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INVESTIGATING WATER STRESS USING HYDROMETEOROLOGICAL AND REMOTE SENSING DATA

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PREFACE

Drought is a recurring phenomenon and affect large part of India. Drought results in depletion of the available water resources including soil water storage. Kharif cultivation in mostly dependent of precipitation and utilize vadose zone soil moisture with supplemental irrigation, if available. Rabi cultivation is dependent on irrigation. The overall groundwater development in India is nearly 58% with nearly 92% withdrawal being for irrigation sector. Jaipur district has high groundwater development with 12 sub-divisions over exploited and one sub-division in critical stage of development. A study is being undertaken here to study water stress using hydro-meteorological and remote sensing data in Jamwa Ramgarh catchment located in Jaipur district of Rajasthan. In the district, Kharif cultivation is mostly dryland cultivation with pearl millet being major crop. Total groundwater recharge is small in the area due to low mean annual precipitation. Large groundwater development is resulting in depletion of the groundwater. Current agricultural practices have resulted in unsustainable groundwater development. Change in cropping pattern and irrigation practices may result in reduced groundwater use. Meteorological drought indices are able to identify Pan Indian major droughts. Due to availability of supplemental irrigation and reduced crop vigour caused by other factors, drought identified using vegetation indices do not always coincide with those from meteorological drought indices. Although many major Pan India droughts are identified by the indices used here, to understand efficacies of these indices, further investigations will be required.

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ABSTRACTS

Soil moisture investigation at point scale, hydrological modeling for studying cropping pattern scenario and meteorological and agriculture drought conditions were investigated in Jamwa Ramgarh catchment. Soil moisture measurements were taken at agriculture plots in Kharif and part of the Rabi season for year 2020- 21. Distinct soil moisture peaks were observed during heavy precipitation and flood irrigation. More significant change was observed in upper 20 cm during flood irrigation than for lower horizons. Soil moisture during Kharif season at few sites and for drip irrigation remained nearly constant. Moreover, non-parametric methods i.e., Mann-Kendall (MK) and Sen's slope estimator were used to quantify the spatial and temporal trends at seasonal and annual scale in rainfall during 1980 to 2017 at 17 rain gauge stations. These monsoon months' trends are not significant at 95% confidence interval, except for Amber station in month of June, which showed significant increasing trend. Further, the unsaturated zone Mike SHE model was run with FAO fine sand, silt loam and sandy laom with sub soil parameters for the sites at Gopalgarh and Roda Nadi. Unsaturated zone model simulation was done for cropping pattern pearl millet- fallow and pearl millet- wheat with two and six irrigation scenario. In two irrigation scenario, reduction of nearly 50% in evapotranspiration was simulated compared to six irrigation scenario. The Rabi season water demand was nearly equal to groundwater recharge. Thus, pearl millet- wheat cropping patter with six irrigations is not sustainable at point scale. Yearly drought magnitude was estimated for 15 stations in the region. Average drought magnitude for the Pan India severe drought years 1987 and 2002 was more than three. For years 1979, 1982, 1986, 1987, 1991, 2002, 2004, 2006, 2009 and 2017, some of which were Pan India major drought years, the average DM was more than two. Average probability of yearly drought magnitude and maximum dry spell weeks were also estimated. For Pan India drought years 1974, 1979, 1982, 1985- 1987, 2002, non- exceedance probability threshold was 70% in either yearly drought magnitude or maximum dry spell weeks. Vegetation Condition Index (VCI) was estimated using MOD13Q1 16-day NDVI. A subset of NDVI data was processed. The data were processed using R- software. Based on reliability raster, cloud and less reliable pixels were removed, the gaps were filled, trend in NDVI data was removed, seasonal data were extracted, VCI was estimated and average VCI for the area was computed. Relationship between average VCI and average probability of DM and dry spell week had small coefficient of determination. This indicated that variables other the

precipitation effects the crop vigour. Similarly the satellite imagery of IRS LISS III were also used to derive the VCI time series for different differet vegetation patches and cooreelated with the DM. The comparision shows the similar results from MODIS and LISS dataseries. Different combinations of clusters were formed and forcefully divided into 2, 3 and 4 classes for regionalization of the catchment . On the basis of these combinations it was revealed that cluster distribution of the variables is almost of similar type and pattern. It is observed that the various combinations of clusters are spatially and statistically correlated with the drought magnitude indicating hydrologically similarity. Moreover, the catchment is under the hydrometerological subzone 1b, hence regionality may not be the cause of drought like situation in the area.The physically distributed model MIKESHE, coupled with the hydraulic MIKE 11 model has been used to simulate the discharge in the Jamwa Ramgarh catchment. The model is simulated for 44 years (1974-2017) but due to lack of observed data its calibrated for 10 years (1974-1983) and validated for 22 years (1984-2005) respectively, considering different efficiency criteria between observed and simulated discharge namely coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE) to analyze the predictability of the simulated discharge.During the calibration R^2 0.8 and NSE -0.68 was achieved wheras during validation, the efficiency criteria (R^2 0.65 & NSE -0.74). Nash coefficient is poor being negative and is due to over estimation of the volume. So further modeling and observation were required to satisfying the modeling needs.

1.0 INTRODUCTION

Drought is a natural phenomenon of shortage of water over extended time and is primarily caused due to deficient precipitation. Dry condition is also abated due to improper management of water resources. Drought also reflect imbalance of demand and supply. Due to growth of population in a region, the increased demands leads to excessive use and depletion of existing water resources resulting in dry conditions and limiting water availability in droughts. Drought is a slowly pervading disaster. Its impact is visible over long period. It leads to loss of lives and livelihood, water and food insecurity, economic loss, migration and displacement, civil unrest, famine etc. Drought has effected more number of people in the world than any other natural disaster. Climate change is intensifying the regional climatic extremes and which is posing challenges to water management (NRDC 2018).

India has 4 % of the fresh water resources of the world. Water resources is available in form of rivers, tanks, lakes and reservoirs and groundwater. There are 12 major and 46 medium river in India. Substantial area in the country face surface water storages. Utilizable water in the country is 1123 bcm (690 bcm surface water and 433 bcm groundwater). Main source of groundwater in precipitation. Countrywide, 58% of the recharge to groundwater is due to precipitation and rest is due to recharge from other sources e.g. canal, water bodies, irrigation etc. Presently India is a water stressed country and with the growing population, the per capita availability of water is decreasing in India further. Surface and groundwater resources of India meet its various demands, e.g. irrigation, domestic, industrial etc. Water demand is increasing in India due to increase in population, urbanization and industrialization. Major part of the demand is from irrigation sector in India. Groundwater is important source of water for irrigation, domestic use and industries. Nearly 45% of irrigation demand and 80% of domestic water demand are met from groundwater. With increased utilization of water, groundwater resource of the country is depleting fast. With depleting water resources, it will be difficult to meet increased demand of water in future (ADRI 2020).

Large area in Rajasthan state has arid and semi-arid climate. Average annual available surface and fresh dynamic groundwater in the state are 25 and 11 bcm. Nearly 17 bcm is imported. Fresh static groundwater resource is nearly 33 bcm. Nearly 34 bcm groundwater is saline in the state, majority of which is static groundwater resource. Storage in the state is nearly 12 bcm. Water abstraction upstream of the projects is impacting water availability in the surface water storages. As per state water policy of 2010, high priority is given to drinking water for human and livestock, domestic, municipal and industrial demand than the agriculture demand. Water supply deficit for present and future planning was estimated for non-agriculture use including for municipal, industrial and power demands. Water resources planning and management requires monitoring of the water resources and catchments, modelling hydrological processes, institutional measures, awareness and capacity building for stakeholders, water resources regulation and conservation, demand management and crop planning, water recycle and reuse, saline water utilization, pollution control, use of water efficient technologies, formation of water user groups etc. (WRD 2014).

Drought Indices

Drought condition can be assessed through hydro-meteorological variables and parameters e.g. precipitation, temperature, streamflow, groundwater, reservoir level/ storage, soil moisture etc. Based on time scale of an indicator, it may represent short and long term conditions. Indices provide information with regard to the drought condition e.g. severity, duration and timing etc. Severity relates to departure from normal value of an index. Threshold is specified for indices. The thresholds are used to define beginning and cessation of drought events. Duration refers to period between start and cessation of a drought event (WMO 2016).

Aridity Index (AI)

Aridity Index (AI) is percent reduction evapotranspiration due to insufficient water availability to the vegetation. The index is computed from soil water balance. Precipitation is first utilized to meet potential evapotranspiration demand. In case the full potential evapotranspiration demand is not met from precipitation, balance required water is extracted from soil moisture storage. The water extraction from soil moisture storage is reduced exponentially with increased accumulated potential water loss (http://www.imdpune.gov.in/hydrology/Drought/methodology.html).

Aridity anomaly index (AAI)

AAI is an agriculture drought index and expresses water stress to the crops due to reduced available water. The index is computed weekly or fortnightly and is a deviation of the AI from its normal value for the duration. Categorization of the drought intensity based on AAI is given in Table 1.1 (http://www.imdpune.gov.in/hydrology/Drought/methodology.html).

Table 1.1 Agricultural drought intensity from AII

Anomaly of AI	Agriculture drought intensity
1- 25	Mild
26- 50	Moderate
>50	Severe

Standardize Precipitation Index (SPI)

SPI is a simple index based on precipitation data. Normally, the index is computed from monthly precipitation. The index is computed at different time scales varying from one to 48 months. It represents basic drought conditions, agriculture and hydrological droughts, when the index is computed for three or less months, six or less months and 12 months or longer periods respectively. For computation of the index, at least 20 years and preferably 30 or more years of data should be available. A drought is said to have occurred when the index remains continuously negative and is equal to or lower than a threshold value at least once during the negative value run (WMO 2016). McKee et al. (1993) uses ‘-1’ as threshold value to define drought events.

Drought event: The incidence of the index continuously negative and equal to or lower than a threshold value at least once represents a drought event.

Duration: The time span of drought event is called drought duration.

Severity or magnitude: The sum of the index values during the drought event is called drought severity or magnitude.

Intensity: Drought intensity is obtained by dividing drought severity or magnitude by the drought duration.

Drought frequency: Drought frequency is derived from count of drought events during a selected period.

Effective Drought Index (EDI)

The index considers consecutive occurrences of water deficiencies. Effective precipitation is used as a proxy for water storage in the area. The effective precipitation is a weighted sum of precipitation over a period. The weight assigned to the past precipitation is dependent on number of days passed since a particular day of precipitation. Higher weight is assigned to recently fallen precipitation. Functions e.g. exponential or linear are used for weights. For linear functions, various slopes are used. Indices derived using weight function with higher slope are more sensitive to rainfall values. A difference of the effective precipitation from mean value over the period is determined. The effective precipitation is standardized and five-day running mean is used. The standard deviation is based on smoothed time series. One-day precipitation needed for restoring normal conditions in case of negative departure of the effective precipitation is computed by normalizing the weight used in effective precipitation computation. This normalized deviation is divided by its standard deviation value to compute the EDI value (Byun and Wilhite 1999).

Blend of Indicators

To provide drought status, a blends of drought indicators were introduced in USA as experimental products. There were two such products providing short and long-term drought status. The short-term blend is useful to assess impact of drought on non-irrigated crops, range and pasture, top soil moisture and unregulated flow. The long-term blend is to assess impact on reservoirs storage, groundwater level and irrigated agriculture etc. (NOAA). The indices for the blends are assigned different weightages (Table 1.2).

Table 1.2: Weightages for drought indicators blends

Short-term blend		Long-term blend	
Drought indicators	Weightage	Drought indicators	Weightage
Palmer Z-index	0.35	Palmer hydrological drought index	0.25
3-month precipitation	0.25	12-month precipitation	0.20

1-month precipitation	0.20	24-month precipitation	0.20
Soil moisture model	0.13	6-month precipitation	0.15
Palmer (modified) drought index	0.07	60-month precipitation	0.10
		Soil moisture model	0.10

Remote Sensing Based Indices

Interaction of electromagnetic radiation (EMR) in near infrared spectral region results in high reflected EMR. EMR interacts with cell structure of healthy leaves which in turn reflects large part of the EMR in the near infrared (NIR) region. Chlorophyll has high absorption of solar radiation in visible red spectral region. This results in low reflectance from vegetation in visible red spectral region. Soil reflectance is higher than green vegetation in red spectral region and lower in NIR spectral region compared to healthy vegetation.

Vegetation indices (VI)

In vegetation indices, signature of the red and NIR region are combined to create composite index. The index enhances difference in vegetation and non-vegetation areas. Apart from vegetation conditions, ecology may also have effect on VI. Higher VI is observed in climatic regions supporting lush green forests than desert regions where vegetation exhibits lower VIs. Cloud is major hindrance in biota investigation with help of VI, especially for Kharif seasons. To minimize cloud contamination, weekly maximum value composite of VI is prepared for AVHRR based VIs (Unagnai and Kogan 1998).

Normalized Difference Vegetation Index (NDVI)

The index is a ratio of the difference of reflectance in NIR and red spectral region to the sum of the two. The value of the ratio varies between -1 and 1. For green healthy vegetation, NDVI value is positive (WMO 2016).

Vegetation Condition Index (VCI)

Pixel wise minimum, maximum and range of VI for a time-span is estimated. VI is smoothed for computation of VI range. The VI is a scaled between 0 to 100. The index is useful in heterogeneous regions (Unagnai and Kogan 1998). Drought severity classification based on VCI values is shown in Table 1.3 (Kogan 1995 vide Datta et al. 2015).

Table 1.3: Drought severity classification based on VCI

S No	Drought severity	VCI (%)
1	Normal	50- 100
2	Drought	35- 50
3	Severe drought	<35

Temperature Condition Index (TCI)

The index is similar to VCI, but is computed from brightness temperature. Pixel wise minimum and maximum brightness temperature for a time-span over multi-year is estimated. The brightness temperature is smoothed for computation of brightness temperature range and the value. For AVHRR data, weekly time-span is used. Brightness temperature is estimated from channel 4 (10.3-11.3 micro-m) of the AVHRR data (Unagnai and Kogan 1998)

Soil Moisture Deficit Index (SMDI)

SMDI is a normalized difference of soil moisture and 80% of the field capacity. The index is normalized by the available water holding capacity of the soil. The index is zero when the soil moisture is equal to 80% of field capacity. The index is scaled by a factor of 10. Negative SMDI signifies drought condition (Zhou et al. 2021).

Country Specific Drought Monitor

USA

A weekly drought monitor (DM) was introduced in USA in 1999. DM is based on selected indicators. Each of these indicators are categorized in to a scale of zero- four depicting condition of dryness/ drought with increasing severity. DM is operational and different agencies take drought mitigation measures based on DM. Additional local indicators are also utilized. DM relies on expert interpretation and ground truth.

India

Guidelines are developed in India for declaration of drought by Indian states. The guidelines is based on various drought indicators. It includes meteorological, agriculture and hydrological indicators. Drought trigger is based on meteorological indicators. Low rainfall deficit/ SPI and dry spell or very large rainfall deficit conditions are used for drought trigger. After the drought trigger, the drought severity is examined using several indicators. Three indicators, one from each of the hydrological/ agriculture groups are used. For trigger-2, at least two indicators are required to be moderate or severe. For regions with high irrigation intensity or for regions where condition is indicated otherwise, the drought intensity is lowered or the region is declared drought free.

Regionalization

Regionalization is a process of finding hydrologically similar catchment and is useful in modelling of ungauged catchment. For hydrologically similar catchment, similar rainfall- runoff processes are assumed for given rainfall. Thus, model parameters can be transferred from one catchment to another. Two approaches are used in regionalization, namely spatial proximity and similarity of catchment attributes (Merz et al. 2006). The approach of spatial proximity assumes that climate and catchment conditions vary smoothly spatially. The approach requires delineation of spatially homogeneous regions. Homogeneous regions are identifying based on climate, topography, hydrogeology, soil, land use, seasonality of hydrological processes etc. To test similarity of hydrological processes, statistical homogeneity tests are applied on hydrological measurements in the regions. For homogeneous regions, regional hydrological characterization is done. Based on regional hydrological characteristics, the hydrological characteristics of ungauged catchment is determined. The methodology requires known hydrological characteristics of some of the catchment in the homogeneous region (Nobert et al. 2011). Second approach is based on similarity of catchment attributes. Hydrological characteristics of catchments with similar catchment attributes are assumed to be similar. In similarity of catchment attribute method, several regionalization approaches e.g. regression analysis, nearest neighbor may be used. In the regression analysis approach, regression analysis is done between model parameters and catchment characteristics. These regression equations are used to determine model parameters for ungauged basins. In the nearest neighbor approach, model parameters from number of similar gauged basin are transposed to the ungauged basin. Several runoff time series are generated using the model parameters and averaged (Merz et al. 2006).

Vadose Zone

Vadose zone moisture storage is an important component of catchment water balance. There is annual cycle in this storage. Soil moisture is replenished due to precipitation or irrigation water supply. Due to evapotranspiration, depletion of soil moisture takes place. At the end of the dry season, maximum depletion in soil moisture occurs. Prolonged dry conditions, causes depletion of deeper soil moisture storage. Large soil moisture depletion needs longer period for normal conditions to return.

Soil moisture measuring equipment

Tensiometer: Tensiometer utilizes a porous cup. The porous cup is placed in the vadose zone and filled with water. An equilibrium is established between soil water and water inside the cup. For unsaturated soils, vacuum is created inside the cup. The negative pressure created inside the cup is measured using pressure transducers. The tensiometers have measurement range of 0 -700 mbar (Gee et al. 2003).

Time-domain reflectometer (TDR): The soil moisture measurement using TDR is based on principle that dielectric constant of water is very high compared to soil solids and air. The travel time of high frequency electromagnetic pulse is increased in presence of water. TDR measures time of travel of high frequency electromagnetic pulse through soil. Travel time is empirically related and directly proportional to volumetric moisture content of soil media. Apparent dielectric constant is computed from travel time. Relationship between volumetric soil moisture and apparent dielectric constant is independent of soil texture, porosity and salinity.

Frequency-domain reflectometer (FDR): In FDR, oscillator is used to propagate electromagnetic signal through metal rod and soil media. The change is frequency in the output and returned signal is measured. The change in frequency is related to soil moisture. The response of FDR is faster than TDR. TDR and FDR require proper installation. The metal rods shall remain in direct contact with soil media without any air gap. The sensors provide integrated measurement of the soil moisture in the soil column. In general, field of influence is 1 cm from the sensor.

Cosmic-ray sensor: Cosmic-ray sensors sense cosmic-ray returned from soil media. Cosmic-ray neutron occurs naturally in the atmosphere. The neutron interacts with hydrogen atoms in water and are backscattered in to the atmosphere. The sensors have large footprint and provide integrated soil moisture measurement in a soil column over an area.

Soil characteristics

Field capacity: Field capacity is soil moisture content at which the gravity drainage becomes negligible, provided no evapotranspiration or infiltration occurs in the soil profile. Percolation of soil water occurs at faster rate at soil moisture higher than field capacity. Thus, field capacity is in general used to calculate the available moisture for the crops. Field capacity is calculated as soil moisture at 340 cm (1/3 bar) soil tension or at a low unsaturated hydraulic conductivity. For contaminant transport problems, a value of 10^{-10} m/sec is recommended. Field capacity computed with this unsaturated hydraulic conductivity value is more realistic for coarse gained soils (Meyer et al 1997).

Wilting point: Wilting point is defined as soil moisture threshold, below which plants are unable to extract water from soil matrix. It is a soil moisture value at a soil tension of 15300 cm (1.5 bar).

Available water: Available water for plants is defined as difference of field capacity and wilting point.

Soil moisture characteristics

Soil moisture characteristics curve is a relationship between metric potential and volumetric moisture content. The curve is also known as retention curve. The metric potential of saturated soil is zero. The potential decreases with decrease in soil water content. The volumetric water content of soil at field capacity is called residual water content. In the absence of evaporation, moisture content reaches a constant over prolonged time period. The so attained soil moisture content is called field capacity. From saturation state to field capacity, drainage in soil occurs due to gravitational force. At and above field capacity, water is readily available to plants. The volumetric water content at which plants can no longer extract water from soils is called wilting point. Metric potential for field capacity varies from -10 to -33 KPa. Metric potential for wilting point in soils is -1500 KPa. Water stress occurs in plants before the state of wilting point is reached. Soil moisture characteristics curve was defined using Van Genuchten equation (Meyer et al. 1997).

Crop water requirement

Crop require water for its physiological function of photosynthesis. In the process, water is converted in to vapour and is evaporated. Evapotranspiration process is depended on climatic variable. Higher evapotranspiration occurs in high temperature and wind conditions. In cloudy, less windy conditions and winter season, less evapotranspiration occurs. The irrigation efficiency is thus higher in winter. Water requirement is measured in terms of duty and delta. Duty is the area irrigated by unit volume of water during the base period. Delta is defined as the total depth of irrigation water during the base period.

Hydrologic Model

The hydrologic model is defining as the simplification of real world system that helps in understanding, predicting and managing various water resource problems. These models are classified as conceptual, physical, lumped and distributed. In this study we have used MIKE suite model Mike SHE and MIKE 11. the details of these models are given below:

Mike SHE

Mike SHE is a physically based distributed hydrological modelling software. The Mike SHE has the model Systeme Hydrologique Europeen (SHE) at its origin. The SHE model was further developed by DHI Water and Environment, Denmark. Its predecessor, SHE development was started by consortium of three European organizations in 1977. The model is organized in terms of hydrological processes, defined by differential equations. Broadly, four hydrological processes, namely overland, unsaturated, groundwater and channel flows area defined in the model. The process modeling is modular and one or more processes can be modeled. Different time steps can be chosen for different components for allowing numerical stability and keeping processing time minimum. Coupled surface and groundwater modeling is supported in the model, thereby allowing modeling of complete hydrological cycle at catchment level. The model is also linked to other models e.g. Mike 11 and Mouse in Mike suite. This allows modeling of processes e.g. channel and sewer flow in the linked models. The model is useful for scales from single cell to large catchment (DHI 2014). Model is a flexible in allowing alternate input and mathematical representation of processes depending on data available, processing time and project requirement. Computer memory size and run time requirements limit the size of the model. The constraints force larger grid size and fewer nodes in unsaturated zone representation. In view of limitations, in initial calibration phase, simpler processes representations, less calibration period etc. can be chosen. The model works only in Windows environment.

