Cloud Publications
International Journal of Advanced Remote Sensing and GIS
2014, Volume 3, Issue 1, pp. 627-641, Article ID Tech-288
ISSN 2320 - 0243

Research Article **Open Access**

Pixel-Wise Surface Water Balance Computation: Lower Yamuna Basin

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Publication Date: 11 July 2014

Article Link: http://technical.cloud-journals.com/index.php/IJARSG/article/view/Tech-288

Abstract Traditional techniques in surface water balance computations revolve around point-based observed results of climatic variables. Basin-wide areal estimates derived from point interpolations may not reflect true character of sub-regional variations. Hence, pixel-wise water balance computation in the case of lower Yamuna river basin falling under Himalayan river system of India, is attempted in this paper using remote sensing and Geographical Information System based approach. A comparison of point and area-based estimates has been done based on both Thornthwaite and Penman methods. Water balance computations, aridity, humidity and moisture indices, surplus and deficit values at given data points have been used in map-based calculations by developing a script in GIS software – ILWIS (Integrated Land Water Information System). It was found that water balance computations, using point-based rainfall and other climatological data, result into broad generalization of deficit and surplus zones around meteorological stations. But, when zonal landuse and soil maps are crossed in GIS environment, then pixel-wise calculations of available water capacity can be used along with isohyetal maps to produce better areal estimates of hydrological regions. The results of pixel-wise computations have clearly brought out meso-level variations in hydrological categories. In addition, indirect energy balance estimates obtained from satellite images at different spatial scales can provide significant clues for better planning of water resources especially in design stage.

Keywords *Hydrological Regionalization; Map Calculations; Areal Estimation*

1. Introduction

Long-term yield estimates based on normal standards can differ significantly in terms of their areal extent especially in the case of extreme events and thus may affect developmental designs of irrigation/multipurpose projects in the region. It is the extension of point-based hydrological data record to areal estimates that decides the practical utility of potential yield. Various predictive models are nowadays being used to estimate frequency and intensity of rainfall and other climatic variables. The areal estimation of rainfall, however, could not be given due importance in many countries of the world. Present day hydrological capabilities, however, demand high level of accuracy in the statistics obtained from collected data. Therefore, based on estimates of time-averaged areal mean of precipitation, configurations of spatial network were analysed particularly with respect to their location, duration of observation and measurement of error (Bras and Colon, 1978).

More important than precipitation is the water need because it defines the utilizable quantity of water. To determine water need the concept of potential evapotranspiration (PET), introduced by Thornthwaite (1948) still remains the most useful parameter. A book-keeping procedure presented in the form of water balance table formed the important basis of his climatic classification. At the same time, another significant attempt towards estimation of evapotranspiration was made by Penman (1948) who tried to combine aerodynamic and energy budget approach in his experiments. Several scholars worked on this principle as exemplified by the works of Tanner (1968) and Chidley & Pike (1970). Although there exist many a number of computer programmes to solve Penman equation but most of these are particular in data input, form of equation and data output. The options in estimation of evapotranspiration as discussed by Penman earlier and later on modified by Monteith (1981) are quite useful and these have incorporated in CROPWAT software of Food and Agriculture Organisation (FAO, 1992). A regional application of PET in different environmental conditions has also been discussed (Bruin, 1988). Another conceptual model of a catchment’s annual water balance has also been developed that can be used to separate annual precipitation into three major components: surface runoff, base flow and vaporization. The model parameters can be estimated from past experience or can be calibrated using measured data (Ponce and Shetly, 1995).

In India, the most significant and leading contribution in the field of water balance studies were made by Subrahmanyam (1956) of Andhra University. He prepared maps covering whole of sub-continent to show spatial pattern of average annual water surplus and deficit computed after Thornthwaite method. Penman method was followed by Rao et al., (1971) to compute PET at all the climatological stations in India. Extent of water surplus and deficit based on these estimates of PET is seldom reliable as flood and droughts are unpredictable. In order to present water problem of an area in its perspective, variability in water balance obtained by averaging the results of 18 individual years showed greater fluctuations in water surplus. Hydrological regions have also been delineated in associations with combinations of surplus and deficit (Pandeya and Prasad, 1983). But, the hydrological region formed on the basis of Penman-based PET pose severe constraints due to limited stations in India recording all climatic parameters (Ahlawat, 1999). Therefore, the applicability of water balance method in the case of a small watershed and for a shorter time-period has been rendered useless.

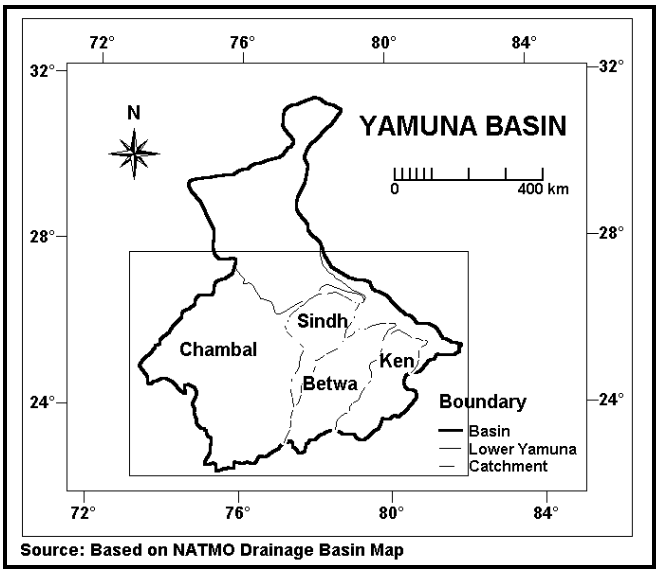
Implications of water balance can be understood properly if basin-wise water budget is computed. Water resource development becomes more prominent in an area of both least and maximum rainfall like that of the Upper Vagai basin (Vishwanath and Ganesh, 1985). Popularity of applied studies of water balance became more important in the field of agriculture in India. Crop water requirements, irrigation scheduling methods (Doorrenbos and Pruitt, 1977), estimation of Hargreaves’s reference crop evapotranspiration (Mandal and Challa, 1991), moisture adequacy index-based classification of agro-climatic zonation, influence on crop yield (Hema Malini, 1986), identification of drought prone areas (Dwivedi, 1993) and problems of water balance (Dwivedi and Bhar, 2003) - are few examples of such studies. However, the regional estimates of PET are interpolations made on the basis of point-based calculations of PET, and average soil and landuse conditions of the area as demonstrated at catchment level in Bundelkhand region (Ahlawat, 2000).

