued that this variation will be more if the analysis will be performed at a finer resolution. Figure 4 represents the calibration and validation of SEBAL with AA.




Calibration (2011-12 to 2012-13) and Validation (2013-14 to 2014-15) of SEBAL
Figure 4: Comparison of satellite-based ETa and ETa by AA method

Table 4: Statistical Analysis of seasonal and annual ETa (mm) of SEBAL and AA

| Season | Mean | | Standard Deviation | | Goodness of fitness of measure | | | |
|---|---|---|---|---|---|---|---|---|
| | SEBAL ETa | AA ETa | SEBAL ETa | AA ETa | R | NSE | PBIASE | RMSE |
| **Kharif** | 87.1 | 100.0 | 27.7 | 34.9 | 0.93 | 0.72 | -12.9 | 34.9 |
| **Rabi** | 47.9 | 55.3 | 15.9 | 16.1 | 0.94 | 0.85 | -4.4 | 5.76 |
| **Annual** | 69.0 | 77.0 | 30.1 | 42.4 | 0.97 | 0.83 | 10.4 | 17.0 |

### 3.3 Spatially distributed ETa

Seasonal analysis of Eta revealed 47% more ETa during the Kharif season as compared to the Rabi season, while the variation in the annual scale analysis showed the less variation (Table 5). High ETa during Kharif was due to the more surface water availability in the irrigation system along with the growing period of the high-water demanding crops like cotton and rice as compared to the wheat. The month-based analysis revealed the variation in ETa with minimum average value of 23 mm in January and maximum average value of 123 mm in August, and four-year average annual value of 897 mm during study period (2010–2011 to 2014-15). In case of temporal analysis, May to august showed the peak rates of ETa, while in case of spatial analysis, peak rates were observed to rice cropped areas. Similarly, December to January showed the lowest ETa rates, due to less water supply along with decreased crop water requirements [37]. During the design of the LCC irrigation system the cropping intensity was considered 75% [42]. Though, it has increased more than double of its design due to green revolution of 1960s. Despite this significant increase

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in demand due to high cropping intensity, the deliveries from the canal water remains stagnant which cause the big gap between canal water availability and its demand and leads towards the sever scarcity in the region.

Table 5: Actual evapotranspiration distribution (mm) in LCC from 2011-12 to 2014-15

| | Rabi Season | | | | | | | | Kharif Season | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Annual** | Nov | Dec | Jun | Feb | March | 1-15 Apr | Total Rabi | | 16-30 Apr | May | Jun | Jul | Aug | Sep | Oct | Total Kharif | Total |
| **2011-12** | 41.2 | 34.4 | 28.2 | 41.6 | 71.4 | 41.4 | 258.2 | | 38.3 | 108.8 | 106.6 | 104.3 | 108.4 | 84.3 | 61.2 | 611.9 | 870 |
| **2012-13** | 32.8 | 38.2 | 32.2 | 51.0 | 85.1 | 46.3 | 285.6 | | 38.7 | 101.4 | 109.4 | 107.5 | 111.6 | 83.4 | 51.5 | 603.5 | 889 |
| **2013-14** | 40.4 | 41.2 | 42.4 | 58.4 | 81.2 | 49.6 | 313.2 | | 35.1 | 107.6 | 105.4 | 108.6 | 112.4 | 86.7 | 59.2 | 615 | 928 |
| **2014-15** | 42.6 | 36.2 | 42.5 | 38.4 | 83.4 | 46.2 | 289.3 | | 36.6 | 104.5 | 108.4 | 121.2 | 110.1 | 84.6 | 54.4 | 619.8 | 902 |
| **Avg** | 39.2 | 37.5 | 36.3 | 47.3 | 80.3 | 45.8 | 286.5 | | 37.2 | 105.5 | 107.5 | 110.4 | 110.6 | 84.7 | 56.5 | 612.5 | 899 |