Mike SHE Setup

The model setup interface is organized around display, model specifications, domain and grid, topography, climate and model-component setup. In model specification, the hydrological process modules, numeric engine for each modules, simulation time and time steps for the modeling are chosen. Objects in the model setup are automatically displayed. In addition to this, other spatial data may be added as foreground and background. The spatial data can be in image or vector data formats. These data are displayed along with module related spatial data during model setup. The display In model domain can be based on GIS data e.g. shp files. The domain grid size and number of grids in two cardinal directions and projection systems are also specified. The boundary of the domain are assigned automatically. Similarly model topography can also be based on spatial data in GIS formats including shp files or may have constant elevation. The contour files are interpolated to convert it in to raster DEM. Interpolation methods available are bilinear, triangular, inverse distance and inverse distance square. Bilinear, triangular and inverse distance methods are suitable for raster, contour and points respectively. Climate data can be specified as uniforms or station based. For uniform climate data, for all grid of the same values are used. The values may be constant or time varying. The results to be saved and time steps for saving results for the hydrological components can also be set. The model setup requires pre-processing prior to its run. Model domain grid may be changed without need of re-specifying the other inputs in the setup.

Initial condition: Initial conditions are very important in simulation. Initial condition can be based on prior observation or can be based on model simulation results. Incorrect initial condition can make simulation unstable. For a given initial condition, the simulation may stabilize after long time. To offset these problems, for initial conditions Hot start option may be chosen. Prior to it, the model is run in Hot start mode. In this mode, a hot start result file is created storing results of all time steps or of the time of end of the simulation. Any stored Hot start result can be chosen as initial condition in actual simulation of the model.

Saturate flow: For saturated zone component, the topography of the geological layers, the hydraulic properties for the layers are input. At least one geological layer is defined. The top of the geological layer is the model surface topography. The initial and boundary conditions are also specified. Initial condition defines the potential head in the aquifer at the start of the simulation. The values can be constant, spatially distributed, based on previous model run or may be defined based on steady state simulation. Outer boundary can be time varying or fixed in terms of head or gradient. The boundary can also be no-flow boundary.

Unsaturated flow: Unsaturated flow takes place mainly in vadose zone. Soil water movement taken place through interconnected soil pores. Soil water content higher than field capacity is free to move under gravity. Soil moisture movement also takes place as a result of extraction by the plant root system, capillary action etc. Some water content is immobile, held by soil particles and is not available to plants. For unsaturated flow modeling, the soil layer, their soil moisture and hydraulic characteristics are defined. Soil moisture characteristics curves and unsaturated hydraulic conductivities values were based on literature and BD value was based on field measurement at two sites. Agriculture area was taken as one vegetation class. Two soils were taken in the catchment.

Mike-11 model

River hydrodynamic model

In Mike SHE, the river component is simulated through Mike-11, a one-dimensional river hydrodynamic simulation model. The model can be simulated in both steady and unsteady mode. For the model setup, extent, parameters and results files, river network, cross sections, boundary and initial conditions, numerical model, simulation time step and period etc. are specified. The numeric time step can be adaptive or fixed. Smaller time step are needed for numerical stability. For allowing larger time step and for flow conditions e.g. steep channels, fast transient flows etc., high order fully dynamic numeric model may be chosen. Different component of channel hydrodynamic model e.g. river network, cross-section, boundary condition etc. are stored in separate files and the files are associated to the model by specifying them in the simulation files.

River routing is time intensive process and thus different routing models may be selected form different branches. Upstream high gradient branches simpler routing procedures may be selected, whereas in the downstream low gradient branches more accurate routing e.g. dynamic model may be selected.

River network: River network can be setup in graphical mode. Background files in various GIS formats can be chosen to allow the onscreen digitization of the river network. The properties of the river branches and chainages can be set. Branches are input by first locating point and then joining them. The display properties can also be set for branches. Boundary conditions are given as water level, flow, Q-h relationship etc. The initial conditions (initial water level or discharge in the channel) are given as hydrodynamic parameters. Various numeric flow models are available, namely high order fully dynamic, fully dynamic, diffusive wave and kinematic wave.

River network in Mike SHE

The river network is setup in Mike-11. Through pre-processing, the vector network representation is transformed to grid representation in Mike SHE. The river is defined at the boundary between two cells and receives flows from two nearby cells. The bank level of the river between two X-sections is linearly interpolated. In case of too sparse X-sections, the interpolated bank level may be higher than adjacent ground cells creating flood cells artefacts. Flux exchange between river and ground takes place one way, namely from overland flow to the river and optionally, the exchange may be allowed both ways i.e. from river to the ground and from ground to the river.

Cross-section: Default cross sections are added at chosen points. The cross-sections are edited graphically by adding points and making changes in the tabular data. Marker are given to specify extent to be used in simulation. The datum is also specified.

Rainfall-runoff model links

The rainfall- runoff models are linked to the river network. The catchment area contributing to each branch are also specified. The branch descriptions, namely names, starting and ending points are also entered.

Mike SHE link

As an alternative to rainfall-runoff model, Mike SHE can be linked to Mike-11 river network. The runoff is simulated in the Mike SHE model and flux exchange between two model takes place based on parameters specified in the model link.

Rainfall-runoff model

Multiple options for lumped rainfall-runoff models are available. In the model setup, the name and area of the catchments and model to use are chosen. The parameters for the selected model are specified. The precipitation, evaporation and observed runoff time series are also input.

Water balance

Water balance may be computed for either the entire catchment or a spatial window. Further, a temporal window can also be chosen. The water balance can be viewed either in graphical form or tabular form. Water balance is computed from the simulation results. For sub-catchment wise water balance, a GIS file (vector or raster) of the sub-catchments is to be provided as input.

Results

Mike SHE simulation results in the form of time series or in raster form for hydrological model component and river discharge and water table etc. can be visualized. The raster or profiles may be animated. Time series of points in a raster can also be viewed.

Mike View

The program is used to view Mike-11 simulation results. The water level and discharge time series, profile and X-section plots may be viewed. In the profile plot, bank and bed level of the channel and minimum and maximum water level or discharges are shown. The data can be loaded for selected time period, time step and variables (water level and discharge).

Mike Zero

A Mike Zero project consists of collection of files and folders organized under a specific project folder. Pre-defined project templates are also provided in Mike Zero. In a project, typically the measured data, model input, results and documentation are kept in separate folders. In General template, folders e.g. external data, final report, model, project document and result are provided. The folders, namely external data and project documents store project related information and measured data. These folders ae provided so that comprehensive information and data for the project are available in the project folder. Main folders where modeling related data and results are stored are model and result folders. Model setup and input are stored in the model folder and the results are stored in the result folder. Mike Zero provides a project management interface for Mike models.

2.0 REVIEW

Rainfall trend analysis

Rainfall trend analyses, on different spatial and temporal scales, has been great concerned among the scientific community for global climate change studies (Longobardi & Villani, 2009). Changing pattern of rainfall, directly impacts on fresh water resources of the concerned region, it is a major climatic problem facing today's society. To understand the variability in rainfall patterns and presence of trends over different spatial horizons have been the vital aspects in climatological, hydrological and meteorological studies worldwide (Kumar et al. 2010; Saboohi et al. 2012; Jain and Kumar 2012; Deka et al. 2013; Jain et al. 2013; Goyal 2014; Rao et al. 2014; Talaee 2014; Xia et al. 2015; Chatterjee et al. 2016; Tian et al. 2017; Yang et al. 2017; Machiwal et al. 2018). It is evident from literature review so many studies are carried out for trend analysis using parametric and nonparametric methods (Machiwal and Jha 2008 & 2016; Jain and Kumar 2012; Sonali and Kumar 2013). The MK test has been extensively used in the literature for trend identification in rainfall data. Martinez et al. (2012) investigated the rainfall and temperature trends for two time periods (1895-2009 and 1970-2009) in Florida, USA. Results of the MK test revealed that the significantly decreasing trend in month of October for first time period one and in month of May for second time period. On the other hand, increasing trends in the mean, maximum and minimum temperature during 1970-2009 period. Jain et al. (2013) investigated trends in the monthly, seasonal, and annual rainfalls of 1871-2008 and minimum, maximum and mean temperatures (1901-2003) in the entire northeast region of India. The study indicates that no trend in rainfall data series for entire region, although the maximum and mean temperatures were found to be significantly rising. Pingale et al. (2013) investigated rainfall and temperature trends at spatio-temporal scale in 33 urban centers of Rajasthan, India for a period 1971-2005. Result of MK and Sen's slope test revealed both positive and negative of trends in mean and extreme events of rainfall and temperature. The spatial variations in mean and extreme events of rainfall and temperature were also examined using the inverse-distance-weighted (IDW) interpolation technique. Machiwal et al. (2018) investigated the rainfall and temperature trend in coastal arid region of India for a period of 35 years (1979-2013) by applying 8 trend tests (i.e. Spearman rank order correlation, Kendall rank correlation, Mann-Kendall (MK), four modified MK tests, and innovative trend analysis) and identifies the most suitable method. The study recommended variance-corrected MK test method for the accurate identification of trends.

Soil moisture measurement

TDR is used to measure soil moisture at Morley Agriculture Research Station, Norfolk, UK. The measurement was done for 10 dates. Two eight cm and one 15 cm probes were used. Measurement error was 3.5% and 1% for individual points and areal average respectively. The number of sample taken for fields with wheat and sugar beet were 30 each. Size of fields was nearly nine ha. Field average values were compared with model simulated values. Simulated values were available for both specific locations and for large grid size of five km. For comparing to large grid product, the value for a nearest grid location and closest time were used. Site specific model used finite difference solution of Darcy- Richards equation. For soil layers of 10, 25, 65 cm and 2 m depth were used. The model simulated fluxes of both water and energy. Limited soil type options were available in the model and thus simulated values for complex soil texture were obtained by averaging the results for individual soil types. Mean bias error and RMSE were estimated using simulated and measured values. RMSE was 3.8 and 7.4 %. There was seasonal bias in the two models. Large bias was observed in late summer and autumn (3.3- 8.3% for site specific and similar biases for large grid size product). Model sensitivity analysis was also performed (Kong et al. 2011).

Drought indices

VCI

Datta et al. (2015) used NOAA-AVHRR Global Inventory Modeling and Mapping Studies (GIMMS) NDVI for Rajasthan for years 1985- 2005 to investigate drought. SPI and rainfall anomaly indices (RAI) were computed using IMD precipitation data. District wise crop yield statistics was collected for Maize, Sorghum and pearl millet crops. NDVI values in August month of 2002 were less than corresponding month of year 2003. In the VCI maps, water stress is visible in 1st fortnight of August. Improvement in the drought condition in eastern part was seen from second fortnight of August. Drought of 2002 was fifth amongst the largest droughts of Rajasthan. The area receives sufficient rainfall for kharif crops even in drought years. SPI values were less than -1 for July and August 2002. SPI values were positive for year 2003. Fortnightly VCI and SPI values were higher in 2003 compared to 2002 in all the districts. Between 1983 and 2004, year 1987 was having highest rainfall deficit followed by year 2002. Average VCI of monsoon had high correlation with yield anomaly index with correlation coefficient greater than 0.76. R^2 of linear regression varies between 57- 64%.

3.0 STUDY AREA AND DATA

Study Area

Jamwa Ramgarh catchment

The catchment is the Upper catchment of Banganga river originating in Arawalli hills. The river originates from northeast part of the catchment, flows southwards and then empties in to Jamwa Ramgarh reservoir. Madhibini is major tributary in this Upper Catchment. The Madhubini river originates in the northwest part of the catchment, flows southward and meets Banganga river before the latter river flows in to Jamwa Ramgarh reservoir. Other minor river in Gumti Ka Nala. The river originates from southwest part of the catchment. The river is an ephemeral river. Total area excluding inland basins is nearly 756 sq. km. The extent of inland basins is nearly 62 sq. km. The water flows from surroundings hills in these inland basins. Waterlogged area is created in some of these inland basins due to absence of outflow from inland basins. Most of the area of the catchment falls in the Bairath, Amber, Jamwa Ramgarh & Shahpura tehsil of the Jaipur district of Rajasthan. A small portion in the eastern part of the basin lies in the Thanagaji tehsil of the Alwar district of the Rajasthan. Normal rainfall at Jaipur is 527 mm. Mean annual rainfall of Jamwa Ramgarh station is nearly 592 mm. At stations nearby the catchment, the mean annual rainfall varies from 469- 686 mm. The basin has flat to undulating topography with isolated hills. Most part of the basin is covered by Quaternary sediments. Extensive pediments are developed over pre-Aravalli gneisses and Alwar and Ajabgarh group of rocks. Quartzite belong to Alwar group of Delhi Super group. Thickness of alluvium increase from east to west. Kankar are found mainly in clay horizons. Silts of the upper horizons have Aeolian origin. Geomorphological features in the area are structural hills, denudational hills, residual hills, pediment, buried pediment, gullies and ravines, weathered hill top and valley fills. Structural hills are made up of Quartzite and Quartzite-Schist interbedding. Pediments have thin veneer of soil and have low to moderate groundwater potential. Extensive pediments are located in eastern part of the catchment. Buried pediments have weather material overburden of 5- 20 m and have good to moderate groundwater potential. Extensive belt of gullies and ravines are found running along northeast to southwest direction. Patches of the landform are also found in northwestern and central part of the catchment. Valley fills are controlled by fractures and joints and consists of unconsolidated material. The landforms have good to excellent groundwater potential. Soils in the catchment are very deep and vary in texture from fine/ medium to course. Bassi- Rajori group cover most of the area. Some area in north-west has Chomu soil series. Former are sandy loam soils and latter is loamy sands. Ravines have sandy soils. Bassi- Rajori group, Chomu series and ravines cover 66, 1 and 12% of the catchment area respectively. Groundwater occurs in the catchment under water table or semi-confined conditions. Groundwater aquifers are found in quaternary sediments, weathered and fractures quartzite and schist. Groundwater show declining trend with maximum decline observed in Shahpura block. Open wells are mostly converted in to dug-cum borewells. Average yield of wells and tubewell are nearly 75 and 110 thousand liters/day (assuming pumping of eight hr/day). In quartzite, the yield varies from 50 to 80 thousand liter/day. Central and western part of the catchment is covered with alluvium. The thickness of alluvium varies from 30 to 70 m. The thickness increases from east to west. Depth of water varies from 16 to 95 m. All blocks in the area are over-exploited blocks as per groundwater estimation. Annual groundwater recharge was more than draft in year 1986. Agriculture area varied from nearly 306 sq. km in 1997 to 360 sq. km in 2006. Double-cropped area was increased from 27 to 67 sq. km. Rabi crop area was increase from 96 to 159 sq. km. Nearly 231 sq. km area is under forest cover. In 1997- 2006, nearly 50 sq. km area was under Kharif agriculture. Nearly 70 sq. km was under ravines. The catchment has 12, 16 and 76 major (>5000 cum storage), medium (1000- 5000 cum storage) and minor (<1000 cum storage) water resources structure respectively. Twenty minor structures have storage capacity of less than 100 cum. Total storage capacity of these structures 2.3 MCM, 35 and 20 thousand cum respectively. Total storage capacity of all structures is nearly 2.4 MCM.

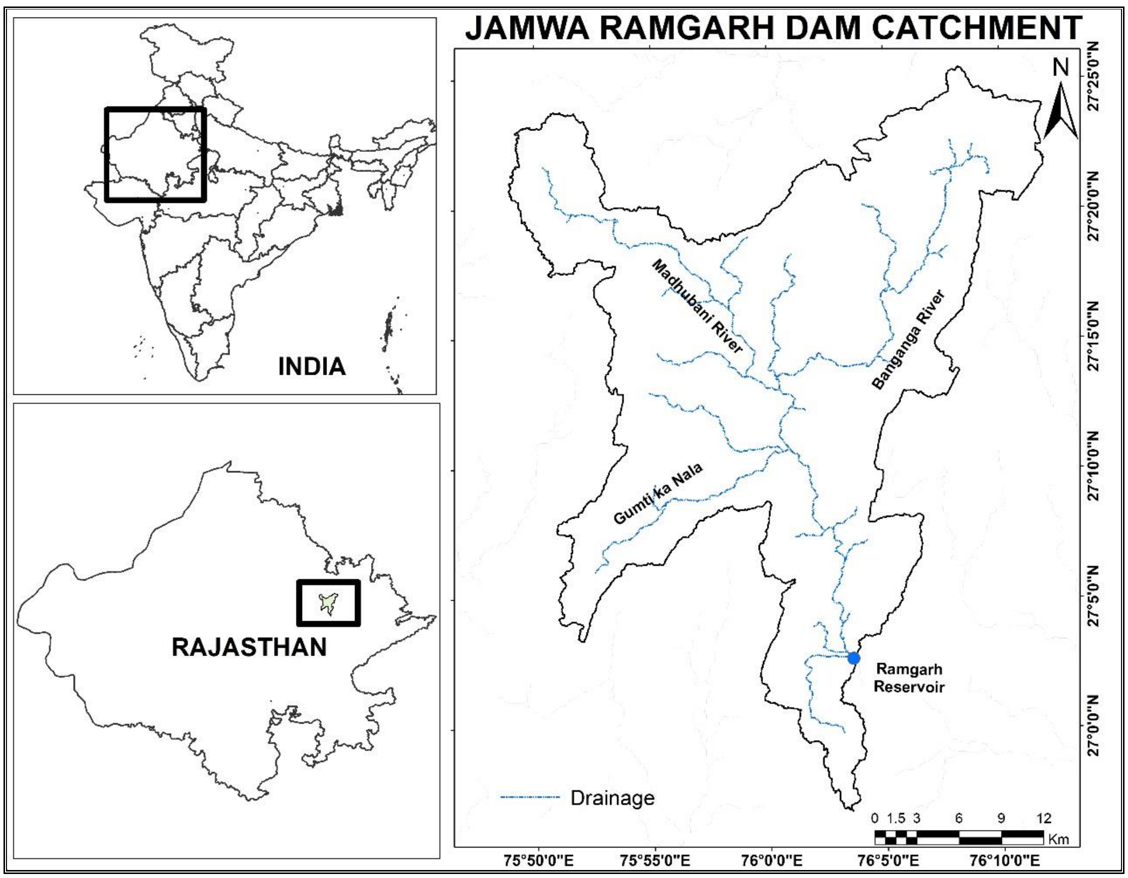


Figure 3.1: Study area

Geology

To prepare geological map firstly we collect the basic data related to geology of the area from GSI, then standardized methodology has been used. The geological maps are further updated by geological interpretation of available satellite imageries and ground truth collection. The basic data of lithology, synthesized for the catchment area have been incorporated into vector layer as shown in Figure 3.2 and its area statistics given in Table 3.1. The schists being erodible usually form subdued landforms, hence contribute to low lying topography while quartzite give rise to prominent relief that is responsible for massive topographic units in catchment area.

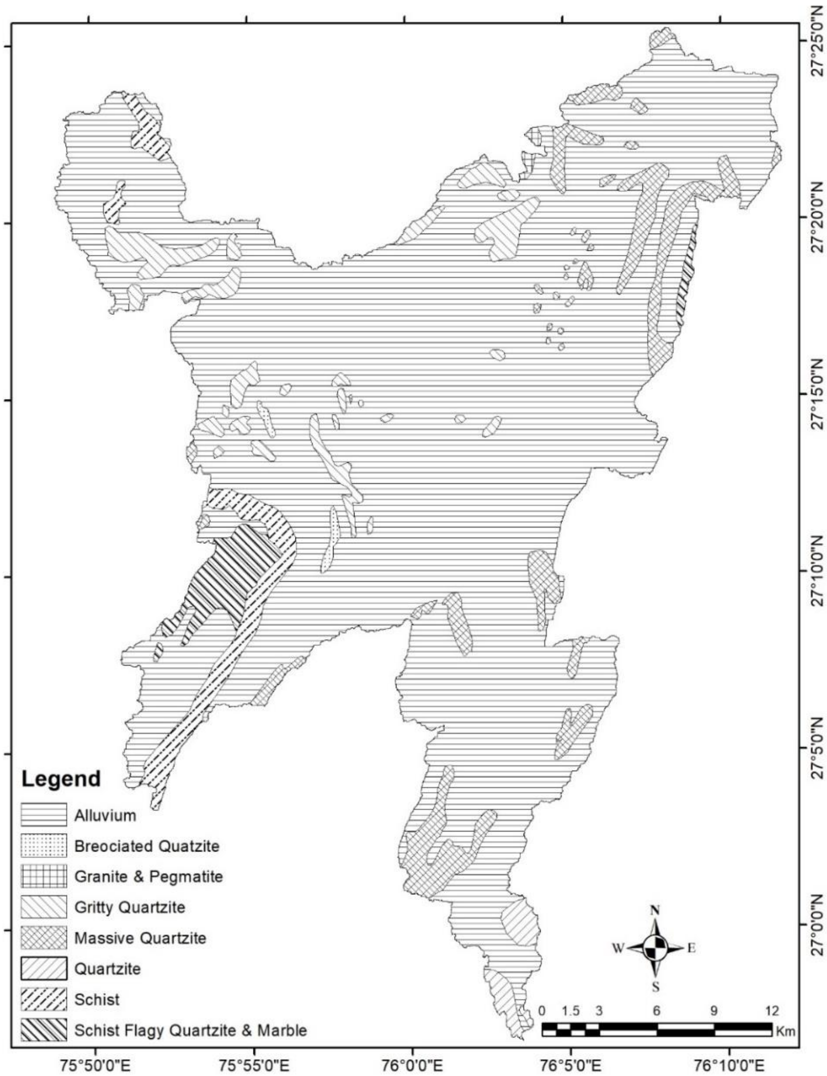


Figure 3.2: Geology Map

Geomorphology

The Ramgarh catchment area is basically a semi-arid zone and geomorphological parameters are one of the major factors that control the surface and inland water flow. So, it is relevant to study the geomorphic characteristics of Ramgarh catchment area, especially drainage system, landforms and denudational processes of main erosional agents in the region viz. streams and wind. The classified geomorphology map is shown in Figure 3.2 and its area statistics is given in Table 3.2.