Of late, the search for theories and models has enhanced the need for precision in observation and analysis. Utility of Geographical Information System (GIS) in large-scale rainfall-runoff modeling, watershed modeling, soil erosion etc. is being demonstrated and applied by many scholars (Singh and Fiorentino, 1996). With the availability of remotely sensed data, regional estimates of evaporation and evapotranspiration have been made using surface temperature, surface *albedo*, vegetative cover and incoming solar radiation (Mallick et al., 2007; Minacapilli et al., 2009). As the reliability of hydrological yield estimates depends upon spatial network of observational points therefore, an attempt has been made here to assess the network of hydrological data stations and their implications in hydrological regionalization. The components of water balance have to be computed in accordance with the corresponding soil and landuse for the smallest spatial unit of pixel chosen in GIS environment at basin scale.

2. Study Area

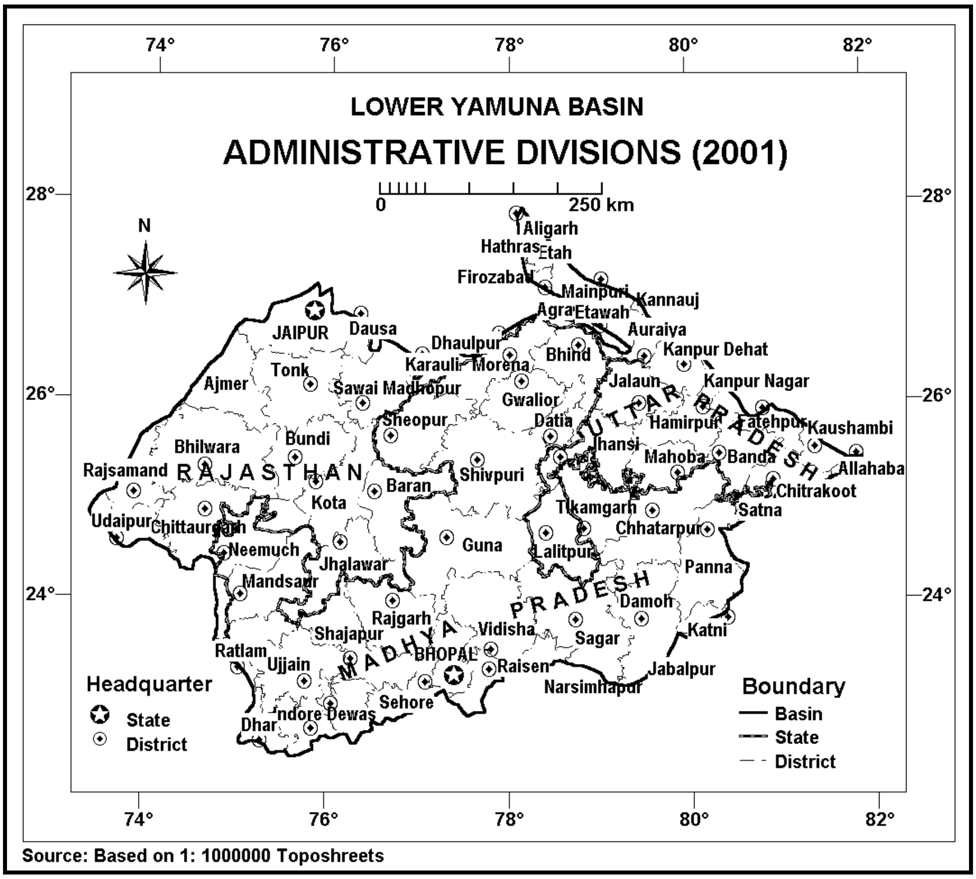
The river Yamuna, originating from Yamunotri glacier in the Mussorie range of the lower Himalayas at an elevation of about 6320 m above mean sea level traverses a journey of 1376 km before joining river Ganga at Allahabad at an elevation of just 94 m. The major input of flow in lower Yamuna is through Chambal near Etawah and, subsequently, through Sindh, Betwa and Ken rivers (Figure 1a). The lower Yamuna basin, being a transitional area of climate and geology with most of its coverage in central India, is selected for the present study. All right and left bank tributaries, downstream of Agra-Etawah ridge till its confluence with the river Ganga at Allahabad, are included in lower Yamuna basin. It drains about 76% of the total area under Yamuna basin falling in three states of Rajasthan, Uttar Pradesh and Madhya Pradesh (Figure 1b). The lower Yamuna basin, covering the catchments of Chambal, Sind, Betwa and Ken rivers on right bank; Rind and Senegar on left bank, extends from $22^{o}30'$ North to $27^{o}20'$ North latitudes and $72^{o}10'$ East to $82^{o}0'$ East longitudes. It is bounded by the Yamuna-Ganga *doab* in the north, Panna-Ajaigarh hills in the east, Vindhyan range in the south and Aravalli range in the west. Their catchments cover an area of about 260 thousand km^2 of which, 20 thousand km^2 (24%) lies in southwestern and southern Uttar Pradesh districts in Bundelkhand region, parts of districts along Yamuna left bank; 79 thousand km^2 in Eastern Rajasthan, parts of districts in Aravalli belt, districts in Mewar region; and remaining 140 thousand km^2 (76%) lies in northern Madhya Pradesh, M.P. Bundelkhand, Malwa plateau region, Sagar, Damoh and parts of districts in Central M.P.

The main problem of the region rests with the improvement of agriculture, which ultimately depends upon development of water resources. Although the region is drained by the Yamuna system, its higher southern bank and increasing gradient of land towards south do not permit the diversion of its flow southwards. Thus, water can be considered as a pivot of the whole regional economy particularly, in the ravinous and underdeveloped tract of the region. The severity of droughts and famines can be reduced if the potential of small ephemeral stream is estimated scientifically. Hence, regional water balance of the basin is presented in the present study.



Source: Based on NATMO Drainage Basin Map

(a)



Source: Based on 1: 1000000 Toposheets

(b)

Figure 1 (a & b): *Location of Study Area (Lower Yamuna Basin)*

3. Materials and Methods

The analysis is based mainly on data collected from secondary sources. Data on station-wise normal climatic tables covering 30-year period for meteorological stations was obtained from Indian Meteorological Department (IMD) report (1999) *Climatological Tables of the Observatories, 1951-80*. Base maps are drawn using toposheets of Survey of India at 1:250,000 scale and plates of drainage and water resources series of National Atlas Thematic Mapping Organisation (NATMO) at 1:1,000,000 scale. Further, primary data regarding the nature and functioning of data stations, maintenance, communication and publication of data, and the economic or other managerial problems, has also been collected at some of the selected sites.