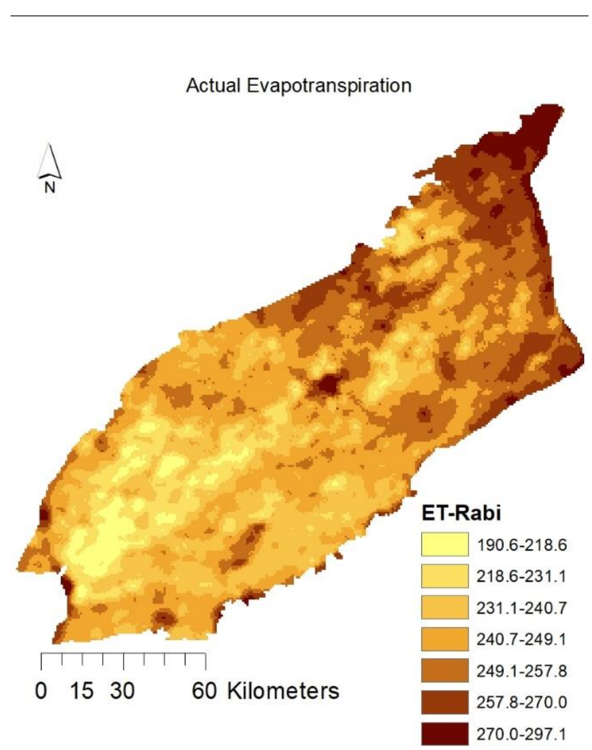


Figure 5: Four-year average SEBAL estimated ETa of the Rabi Season

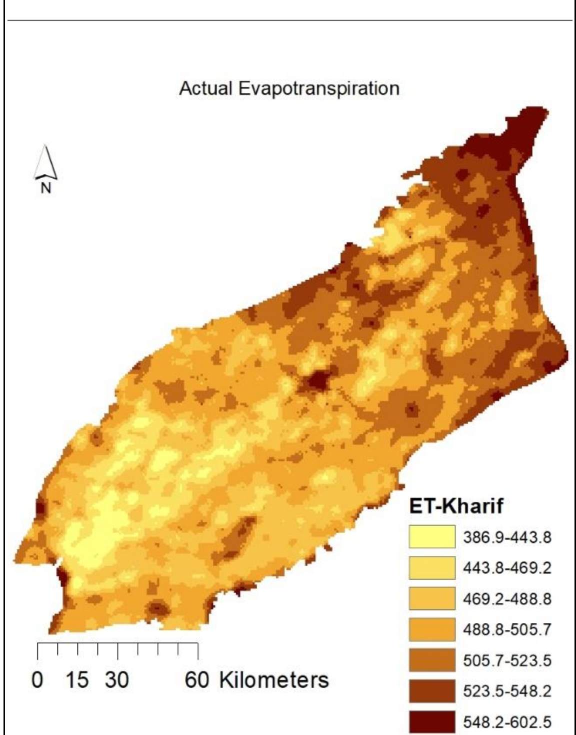


Figure 6: Four years average SEBAL estimated ETa of the Kharif Season

Figures 5 and 6 shows the four years average of Rabi and Kharif season ETa respectively at the LCC system. The ETa map shows the significant variation in the actual evapotranspiration, the actual evapotranspiration is high at the head reaches of the LCC system. This higher ETa is due to the more rice cultivation at the head reaches than the tail of the irrigation system. While in the Rabi season, ETa was found higher from the central to the lower part of the system. This higher ET is due to the cultivation of more Rabi fodder crop than the Kharif crop. Especially the cultivation of the berseem crop.

Figure 7 shows the distribution of ETa in different Canal Command Areas (CCAs) during the last four years (2010-11 to 2014-15). There was no significant temporal variation in the ETa between different CCAs. In case of Sagar CCA, the average ETa is 903 mm with standard deviation of 12.5 mm. Mian Ali canal command showed the maximum standard deviation 20 mm and Jhang canal command shows the lowest standard deviation of 12 mm. Due to fixed water allowance, stagnant resources and locally fixed cropping zone, there was no change in the supply of irrigation water, practices of irrigation method and even no change in the cropping patterns. Rakh and Mian Ali canal command showed the low average ETa values as compared to the CCAs in the system. Likewise, Mian Ali and Rakh canal command areas have poor quality groundwater. Maximum ET at the Sagar canal commands are due to its location at the upstream of the irrigation system and cultivation of rice crop.