Table 3.1: Area statistics of geology layer

S.No.	Geology	Area (Km^2)	Area (%)	Inland Basin Area (Km^2)	Inland Basin Area (%)	Actual Basin Area (Km^2)	Actual Basin Area (%)
1	Alluvium	681.15	83.39	51.2	83.39	629.95	83.39
2	Breociated Quatzite	2.09	0.26	0	0.00	2.09	0.28
3	Granite & Pegmatite	1.2	0.15	0.68	1.11	0.52	0.07
4	Gritty Quartzite	31.38	3.84	5.8	9.45	25.58	3.39
5	Massive Quartzite	50.7	6.21	1.70	2.77	49	6.49
6	Quartzite	7.09	0.87	0.00	0.00	7.09	0.94
7	Schist	24.95	3.05	1.55	2.52	23.4	3.10
8	Schist Flagy Quartzite & Marble	18.31	2.24	0.47	0.77	17.84	2.36
Total Area		816.87		61.40		755.47	

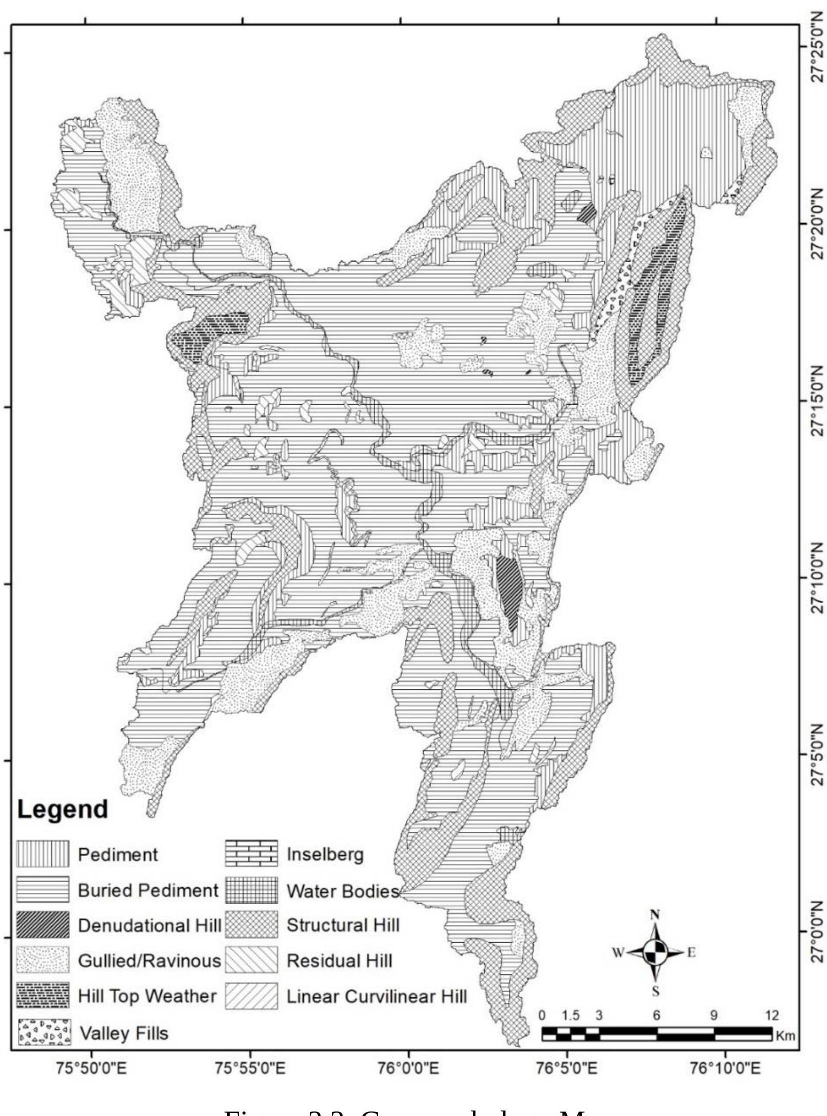


Figure 3.3: Geomorphology Map

Table 3.2: Area statistics of geomorphology layer

S.No.	Geomorphology	Basin Area (Km^2)	Area (%)	Inland Basin Area (Km^2)	Area (%)	Actual Basin Area (Km^2)	Area (%)
1	Buried Pediment	378.35	46.32	24.60	40.07	353.75	46.83
2	Denudational Hill	4.35	0.53	0.65	1.06	3.70	0.49
3	Gullied/Ravinous	105.80	12.95	5.00	8.14	100.80	13.34
4	Hill Top Weather	13.84	1.69	0.00	0.00	13.84	1.83
5	Inselberg	0.30	0.04	0.10	0.16	0.20	0.03
6	Linear Curvilinear Hill	2.50	0.31	0.00	0.00	2.50	0.33
7	Pediment	115.64	14.16	15.00	24.43	100.64	13.32
8	Residual Hill	16.48	2.02	0.45	0.73	16.03	2.12
9	Structural Hill	150.51	18.43	14.00	22.80	136.51	18.07
10	Valley Fills	5.50	0.67	0.00	0.00	5.50	0.73
11	Water Bodies	23.60	2.89	1.60	2.61	22.00	2.91
Total Area		816.87		61.40		755.47	

Various landforms have been demarcated on a micro level which have been depicted on IRD-ID LISS-III imageris and are corrected using digital elevation model prepared using contours.
The landform divisions are based on the existing relief features and provide a basis of the study of geomorphic evolution of the terrain which has been sculptured by a number of erosional cycles represented by various surfaces (Figure 3.3). Most of the landforms are not older than quaternary period [Thornburry, Principles of Geomorphology]. Lithology and structure have necessarily played a dominant role in carrying out the present configuration of the landforms in the study area as evident from their spectacular correlation, so picturesquely imprinted on the satellite imageries.

Rainfall Map

Rainfall areal distribution map has been prepared by using Thiessen polygon method on the basis of 15 raingauge stations lying inside and nearby the catchment as shown in Figure 3.4.

The resulting map was categorized into three classes namely < 600; 600–650 and >650 mm/year. From the Figure 3.4 and Table 3.3 it will be observed that most of the area falls in the range of 600-650 mm annual average rainfall and the northeast part of the area receives the largest amount of rainfall, while the southern part receives the lowest amount of rainfall.

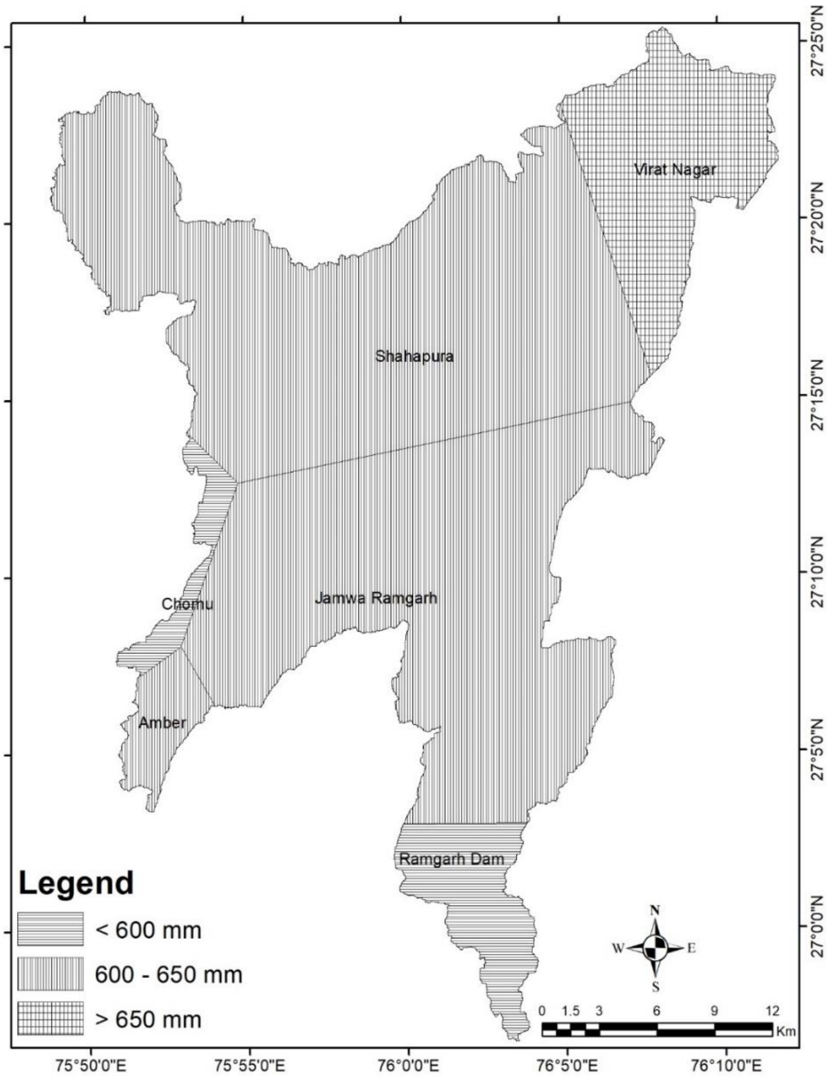


Figure 3.4: Rainfall Map

Table 3.3: Area statistics of rainfall layer

S.No.	Rainfall (mm)	Basin Area (Km^2)	Area (%)	Inland Basin Area (Km^2)	Area (%)	Actual Basin Area (Km^2)	Area (%)
1	< 600	59.87	7.33	2.6	4.23	57.27	7.58
2	600 - 650	657.722	80.52	55.7	90.72	602.03	79.69
3	> 650	99.27	12.15	3.1	5.05	96.17	12.73
Total		816.862		61.4		755.47	

Soil

The available soil map was digitized in ArcGIS software. The soils of the study area are broadly classified into four classes as shown in Figure 3.5 and its area statistics are given in Table 3.4.

Soils are mostly very deep, varying in texture in order of their extent of occurrence from fine/medium to coarse textured soils.

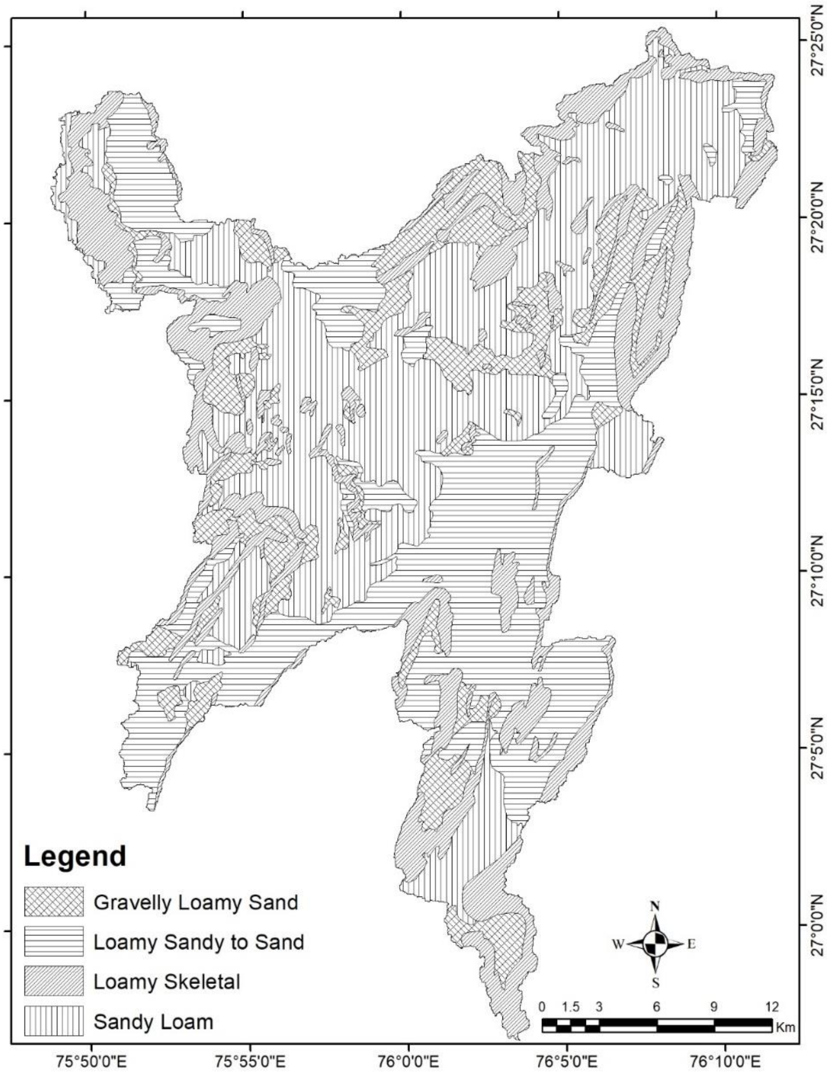


Figure 3.5: Soil Map

Table 3.4: Area statistics of soil layer

S.No.	Soil Texture	Area (Km^2)	Area (%)	Inland Basin Area (Km^2)	Inland Basin Area (%)	Actual Basin Area (Km^2)	Actual Basin Area (%)
1	Gravelly Loamy Sand	117.00	14.32	15.70	25.57	101.30	13.41
2	Sandy Loam	234.68	28.73	6.60	10.75	228.08	30.19
3	Loamy Sandy to Sand	180.49	22.10	13.36	21.76	167.13	22.12
4	Loamy Skeletal	284.70	34.85	25.74	41.92	258.96	34.28
Total Area		816.87		61.40		755.47	

Aquifer Distribution

The available aquifer distribution map was digitized in ArcGIS software. There are four types of aquifers found in this reason as shown in Figure 3.6 and its area statistics are given in Table 3.5. Groundwater occurs in the catchment under water table or semi-confined conditions. Groundwater aquifers are found in quaternary sediments, weathered and fractures quartzite and schist

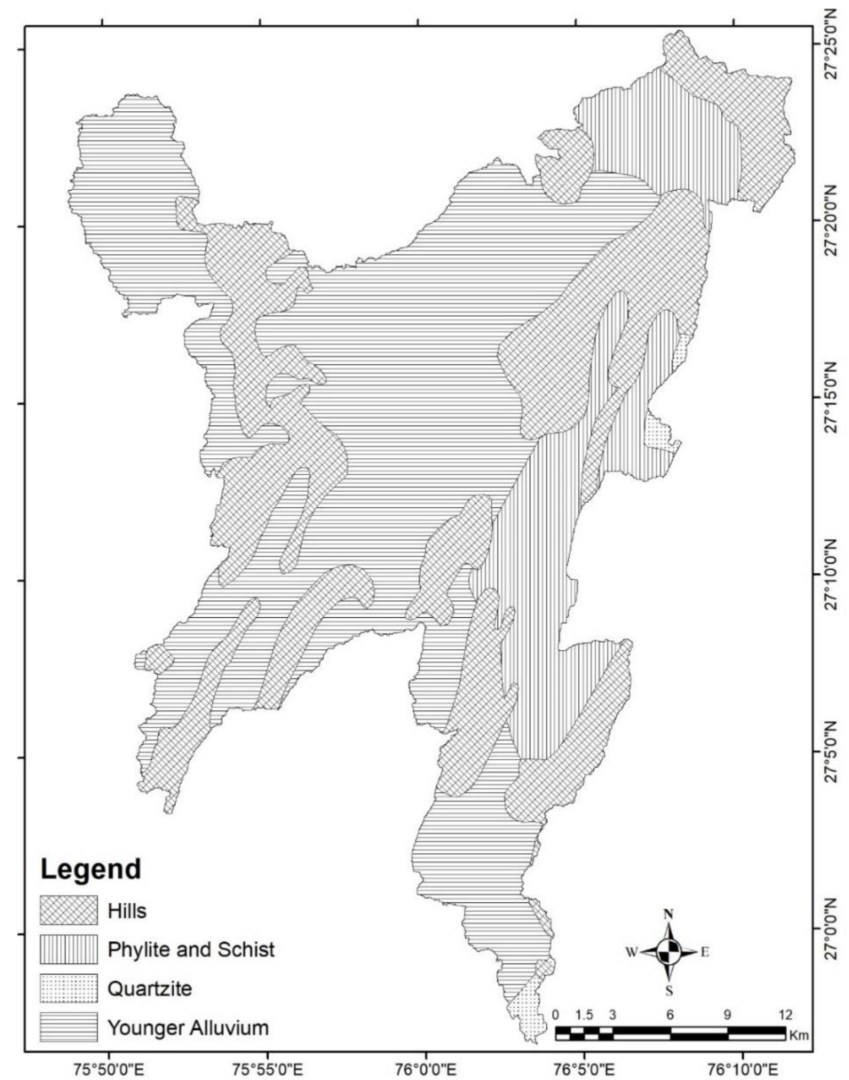


Figure 3.6: Aquifer Distribution Map

Table 3.5: Area statistics of aquifer distribution layer

S.No.	Aquifer Distribution	Area (Km^2)	Area (%)	Inland Basin Area (Km^2)	Inland Basin Area (%)	Actual Basin Area (Km^2)	Actual Basin Area (%)
1	Hills	262.09	32.08	19.53	31.81	242.56	32.11
2	Phylite and Schist	131.84	16.14	10.16	16.55	121.68	16.11
4	Quartzite	7.27	0.89	0.75	1.22	6.52	0.86

5	Younger Alluvium	415.67	50.89	30.96	50.42	384.71	50.92
Total Area		816.87		61.40		755.47	

Landuse/landcover

The Landuse/Landcover plays an important role in the identification of the water status of an area. The land use/cover map of the study area is prepared using supervised classification and manual digitization technique and it's further classified into 5 classes namely, water bodies (River & Pond), built-up land (Settlement), agricultural land, wasteland and open forest map as shown in Figure 3.7. Table 3.6 shows area statistics of landuse/landcover classes.

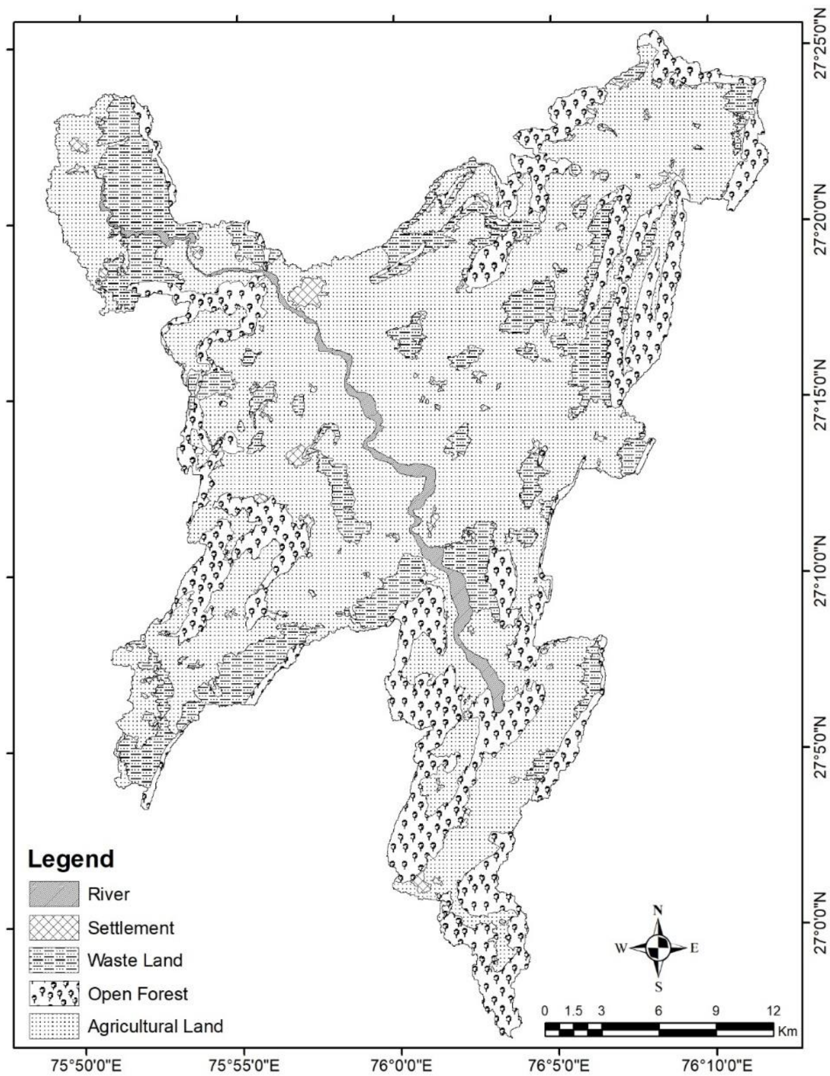


Figure 3.7: Landuse/landcover Map

Table 3.6: Area statistics of landuse/landcover layer

S.No.	LULC	Basin Area (Km^2)	Area (%)	Inland Basin Area (Km^2)	Area (%)	Actual Basin Area (Km^2)	Area (%)
1	Agricultural Land	477.68	58.48	39.47	64.28	438.21	58.00
2	Open Forest	144.41	17.68	2.61	4.25	141.8	18.77
3	Settlement	14.37	1.76	0.97	1.58	13.4	1.77
4	Waste Land	165.15	20.22	18.35	29.89	146.8	19.43
5	River	15.26	1.87	0.00	0.00	15.26	2.02
Total Area		816.87		61.40		755.47	

Data

For the present study, data have been collected from various Government agencies and Organizations, like National Remote Sensing Centre (NRSC), Geological Survey of India (GSI), State Ground Water Board (SGWB), Central Ground Water Board (CGWB), National Bureau of Soil Survey & Landuse Planning (NBSS&LUP), Jal Nigam, Indian Meteorological Department (IMD) in the form of maps, images and tabular. The details of the data acquired from various resources are given in Table 3.7.

Table 3.7: Details of dataset used in the study.