Realising the data constraints, the boundaries of the lower Yamuna basin were drawn and it was, first, divided into 5 sub-catchments according to relief and drainage characteristics according to Watershed Atlas of India. Then, hydro-meteorological stations were located on base map. According to published records of meteorological observatories, stations having more than 30 years of record (1951-80) were included to get estimates of mean values of various hydrological parameters. For estimation of their areal means, Thiessen polygons and isohyetal maps based on moving average pixel-wise computations were drawn in a GIS system ILWIS (Integrated Land and Water Information System) 3.6 version.

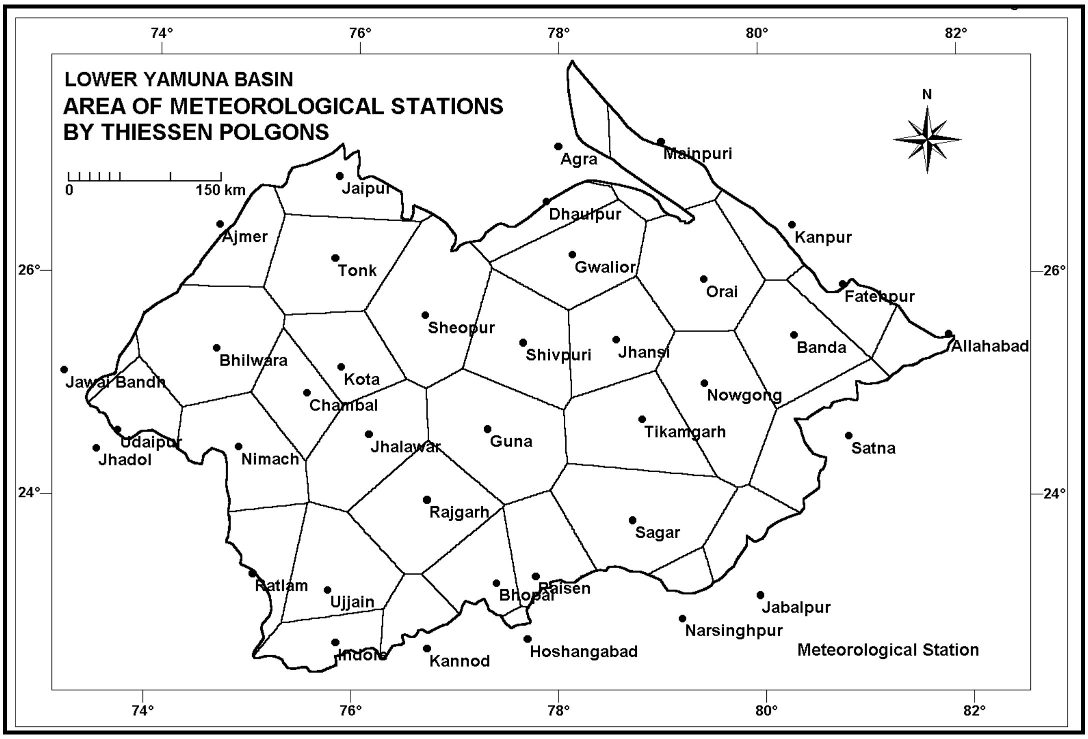
For Penman-based PET determination, CROPWAT software of FAO was used. Point estimates were obtained in MS EXCEL using water balance equations. Now with the possibility of pixel-wise map-based computations in GIS for all equations of water balance based on both the methods of PET, an improvement was made by writing a script in ILWIS. Pixel-size of 1000 m in case of lower Yamuna basin was used in order to get a better spatial picture. It was run successfully after many trials of 156 map-based calculations and comparison of values was also made at given points for verification. Depending upon the range of water surplus and deficit, a general picture of regional water balance was obtained by interpolating between their values. Thereafter, a comparison of surface water runoff pattern was also done with remote sensing data for the next 30 year period (1981-2010) GLDA (global land data assimilation system) time-averaged data. Analyses and visualizations used in this study were produced with the Giovanni online data system, developed and maintained by the NASA GES DISC.

4. Results and Discussions

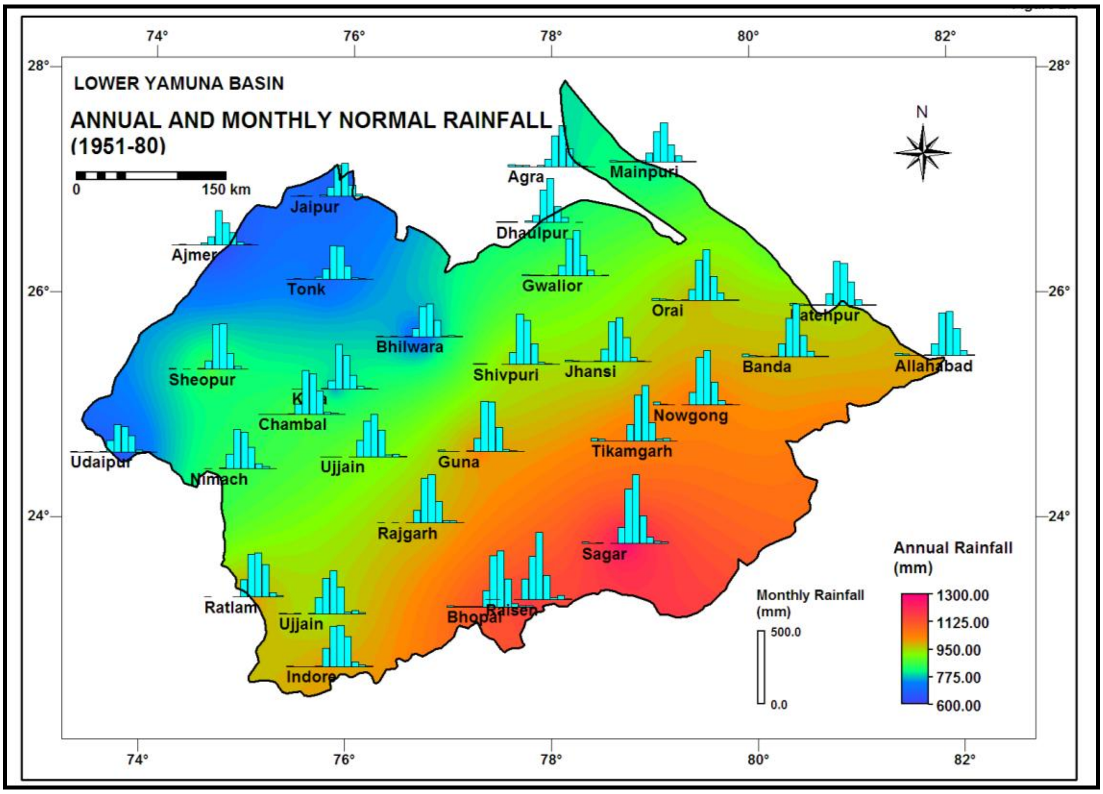
As the description of rainfall characteristics and resultant water balance depends upon distribution of meteorological stations, accuracy and precision of their record, therefore, quantitative analysis of data becomes essential to determine its suitability and optimality. Hence, an assessment of the hydro-meteorological data network was considered in detail here first for explaining the relationship between number of stations and spatial variations in average annual values.