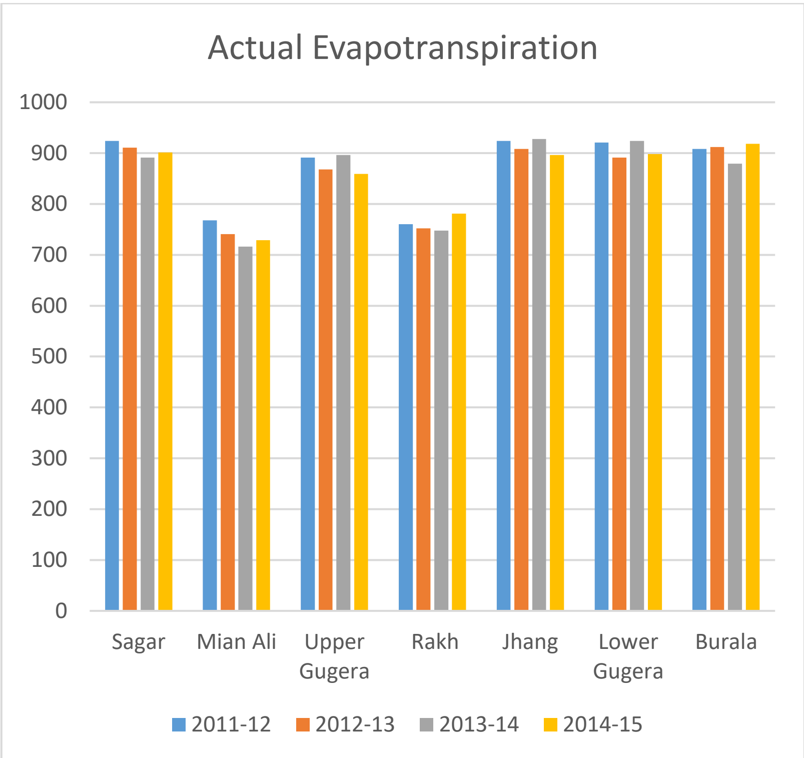


Figure 7: Actual Evapotranspiration at different CCAs of LCC

### 3.4 Spatially Distributed Rainfall

The existing studies describe the over and under estimation of rainfall from the TRMM in relation to the changes in topography. [20] described in detail the over and under estimation of rainfall from the TRMM in the Indus basin. Similarly, [43] describe the similar trend of rainfall over and underestimation in Bangladesh. Further, [44] described that that satellite overestimated the rainfall in areas with the rainfall <400 mm month$^{-1}$ and underestimated in the areas of rainfall >400 mm month$^{-1}$. These results were further strengthened by findings of [43]. They concluded that the TRMM has limitations in accurate rainfall detection at low or high rainfall rates. So, in the study area, TRMM overestimated the rainfall that was

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calibrated with the point observatory data. Spatial distribution of rainfall for Rabi and Kharif season is shown in figure 5 and 6 respectively. These figures clearly show the decrees in rainfall towards the tail of the irrigation system. Tables 6 and 7 described the temporal analysis of the gross and effective rainfall. Table 6 shows the temporal rainfall distribution. The maximum mean monthly of four years rainfall was found maximum 95.6 mm in September and minimum 2.6 mm in November. The average annual rainfall was for the four years was found 343.5 mm.