Date Type	Date Resource	Spatial Discretization
Distributed maps		
Topography/DEM	ALOS PALSAR DEM	12.5 × 12.5 m
LISS III Images (1999-2019)	NRSC, Hyderabad	23.5 × 23.5 m
MOD13Q1 data (2000-2017)	Oak Ridge National Laboratory DAAC, 2017	0.5 × 0.5 Km
Landscape (vegetation)	IRS-P6 LISS III (NRSC) and Google earth	23.5 × 23.5 m
Soil types	NBSS&LUP, Nagpur	
Precipitation zones (1974-2017)	Stations distributed by Thiessens Polygon Method	15 stations data
Geology	GSI, India	
Aquifer distribution	GSI, India	
Geomorphology	DST report and updated with LISS III Image	
Time series		
Precipitation	Sinchai Vibhag, Jaipur & IMD, Pune	
Potential evapotranspiration	DST Report & IMD, Pune	
LAI	Measured or from reference	
Kc	Measured or from reference	
Root Depth	Measured or from reference	
Other data		
Overland flow parameters	Measured or from reference	
Soil parameters	Measured or from reference	
Groundwater Depth (well data, Lithologs data)	SGWB & CGWB, Jaipur	
River, Cross-section, boundary etc.	Digitize and delineate from satellite data or from reference	

4.0 METHODOLOGY

The methodology adopted the meet out the various objectives of the study are described in coming sections

Rainfall data analysis

Secondary validation of rainfall data was carried out by screening of daily and annual data series, spatial homogeneity and double mass curve tests. The validation was done in MS Excel. The period for data validation was 1980- 2017. The methodology is described.

Data screening

Due to data entry error and systematic error in data, outliers may occur in the data. This requires screening of the data at smaller and longer duration and flagging of the outliers. The flagged values are then compared with neighbouring values in the tabulated data and large deviations are noted. In case of large deviations in the data compared to neighbouring stations, the date may be considered erroneous and may need to be cross verified with data collection agency. The data screening was done using daily and annual time series. The flagged values are compared with six neighbouring stations.

Daily data: Screening of daily rainfall data was done by plotting the daily data. The daily rainfall values exceeding a maximum value were flagged. A threshold value of 200 mm was selected.

Annual data: Small systematic error in the data and frequent data entry error are more noticeable when data are accumulated over longer duration e.g. at yearly level. The daily data was accumulated year wise to obtained yearly time series. Two data limits were selected, namely Upper Warning Levels (UWL) and Lower Warning Levels (LWL). The limits were calculated using mean (M), standard deviation (S.D.) of annual data. The multipliers to the standard deviation for the lower and upper warning levels have been taken differently in view of the data being positively and negatively skewed with a finite lower bound. The values beyond these warning levels were flagged.

$$\text{Lower warning level} = \text{mean} - 1.5 \times (\text{standard deviation})$$

$$\text{Upper warning level} = \text{mean} + 2.0 \times (\text{standard deviation})$$

Spatial Homogeneity Test (Nearest Neighbour Analysis)

Spatial homogeneity test assumes that there exists spatial consistency in the data within a maximum spatial distance called spatial correlation distance. This is a screening method. Spatially inconsistent values are flagged and the data are compared with neighbouring station value. If similar values occurs at close time interval in the data at neibhouring stations, it is assumed that the data are consistent. Otherwise, data need to be verified with data collection agency. For screening the data, the data is interpolated at a stations as weighted average of the neighbouring stations values. If station value vary considerably from the interpolated value, the data is considered suspect and is flagged. The following criteria are used to select the neighbouring stations:

- the distance between the test and the neighbouring station must be less than a specified maximum correlation distance, say R_{max} kms.
- a maximum of 8 neighbouring stations can be considered for interpolation.
- to reduce the spatial bias in selection, it is appropriate to consider a maximum of only two stations within each quadrant.

Maximum correlation distance is assumed to be 35 km. Absolute and relative errors for station larger than 35 mm and twice of the standard deviation respectively were flagged. The test was applied to Amber, Bairath or Viratnagar, Chomu, Jamwa Ramgarh, Thanagaji and Shahapura stations. The data were found to be spatially homogeneous.

Double Mass Analysis

Systematic shift may exist in the data. These shifts can be identified using double mass curve, in which accumulated time series of a station is compared with that of neighbouring stations. The systematic shift may occurs due to change is the location of the observation station or changes in the surroundings of a stations. For example due to logistic reasons, a stations may be shifted at a nearby location. Trees around the station has become taller or are removed, new buildings have come up in the neibouring area. Raingauge is changed or has become faulty etc. The methodology assumes that the changes have occurred at the station under consideration only. The value of a station is compared with one or more neighbouring stations. In case, data are found inconsistent, the past data from the point of change may be corrected. The test was applied to Amber, Bairath or Viratnagar, Chomu, Jamwa Ramgarh, Thanagaji and Shahapura stations. No systematic shift was observed in the station data.

Mann Kendall Trend Test & Sen's Slope Estimator

The non-parametric Mann–Kendall trend test is the most common of the various statistical procedures used to analyze time series datasets. The technique was firstly developed by Mann in 1945. Kendall in 1975 derived the test statistic distribution. The Mann Kendall's test considers only the relative values of all terms in the series $X = \{x_1, x_2, \ldots, x_n\}$ to be analyzed. In this test, the null hypothesis H_0 states that the series X is a sample of 'n' independent and identically distributed random variables having no trend (Yu *et al.*, 1993). The alternative hypothesis H_1 of a two-sided test is that the distribution of x_k and x_j is not identical for all $k; j \leq n$ with $k \neq j$:

The Mann Kendall's test statistic S is given by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i) \qquad (1)$$

Where x_j and x_k are the sequential data values and n is the number of data points, and

$$\operatorname{sgn}(x_j - x_i) = \begin{matrix} +1 & if & (x_j - x_i) > 0 \\ 0 & if & (x_j - x_i) = 0 \\ -1 & if & (x_j - x_i) < 0 \end{matrix} \quad (2)$$

Under the null hypothesis of no trend, and the assumption that the data are independent and identically distributed, the zero mean and variance of the S denoted is computed as:

$$Var(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} n_P(n_P - 1)(2n_P + 5)\right] \quad (3)$$

where n is the number of observations, q is the number of tied groups and n_P is the number of data in the p^{th} tied group. For sample size n is larger than 10, the standard normal variant Z is used for hypothesis testing, and is computed as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & S < 0 \end{cases} \quad (4)$$

In a two-tailed test for trend, the null hypothesis H_0 is either rejected or accepted depending on whether the calculated Z is more than or less than the critical value of Z obtained from the normal distribution table at significance level of α. Therefore, the values of Z are computed and it is seen that if the values lies in the limits -1.96 and 1.96, the null hypothesis that the series have no trend cannot be rejected at 5% level of significance using a two-tailed test.

Sen in 1968 developed a nonparametric method for estimating the slope of trend in a sample of n pairs of data. It is widely used method for measuring magnitude and variation of long term time series data. In this method linear model is used to estimate the slope of the trend, and the variance of the residuals should be constant in time calculated as:

$$Q_i = \frac{X_j - X_k}{j - k} \; for \; i = 1,2, \ldots., n \quad (5)$$

where X_j and X_k are the data values at times j and k ($j > k$), respectively. If there is only one datum in each time period, then $N = \frac{n(n-1)}{2}$, where n is the number of time periods. If there are multiple observations in one or more time periods, then $N < \frac{n(n-1)}{2}$. The n values of Q_i are ranked from smallest to largest, and the median of slope or Sen's slope estimator is computed as:

$$Q_{med} = \begin{cases} Q_{\left[\frac{n+1}{2}\right]}, & if\ n\ is\ odd \\ \frac{Q_{\left[\frac{n}{2}\right]} + Q_{\left[\frac{n+2}{2}\right]}}{2}, & if\ n\ is\ even \end{cases} \qquad (6)$$

The Q_{med} sign reflects data trend, while its value indicates the steepness of the trend. To determine whether the median slope is statistically different than zero, one should obtain the confidence interval of Q_{med} at specific probability. The confidence interval about the time slope can be computed as follows:

$$c_\alpha = z_{1-\alpha/2}\sqrt{Var(S)} \qquad (7)$$

where $Var(S)$ is defined in Eq. (3) and $z_{1-\alpha/2}$ is obtained from the standard normal distribution table. In this study, the confidence interval was computed at significance level (α = 0.05). Then, $M_1 = (n - C_\alpha)/2$ and $M_2 = (n + C_\alpha)/2$ are computed The lower and upper limits of the confidence interval, Q_{min} and Q_{max}, are the M_1th largest and the $(M_2 + 1)$th largest of the n-ordered slope estimates. The slope Q_{med} is statistically different than zero if the two limits (Q_{min} and Q_{max}) have similar sign.

Plot experiment

Soil moisture measurement were taken using soil moisture profile probe in the agriculture fields. Measurements were carried out in Kharif and part of the Rabi season in one year. Several precipitation stations exist in the catchment. Effort was made to locate plots near the precipitation stations. For at least three plots, the stations are located in same village. The outflow from the plots was not measured and was assumed to be zero. Mean monthly evapotranspiration data of CLIMWAT (FAO) were utilized. Soil moisture observations are made for fallow, dry land crops and irrigated crops (flood, sprinkler and drip). Water application rate was measured for sprinkler and flood irrigation. For flood irrigation, pump discharge was measured and information on irrigation period was collected.

Vegetation Condition Index (VCI)

VCI is computed from MOD13Q1 NDVI data. MOD13Q1 data were subset and downloaded for the study area. MOD13Q1 NDVI data were processed in R- software (Figure 4.1). NDVI data may be used in native sinusoidal projection. For using data in other projection system, the data need to be projected. The NDVI raster was subset to get an agriculture area for further processing. The NDVI data may contain poor quality pixel and cloud pixels. A trend was seen in the NDVI. The 'reliability' layer was used to remove poor quality pixel and cloud pixels. The 'Gapfill' R-package was used to fill the gaps created by removing these pixels. The trend in NDVI was removed by subtracting yearly mean NDVI of the layer from pixel NDVI and adding all year mean of the layer. For VCI computations, a vegetation layer was computed using a threshold NDVI value. NDVI raster stack was masked using the vegetation layer. VCI was computed from the pre-processed NDVI. Seasonal VCI raster stack was computed. Layer mean for the seasonal stack was computed. The processing was limited to smaller subset of the area. The processing may be repeated for more vegetation areas. VCI values for summed for period July 27- September 12 to find seasonal VCI value. LISS III data are also used for computation of VCI. The entire methodology for computation of VCI using LISS III data are given in Figure 4.2.

Standard precipitation Index (SPI)

SPI was estimated for 15 stations including Amber, Chomu, Ramgarh and Thanagaji stations, the stations close to and in the Jamwa Ramgarh catchment. The data records of 1974- 2017 were used. From daily data, monthly time series were extracted. SPI was estimated using computer program developed by National Drought Mitigation Centre, University of Nebraska, USA (Figure 4.3). Missing data are handled by the program. The program requires input of monthly precipitation data in space-delimited text format. The data file contains a header line and followed by the year, month and precipitation values each row. The precipitation values have a unit of one hundredth of a mm. Zero precipitation values were replaced with 0.01 mm. SPI was computed for five time scales, namely 1, 2, 3, 4 and 12 months.

Drought magnitude and dry spell

Drought magnitude for station

To obtain drought magnitude, the computation was limited to monsoon months. The contiguous negative value was located and SPI values of each run were summed. Its absolute value was determined. There may be one or more such runs in a year and run with a maximum magnitude was determined. The corresponding sum and time span are yearly drought magnitude and durations respectively. The computations were carried out in excel.

Drought magnitude probability

Gamma probability distribution was fit to yearly drought magnitude (SPI-1) of each station using R-software. Using the distribution parameters, the yearly probability of drought magnitude was computed for each station.

Dry spell

The daily rainfall data were converted to weekly data. The weekly normal rainfall was estimated. The weeks with rainfall less than 50% of normal values were identified. The consecutive weeks of dry spell were counted. The yearly maximum dry spell count is determined.

Dry spell probability

Gamma probability distribution was fit to yearly dry spell week counts of each station using R-software. Using the distribution parameters, the yearly probability of dry spell weeks was computed for each station.

Unsaturated zone models setup

The MIKESHE model are setups for unsaturated zone modeling at two different sites (Site B and Site F). For site B we used two different soil types (In first case we assumed soil type will be FAO subsoil O1 & In second case we used actual soil silt loam measure in soil laboratory using field samples. Similarly, measured soil sandy loam soil is used for site F. All the model setups are almost same but soil parameters are different.

Fallow land

The unsaturated zone model was setup as a single cell model. Single soil type was assumed up to a depth on nearly 17 m. The soil column was discretized with cell heights of 5, 15 and 20 cm up to depths of 1.25, 5.75 and 16.55 m. Larger cell height was selected at lower depths. In case 1. Soil type was assumed to be FAO Subsoil O1 having fine sand- moderately fine sand texture, case 2. soil type silt loam and case 3. soil type sandy loam (location site F). For retention curve and hydraulic conductivity, Van Genuchten and tabulated values were used respectively (Table 4.1 and 4.2). Bare land use was selected. The land use characteristics are given in Table 4.3. Precipitation of Jamwa Ramgarh station was used. The base simulation was run up to 21 June 2021 (zero rainfall were assumed after monsoon season of 2020). The hot start simulation was run between 16 June 2020 to December 2020 with 16 June 2021 as hot start date.

Pearl millet-fallow cropping pattern

The unsaturated zone model was setup as a single cell model. Soil characteristics and vertical discretization was selected same as that for fallow land setup above. The land use characteristics for pearl millet are given in Table 4.4. Average precipitation of the catchment was used. The millet crop sowing and harvesting dates are specified as June 25 and October 7 respectively. Fallow land use characteristics for summer and other seasons are given in Table 4.5. The summer season was specified as March 20- June 24. Base simulation was done for the period January 1974 to December 2017. Hot start simulation was run between 20 June 1974 to 21 June 2017, with 20 June 2017 as hot start date. Initial time step of 6 hrs. was specified.

Pearl millet-wheat cropping pattern

The unsaturated zone model was setup as a single cell model. Soil characteristics and vertical discretization was selected same as that for fallow land setup above. The land use characteristics for wheat are given in Table 4.6. Average precipitation of the catchment was used. The pearl millet crop sowing and harvesting dates are specified as June 25 and October 7 respectively. The wheat crop sowing and harvesting dates are specified as November 1 and March 20 respectively. The summer season was specified as March 21- June 24. Base simulation was done for the period January 1974 to December 2017. Hot start simulation was run between 20 June 1974 to 21 June 2017, with 20 June 2017 as hot start date. Initial time step of 6 hrs. was specified. Cropping pattern was pearl millet- fallow in the year 2017. Irrigation depths for scenario of six and two irrigations is given in Table 4.7. Irrigation depth was added to precipitation values.

Comparison of irrigation scenario

Long term water balance was computed from the results of the unsaturated zone simulation of winter irrigated cropping pattern with six and two irrigation and dryland cropping pattern. Evapotranspiration values in pearl millet- fallow cropping pattern was assumed to be Kharif evapotranspiration (assuming negligible evapotranspiration from the fallow land in non- Kharif season). Evapotranspiration in pearl millet- wheat cropping pattern was assumed to be summation of Kharif and Rabi evapotranspiration (assuming negligible evapotranspiration from the fallow land in non-crop season). The Rabi evapotranspiration was determined by subtracting evapotranspiration in millet- fallow cropping pattern from that in millet- wheat cropping pattern. Blue water was estimated as minimum of the irrigation and evapotranspiration in Rabi season. For evapotranspiration higher than irrigation, green water was estimated as difference of evapotranspiration and irrigation, otherwise a zero value was assigned.

Table 4.1: Van Genuchten parameters for retention curve for different-2 soils

Soil Type	Saturated soil moisture content	Residual soil moisture content	α (cm^{-1})	n	pF_{fc} bar	pF_w bar
Subsoil O1	0.36	0.01	0.0224	2.286	2	4.2
Silt Loam	0.47	0.037	0.0193	1.61	2	4.2
Sandy Loam	0.41	0.06	0.0757	1.89	2	4.2

Table 4.2: Unsaturated zone hydraulic conductivity for different-2 Soils

pF bar	Subsoil O1 K(q) m sec^{-1}	Silt Loam K(q) m sec^{-1}	Sandy Loam K(q) m sec^{-1}
0	1.76E-06	1.05E-06	1.26E-06
1	1.29E-06	2.70E-07	6.61E-07
1.3	7.96E-07	1.61E-07	4.03E-07
1.5	4.21E-07	1.04E-07	2.43E-07
1.7	1.33E-07	5.67E-08	1.11E-07
2	1.11E-08	1.85E-08	2.20E-08
2.4	2.08E-10	3.01E-09	1.39E-09
2.7	8.80E-12	6.25E-10	1.39E-10
3	3.70E-13	1.27E-10	1.27E-11
3.4	5.79E-15	1.39E-11	5.56E-13
3.7	2.55E-16	2.66E-12	5.21E-14
4	1.39E-16	4.98E-13	4.86E-15
4.2	1.16E-16	1.62E-13	9.61E-16

Table 4.3: Land use characteristics for bare soil

LAI	Root mm	Kc
0.1	200	0.05

Table 4.4: Land use characteristics for pearl millet

Characteristics	1	2	3	4	5
End day	0	15	40	80	105
LAI	2	2	5	5	3
Root mm	200	200	1000	1000	1000
Kc	0.3	0.3	1.0	1.0	0.3

Table 4.5: Land use characteristics for bare soil (scenario)

Season	LAI	Root mm	Kc
Other seasons	0.1	200	0.05
Summer	0	500	0

Table 4.6: Land use characteristics for wheat

Characteristics	1	2	3	4	5	6
End day	0	20	70	110	130	140
LAI	2	2	5	5	4	3
Root mm	200	200	1000	1100	1200	1200
Kc	0.3	0.3	1.15	1.15	0.7	0.25

Table 4.7: Irrigation depth (mm) for scenario

Scenario	1-Nov	22-Nov	16-Dec	5-Jan	25-Jan	14-Feb	1-Mar
Six irrigation	-	37	37	37	37	37	37
Two irrigation	-	37	-	-	37	-	-

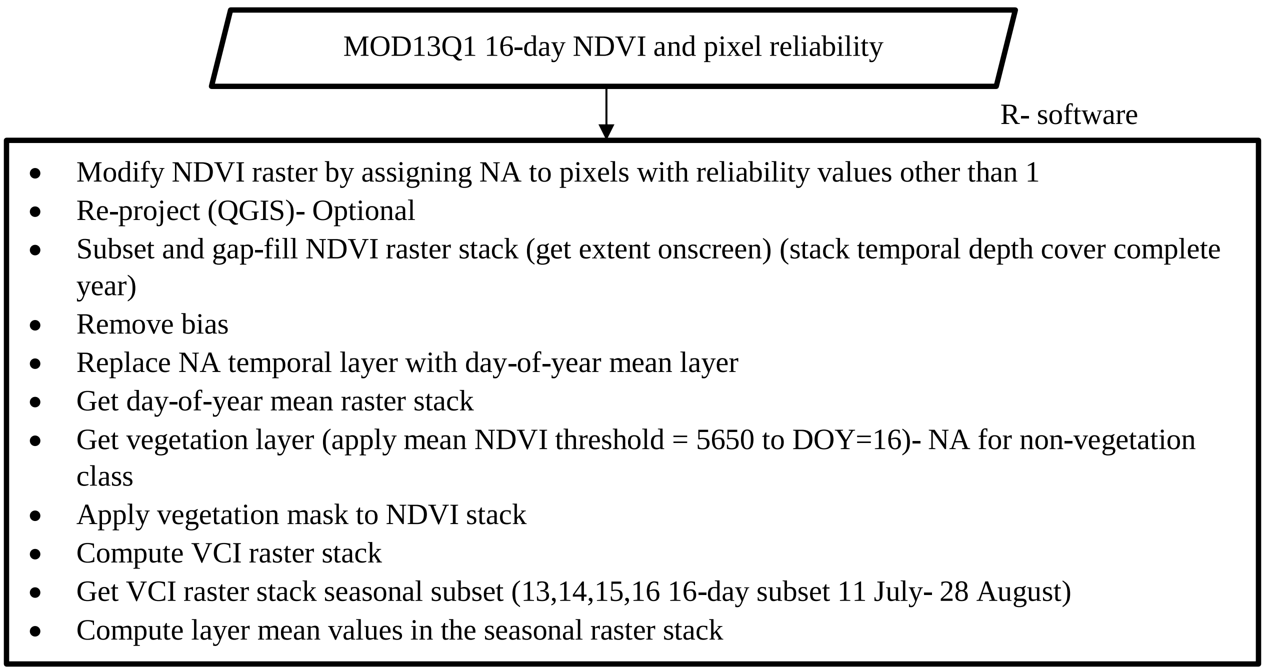


Figure 4.1: Flow chart for mean VCI time series of an area

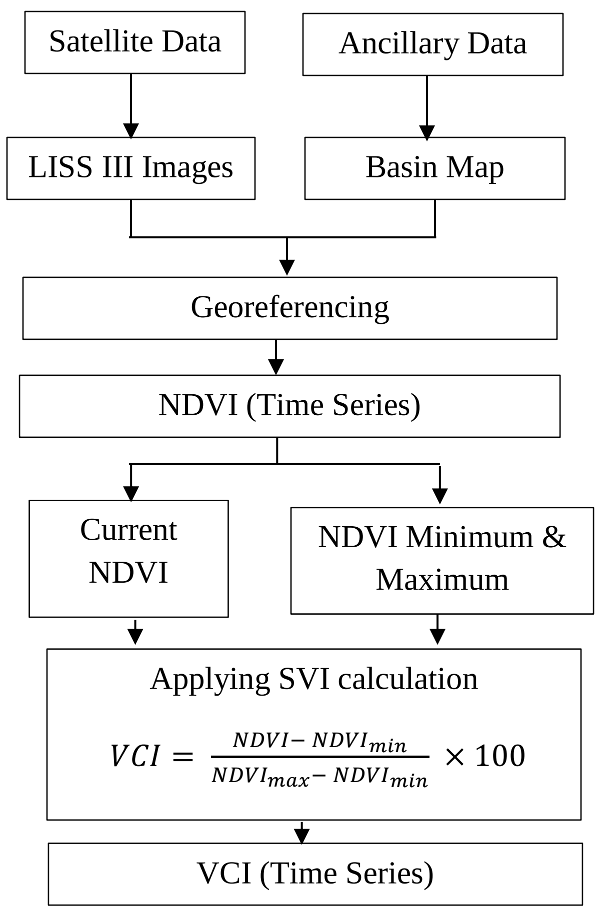


Figure 4.2: Flow chart for mean VCI time series of an area by using LISS III data

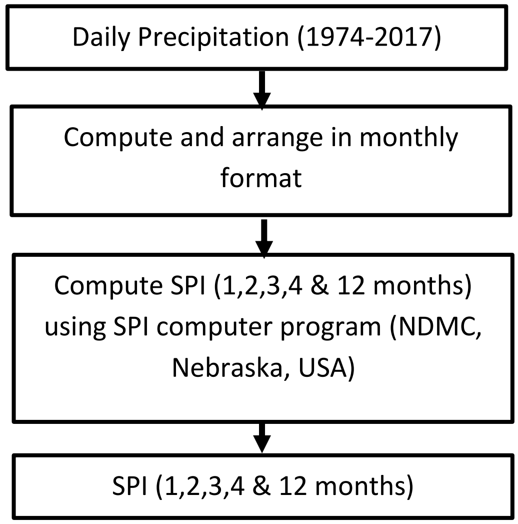


Figure 4.3: Flow chart for SPI calculation

Regionalizing drought indices

For regionalization firstly, we create the raster data set of various meteorological and topographical parameters using kriging interpolation technique in ArcGIS 10.3. After that several combinations of raster data set has been formed and forcefully divided into 2, 3 and 4 clusters classes using clustering tool in ArcGIS. Combinations of clusters are spatially and statistically (T-test, probability distribution using Gamma function etc.) correlate with the drought magnitude parameters to identifying the similarity and dissimilarity in the study regions.