4.1. Status of Hydro-Meteorological Data Network

There are about 38 meteorological stations having long-term data published record in the study region, 6 covering area of main lower Yamuna tract, 18 in Chambal, 3 in Sindh, 6 in Betwa and 4 in Ken river catchment (Figure 2). Out of these, only 10 stations belong to class I observatories that record data on climatic variables. The average density of meteorological stations network in the study region works out to be 6842 Km^2 for the stations having sufficient long-term record. According to modern WMO standards, minimum density of 1000-2500 Km^2 per station is required in the interior plains and undulating regions like lower Yamuna basin. Hence, adequacy of stations required for arriving at better areal estimates will have impact at sub-catchment level.



(a)



(b)

Figure 2 (a & b): *Meteorological Stations and Rainfall*
(**Source:** Author Based on IMD Data)

4.2. Mean Estimates of Basin Rainfall

The arithmetic average, the most commonly used method puts the mean annual rainfall in the lower Yamuna basin as 918.29 mm. But, this approach provides a reasonable estimate if, the gauges are distributed uniformly and the topography is flat which, except for the northern region, is not found in abundance in the study area. Areal mean rainfall estimate based on Thiessen polygon method, calculated in GIS, works out to be 931.57 mm with large variations found in the size of polygons (Figure 2a). Isohyetal average, obtained here by interpolating precipitation values using moving average method results into mean rainfall at 928.32 mm (Figure 2b). Both the methods compute higher mean rainfall than the one by arithmetic method. Hence, for all regional water balance computations weighted isohyetal average values were used.

4.3. Surface Water Balance

Water balance based on climatological approach is one of the most common methods of hydrological regionalization. However, the spatial extent of hydrological regions and magnitude of surplus and deficit values was found to vary according to the method used, *i.e*. Thornthwaite/Penman for determination of PET needs and available water capacity (AWC). Average regional value of AWC varies from 131.3 mm in north to 300 mm in southeast (Figure 3).

It was clear from all water balance tables that all stations in the region are dry, with annual summation of positive P-PET values always lesser than that of negative P-PET values. Annual rainfall in the region remains short of annual potential evapotranspirative demands. It is not sufficient even to recharge soil up to its field capacity at most of the places. Accumulative potential water loss at these stations is therefore adjusted for its balance amount from wet season.

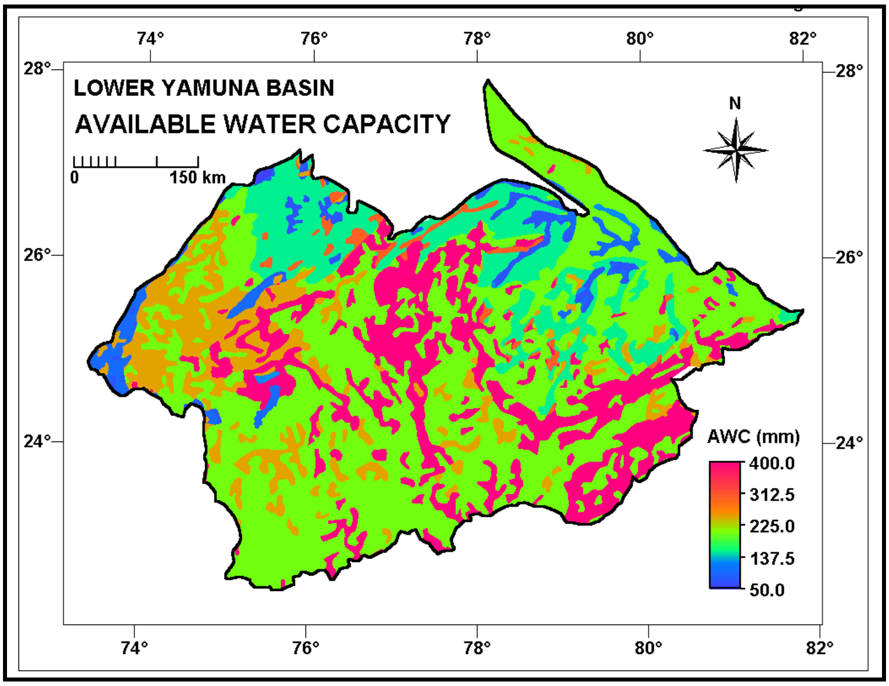


Figure 3: *Spatial Variability in Available Water Capacity of Fields*
(**Source**: Author using ILWIS based on NATMO Soil and Landuse Plates)

4.4. Aridity, Humidity and Moisture Indices

Moisture index was found to be negative everywhere except at Jabalpur, thus, defining the limit between dry and wet climate. According to Thornthwaite scheme of climatic classification, climatic condition in the region varies form semi-arid conditions (D) in the west to dry subhumid (C_1) type in the central part. Towards the southeastern section, it graduates towards moist subhumid (C_2) conditions. The slight increase of surplus over deficit (Figure 4 and Figure 5) here results in positive moisture index. In rest of the region, moisture index values show close correspondence with the rainfall pattern. Thus, leaving aside the differences in magnitude of moisture indices following both the methods of computation, the spatial pattern of moisture condition reveals that there exists an overall deficiency in the region particularly in the northern plains.

Seasonality of moisture condition becomes clearer by comparing aridity and humidity index separately. Aridity index in the region shows large winter deficiency of more than 50% at most of the places. This deficit cannot be made up even by soil moisture storage. Humidity index, on the other hand, is not even one-fourth of the annual PET demand computed after Penman method. Further, it shows larger spatial variation as compared to aridity index. Moisture adequacy index also shows the varying proportion of the ratio of AET to PET. It varies from 33 to 60%, thereby reflecting the suitability of crops, which can grow even if half or one-third of their evapotranspiration demands are met by rainfall and the rest can be supplemented by irrigation, if necessary.