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Table 6: Rainfall distribution (mm) in LCC from 2011-12 to 2014-15

| Annual | Rabi Season | | | | | | | | Kharif Season | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nov | Dec | Jun | Feb | March | 1-15 Apr | Total Rabi | | 16-30 Apr | May | Jun | Jul | Aug | Sep | Oct | Total Kharif | Total Annual |
| **2011-12** | 0 | 0 | 3.8 | 8 | 1.5 | 7.5 | 20.8 | | 2.7 | 0 | 23.6 | 45.4 | 38.5 | 163.7 | 11.5 | 285.4 | 306.2 |
| **2012-13** | 0 | 17.2 | 1.5 | 55 | 1.3 | 12.7 | 87.7 | | 8.9 | 4.6 | 67.5 | 4.7 | 114.9 | 3.3 | 0 | 203 | 290.7 |
| **2013-14** | 0.5 | 0 | 0 | 14.3 | 41.7 | 10.3 | 66.8 | | 18 | 41.2 | 7.1 | 57.5 | 4.8 | 140.2 | 3.6 | 272.4 | 339.2 |
| **2014-15** | 10 | 0 | 12.2 | 20.5 | 67.9 | 32.8 | 143.4 | | 0 | 17 | 11.6 | 128 | 48.4 | 75.2 | 14.5 | 294.7 | 438.1 |
| **Average** | 2.63 | 4.3 | 4.38 | 24.5 | 28.1 | 15.8 | 79.7 | | 7.4 | 15.7 | 27.5 | 58.9 | 51.7 | 95.6 | 7.4 | 264.2 | 343.5 |

Table 7: Effective rainfall distribution (mm) in LCC from 2011-12 to 2014-15

| Annual | Rabi Season | | | | | | | | Kharif Season | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nov | Dec | Jun | Feb | March | 1-15 Apr | Total Rabi | | 16-30 Apr | May | Jun | Jul | Aug | Sep | Oct | Total Kharif | Total Annual |
| **2011-12** | 0 | 0 | 3.1 | 6.4 | 1.2 | 6 | 16.7 | | 2.2 | 0 | 18.9 | 36.3 | 30.8 | 130.9 | 9.2 | 228.3 | 244.9 |
| **2012-13** | 0 | 13.8 | 1.2 | 44 | 1.04 | 10.5 | 70.2 | | 7.1 | 3.7 | 54 | 3.8 | 91.9 | 2.6 | 0 | 163.1 | 232.6 |
| **2013-14** | 0.4 | 0 | 0 | 11.4 | 33.4 | 8.2 | 53.4 | | 14.4 | 33 | 5.7 | 46 | 3.8 | 112.6 | 2.9 | 217.9 | 271.4 |
| **2014-15** | 8 | 0 | 9.8 | 16.4 | 54.3 | 26.2 | 114.7 | | 0 | 13.6 | 9.3 | 102.4 | 38.7 | 60.2 | 11.6 | 235.8 | 350.5 |
| **Avg.** | 2.1 | 3.5 | 3.5 | 19.6 | 22.5 | 12.7 | 63.9 | | 5.9 | 12.6 | 21.9 | 47.2 | 41.3 | 76.6 | 5.9 | 211.4 | 274.8 |

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Rainfall results are shown in Table 7, the annual effective rainfall variation ranges between 232.6 mm year$^{-1}$and 350.8 mm year$^{-1}$, with an average of 274 mm year$^{-1}$during 2010-11 to 2014-15. Variation in the mean monthly analysis for effective rainfall shows the variation of 2.1 mm (minimum) in November and 76.5 mm (maximum) in September. The rainfall occurrence during the months of monsoon (June-September) was found more than 55 mm month$^{-1}$. The analysis of seasonal rainfall occurrence was found an average of 23% during Rabi and 77% during Kharif of the total rainfall amount.