Catchment modeling

In the present study MIKESHE and MIKE-11 model has been used, Figure 4.4 gives a brief methodology of the adopted technique, which includes input data preparation, initial and boundary conditions, simulation time steps, model calibration, and performance evaluation criteria.

MIKESHE model

The MIKESHE model is developed on a grid-to-grid basis. The whole catchment is discretise into 2106 grids of size 1000 x 1000 m. The ALOS PALSAR DEM data were aggregated to the model grid specification and utilised as the surface elevation in the MIKESHE model, with a resolution of 12.5 m. Rainfall areal distribution map has been prepared by using Thiessen polygon method on the basis of 15 raingauge stations lying inside and nearby the catchment as shown in Figure 3.4. The average potential evapotranspiration (PET) monthly data is taken from DST report. The supervised classification and manual digitization technique is used for preparation the land use/cover map of the study area (Figure 3.7). Table 4.8 shows landuse, their related percentage areas, and their Manning's M values for calculating overland flow. Manning's M (inverse of

Manning's roughness coefficient, n) values for varied spatial landuse patterns in the catchment were chosen from literature (Engman 1986; Chow et al. 1988; Vieux 2001; Kothyari et al. 2010). The vegetation parameters used for evaluation of actual evapotranspiration (AET) are leaf area index (LAI) and rooting depth (RD). The value of these parameters are chosen on the basis of literature and available cropping pattern in the study area. The available maps (soil, geology, geomorphology) were digitized in ArcGIS software. The soils of the study area are broadly classified into four classes as shown in Figure 3.5. Soils are mostly very deep, varying in texture in order of their extent of occurrence from fine/medium to coarse textured soils. For processing of soil, geology, geomorphology and landuse map in MIKESHE numeric codes are assigned to each class. Aquifer layer is created up to 60 metres depth was created using exploratory wells data. The geological thickness of the soil/rock formation below ground level was determined using well lithology, and the raster of sediment thickness raster was created using ArcGIS 10.4's topo to raster interpolation tool. The aquifer zones layer was obtained by subtracting the sediment thickness layer from DEM. After preparation of database the MIKESHE model setup was done for different hydrological processes modules (Table 4.9).

MIKE-11 model

Mike-11 model was setup for unsteady hydrodynamic simulation (Table 4.10). The simulation period, initial conditions options, result files and storing frequency were specified. Hydrodynamic simulation model and river network documents were created. The groundwater and overland flow simulation models were selected. Initially, the manning’s roughness was assigned zero values to allow no overland flow. The performance of model was measured on the basis of observed flow.

Table 4.8: LAI, RD and Manning’s M values for land use pattern of Jamwa Ramgarh catchment

S.No.	LULC	LAI	RD (mm)	Manning’s (M)
1	Agricultural Land	1-5	100-1000	25
2	Open Forest	2	300	18.18
3	Settlement	0	0	6.67
4	Waste Land	1	200	25
5	River	0	0	35.71

Table 4.9: Mike SHE model setup was done for different hydrological processes modules

S No	Model component	Description	Data
1.	Foreground	Catchment boundary, drainage, inland basin areas	ALOS 12.5 m DEM
2.	Domain	1000 m grid size, 39 and 54 (NX, NY) grids	ALOS 12.5 m DEM

		2000 m grid size, 20 by 27 (NX by NY) 580535.9375, 2980998.25 619535.9375, 3034998.25	
3.	Topography	Triangular interpolation	ALOS 12.5 m DEM 10 m contour
4.	Climate data		
5.	Precipitation rate	Precipitation rate (mm/day) mean step accumulated	Average daily precipitation rate (Average of stations Jamwa Ramgarh, Amber, Chomu, Shahpura, Thanagaji)
6.	Net rainfall fraction	0.2	-
7.	Geological layer		
8.	Lower level	-60 m relative to the ground	
9.	Hydrologic prorperties	Saturated horizontal (5.2 e-4) and vertical hydraulic conductivity (9.3e-5), specific yield (0.2) and specific storage (1e-3)	
10.	Computational layer (Aquifer)		
11.	Initial head	-3 m relative to the ground	
12.	Boundary conditions	Zero flux	
13.	Drainage	Not routed and removed from the model, level relative to the ground (-0.5 m),)	
14.	level	-0.5 m relative to ground	
15.	Time constant	5.6e-7/sec	
16.	Results	Water balance	
17.	Frequency	10 days	
18.	Time series	Water logged area Madubini middle reach Upland area east part Jamwa Ramgarh	
19.	Grid series	Depth to phreatic surface	
Computational layer (Aquifer)			
20.	Initial head	-3 m relative to the ground	
21.	Boundary conditions		
	Zero flux	Zero flux Fixed head (near outlet)	
22.	Fixed head	-30, -200 m	
23.	Hot start	Store complete simulation	
24.	Interval	24 hr	

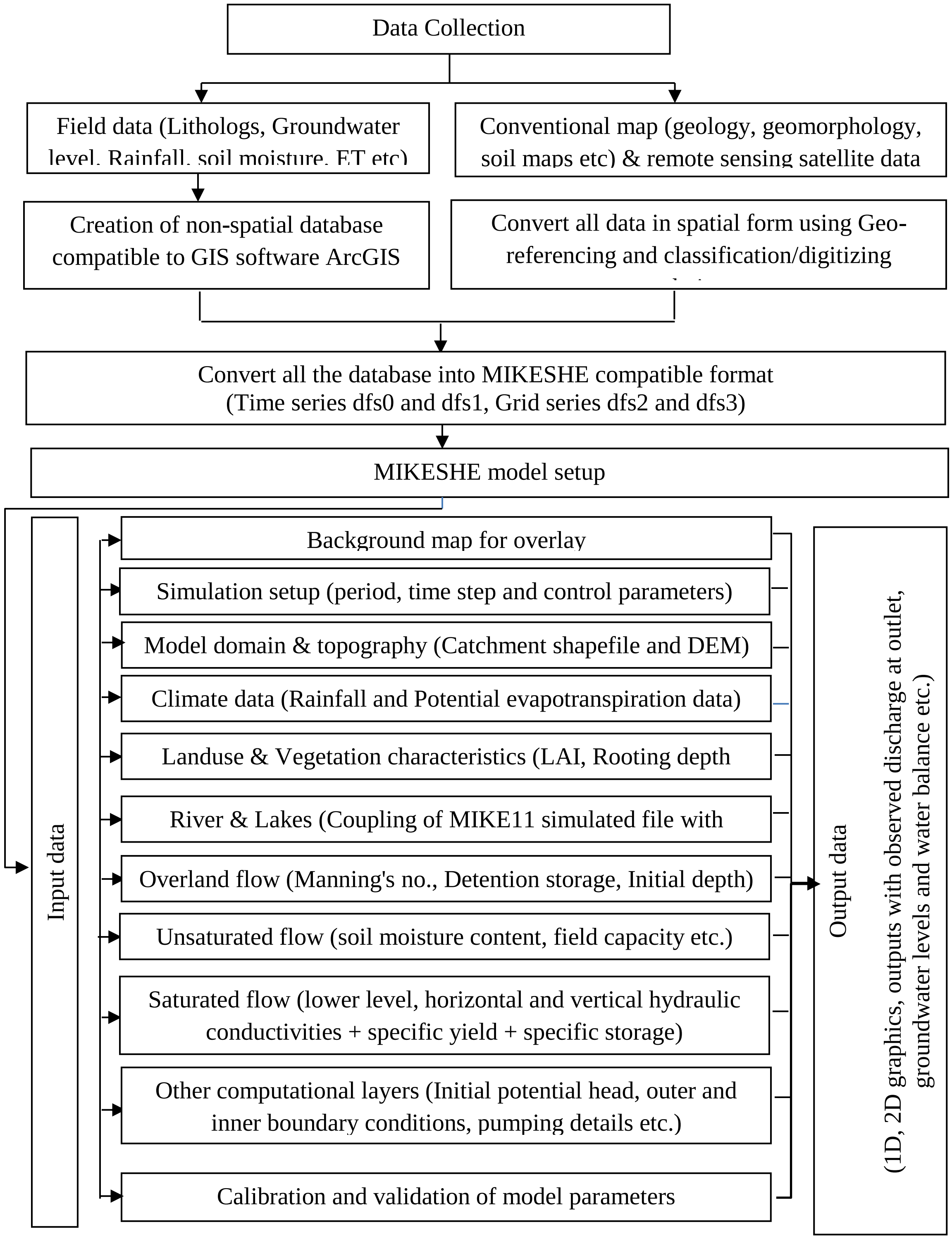


Figure 4.4: Methodology for catchment modeling

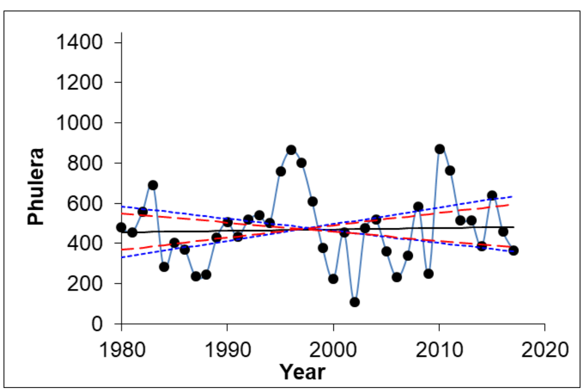
Table 4.10: Initial condition for MIKE-11 hydrodynamic model setup

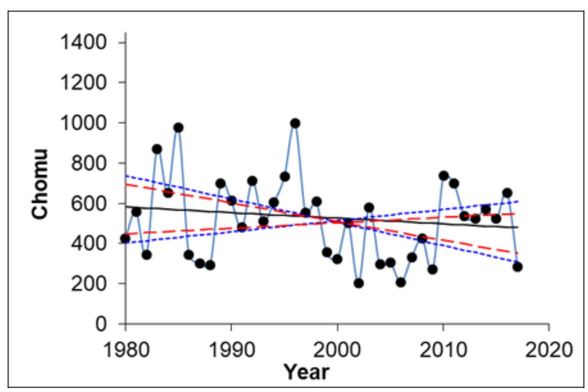
Simulation time step	5 minutes	
Extent	Lower left	580000,2980000
	Upper right	620000, 3035000
Branch coordinates	Banganga	38150
X-section	U/S	100 X 2
	D/S	200 X 3
Datum	Lower by twice the X-section depth from DEM elevation	
Boundary	U/S Flow	0
	D/S water level	0.1
Initial condition	Waterlevel	0.1
Flow model	High order fully dynamic	
Catchment Name	Banganga	
Area sq. km	756	
Rainfall mm	step accumulated	Catchment average
Evaporation mm	step accumulated	Average monthly
CQOF	0.5, 0.3	
Time constant Groundwater	2000, 500	

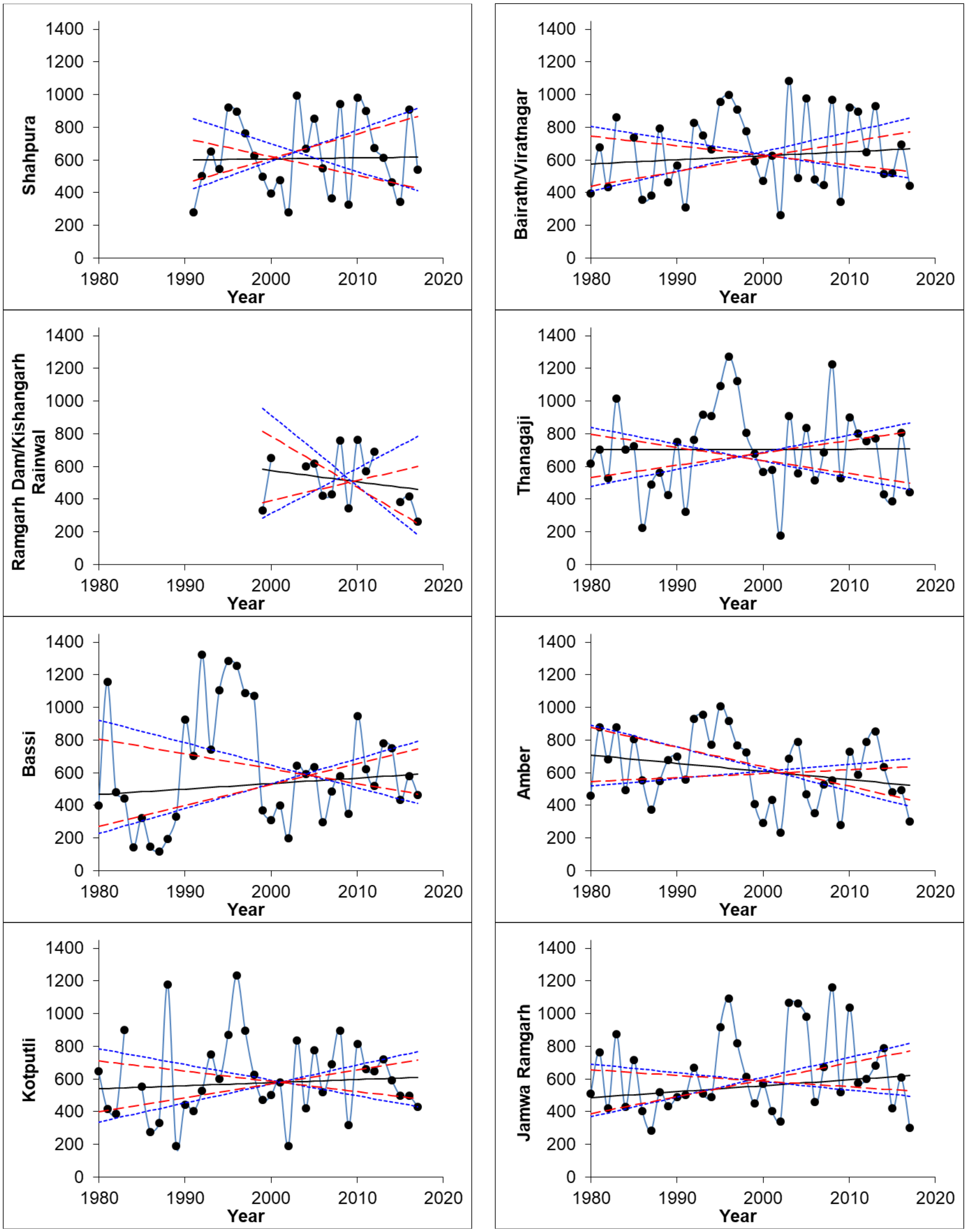
5.0 RESULTS AND DISCUSSIONS

Rainfall data analysis

The Mann Kendall's (MK) and Sen slope's method has been applied on our stations data (Amber, Bairath or Viratnagar, Chomu, Jamwa Ramgarh, Thanagaji, Shahapura, Phulera, Kotputli, Sanganer, Neem Ka Thana, Srimadhopur, Alwar, Senthal Sagar/ Nangal Rajawatan, Kanota/ Kotkhawada, Dausa and Rajgarh) on monthly and yearly scales for the period of 1980-2017 as shown in Figure 5.1 and 5.2. On the basis of test we observed that there is not any systematic shift in the rainfall dataset. The statistical analysis of the annual time series indicates that the trend is increasing in twelve stations and decreasing in the remaining five stations. These trends are not significant at 95% confidence interval, except for Neem Ka Thana station, which showed increasing trend. Similarly, the statistical analysis of selected 7 stations for monsoon months in the catchment area of the dam shows (1) increasing trend in month of June; (2) decreasing trend in month of July; (3) increasing trend in 5 stations and decreasing in 2 stations; (4) increasing trend in 4 stations and decreasing in 3 stations. These monsoon months' trends are not significant at 95% confidence interval, except for Amber station in month of June, which showed significant increasing trend. Sen's Slope revealed that average annual rainfall increased in 10 stations from 0.65 to 10 mm/year, decreased in 6 stations from 2.8 to 6.8 mm/year and no change in remaining 2 stations. Similarly, average monthly rainfall increased in the month of June from 0.5 to 1.1 mm/year, decreased in month of July from 1.2 to 3.6 mm/year, decreased in month of August in Amber & Chomu from 0.86 to 1.38 mm/year and increase in remaining stations from 1.1 to 3.1 mm/year, decrease in month of September in Ramgarh Dam & Shahapura from 0.4 to 2 mm/year, no change in Chomu & increase in remaining stations from 0.2 to 1 mm/year.






Shahpura
Bairath/Viratnagar
Ramgarh Dam/Kishangarh Rainwal
Thanagaji
Bassi
Amber
Kotputli
Jamwa Ramgarh
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0
200
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1980
1990
2000
2010
2020