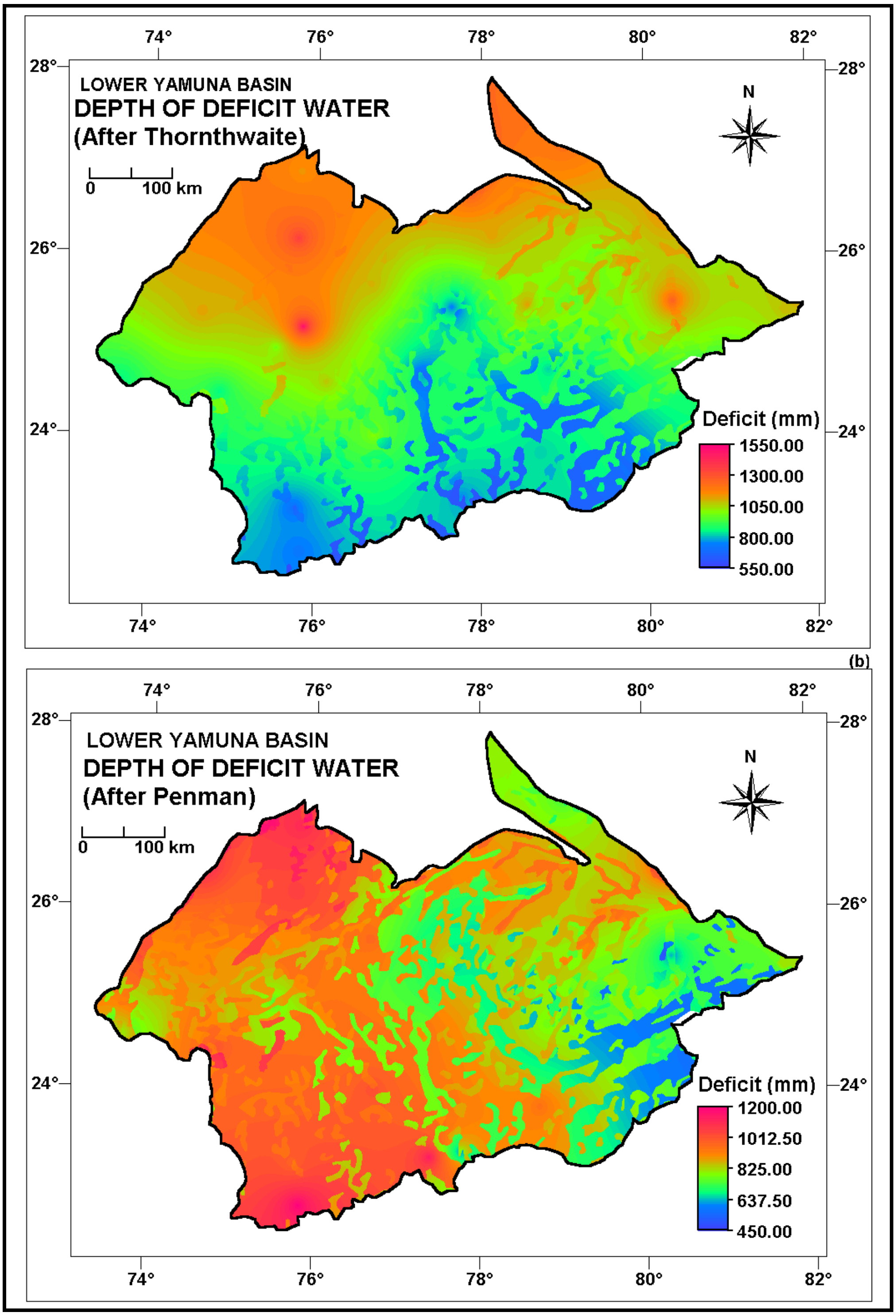


Figure 4 (a & b): *Spatial Pattern of Water Deficit*

(**Source**: Author using ILWIS Based on Pixel-wise computations of Water Balance Components)