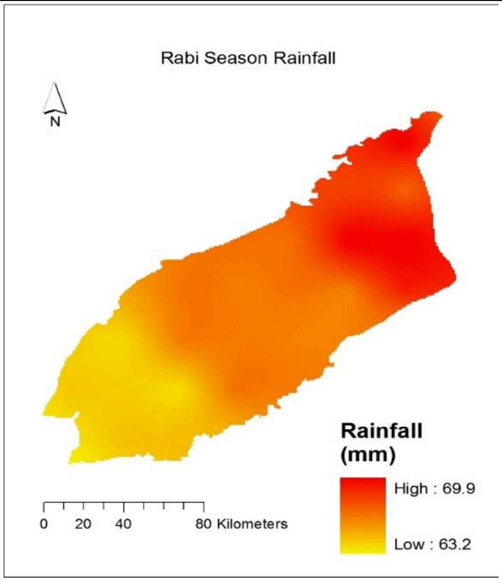


Figure 8: Four years average Rabi Season Satellite Derived Rainfall

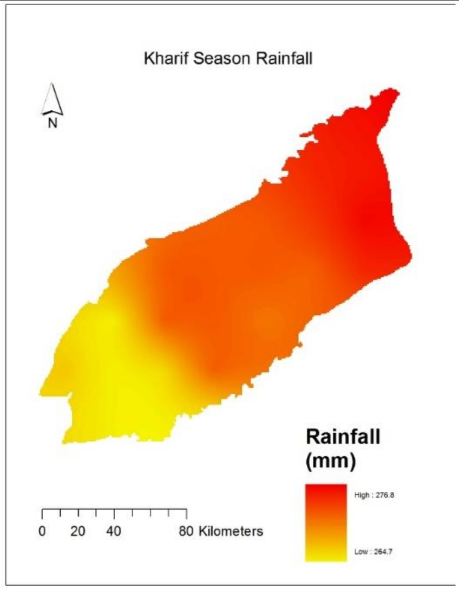


Figure 9: Four years average Kharif Season Satellite Derived Rainfall

Figure 10 shows the effective rainfall in different CCAs during the last four years (2011-12 to 2014-15). The maximum four years average annual effective rainfall in LCC irrigation scheme was found 302 mm at the Sagar. Figure 10 shows that there are significant temporal variations of the effective rainfall at each CCA. While there is no significant average annual rainfall between different CCAs as shown in the figure. The maximum average four years effective rainfall was 302 mm at Sagar and minimum was 258 mm at the Burala branch.

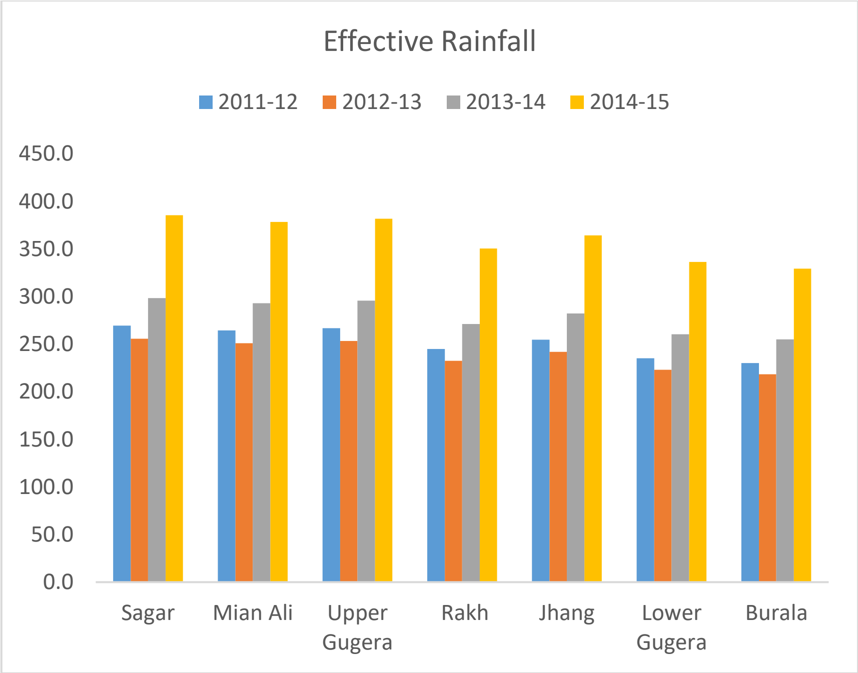


Figure 10: Effective Annual Rainfall at CCAs (2011-12 to 2014-15)