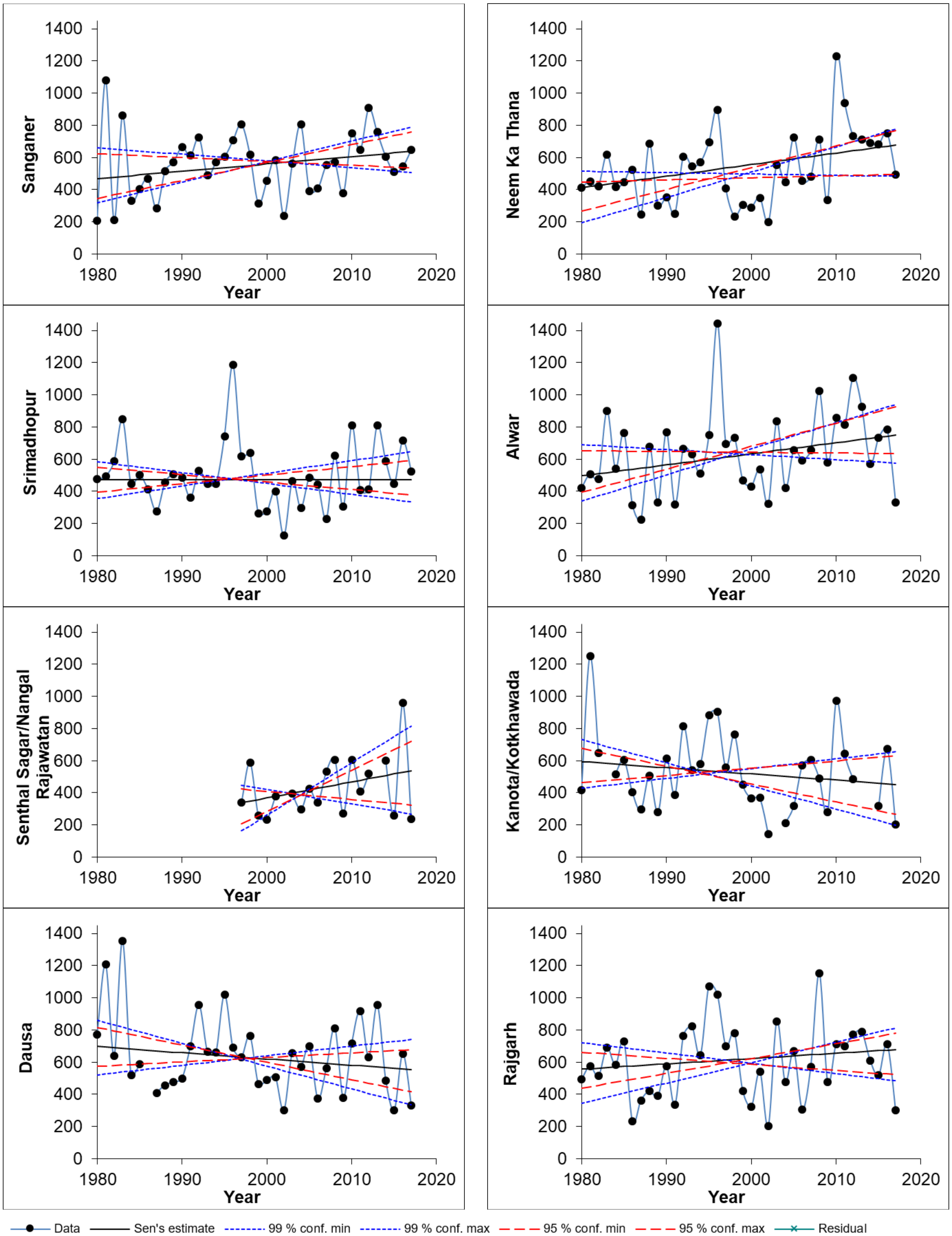


Figure 5.1: Trend of Annual Rainfall

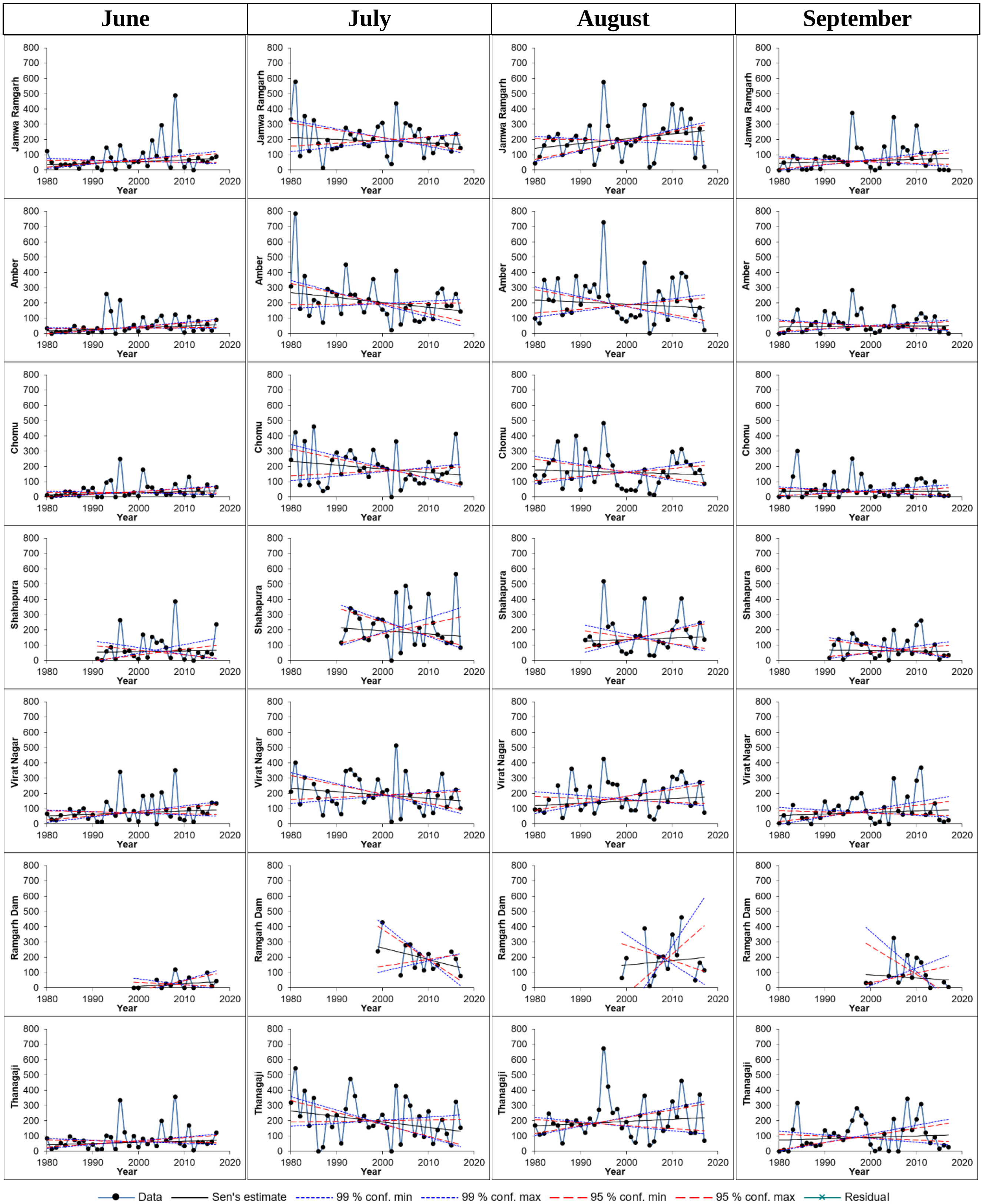


Figure 5.2: Trend of Monthly Rainfall

Soil moisture observations

Soil moisture was measured using soil moisture profile probe at nine sites within the catchment during January and February and August- December 2020. Site details are provided in Table 5.1. During later period, each month nearly 15 observations were taken. The observations were taken for Kharif and Rabi crops, fallow areas and flood, sprinkler and drip irrigation systems. Irrigated crops includes vegetables (Carrot and tomato) and cereal (wheat). Details of field visits and investigation sites are given in Table A.1- A.2.

At site B soil moisture variation over the monsoon season for fallow land has shown exponential depletion curve. During high precipitation event in August, soil moisture has peaked and thereafter exponentially reduced over the season. At site E, soil moisture has remained nearly constant in the monsoon season. At site F, soil moisture was measured for monsoon and autumn seasons. The soil moisture variations over the period for 60 and 100 cm depths was different than at shallower depths. Around mid-November, the field was flood irrigated. Post irrigation, the soil moisture substantially increased for 20 cm depth. For other depths also, changes in soil moisture was noted. Soil moisture variation at site G was less significant for deeper horizon than for the shallower depths in the monsoon season. At site H, soil moisture was observed in the autumn season. Soil moisture did not vary significantly in November season. In the first fortnight of December increase in the soil moisture was observed. At site J, measurement for only fewer depths were readable. At site K, not much variation in soil moisture was observed except at shallower depths. Soil moisture plots are given in Figure 5.3- 5.9.

Soil characteristics

Soil properties bulk density varied from 1.42 to 2.12 gm/cm^3. Volumetric moisture content measured for undisturbed samples varied between 13 and 36% and permeability varied between 0.013 and 2.3 m/day (Table 5.2). In some of the highly permeable undisturbed samples, permeability could not be determined. Soil moisture characteristics curve were nearly similar for all sites except Charanwas Gajja and Kanawarpura. Soil moisture retention curves are given in Figure 5.10. Soil test results are given in Table A.3- A.10.

Drought magnitude

Drought magnitude SPI-1,2,3,4 is given in Table 5.3 (a-d). Average drought magnitude (SPI-1 to SPI-4) for 15 stations is shown in Figure 5.11 and Table 5.4. Average drought magnitude for all SPI is given in Figure 5.12. Average drought magnitude for year 1987 and 2002 is more than three. Yearly average of drought magnitudes of SPI-1 to SPI-4 have values greater than 2 for years 1979, 1982, 1986, 1987, 1991, 2002, 2004, 2006, 2009 and 2017. Year 1979, 1982, 1986, 1987, 2002 were one of the major pan India drought years. In 1987 and 2002, a record number of nearly 0.3 billion people were affected by drought (Samra 2004).

Drought magnitude probability

Probability (non-exceedance) of yearly maximum drought magnitude are given in Table 5.5 (a-d). Years with equal to or more than 70% probability (non-exceedance) are given in Table 5.6.

Dry spell

Yearly maximum dry spell weeks for 15 stations are given in Table 5.7. Non-exceedance probability of yearly maximum dry spell weeks is given in Table 5.8. Average probability of yearly maximum dry spell weeks is plotted in Figure 5.13. The relationship of average probabilities of the yearly maximum DM and yearly maximum dry spell weeks are plotted in Figure 5.14 and their spatial relationship will be shown in Figure 5.15. The relationship has high to low coefficient of determination from SPI 1 to SPI 4. Years with equal to or more than 70% probability (non-exceedance) are given in Table 5.6. Pan India drought years given by Samra (2004) and Kaur are also shown in Table 5.6 for comparison.

Vegetation Condition Index (VCI)

The kharif season NDVI and VCI of MODIS (MOD13Q1, 16-day) and LISS III data are given in Figure 5.16 (a & b) & Figure 5.17 (a & b). Vegetation masked Kharif season MOD13Q1 NDVI and Kharif season 16-day VCI are given in Figure 5.18 (a – c) respectively. Figure 5.19 shows plots of average VCI and their relationship with average probability DM and average probability dry spell week. The coefficient of determination for the relationships are small. This indicated that variables other the precipitation effects the crop vigour. For example, irrigation and crop type may influence drought condition. Better correlation exists between VCI and average probability dry spell week compared to that between VCI and average probability DM.

Unsaturated zone models

The simulation results for unsaturated zone models at site B (At this site two different soils were used. In first case we assumed soil will be FAO subsoil O1 & In second case we used actual soil silt loam measure in soil laboratory using filed samples) and site F (Sandy loam) are given in Figure 5.20, 5.21 & 5.22. Highest precipitation occurred during mid-August. Thereafter very less rainfall occurred at the station. This resulted in high soil moisture during mid-August. Soil moisture exponentially decreases thereafter. There is higher variation in soil moisture in upper layers. August onwards, soil moisture in lower layers remains higher than the upper layers, except during rainfall events. The models are calibrated only for actual soils (silt loam and sandy loam) measured in laboratory. Both the models are calibrated with the help of observed soil moisture data measured from field with the help of soil moisture probe at differen-2 depths. Good correlation and Nash Sutcliffe efficiency are achieved between observed and simulated data as shown in Figure 5.21 & 5.22.

Scenario

For the site B (In case 1. assumed soil will be FAO subsoil O1 & In case 2. actual soil Silt loam is used) and site F (Sandy loam), high groundwater recharge was estimated (Figure 5.23 and 5.24). In irrigation scenario of two irrigations compared to six irrigations, a reduction of nearly 50% in evapotranspiration was observed. For six irrigations scenario, crop water demand is nearly equal to the groundwater recharge. Thus, at a point scale, the irrigation scenario is not sustainable. In both the scenario, all the irrigated water is utilized and small part of the demand is also met from the soil moisture storage. The groundwater recharge is not affected by the irrigation scenario. Scenario results are given in Table 5.9.

Table 5.1 Soil moisture observation sites and nearby sites

S No	Site code	Plot area sq m	Crop rotation
1	B	888	Fallow - Fodder
2	C, D	-	Wheat
3	E	-	Pearl millet
4	F	3582	Fallow - Wheat
5	G	2922	Pearl millet
6	H	1804	Fallow- Carrot
7	J	3060	Carrot
8	K	1342	Tomato
9	Plot nearby K	2773	Cabbage/ Cauliflower

Table 5.2 Soil properties (undisturbed sample)

Location code	Location	Depth (cm)	Bulk density (gm/cu cm)	Volumetric moisture content %	Permeability (m/day)
B1	Gopalgarh	10	1.61	13.53	-
		40	1.55	14.13	-
		80	1.42	12.93	-
C	Charanwas Gajja	10	1.45	26.69	-
		40	1.58	32.25	-
		80	1.76	35.93	-
H	Maaru Ki Dhani	20	1.67	19.31	2.3069
		60	1.82	26.21	0.0810
		80	1.98	36.06	0.0127
B2	Gopalgarh	20	1.75	22.07	0.5568
		60	1.69	19.34	1.3847
		80	1.68	13.30	1.4955
E	Mamtori Kalan	20	1.82	21.84	-
		60	1.91	27.59	-
		80	1.94	28.21	-
J	Gopalgarh	20	1.871	22.30	-
		60	1.873	23.49	0.4570
		80	1.925	24.57	0.1724
K	Kanwarpura	20	2.077	29.32	0.0293
		60	2.120	34.16	0.0586
		80	2.105	35.92	< 0.0293

Table 5.3 (a): Drought magnitude for raingauge stations (SPI-1)

Year	Alwar	Amber	Bairath	Bassi	Chomu	Dausa	Kanota	Kotputli	Neem Ka Thana	Phulera	Rajgarh	Ramgarh	Sanganer	Srimadhopur	Thanagaji
1974	0.47	3.66	2.40	2.38	1.31	2.29	0.47	1.70	2.09	6.77	0.94	0.34	2.57	2.10	1.78
1975	0.00	0.25	2.73	2.68	2.31	0.39	0.00	0.24	0.00	7.03	0.21	0.15	0.00	0.00	1.19
1976	0.00	0.61	0.55	0.00	0.40	0.07	0.00	0.76	0.26	0.77	0.60	0.24	0.17	0.44	0.04
1977	0.00	0.04	0.87	0.00	0.03	0.00	6.25	0.00	0.00	0.00	0.42	0.44	0.00	0.00	0.00
1978	0.61	0.23	0.74	0.00	0.45	0.00	0.00	0.36	0.54	0.34	1.26	0.00	0.32	0.00	0.34
1979	0.87	2.33	2.24	3.29	2.20	4.35	3.18	7.85	1.73	2.87	2.99	3.48	6.26	2.68	2.47
1980	1.98	2.01	1.94	2.54	1.13	0.41	3.12	2.81	2.44	0.86	2.50	2.99	4.36	2.00	1.63
1981	0.81	2.99	0.71	0.80	2.31	2.97	0.44	1.01	3.25	2.13	0.77	0.89	2.54	1.14	2.01
1982	2.47	1.12	3.44	2.22	1.08	1.35	1.24	4.88	3.98	0.11	3.43	2.42	3.45	2.84	2.12
1983	0.54	0.87	0.00	1.00	0.41	0.00	0.40	0.26	0.63	0.10	0.07	0.27	0.06	0.00	0.16
1984	0.56	1.71	0.48	3.06	0.72	0.12	0.19	0.65	1.03	0.72	1.04	1.02	1.58	1.14	0.45
1985	0.91	0.34	0.11	1.04	1.79	2.87	1.02	0.59	0.27	2.13	0.67	1.15	1.85	0.96	0.56
1986	3.66	0.79	2.29	3.99	1.85	5.27	1.43	3.10	0.44	0.94	4.21	2.78	2.54	0.51	5.81
1987	6.70	2.31	4.68	4.43	1.80	1.82	2.04	3.93	2.79	3.91	2.37	4.93	3.70	3.16	1.32
1988	0.00	0.29	0.00	1.97	1.20	0.43	0.00	0.00	0.00	0.64	1.93	0.24	0.31	0.30	0.57
1989	2.47	2.77	0.82	2.22	2.45	1.31	1.50	3.12	0.74	0.41	1.72	0.93	2.31	0.56	1.23
1990	1.20	0.63	1.28	0.00	1.30	0.69	0.00	1.20	1.28	0.49	2.36	1.06	0.14	0.67	0.33
1991	4.72	0.77	2.86	2.68	2.39	2.87	0.97	1.55	2.93	0.22	2.60	1.14	0.03	2.07	3.03
1992	0.28	0.85	1.09	2.68	2.31	0.12	1.11	1.04	1.19	2.33	0.00	3.20	2.54	2.84	1.29
1993	0.83	0.00	1.19	0.72	2.94	0.93	0.08	0.55	0.05	0.20	0.60	1.80	1.16	0.57	1.00
1994	0.17	0.00	0.16	0.00	0.00	0.78	0.17	0.58	0.33	0.00	0.31	0.45	0.20	0.41	0.00
1995	2.73	3.06	0.12	0.10	2.31	0.98	0.70	0.56	0.04	0.00	1.71	1.31	0.45	0.20	1.33
1996	0.00	0.62	0.39	0.00	0.00	0.29	0.32	0.00	0.33	0.00	0.00	0.35	0.03	0.35	0.00
1997	0.30	0.45	0.00	0.00	0.63	0.28	0.96	0.00	1.41	0.00	0.00	0.65	0.06	0.59	0.00
1998	0.11	0.27	0.73	0.55	0.78	0.32	0.00	0.80	2.74	0.15	0.90	0.60	0.71	0.38	0.60
1999	2.23	0.00	0.56	0.27	1.17	1.89	0.61	0.91	1.40	0.95	0.99	1.38	2.07	1.75	0.37
2000	1.69	2.08	1.01	1.50	1.40	0.86	2.15	0.14	0.80	2.13	1.83	0.44	0.83	1.22	0.84
2001	2.41	2.22	2.36	1.80	2.67	2.28	1.44	1.37	4.04	3.11	3.16	4.06	1.97	2.06	2.75
2002	4.13	3.67	4.47	5.15	6.24	4.96	3.47	6.84	6.42	3.98	4.70	2.58	4.85	8.84	6.70
2003	0.00	0.45	0.00	0.39	0.78	0.41	0.05	0.00	0.74	0.00	0.00	0.00	0.75	0.30	0.00
2004	1.84	1.65	6.05	0.72	1.19	2.33	2.41	1.44	1.15	1.15	3.07	0.38	0.14	1.28	1.93
2005	2.12	3.84	1.59	3.23	2.33	2.10	5.21	2.32	2.46	0.87	2.66	2.36	2.95	1.64	2.15
2006	3.60	1.36	2.16	1.67	2.79	0.95	0.74	1.73	2.35	1.83	3.75	1.56	1.74	1.60	4.69
2007	0.66	1.25	0.99	0.69	0.96	0.86	0.73	0.00	1.19	0.94	1.20	0.72	0.58	3.47	0.33
2008	0.46	1.37	0.77	0.72	0.60	0.26	1.17	0.65	0.68	0.00	0.15	0.00	1.35	0.58	0.56
2009	0.22	2.24	2.24	0.68	3.16	1.86	0.78	1.20	0.80	0.97	0.73	1.34	0.64	3.82	0.85

2010	0.61	1.19	0.74	0.58	0.01	1.27	0.58	0.17	0.48	0.77	1.20	0.68	0.00	0.02	0.57
2011	0.42	1.12	1.29	0.79	0.00	0.71	0.40	0.42	0.00	0.00	0.10	0.92	0.22	0.47	0.82
2012	1.05	0.48	1.14	1.86	0.92	3.21	3.63	3.22	2.91	3.07	0.23	3.52	1.19	4.25	1.89
2013	0.76	0.14	0.00	0.00	0.52	0.00	0.00	0.48	0.00	0.20	0.17	0.00	0.84	0.00	0.11
2014	1.68	0.45	1.17	1.02	0.02	1.07	0.64	0.44	0.00	0.71	1.16	0.35	1.16	0.29	1.06
2015	0.91	1.40	0.54	2.45	0.30	3.51	2.65	0.91	2.40	1.15	2.12	3.03	2.39	2.80	2.74
2016	0.80	0.45	0.69	0.34	0.73	0.31	3.17	1.27	0.89	0.00	0.36	1.39	0.81	0.23	0.33
2017	2.89	5.39	2.33	0.39	1.80	1.77	2.54	1.19	0.84	0.55	2.83	5.57	0.00	0.24	2.01

Table 5.3 (b): Drought magnitude for raingauge stations (SPI-2)

Year	Alwar	Amber	Bairath	Bassi	Chomu	Dausa	Kanota	Kotputli	Neem Ka Thana	Phulera	Rajgarh	Ramgarh	Sanganer	Srimadhopur	Thanagaji
1974	0.28	1.44	3.81	0.64	1.75	1.66	0.00	1.89	1.61	4.45	0.89	0.41	0.78	0.98	1.67
1975	0.14	0.49	2.12	2.81	2.43	0.66	0.32	0.66	0.34	7.55	0.38	0.34	0.00	0.00	1.49
1976	0.00	0.54	0.49	0.00	0.80	0.19	0.07	0.91	0.00	1.41	0.58	0.34	0.28	0.28	0.00
1977	0.00	0.11	0.58	0.00	0.20	0.00	5.17	0.00	0.00	0.00	0.05	0.00	0.00	0.00	0.00
1978	0.56	0.16	1.41	0.00	0.67	0.00	0.00	0.76	0.49	0.60	1.37	0.00	0.35	0.00	0.68
1979	1.41	2.44	3.33	2.07	2.29	2.30	1.48	8.43	3.53	1.19	3.09	3.63	4.69	3.77	2.19
1980	2.16	1.22	1.75	1.03	0.49	0.00	1.27	0.81	2.34	0.55	0.38	2.29	4.37	1.49	0.78
1981	0.81	3.20	0.78	0.81	2.43	0.65	0.58	0.50	1.34	2.48	0.52	0.85	3.16	0.80	1.64
1982	2.00	0.87	4.19	1.57	2.48	1.30	0.14	3.28	2.64	0.04	1.06	3.13	4.49	0.03	1.68
1983	0.12	0.00	0.00	1.96	0.00	0.00	0.00	0.00	0.60	0.00	0.00	0.00	0.00	0.00	0.00
1984	1.16	2.96	1.43	5.43	1.21	0.37	0.91	1.41	2.26	1.63	1.32	1.92	2.75	2.42	1.48
1985	0.42	0.83	0.00	2.52	0.00	3.23	0.76	0.63	0.49	0.91	0.81	0.50	1.60	0.99	0.52
1986	5.50	1.49	3.32	5.08	3.67	6.74	1.55	4.84	0.26	1.10	5.83	2.60	0.76	1.12	6.23
1987	6.24	3.34	3.76	6.00	3.15	2.86	3.76	3.25	5.04	2.94	3.19	5.42	4.98	4.42	2.91
1988	0.00	0.19	0.00	3.74	2.40	1.07	0.00	0.00	0.00	1.70	2.16	0.75	0.55	0.08	0.51
1989	4.14	1.42	1.77	2.30	0.00	1.85	3.17	6.16	2.60	0.85	0.00	1.30	1.84	0.19	2.68
1990	1.26	0.77	1.82	0.00	0.67	1.33	0.00	1.88	2.75	0.69	2.67	1.64	0.31	0.73	0.00
1991	6.12	1.20	5.45	2.81	3.08	3.26	1.89	2.95	3.99	0.47	4.11	1.74	0.40	1.77	5.50
1992	0.70	0.17	0.13	2.81	2.43	0.00	0.20	0.93	1.62	2.99	0.00	3.47	3.16	2.13	0.00
1993	0.44	0.00	0.40	0.10	0.95	0.74	0.21	0.00	0.34	0.28	0.00	2.14	1.30	0.52	0.08
1994	0.32	0.00	0.26	0.00	0.00	0.72	0.00	0.68	0.49	0.00	0.26	0.95	0.26	0.92	0.00