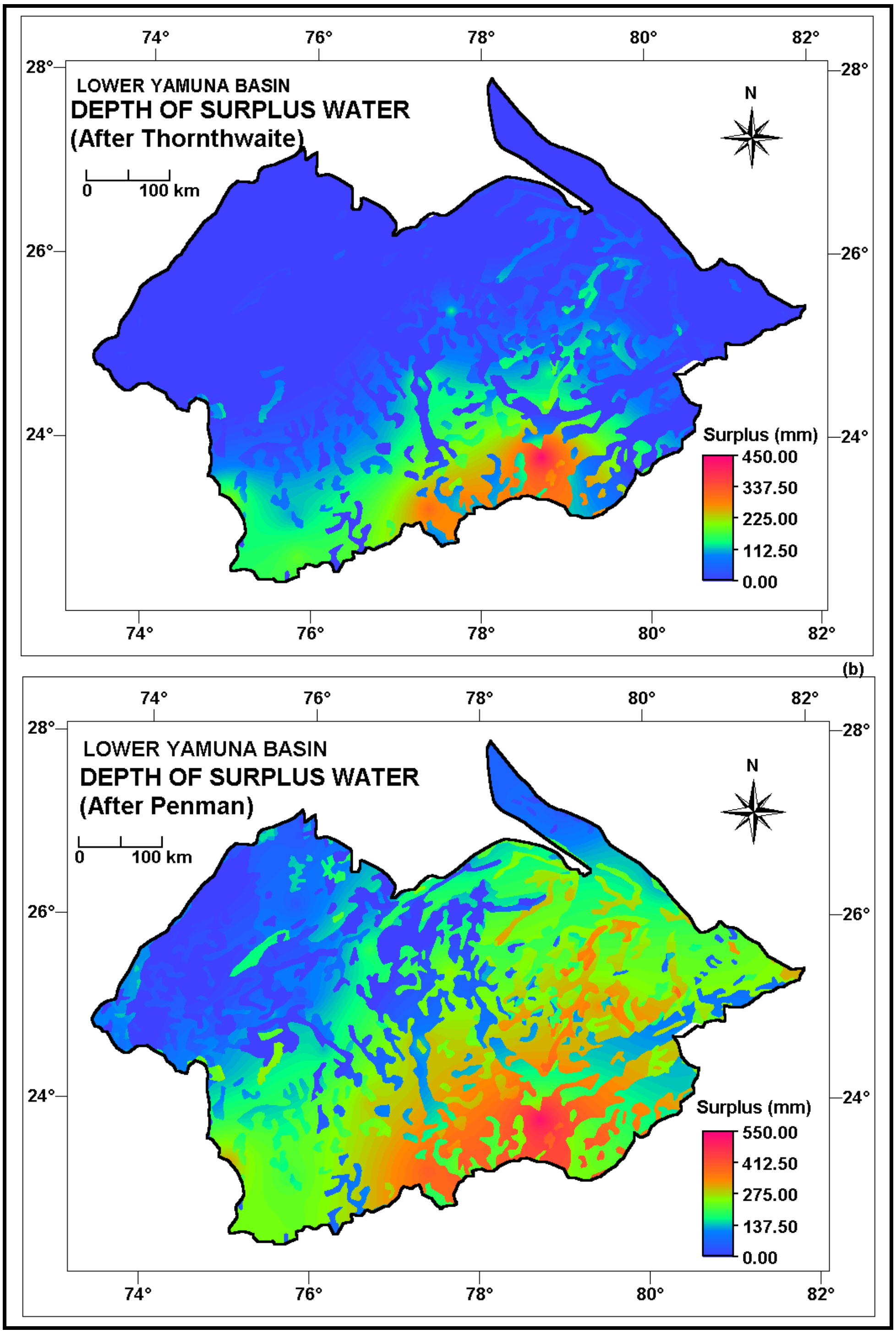


Figure 5 (a & b): *Spatial Pattern of Water Surplus*

(**Source:** Author using ILWIS Based on Pixel-wise computations of Water Balance Components)

4.5. Hydrological Regions and Spatial Network of Data Stations

In case of hydrological regions, five categories, each of annual surplus and deficit values of water have been identified (Figure 6 and Table 1). Ten hydrological regions were formed based on Thornthwaite's PET estimates, whereas Penman-based PET results into twelve hydrological regions. In both the methods, the predominant combination is that of low surplus and high deficit. However, the magnitude of surplus is underestimated and deficit is overestimated by Thornthwaite method. Interestingly, high surplus region towards southeast also witnessed high deficit in the lean season.