### 3.5 Groundwater Irrigation

In the arid and semi-arid areas groundwater is a complementary source of irrigation under high cropping intensity. Groundwater contribution is significant in the in the IBIS. [17] described the 42% of the groundwater pumping at the head of the irrigation system. Groundwater irrigation results showed that groundwater has significant share to fulfil the irrigation water demand. The groundwater irrigation map obtained from the water balance of described the significant groundwater contribution at the head of the canal system. Irrigation water supply from the system was aggregated to monthly, seasonal and annual irrigation water volumes. Four years average net groundwater irrigation was found 195-88 mm and 314-99 mm during Kharif season. The four years average of gross groundwater abstraction (GWA) is maximum 750 mm at the upstream areas of the irrigation system. The minimum GWA was 275 mm at tail of the LCC system. This described the more use of canal water at the head of an irrigation system. Four years average share of the net groundwater irrigation (NGWI) is 283 mm that represents 44 % of the average annual supply of canal water (Fig. 11 & 12). Though, the contribution of the average annual groundwater in the ETa is 42 %. Monthly maximum average NGWI is during the month of May whereas the minimum is during the month of November.

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Table 8: Distribution of net groundwater irrigation (mm) in LCC from 2011-12 to 2014-15

| **Annual** | Rabi Season | | | | | | | | Kharif Season | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nov | Dec | Jun | Feb | March | 1-15 Apr | Total Rabi | | 16-30 Apr | May | Jun | Jul | Aug | Sep | Oct | Total Kharif | Total Annual |
| **2011-12** | 31.2 | 24.6 | 20.0 | 47.6 | 61.0 | 30.9 | 215.2 | | 31.7 | 101.1 | 77.4 | 53.4 | 62.8 | 0 | 41.3 | 308.0 | 523.0 |
| **2012-13** | 23.4 | 15.2 | 26.3 | 4.0 | 73.5 | 30.5 | 173.0 | | 25.7 | 85.9 | 41.8 | 89.0 | 4.6 | 67.6 | 40.5 | 355.8 | 528.7 |
| **2013-14** | 29.0 | 31.6 | 37.5 | 41.1 | 38.3 | 36.0 | 213.4 | | 15.8 | 62.9 | 85.9 | 47.6 | 93.4 | 0 | 43.6 | 31.7.0 | 530.4 |
| **2014-15** | 23.4 | 25.4 | 29.0 | 18.7 | 21.1 | 15.1 | 132.6 | | 30.5 | 77.4 | 86.8 | 4.4 | 56.5 | 10.4 | 31.4 | 297.4 | 297.9 |
| **Average** | 26.7 | 24.2 | 28.2 | 27.8 | 48.5 | 28.1 | 183.6 | | 25.9 | 81.8 | 73.0 | 48.6 | 54.3 | 19.5 | 39.2 | 319.5 | 503.0 |

Table 9: Distribution of gross groundwater abstraction (mm) in LCC from 2011-12 to 2014-15

| **Annual** | Rabi Season | | | | | | | | Kharif Season | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Nov | Dec | Jun | Feb | March | 1-15 Apr | Total Rabi | | 16-30 Apr | May | Jun | Jul | Aug | Sep | Oct | Total Kharif | Total Annual |
| **2011-12** | 45.8 | 36.1 | 29.4 | 70.0 | 89.7 | 45.4 | 316.5 | | 46.6 | 148.7 | 113.9 | 78.6 | 92.3 | 0 | 60.7 | 452.9 | 769.0 |
| **2012-13** | 34.4 | 22.4 | 38.7 | 5.8 | 108.1 | 44.9 | 254.4 | | 37.9 | 126.3 | 61.4 | 130.8 | 6.8 | 99.4 | 59.5 | 523.2 | 777.6 |
| **2013-14** | 42.6 | 46.4 | 55.2 | 60.4 | 56.4 | 52.9 | 313.9 | | 23.3 | 92.6 | 126.4 | 70.0 | 137.3 | 0 | 64.1 | 466.1 | 780.0 |
| **2014-15** | 34.3 | 37.4 | 42.6 | 27.5 | 31.0 | 22.2 | 194.9 | | 44.8 | 133.8 | 127.6 | 6.5 | 83.2 | 15.3 | 46.1 | 437.3 | 632.3 |
| **Avg.** | 39.3 | 35.6 | 41.5 | 40.9 | 71.3 | 41.4 | 269.9 | | 38.1 | 120.3 | 107.3 | 71.5 | 79.9 | 28.7 | 57.6 | 469.9 | 739.7 |