1995	3.51	3.74	0.63	0.28	2.87	1.40	1.27	1.49	0.33	0.21	2.27	1.55	0.97	0.92	2.03
1996	0.00	0.18	0.00	0.00	0.00	0.43	0.00	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00
1997	0.84	0.63	0.00	0.00	1.00	0.59	1.88	0.00	2.98	0.00	0.00	1.12	0.29	0.91	0.00
1998	0.08	0.26	1.01	0.74	0.19	0.59	0.33	0.82	5.60	0.22	1.14	1.20	0.05	0.71	0.79
1999	2.25	1.84	0.33	1.23	1.64	1.46	0.90	1.26	2.41	1.33	1.86	1.59	3.57	3.16	0.27
2000	1.49	3.52	1.04	2.01	1.97	1.00	1.50	0.80	3.28	4.42	2.04	0.33	0.94	3.31	0.43
2001	3.24	2.33	1.83	1.84	2.51	1.08	2.14	1.65	3.29	0.86	1.29	2.25	1.21	2.29	2.61
2002	4.70	5.47	5.66	4.24	6.07	4.86	5.45	6.84	5.46	5.83	6.31	3.73	5.54	9.33	7.67
2003	0.00	0.51	0.00	0.00	0.75	0.53	0.01	0.00	1.27	0.00	0.00	0.00	1.02	0.77	0.00
2004	2.49	1.13	3.92	0.35	2.63	2.48	3.30	1.49	2.06	1.05	2.82	0.18	0.15	2.39	2.42
2005	0.87	2.19	0.00	1.12	2.94	0.88	3.43	0.16	0.35	1.30	0.92	0.57	2.81	0.83	0.23
2006	1.79	2.59	2.24	2.81	4.29	2.15	0.82	1.05	1.90	2.73	2.88	1.82	2.27	1.38	2.22
2007	0.77	1.81	2.70	1.46	2.35	1.55	0.82	0.09	2.33	1.81	1.69	0.90	0.96	6.26	0.81
2008	0.21	1.30	0.14	0.71	0.98	0.10	1.16	0.00	0.41	0.00	0.10	0.00	1.27	0.79	1.26
2009	0.49	3.78	3.66	1.79	2.35	3.28	2.10	2.77	2.10	2.16	1.34	1.12	1.46	2.96	1.76
2010	1.12	1.89	1.60	1.16	0.18	1.91	1.12	0.91	0.96	0.84	1.59	1.26	0.10	0.68	0.82
2011	0.25	1.22	0.77	0.66	0.00	0.19	0.27	0.40	0.00	0.00	0.00	1.05	0.21	1.30	1.03
2012	0.00	0.70	1.14	1.88	1.36	2.19	5.18	1.69	1.36	1.75	0.30	4.21	2.01	3.45	2.43
2013	0.00	0.00	0.00	0.00	0.15	0.00	0.00	0.76	0.16	0.17	0.00	0.00	0.00	0.26	0.05
2014	1.73	0.90	1.62	1.50	0.35	2.48	1.25	0.49	0.00	1.19	1.53	0.38	1.41	0.15	2.57
2015	0.73	1.80	1.53	2.64	0.19	4.43	2.38	0.79	0.00	0.51	2.75	3.93	2.53	2.34	4.79
2016	0.35	0.35	0.00	0.00	0.54	0.04	0.02	1.16	0.00	0.00	0.00	0.00	0.83	0.19	0.32
2017	3.93	4.83	3.11	0.90	2.77	3.26	4.25	1.89	1.34	1.28	3.60	4.98	0.00	0.03	2.55

Table 5.3 (c): Drought magnitude for raingauge stations (SPI-3)

Year	Alwar	Amber	Bairath	Bassi	Chomu	Dausa	Kanota	Kotputli	Neem Ka Thana	Phulera	Rajgarh	Ramgarh	Sanganer	Srimadhopur	Thanagaji
1974	0.40	0.00	4.32	0.55	1.81	0.44	0.10	2.00	0.00	2.46	0.84	0.46	0.79	0.00	2.56
1975	0.24	0.57	2.33	2.85	2.44	0.72	0.40	0.71	0.42	7.68	0.45	0.39	0.00	0.00	1.57
1976	0.00	0.66	0.96	0.00	0.72	0.15	0.00	0.94	0.00	1.53	0.72	0.40	0.07	0.30	0.00
1977	0.00	0.00	0.00	0.00	0.00	0.00	3.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1978	0.42	0.00	1.53	0.00	0.35	0.00	0.00	0.81	0.00	0.83	1.57	0.00	0.00	0.00	0.66

1979	1.47	1.64	3.19	1.41	1.46	1.15	1.14	8.18	4.70	1.47	2.78	2.94	5.62	3.55	1.44
1980	1.33	0.61	1.77	0.96	0.56	0.04	0.46	0.00	1.26	0.00	0.37	0.56	4.25	0.07	0.12
1981	0.37	3.17	0.00	0.90	2.44	0.71	0.14	0.46	0.54	2.46	0.00	0.22	3.16	0.83	1.71
1982	2.19	0.66	3.80	2.03	2.87	1.26	0.34	3.18	2.75	0.00	1.34	3.94	5.32	0.00	1.13
1983	0.00	0.00	0.00	1.56	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00
1984	1.73	3.54	2.00	6.62	1.49	0.43	1.05	1.85	2.60	2.58	1.55	2.86	3.43	2.96	1.95
1985	0.14	0.57	0.00	2.97	0.00	3.20	0.00	0.13	0.94	1.55	0.56	0.17	2.27	1.07	0.00
1986	6.46	1.41	2.97	4.81	3.11	6.58	1.68	5.36	0.09	0.93	5.83	2.64	0.83	1.00	6.54
1987	6.78	4.33	4.61	6.90	4.06	3.17	4.41	2.98	5.43	3.70	3.71	6.36	5.63	5.23	2.86
1988	0.00	0.27	0.00	4.26	3.29	1.18	0.00	0.00	0.26	2.62	1.32	1.23	0.70	0.14	0.30
1989	5.05	1.62	2.48	2.95	0.00	2.36	4.48	7.44	3.33	0.00	3.37	2.18	2.14	0.39	3.46
1990	1.26	1.10	2.40	0.00	0.00	1.63	0.00	2.27	3.17	0.47	2.56	2.09	0.38	0.54	0.15
1991	7.57	1.50	6.54	2.85	3.27	3.31	2.60	4.05	4.42	0.58	4.98	2.44	0.59	2.09	6.91
1992	0.95	0.25	0.24	2.85	2.44	0.00	0.30	1.02	1.94	3.36	0.00	3.56	3.16	2.26	0.03
1993	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.00	0.42	0.14	0.00	1.20	1.11	0.12	0.00
1994	0.54	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	1.09	0.45	0.81	0.00
1995	3.67	3.87	0.58	0.37	3.04	1.53	1.31	1.71	0.55	0.29	2.46	1.73	1.18	1.24	2.05
1996	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1997	1.30	0.67	0.02	0.00	1.26	0.77	2.26	0.00	3.66	0.00	0.00	1.40	0.30	0.68	0.01
1998	0.18	0.34	0.80	0.25	0.25	0.46	0.41	0.96	6.90	0.13	1.14	1.72	0.00	0.66	0.73
1999	2.33	1.87	0.06	1.52	1.17	1.14	0.59	1.40	2.74	1.02	2.05	1.03	4.22	3.52	0.17
2000	0.81	4.15	1.29	1.64	2.11	0.73	1.85	0.71	3.69	5.21	3.15	0.04	1.03	3.48	0.50
2001	2.14	2.17	0.77	1.25	1.03	1.00	2.01	0.78	1.61	0.03	0.94	2.52	0.25	1.26	2.04
2002	5.01	7.00	6.57	5.24	6.83	6.29	7.24	6.96	6.58	7.65	6.81	4.94	6.86	10.67	8.99
2003	0.00	0.06	0.00	0.00	0.00	0.59	0.11	0.00	1.35	0.00	0.00	0.00	0.58	0.86	0.11
2004	3.17	0.93	3.85	0.58	3.78	2.57	4.86	2.00	2.33	1.01	3.31	0.00	0.00	3.41	2.95
2005	0.02	2.05	0.00	0.23	3.24	0.00	3.38	0.00	0.00	1.60	0.06	0.00	2.30	0.03	0.00
2006	0.24	2.78	1.63	2.47	3.93	2.46	1.00	0.19	0.42	3.21	2.91	0.95	1.92	0.44	0.87
2007	0.94	2.35	3.04	1.80	2.94	1.72	1.00	0.14	2.66	2.35	1.52	1.18	1.00	7.19	0.90
2008	0.00	1.41	0.00	0.50	1.20	0.00	1.09	0.00	0.11	0.00	0.00	0.00	0.61	0.25	0.00
2009	0.52	4.65	4.67	2.23	3.15	4.32	2.85	3.42	2.78	2.77	1.77	1.41	1.66	2.93	2.01
2010	1.49	1.98	1.88	1.05	0.25	2.34	1.18	1.13	1.04	0.91	1.90	1.47	0.19	0.77	0.91
2011	0.25	1.24	0.83	0.43	0.00	0.27	0.29	0.00	0.00	0.00	0.00	1.24	0.03	1.77	0.60
2012	0.00	0.65	1.09	1.53	1.52	1.73	5.23	1.66	0.63	1.49	0.36	4.39	1.96	3.35	2.21

2013	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.81	0.24	0.26	0.00	0.01	0.00	0.26	0.53
2014	1.76	1.13	1.93	1.55	0.33	3.20	1.20	0.33	0.00	1.47	1.52	0.43	1.05	0.05	3.30
2015	0.37	2.03	1.40	1.65	0.15	4.92	2.90	1.72	0.00	0.00	3.51	4.25	0.98	1.08	5.53
2016	0.00	0.43	0.00	0.00	0.52	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.95	0.30	0.42
2017	3.60	4.00	2.52	0.86	3.07	3.59	5.12	1.41	0.60	1.18	3.41	4.00	0.00	0.09	1.98

Table 5.3 (d): Drought magnitude for raingauge stations (SPI-4)

Year	Alwar	Amber	Bairath	Bassi	Chomu	Dausa	Kanota	Kotputli	Neem Ka Thana	Phulera	Rajgarh	Ramgarh	Sanganer	Srimadhopur	Thanagaji
1974	0.66	0.00	4.86	0.80	1.91	0.65	0.22	2.23	0.07	2.44	1.01	0.53	0.88	0.00	3.19
1975	0.34	0.94	2.46	2.14	2.87	0.93	0.38	0.79	0.45	7.69	0.43	0.46	0.05	0.00	0.97
1976	0.00	0.16	1.01	0.00	0.50	0.14	0.00	0.87	0.00	1.05	0.85	0.33	0.08	0.45	0.00
1977	0.00	0.00	0.00	0.00	0.00	0.00	4.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1978	0.50	0.00	1.61	0.00	0.57	0.00	0.00	0.89	0.00	0.86	1.21	0.00	0.00	0.00	0.61
1979	1.69	1.80	3.41	1.55	1.65	0.98	1.29	8.63	5.24	1.35	2.87	2.56	6.03	3.98	1.03
1980	1.50	0.82	2.06	0.76	0.80	0.00	0.44	0.00	0.86	0.00	0.18	0.34	4.56	0.00	0.03
1981	0.31	1.09	0.00	0.92	2.87	0.95	0.00	0.61	0.57	2.44	0.06	0.28	3.25	0.95	1.81
1982	2.31	0.40	3.53	1.90	2.58	0.97	0.35	3.05	2.66	0.00	1.08	3.97	5.54	0.03	1.27
1983	0.00	0.00	0.00	1.30	0.00	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00
1984	2.24	4.52	2.30	7.24	1.76	0.63	1.20	2.09	3.00	2.89	1.86	3.22	3.86	3.29	2.27
1985	0.32	0.71	0.00	3.26	0.00	1.37	0.00	0.16	1.18	1.93	0.72	0.23	2.69	1.20	0.06
1986	6.93	1.01	3.04	5.10	2.26	6.87	1.49	5.72	0.24	1.06	5.96	2.65	0.93	0.81	6.08
1987	6.85	4.71	4.31	7.24	4.39	2.70	4.10	2.64	5.14	3.14	3.71	6.38	5.70	5.04	2.38
1988	0.00	0.59	0.00	4.72	3.34	1.16	0.00	0.00	0.19	2.77	1.52	1.45	0.78	0.14	0.44
1989	5.12	2.33	2.84	3.64	0.09	2.87	4.92	7.95	3.72	1.08	3.94	2.44	2.25	0.47	4.07
1990	0.00	1.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.14	0.00	0.00	0.18
1991	6.38	2.07	7.02	3.34	3.73	3.77	2.87	4.46	4.96	0.54	5.30	2.84	0.70	2.04	7.58
1992	1.27	0.46	0.34	1.66	0.96	0.00	0.13	1.19	2.17	3.47	0.00	3.64	2.71	2.13	0.08
1993	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.51	0.00	0.00	0.85	0.77	0.07	0.00
1994	0.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	1.09	0.46	0.88	0.00

1995	3.92	2.40	0.39	0.46	1.20	1.42	1.30	1.43	0.40	0.14	2.11	1.53	1.07	1.27	1.79
1996	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1997	1.79	0.87	0.04	0.00	1.29	0.78	2.32	0.00	3.99	0.00	0.00	1.26	0.02	0.56	0.05
1998	0.29	0.00	0.76	0.00	0.20	0.48	0.04	0.99	7.29	0.00	0.81	1.81	0.06	0.69	0.66
1999	2.74	1.99	0.16	1.91	1.37	1.30	0.49	1.40	2.56	0.71	2.57	1.20	4.58	3.84	0.23
2000	0.81	4.87	1.57	2.02	2.61	0.76	2.30	0.51	4.15	5.68	3.69	0.10	0.92	3.99	0.44
2001	0.88	1.55	0.15	1.01	0.19	0.58	1.54	0.23	1.70	0.17	0.27	2.02	0.01	0.50	1.38
2002	4.44	7.31	6.36	5.52	6.42	6.71	7.48	6.31	6.51	7.55	6.57	5.02	6.78	10.70	9.21
2003	0.18	0.33	0.00	0.13	0.00	0.76	0.22	0.00	1.72	0.00	0.00	0.00	0.23	0.86	0.22
2004	3.08	0.96	3.70	0.32	4.15	3.03	5.07	2.10	2.69	1.08	3.50	0.00	0.02	3.57	3.24
2005	0.04	1.90	0.00	0.00	3.25	0.00	2.99	0.00	0.00	1.81	0.00	0.00	1.81	0.00	0.00
2006	0.15	2.44	1.32	2.30	4.37	2.51	1.00	0.27	0.46	3.24	2.83	0.97	1.25	0.32	0.79
2007	0.82	2.43	2.68	1.84	3.03	1.71	1.00	0.22	2.50	2.28	1.44	0.77	1.02	6.77	0.96
2008	0.00	0.76	0.00	0.09	1.03	0.00	0.47	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
2009	0.62	5.00	4.91	2.21	3.37	4.62	3.21	3.39	2.91	2.93	2.24	1.28	1.68	2.00	1.92
2010	1.99	2.59	2.01	1.25	0.44	2.78	1.34	1.24	0.61	0.95	2.18	1.58	0.26	0.89	1.09
2011	0.30	1.09	0.90	0.35	0.00	0.29	0.31	0.00	0.00	0.00	0.00	1.30	0.14	2.14	0.70
2012	0.00	1.05	1.23	1.67	1.78	1.85	5.38	1.76	0.49	1.47	0.51	4.47	2.02	3.51	2.29
2013	0.00	0.00	0.00	0.00	0.30	0.00	0.00	0.89	0.33	0.29	0.00	0.04	0.00	0.36	0.20
2014	1.57	1.02	1.94	1.13	0.31	3.03	0.68	0.10	0.00	1.79	1.65	0.46	0.59	0.03	3.42
2015	0.50	2.02	1.38	1.44	0.00	4.86	2.45	1.70	0.00	0.00	3.24	4.19	0.85	1.12	5.23
2016	0.00	1.44	0.00	0.00	0.68	0.12	0.00	0.42	0.00	0.06	0.00	0.00	1.07	0.00	0.51
2017	3.15	3.68	1.79	0.66	2.91	3.43	5.06	0.94	0.18	0.90	3.10	3.65	0.00	0.00	1.59

Table 5.4 Average drought magnitude

Year	SPI-1	SPI-2	SPI-3	SPI-4	Average	Year	SPI-1	SPI-2	SPI-3	SPI-4	Average
1974	2.08	1.48	1.12	1.30	1.50	1996	0.18	0.05	0.00	0.00	0.06
1975	1.15	1.32	1.38	1.39	1.31	1997	0.36	0.68	0.82	0.86	0.68
1976	0.33	0.39	0.43	0.36	0.38	1998	0.64	0.92	1.00	0.94	0.87
1977	0.54	0.41	0.23	0.27	0.36	1999	1.10	1.67	1.66	1.80	1.56
1978	0.35	0.47	0.41	0.42	0.41	2000	1.26	1.87	2.03	2.29	1.86
1979	3.25	3.06	2.81	2.94	3.01	2001	2.51	2.03	1.32	0.81	1.67
1980	2.18	1.40	0.82	0.82	1.31	2002	5.13	5.81	6.91	6.86	6.18
1981	1.65	1.37	1.14	1.07	1.31	2003	0.26	0.32	0.24	0.31	0.28
1982	2.41	1.93	2.05	1.98	2.09	2004	1.78	1.92	2.32	2.43	2.11
1983	0.32	0.18	0.11	0.09	0.18	2005	2.52	1.24	0.86	0.79	1.35
1984	0.96	1.91	2.44	2.82	2.04	2006	2.17	2.20	1.69	1.61	1.92
1985	1.08	0.95	0.90	0.92	0.96	2007	0.97	1.75	2.05	1.96	1.68
1986	2.64	3.34	3.35	3.34	3.17	2008	0.62	0.56	0.34	0.16	0.42
1987	3.33	4.08	4.68	4.56	4.16	2009	1.44	2.21	2.74	2.82	2.30
1988	0.53	0.88	1.04	1.14	0.90	2010	0.59	1.08	1.23	1.41	1.08
1989	1.64	2.02	2.75	3.18	2.40	2011	0.51	0.49	0.46	0.50	0.49
1990	0.84	1.10	1.20	0.26	0.85	2012	2.17	1.98	1.85	1.97	1.99
1991	2.06	2.98	3.58	3.84	3.11	2013	0.21	0.10	0.16	0.16	0.16
1992	1.52	1.38	1.49	1.35	1.44	2014	0.75	1.17	1.28	1.18	1.10
1993	0.84	0.50	0.21	0.15	0.43	2015	1.95	2.09	2.03	1.93	2.00
1994	0.24	0.32	0.19	0.23	0.25	2016	0.78	0.25	0.18	0.29	0.38
1995	1.04	1.56	1.71	1.39	1.42	2017	2.02	2.58	2.36	2.07	2.26

Table 5.5 (a): Drought magnitude probability (non-exceedance) SPI-1

Year	Alwar	Amber	Bairath	Bassi	Chomu	Dausa	Kanota	Kotputli	Neem Ka Thana	Phulera	Rajgarh	Ramgarh	Sanganer	Srimadhopur	Thanagaji
1974	0.43	0.92	0.81	0.81	0.64	0.80	0.47	0.73	0.78	0.97	0.54	0.31	0.82	0.78	0.74
1975	0.02	0.24	0.84	0.83	0.80	0.35	0.03	0.32	0.02	0.97	0.24	0.19	0.02	0.02	0.64
1976	0.02	0.42	0.43	0.03	0.33	0.13	0.03	0.53	0.33	0.60	0.43	0.25	0.25	0.41	0.11
1977	0.02	0.06	0.54	0.03	0.06	0.01	0.97	0.02	0.02	0.05	0.35	0.36	0.02	0.02	0.01
1978	0.49	0.22	0.50	0.03	0.35	0.01	0.03	0.38	0.47	0.46	0.62	0.01	0.35	0.02	0.36
1979	0.57	0.81	0.79	0.87	0.79	0.93	0.88	0.98	0.74	0.86	0.85	0.89	0.97	0.84	0.82
1980	0.77	0.77	0.75	0.82	0.59	0.36	0.87	0.84	0.82	0.63	0.81	0.86	0.92	0.77	0.72
1981	0.55	0.87	0.49	0.56	0.80	0.86	0.45	0.60	0.88	0.81	0.49	0.53	0.82	0.63	0.77
1982	0.82	0.59	0.89	0.79	0.58	0.66	0.68	0.94	0.91	0.30	0.88	0.81	0.89	0.85	0.79
1983	0.46	0.52	0.01	0.61	0.33	0.01	0.44	0.33	0.50	0.29	0.12	0.27	0.15	0.02	0.24
1984	0.47	0.72	0.40	0.86	0.46	0.18	0.32	0.50	0.61	0.59	0.57	0.57	0.71	0.63	0.41
1985	0.58	0.29	0.18	0.62	0.73	0.85	0.63	0.48	0.34	0.81	0.46	0.60	0.75	0.59	0.46
1986	0.90	0.49	0.80	0.90	0.74	0.96	0.71	0.86	0.42	0.64	0.92	0.84	0.82	0.44	0.97
1987	0.97	0.81	0.94	0.92	0.73	0.74	0.79	0.90	0.85	0.91	0.80	0.95	0.90	0.87	0.67
1988	0.02	0.26	0.01	0.76	0.61	0.37	0.03	0.02	0.02	0.57	0.74	0.25	0.34	0.34	0.46
1989	0.82	0.86	0.53	0.79	0.82	0.65	0.72	0.86	0.53	0.49	0.71	0.54	0.80	0.46	0.65
1990	0.64	0.43	0.64	0.03	0.63	0.48	0.03	0.64	0.66	0.52	0.80	0.58	0.23	0.50	0.35
1991	0.94	0.48	0.85	0.83	0.81	0.85	0.62	0.70	0.86	0.39	0.82	0.60	0.10	0.78	0.87
1992	0.34	0.51	0.60	0.83	0.80	0.18	0.65	0.61	0.65	0.83	0.01	0.87	0.82	0.85	0.66
1993	0.56	0.00	0.62	0.54	0.86	0.55	0.22	0.46	0.15	0.38	0.43	0.73	0.63	0.47	0.59
1994	0.26	0.00	0.22	0.03	0.01	0.51	0.30	0.48	0.37	0.05	0.30	0.36	0.28	0.40	0.01
1995	0.84	0.88	0.18	0.23	0.80	0.57	0.55	0.47	0.13	0.05	0.71	0.64	0.41	0.28	0.67
1996	0.02	0.43	0.36	0.03	0.01	0.30	0.40	0.02	0.37	0.05	0.01	0.31	0.10	0.37	0.01
1997	0.35	0.35	0.01	0.03	0.43	0.29	0.62	0.02	0.69	0.05	0.01	0.45	0.15	0.47	0.01
1998	0.21	0.25	0.50	0.49	0.49	0.31	0.03	0.55	0.84	0.34	0.53	0.43	0.51	0.39	0.47
1999	0.80	0.00	0.43	0.36	0.60	0.75	0.52	0.58	0.69	0.65	0.56	0.65	0.77	0.74	0.37
2000	0.73	0.78	0.58	0.70	0.66	0.53	0.80	0.24	0.55	0.81	0.73	0.36	0.55	0.65	0.55
2001	0.81	0.80	0.80	0.74	0.84	0.80	0.71	0.67	0.92	0.88	0.87	0.92	0.76	0.78	0.85
2002	0.92	0.92	0.93	0.94	0.98	0.95	0.89	0.97	0.97	0.92	0.94	0.82	0.94	0.99	0.98
2003	0.02	0.35	0.01	0.42	0.49	0.36	0.17	0.02	0.53	0.05	0.01	0.01	0.52	0.34	0.01
2004	0.75	0.71	0.97	0.54	0.61	0.80	0.82	0.69	0.64	0.69	0.86	0.33	0.23	0.66	0.76
2005	0.78	0.92	0.70	0.87	0.80	0.78	0.95	0.80	0.82	0.63	0.83	0.80	0.85	0.72	0.79
2006	0.89	0.65	0.78	0.73	0.85	0.56	0.56	0.73	0.81	0.78	0.90	0.69	0.73	0.71	0.94
2007	0.50	0.63	0.57	0.53	0.54	0.53	0.56	0.02	0.65	0.64	0.61	0.47	0.47	0.89	0.35
2008	0.43	0.66	0.51	0.54	0.42	0.28	0.66	0.50	0.52	0.05	0.19	0.01	0.67	0.47	0.46
2009	0.30	0.80	0.79	0.53	0.88	0.74	0.57	0.64	0.55	0.65	0.48	0.64	0.49	0.91	0.55
2010	0.49	0.61	0.50	0.50	0.03	0.64	0.51	0.27	0.44	0.60	0.61	0.46	0.02	0.08	0.46
2011	0.41	0.59	0.64	0.56	0.01	0.49	0.44	0.41	0.02	0.05	0.15	0.54	0.29	0.43	0.54
2012	0.61	0.36	0.61	0.75	0.53	0.88	0.90	0.87	0.86	0.88	0.25	0.89	0.64	0.92	0.76
2013	0.54	0.16	0.01	0.03	0.38	0.01	0.03	0.44	0.02	0.38	0.21	0.01	0.55	0.02	0.20