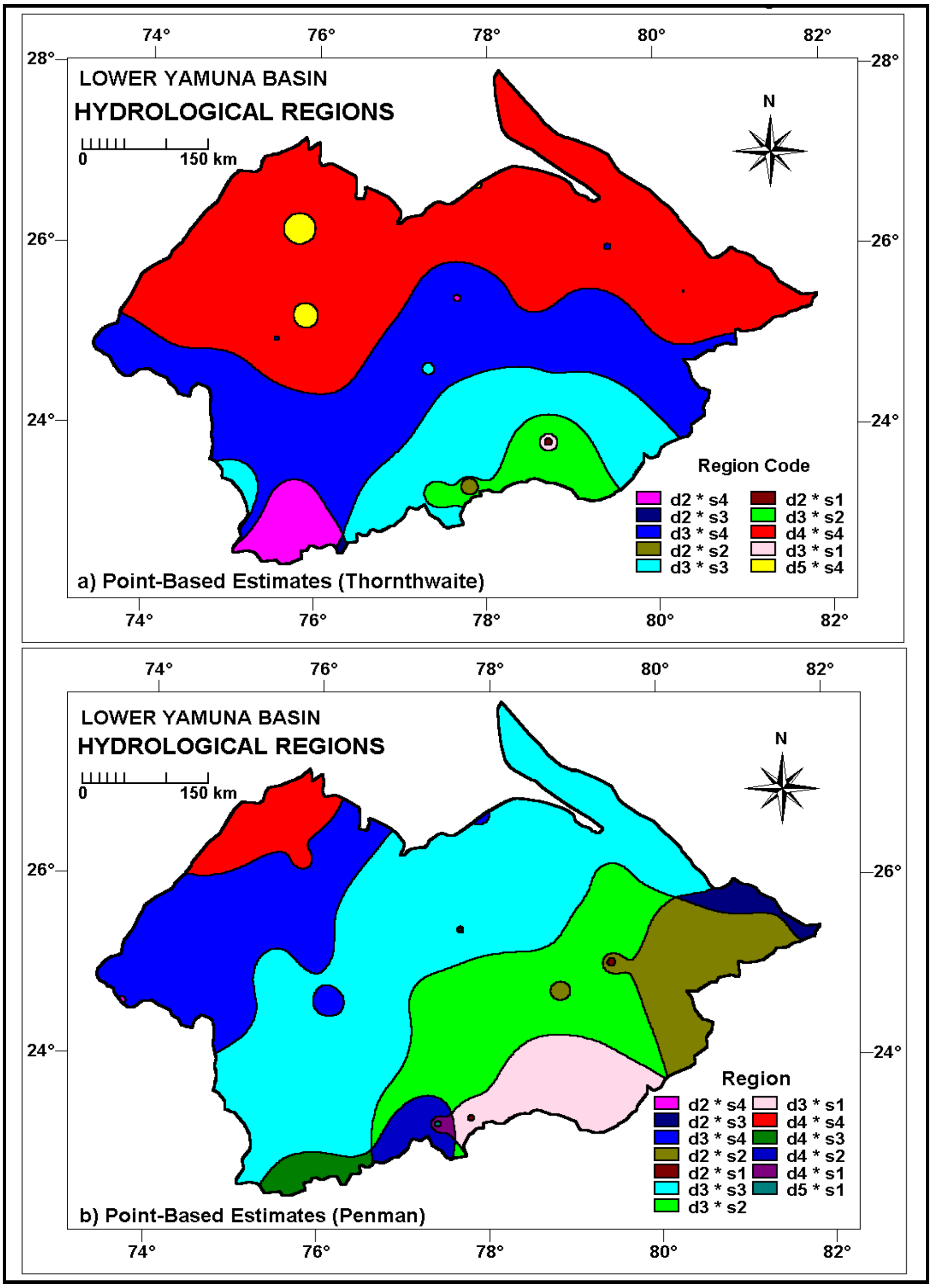


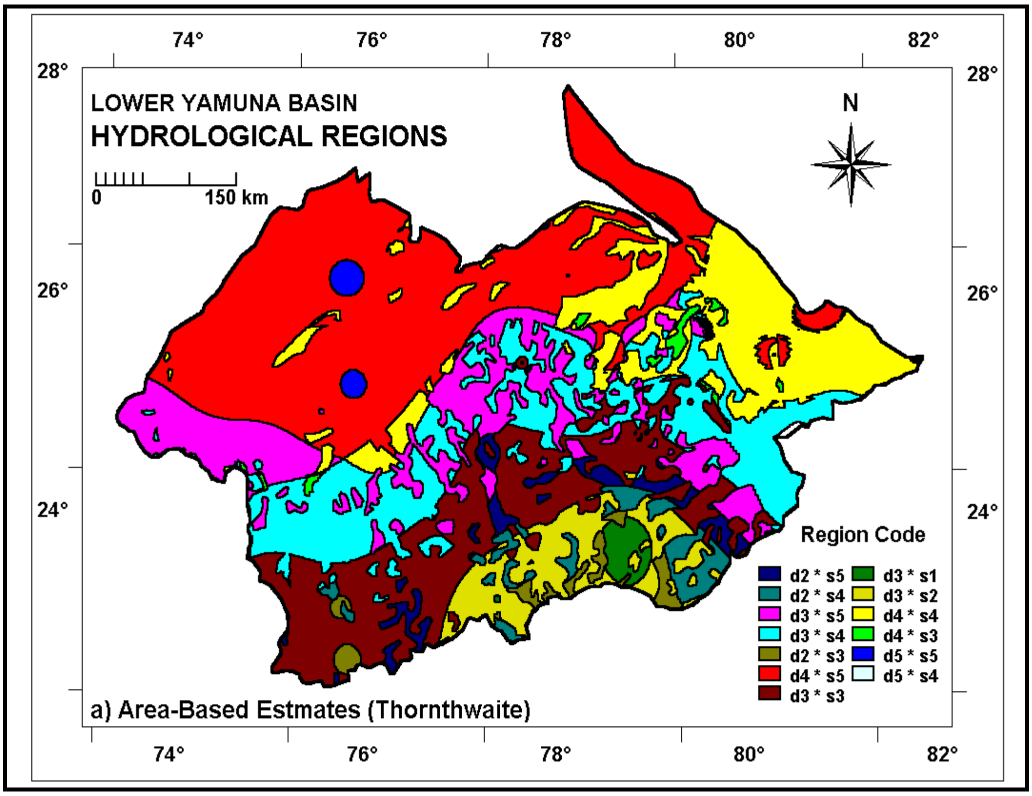
Figure 6 (a & b): *A Comparative View of Point-Based Hydrological Regionalization*
(**Source:** Author using ILWIS Based on Water Balance Tables computations in MS-EXCEL)

Table 1: *Hydrological Regions*

Hydro-logical Region	**Surplus Regions**	**Deficit Regions**	**Area (km^2)**			
			Thornthwaite		**Penman**	
			(1)	**(2)**	**(1)**	**(2)**
s5 * d4	No surplus	Very high deficit	--	1.05	--	--
s4 * d2	Very low surplus	Moderate deficit	3,969.02	14.63	--	--
s4 * d3	Very low surplus	High deficit	65,729.73	44,101.36	45,671.40	44,082.54
s4 * d4	Very low surplus	Very high deficit	133,403.73	153,564.49	15,439.13	12,142.25
s4 * d5	Very low surplus	Very very high deficit	2,160.64	745.30	--	--
s3 * d2	Low surplus	Moderate deficit	1,341.12	988.86	4,259.61	3,680.51
s3 * d3	Low surplus	High deficit	42,586.71	49,302.79	100,478.76	105,663.46
s3 * d4	Low surplus	Very high deficit	--	--	1,010.81	2,094.79
s2 * d2	Moderate	Moderate Deficit	145.30	--	21,685.87	17,826.61
s2 * d3	Moderate	High Deficit	12,684.76	13,171.87	46,443.88	47,526.82
s2 * d4	Moderate	Very High Deficit	--	--	237.28	1,489.56
s1 * d2	High surplus	Moderate deficit	36.59	18.82	10,731.09	9,491.36
s1 * d3	High surplus	High deficit	187.11	335.54	15,246.80	16,483.39
s1 * d4	High surplus	Very high deficit	--	--	1,019.17	1,720.57
s1 * d5	High surplus	Very very high deficit	--	--	20.91	42.86
			262,244.70	262,244.70	262,244.70	262,244.70

Source: Computed in ILWIS from Figure 6 a & b. Note: (1) Computations based on 37 stations; (2) 32 stations

The macro-hydrological regions carved out in Figure 6 (a & b) do not reflect meso-level variations due to lower density of meteorological data stations. The fact can be ascertained by excluding five stations that have less number of years of record from the analysis (Table 1; Column (2) under both the methods). Boundaries of each zone get shifted and the respective areas change depending upon location and number of stations included in spatial analysis. A significant difference in sub-zonal boundaries can be seen when pixel-wise calculations are done in GIS (Figure 7 a & b).