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The remaining crop water requirement is highly dependent on the groundwater use as the sum of the rainfall plus the irrigation water supply is less than the demand. Sum of the both surface water sources (netCanal + Rainfall) four years average in study period was found 548 mm (36% of ETa). Therefore, farmers depend on the use of groundwater to fulfil the irrigation water need. Average of the study period shows 739.6 mm of groundwater abstraction, while the annual based variation ranges between 632 mm and 780 mm. Seasonal analysis revealed 39% and 61% of groundwater abstraction proportion during Rabi and Kharif season, respectively (Table 8). The fluctuations in four cropping year's monthly groundwater abstraction ranges between 28.7 mm to 120.3 mm. This variation was high in the 2011-12 to 2012-13 cropping year (0 mm to 148.7 mm), this variation is dependent upon the occurrence of rainfall and crop phenology. This lowest abstraction in September could be due to high monsoon rainfall and due to the less water demand. Net groundwater irrigation, estimated after incorporating the efficiencies was 503 mm year$^{-1}$(Table 9) on average for the four cropping years. Unlike surface water use from canals, the maximum groundwater use in the month of May was due to the cultivation of rice, as well as insufficient rainfall and canal water availability.

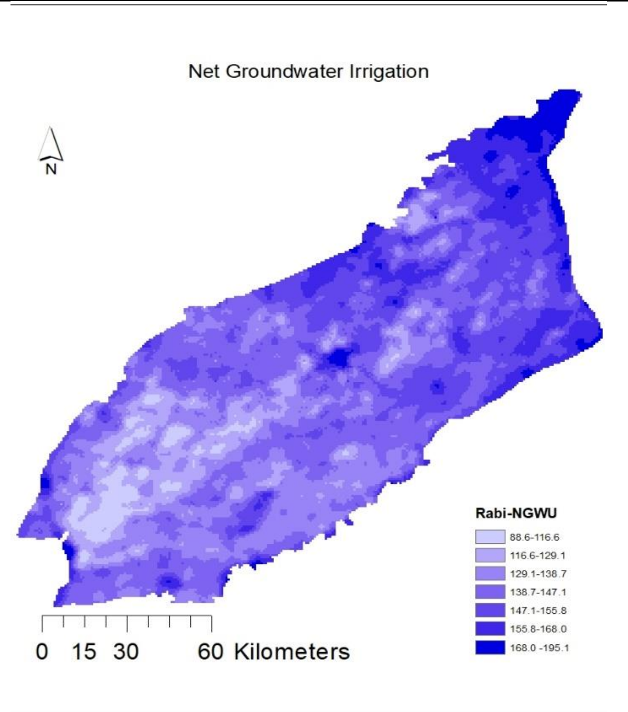


Figure 11: Four years average Rabi season Groundwater Irrigation in the LCC

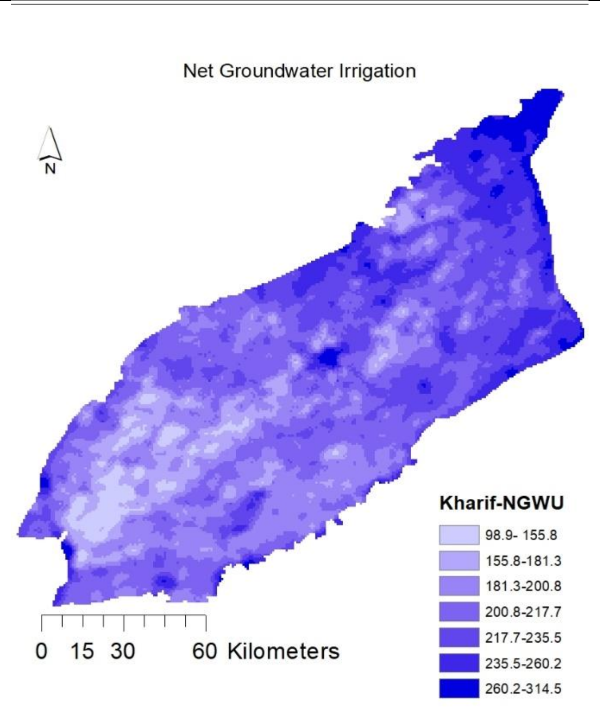


Figure 12: Four years average Kharif season Groundwater Irrigation in the LCC