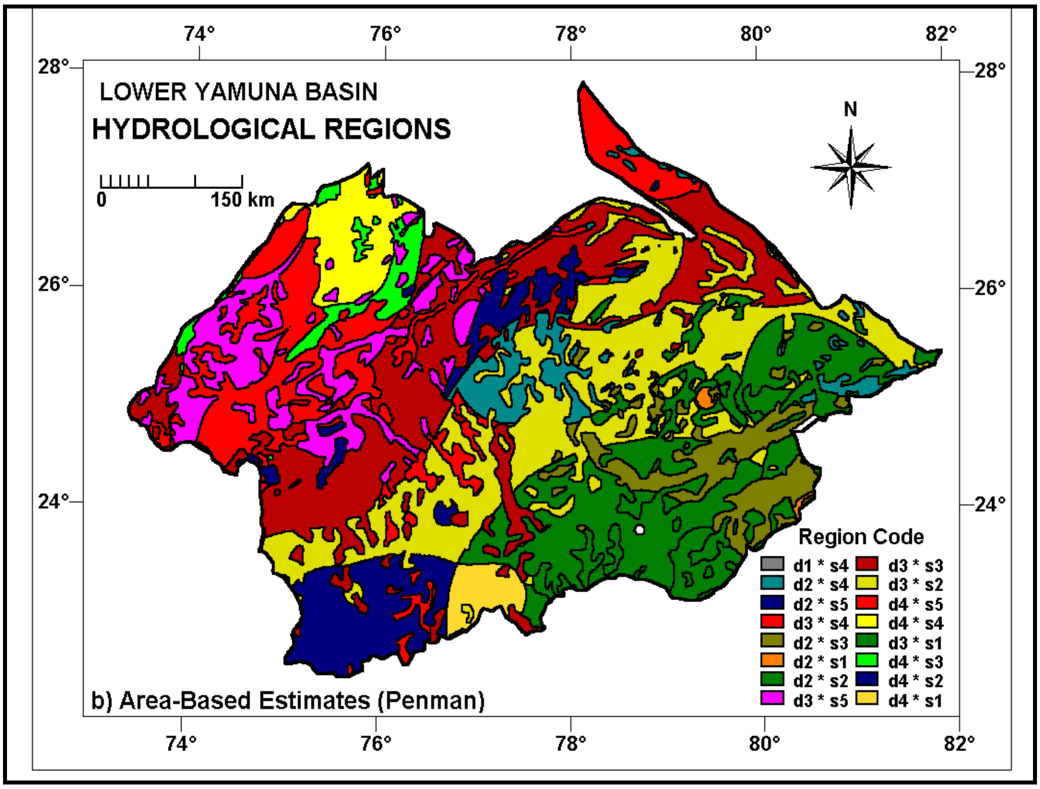
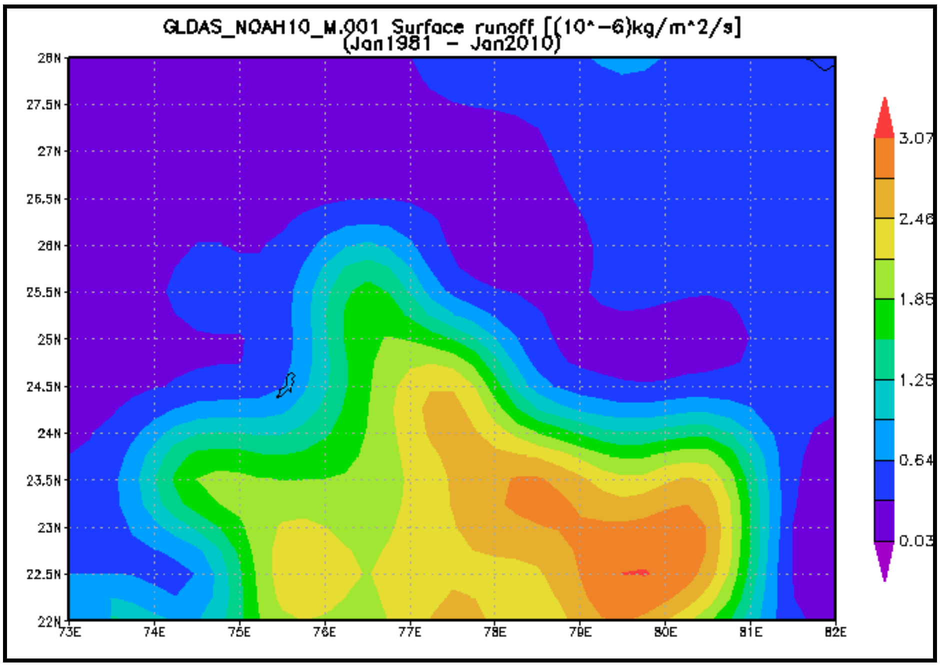
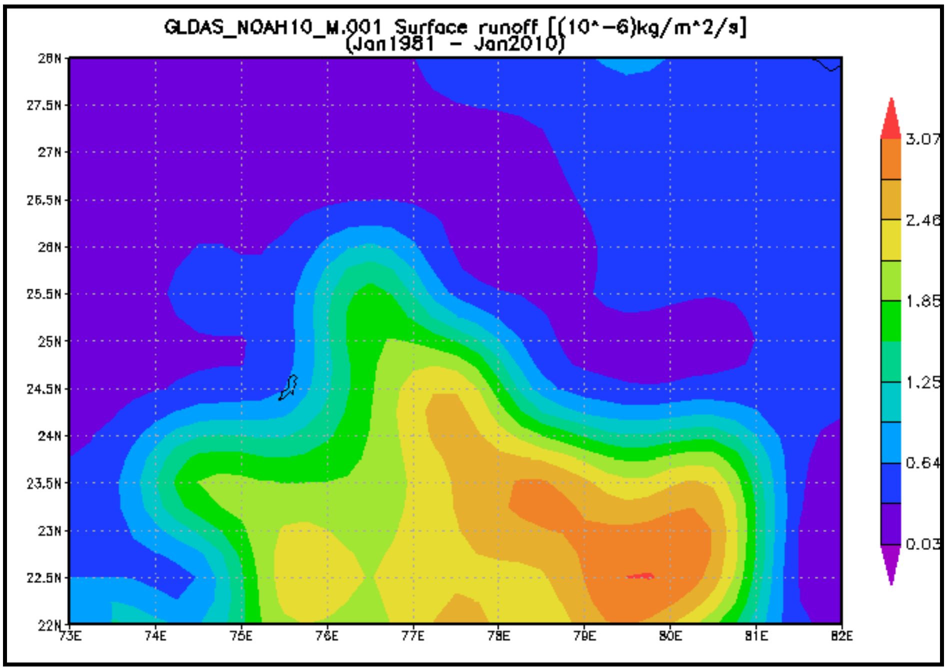


Figure 7 (a & b): *A Comparative View of Area-Based Hydrological Regionalization*
(**Source:** Author using ILWIS Based on Pixel-wise computations from Figure 4 & 5)

Further, a comparison of surface runoff pattern obtained from online remotely sensed recent data shows the similar trend of south-eastward increase (Figure 8 a & b). Here again, broad zones change when different simulation models like community land model (CLM) 1 degree and NOAH 0.25 degree subsets are used. Thus, area based calculations have been demonstrated here to represent their role in water resource planning at macro-level. It can be further broken down to medium scale and small scale catchments with the availability of high resolution remote sensing data.



(a)



(b)

Figure 8 (a & b): *A Comparison of Grid-wise Surface Runoff Computation based on Remote Sensing Data*
(**Source:** Giovani Online Visualization Plot, NASA, http://daac.gsfc.nasa.gov/)

5. Conclusion

The method used for spatial estimates also affects the results as can be seen from differing results of mean basin rainfall and water balance. Corresponding zone of influence of each station would also vary if area based computations are used. The choice of method used and the number of stations included in optimum analysis is a question yet to be satisfactorily answered.

The choice of available water capacity is another important issue in these water balance computations based on crossed map of landuse and soil cover. This change of value for a given pixel-size and discretionary choice of putting several categories under similar available water capacity zone can significantly alter results. Same could be observed in case of remotely sensed grid plot based on different resolutions. An exclusively detailed study utilizing more stations is required to prove conclusively that the results shown here are not a function of the stations chosen for spatiotemporal study.

Acknowledgement

The author sincerely thanks Prof. B. Thakur (Retd.), supervisor of Ph.D, from Department of Geography, University of Delhi to write this research paper. Prof. S.K. Pal (Retd.) also motivated the author initially in understanding of basic concept, solution of problem and in conducting further research in the area. Training rendered by Scientists of Indian Institute of Remote Sensing, Dehradun assisted in making better use of GIS software and in analysis of mapping work. Financial assistance provided by University Grants Commission in the form of minor research project for the research work is duly acknowledged. Support of officials of Indian Meteorological Department both at headquarter and field level who provided gainful insight into the process of data handling was of immense help in completion of the work.

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