Figure 13 shows the gross groundwater irrigation (GGWA) in LCC system CCAs during the last four years (2010-11 to 2014-15). The four years average annual GGWA was found 526 mm for the whole LCC system. There is significant temporal variation in GGWA in the CCAs of the LCC system (figure 4.16). The four years average gross groundwater abstraction was 887 mm at the Sagar and minimum was at the Upper Gugera with zero ground water Abstraction for this study period. This was due to the maximum canal water supply to the Upper Gugera. The maximum abstraction was in the Sagar CCA while the minimum abstraction was in the Upper Gugera CCA. Higher GGWA in the Sagar CCAS was due to the intensive cultivation of rice crop.

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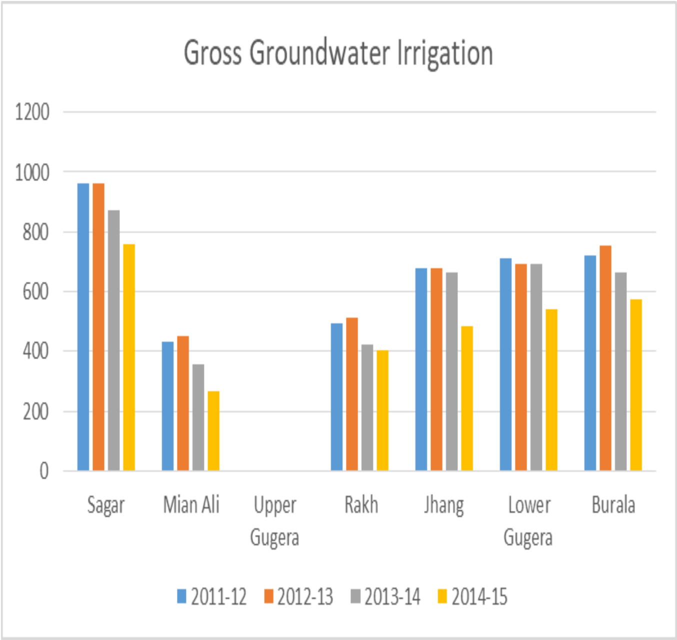


Figure 13: Gross Groundwater Irrigation at different CCAs of the LCC system

## 4 Conclusion

Surface water supply variation at the different scale was found very significant, the highest canal water availability at the Upper Gogera canal command while the lowest at the Sagar canal Command. Therefore, groundwater extraction was found maximum at Sagar command due to less supply and cultivation of the high irrigation demanding crop (rice). Similarly, Jhang canal command, Burala canal command and lower Goger canal command shows the significant groundwater irrigation. On the basis of the study period, this study directed for the serious focus on the water allocation planning to avoid the water logging in some areas and higher chances of secondary salinization in the major portion of the study area. It directed the water managers for the effective management of canal water resources to sustain the soil and water productivity of the system for the contribution in the achievement of sustainable development goals.

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