2014	0.73	0.35	0.62	0.62	0.04	0.59	0.53	0.42	0.02	0.59	0.60	0.31	0.63	0.34	0.61
2015	0.58	0.66	0.43	0.81	0.27	0.89	0.84	0.58	0.82	0.69	0.77	0.86	0.81	0.85	0.85
2016	0.55	0.35	0.48	0.40	0.47	0.31	0.88	0.66	0.58	0.05	0.32	0.65	0.54	0.30	0.35
2017	0.85	0.97	0.80	0.42	0.73	0.73	0.83	0.64	0.56	0.54	0.84	0.96	0.02	0.31	0.77

Table 5.5 (b): Drought magnitude probability (non-exceedance) SPI-2

Year	Alwar	Amber	Bairath	Bassi	Chomu	Dausa	Kanota	Kotputli	Neem Ka Thana	Phulera	Rajgarh	Ramgarh	Sanganer	Srimadhopur	Thanagaji
1974	0.37	0.65	0.87	0.53	0.71	0.71	0.05	0.74	0.69	0.92	0.61	0.42	0.54	0.58	0.72
1975	0.28	0.38	0.76	0.82	0.79	0.49	0.43	0.52	0.37	0.98	0.46	0.39	0.02	0.02	0.70
1976	0.03	0.40	0.47	0.04	0.51	0.27	0.24	0.59	0.03	0.71	0.53	0.39	0.34	0.33	0.04
1977	0.03	0.15	0.50	0.04	0.26	0.02	0.94	0.03	0.03	0.04	0.22	0.03	0.02	0.02	0.04
1978	0.49	0.19	0.68	0.04	0.48	0.02	0.05	0.55	0.44	0.54	0.70	0.03	0.38	0.02	0.54
1979	0.68	0.80	0.85	0.76	0.77	0.78	0.72	0.98	0.86	0.68	0.85	0.88	0.92	0.88	0.78
1980	0.78	0.61	0.72	0.62	0.41	0.02	0.68	0.56	0.78	0.52	0.46	0.79	0.91	0.68	0.57
1981	0.56	0.86	0.55	0.57	0.79	0.49	0.53	0.47	0.65	0.82	0.51	0.57	0.85	0.53	0.72
1982	0.76	0.51	0.89	0.70	0.79	0.65	0.31	0.86	0.80	0.19	0.65	0.85	0.92	0.11	0.72
1983	0.26	0.01	0.04	0.75	0.02	0.02	0.05	0.03	0.47	0.04	0.05	0.03	0.02	0.02	0.04
1984	0.64	0.85	0.68	0.93	0.61	0.38	0.62	0.68	0.77	0.74	0.69	0.75	0.83	0.79	0.70
1985	0.44	0.50	0.04	0.80	0.02	0.86	0.58	0.51	0.44	0.62	0.59	0.46	0.70	0.58	0.49
1986	0.94	0.66	0.85	0.92	0.87	0.97	0.73	0.92	0.33	0.66	0.95	0.81	0.53	0.61	0.95
1987	0.96	0.87	0.87	0.94	0.84	0.83	0.89	0.86	0.92	0.86	0.86	0.94	0.93	0.91	0.83
1988	0.03	0.22	0.04	0.87	0.78	0.60	0.05	0.03	0.03	0.75	0.79	0.54	0.46	0.18	0.49
1989	0.90	0.65	0.72	0.78	0.02	0.73	0.86	0.95	0.80	0.61	0.05	0.66	0.73	0.28	0.82
1990	0.66	0.48	0.73	0.04	0.48	0.65	0.05	0.74	0.81	0.57	0.83	0.71	0.36	0.51	0.04
1991	0.95	0.60	0.93	0.82	0.84	0.86	0.77	0.84	0.88	0.49	0.90	0.73	0.40	0.72	0.93
1992	0.53	0.20	0.28	0.82	0.79	0.02	0.36	0.59	0.69	0.86	0.05	0.87	0.85	0.76	0.04
1993	0.45	0.01	0.43	0.27	0.55	0.51	0.37	0.03	0.37	0.41	0.05	0.77	0.65	0.44	0.25
1994	0.39	0.01	0.37	0.04	0.02	0.51	0.05	0.53	0.44	0.04	0.40	0.59	0.33	0.56	0.04
1995	0.87	0.90	0.51	0.39	0.82	0.66	0.68	0.69	0.37	0.37	0.80	0.70	0.58	0.56	0.76
1996	0.03	0.21	0.04	0.04	0.02	0.40	0.05	0.03	0.25	0.04	0.05	0.03	0.02	0.02	0.04
1997	0.57	0.43	0.04	0.04	0.57	0.47	0.77	0.03	0.83	0.04	0.05	0.63	0.35	0.56	0.04
1998	0.22	0.26	0.61	0.55	0.26	0.47	0.43	0.56	0.94	0.37	0.66	0.64	0.15	0.51	0.57
1999	0.79	0.72	0.40	0.65	0.69	0.68	0.61	0.66	0.78	0.70	0.76	0.71	0.88	0.85	0.39
2000	0.70	0.88	0.61	0.75	0.73	0.58	0.72	0.56	0.85	0.92	0.78	0.39	0.58	0.86	0.46

2001	0.86	0.79	0.73	0.74	0.79	0.60	0.79	0.71	0.85	0.61	0.69	0.78	0.64	0.78	0.81
2002	0.92	0.96	0.93	0.89	0.95	0.93	0.94	0.96	0.93	0.95	0.95	0.88	0.94	0.99	0.97
2003	0.03	0.39	0.04	0.04	0.50	0.44	0.11	0.03	0.63	0.04	0.05	0.03	0.60	0.52	0.04
2004	0.81	0.58	0.88	0.43	0.80	0.80	0.87	0.69	0.75	0.65	0.84	0.30	0.26	0.79	0.80
2005	0.58	0.77	0.04	0.64	0.83	0.55	0.88	0.29	0.38	0.69	0.62	0.48	0.83	0.54	0.37
2006	0.74	0.81	0.77	0.82	0.90	0.77	0.60	0.62	0.73	0.84	0.84	0.74	0.78	0.66	0.78
2007	0.55	0.72	0.81	0.69	0.78	0.69	0.60	0.23	0.77	0.76	0.74	0.58	0.58	0.96	0.58
2008	0.33	0.62	0.29	0.55	0.56	0.20	0.67	0.03	0.40	0.04	0.28	0.03	0.65	0.53	0.66
2009	0.47	0.90	0.87	0.73	0.78	0.86	0.79	0.82	0.75	0.80	0.69	0.63	0.68	0.84	0.73
2010	0.63	0.73	0.70	0.64	0.25	0.74	0.66	0.59	0.57	0.60	0.73	0.65	0.21	0.50	0.58
2011	0.35	0.61	0.55	0.53	0.02	0.27	0.40	0.43	0.03	0.04	0.05	0.61	0.30	0.64	0.62
2012	0.03	0.46	0.63	0.74	0.64	0.77	0.94	0.72	0.65	0.76	0.42	0.90	0.76	0.87	0.80
2013	0.03	0.01	0.04	0.04	0.23	0.02	0.05	0.55	0.27	0.34	0.05	0.03	0.02	0.32	0.20
2014	0.73	0.52	0.70	0.69	0.35	0.80	0.68	0.46	0.03	0.68	0.72	0.41	0.67	0.25	0.81
2015	0.54	0.72	0.69	0.81	0.26	0.92	0.81	0.56	0.03	0.51	0.83	0.89	0.81	0.78	0.91
2016	0.41	0.31	0.04	0.04	0.43	0.13	0.15	0.64	0.03	0.04	0.05	0.03	0.55	0.28	0.41
2017	0.89	0.94	0.84	0.59	0.82	0.86	0.91	0.74	0.65	0.69	0.88	0.93	0.02	0.11	0.81

Table 5.5 (c): Drought magnitude probability (non-exceedance) SPI-3

Year	Alwar	Amber	Bairath	Bassi	Chomu	Dausa	Kanota	Kotputli	Neem Ka Thana	Phulera	Rajgarh	Ramgarh	Sanganer	Srimadhopur	Thanagaji
1974	0.50	0.03	0.88	0.52	0.73	0.50	0.30	0.77	0.06	0.82	0.61	0.48	0.58	0.04	0.81
1975	0.43	0.49	0.79	0.82	0.79	0.58	0.47	0.60	0.48	0.96	0.51	0.45	0.05	0.04	0.71
1976	0.07	0.51	0.63	0.06	0.55	0.35	0.06	0.64	0.06	0.74	0.59	0.45	0.24	0.41	0.06
1977	0.07	0.03	0.08	0.06	0.05	0.06	0.86	0.08	0.06	0.08	0.08	0.05	0.05	0.04	0.06
1978	0.51	0.03	0.71	0.06	0.43	0.06	0.06	0.62	0.06	0.63	0.72	0.05	0.05	0.04	0.55
1979	0.72	0.71	0.84	0.69	0.69	0.66	0.66	0.96	0.90	0.73	0.82	0.83	0.93	0.87	0.70
1980	0.70	0.50	0.74	0.62	0.51	0.22	0.50	0.08	0.67	0.08	0.48	0.51	0.90	0.23	0.31
1981	0.49	0.85	0.08	0.60	0.79	0.58	0.33	0.53	0.52	0.82	0.08	0.37	0.85	0.58	0.73
1982	0.79	0.51	0.87	0.76	0.82	0.68	0.45	0.85	0.82	0.08	0.69	0.88	0.93	0.04	0.65
1983	0.07	0.03	0.08	0.71	0.05	0.06	0.06	0.08	0.32	0.08	0.08	0.05	0.05	0.04	0.06
1984	0.75	0.87	0.76	0.95	0.69	0.49	0.64	0.76	0.81	0.83	0.72	0.83	0.86	0.84	0.76
1985	0.36	0.49	0.08	0.83	0.05	0.85	0.06	0.37	0.62	0.74	0.55	0.33	0.79	0.63	0.06
1986	0.95	0.67	0.83	0.91	0.84	0.95	0.73	0.92	0.29	0.65	0.93	0.81	0.59	0.62	0.95
1987	0.95	0.90	0.89	0.95	0.88	0.85	0.90	0.84	0.92	0.88	0.87	0.95	0.93	0.93	0.83
1988	0.07	0.36	0.08	0.89	0.85	0.67	0.06	0.08	0.41	0.83	0.69	0.66	0.55	0.30	0.43

1989	0.92	0.71	0.80	0.83	0.05	0.80	0.90	0.96	0.85	0.08	0.85	0.78	0.77	0.45	0.86
1990	0.69	0.62	0.79	0.06	0.05	0.73	0.06	0.80	0.84	0.54	0.81	0.77	0.45	0.50	0.34
1991	0.96	0.69	0.94	0.82	0.85	0.86	0.81	0.89	0.89	0.57	0.91	0.80	0.52	0.77	0.95
1992	0.64	0.35	0.43	0.82	0.79	0.06	0.43	0.66	0.75	0.87	0.08	0.87	0.85	0.79	0.19
1993	0.07	0.03	0.08	0.06	0.05	0.06	0.30	0.08	0.48	0.37	0.08	0.66	0.64	0.29	0.06
1994	0.54	0.03	0.08	0.06	0.05	0.06	0.06	0.08	0.14	0.08	0.08	0.64	0.48	0.58	0.06
1995	0.88	0.88	0.55	0.45	0.83	0.72	0.68	0.75	0.53	0.46	0.80	0.73	0.65	0.66	0.77
1996	0.07	0.03	0.08	0.06	0.05	0.06	0.06	0.08	0.06	0.08	0.08	0.05	0.05	0.04	0.06
1997	0.70	0.52	0.20	0.06	0.66	0.59	0.79	0.08	0.86	0.08	0.08	0.69	0.41	0.55	0.13
1998	0.39	0.40	0.60	0.40	0.38	0.50	0.48	0.65	0.95	0.36	0.67	0.73	0.05	0.54	0.57
1999	0.80	0.74	0.28	0.70	0.64	0.66	0.54	0.71	0.82	0.66	0.77	0.63	0.90	0.87	0.35
2000	0.61	0.90	0.68	0.72	0.76	0.58	0.75	0.60	0.87	0.93	0.84	0.19	0.63	0.87	0.51
2001	0.79	0.77	0.60	0.67	0.62	0.64	0.77	0.61	0.72	0.23	0.63	0.80	0.39	0.67	0.76
2002	0.92	0.96	0.94	0.92	0.95	0.95	0.96	0.95	0.94	0.96	0.95	0.92	0.96	0.99	0.97
2003	0.07	0.19	0.08	0.06	0.05	0.54	0.31	0.08	0.68	0.08	0.08	0.05	0.52	0.59	0.30
2004	0.85	0.58	0.87	0.53	0.87	0.81	0.91	0.77	0.79	0.66	0.85	0.05	0.05	0.87	0.83
2005	0.19	0.76	0.08	0.39	0.84	0.06	0.86	0.08	0.06	0.74	0.28	0.05	0.79	0.17	0.06
2006	0.43	0.82	0.72	0.80	0.88	0.81	0.63	0.41	0.48	0.86	0.83	0.61	0.75	0.47	0.60
2007	0.64	0.79	0.83	0.74	0.83	0.74	0.63	0.37	0.81	0.81	0.72	0.65	0.62	0.96	0.61
2008	0.07	0.67	0.08	0.50	0.65	0.06	0.65	0.08	0.31	0.08	0.08	0.05	0.53	0.38	0.06
2009	0.54	0.91	0.90	0.78	0.84	0.90	0.83	0.86	0.82	0.84	0.74	0.69	0.72	0.84	0.76
2010	0.72	0.75	0.75	0.63	0.38	0.80	0.66	0.67	0.64	0.64	0.76	0.70	0.35	0.57	0.61
2011	0.43	0.65	0.61	0.48	0.05	0.42	0.43	0.08	0.06	0.08	0.08	0.66	0.18	0.74	0.54
2012	0.07	0.51	0.65	0.71	0.70	0.74	0.92	0.74	0.55	0.73	0.48	0.90	0.76	0.86	0.78
2013	0.07	0.03	0.08	0.06	0.41	0.06	0.06	0.62	0.40	0.45	0.08	0.11	0.05	0.38	0.52
2014	0.75	0.63	0.75	0.71	0.42	0.85	0.67	0.48	0.06	0.73	0.72	0.47	0.63	0.20	0.85
2015	0.49	0.76	0.70	0.72	0.32	0.92	0.83	0.75	0.06	0.08	0.86	0.90	0.62	0.64	0.93
2016	0.07	0.44	0.08	0.06	0.49	0.06	0.06	0.08	0.06	0.20	0.08	0.05	0.61	0.41	0.48
2017	0.87	0.89	0.80	0.60	0.83	0.87	0.92	0.71	0.54	0.69	0.86	0.89	0.05	0.26	0.76

Table 5.5 (d): Drought magnitude probability (non-exceedance) SPI-4

Year	Alwar	Amber	Bairath	Bassi	Chomu	Dausa	Kanota	Kotputli	Neem Ka Thana	Phulera	Rajgarh	Ramgarh	Sanganer	Srimadhopur	Thanagaji
1974	0.57	0.04	0.90	0.60	0.75	0.57	0.42	0.80	0.30	0.82	0.65	0.50	0.61	0.09	0.85
1975	0.46	0.59	0.80	0.77	0.82	0.63	0.49	0.62	0.52	0.96	0.51	0.47	0.22	0.09	0.62
1976	0.06	0.30	0.65	0.07	0.49	0.35	0.08	0.64	0.08	0.67	0.62	0.42	0.27	0.53	0.05
1977	0.06	0.04	0.09	0.07	0.05	0.07	0.89	0.09	0.08	0.09	0.08	0.04	0.05	0.09	0.05
1978	0.52	0.04	0.73	0.07	0.51	0.07	0.08	0.64	0.08	0.64	0.68	0.04	0.05	0.09	0.53
1979	0.74	0.73	0.85	0.71	0.72	0.64	0.70	0.97	0.92	0.72	0.83	0.81	0.94	0.89	0.63

1980	0.72	0.56	0.77	0.59	0.58	0.07	0.52	0.09	0.62	0.09	0.40	0.42	0.91	0.09	0.18
1981	0.45	0.62	0.09	0.62	0.82	0.64	0.08	0.58	0.55	0.82	0.29	0.39	0.86	0.65	0.74
1982	0.80	0.43	0.86	0.75	0.80	0.64	0.48	0.85	0.81	0.09	0.66	0.89	0.93	0.24	0.67
1983	0.06	0.04	0.09	0.68	0.05	0.07	0.08	0.09	0.33	0.09	0.08	0.04	0.05	0.09	0.05
1984	0.79	0.90	0.79	0.95	0.73	0.57	0.68	0.79	0.83	0.84	0.76	0.85	0.88	0.86	0.78
1985	0.45	0.53	0.09	0.85	0.05	0.70	0.08	0.40	0.67	0.78	0.60	0.37	0.82	0.69	0.23
1986	0.96	0.61	0.84	0.91	0.78	0.95	0.72	0.93	0.43	0.68	0.93	0.81	0.62	0.62	0.94
1987	0.96	0.91	0.89	0.95	0.90	0.83	0.89	0.82	0.91	0.86	0.87	0.95	0.94	0.92	0.79
1988	0.06	0.50	0.09	0.90	0.85	0.67	0.08	0.09	0.40	0.84	0.72	0.69	0.58	0.38	0.47
1989	0.92	0.78	0.83	0.86	0.27	0.84	0.91	0.96	0.87	0.68	0.88	0.80	0.79	0.54	0.89
1990	0.06	0.70	0.09	0.07	0.05	0.07	0.08	0.09	0.08	0.09	0.08	0.77	0.05	0.09	0.34
1991	0.95	0.76	0.95	0.85	0.87	0.88	0.84	0.90	0.91	0.57	0.92	0.83	0.56	0.78	0.96
1992	0.69	0.45	0.49	0.73	0.61	0.07	0.36	0.69	0.78	0.87	0.08	0.87	0.82	0.79	0.26
1993	0.30	0.04	0.09	0.07	0.05	0.07	0.08	0.09	0.54	0.09	0.08	0.58	0.58	0.31	0.05
1994	0.62	0.04	0.09	0.07	0.05	0.07	0.08	0.09	0.08	0.09	0.34	0.63	0.49	0.64	0.05
1995	0.89	0.79	0.51	0.51	0.65	0.71	0.70	0.72	0.50	0.39	0.78	0.70	0.64	0.70	0.74
1996	0.06	0.04	0.09	0.07	0.05	0.07	0.08	0.09	0.08	0.09	0.08	0.04	0.05	0.09	0.05
1997	0.75	0.57	0.27	0.07	0.67	0.60	0.80	0.09	0.88	0.09	0.08	0.66	0.16	0.57	0.22
1998	0.44	0.04	0.61	0.07	0.36	0.52	0.25	0.66	0.95	0.09	0.61	0.74	0.24	0.60	0.54
1999	0.83	0.75	0.40	0.75	0.68	0.69	0.53	0.72	0.81	0.61	0.81	0.65	0.91	0.88	0.38
2000	0.60	0.92	0.73	0.76	0.81	0.60	0.80	0.55	0.88	0.93	0.87	0.27	0.62	0.89	0.47
2001	0.62	0.70	0.39	0.64	0.35	0.55	0.73	0.44	0.74	0.41	0.45	0.76	0.12	0.55	0.68
2002	0.91	0.96	0.94	0.92	0.95	0.95	0.96	0.94	0.94	0.96	0.94	0.92	0.96	0.98	0.98
2003	0.37	0.40	0.09	0.34	0.05	0.60	0.42	0.09	0.74	0.09	0.08	0.04	0.39	0.63	0.37
2004	0.85	0.59	0.87	0.45	0.89	0.85	0.92	0.79	0.82	0.68	0.86	0.04	0.16	0.87	0.85
2005	0.22	0.74	0.09	0.07	0.85	0.07	0.84	0.09	0.08	0.77	0.08	0.04	0.75	0.09	0.05
2006	0.35	0.79	0.70	0.79	0.90	0.81	0.65	0.46	0.52	0.86	0.83	0.61	0.67	0.48	0.58
2007	0.61	0.79	0.82	0.75	0.83	0.75	0.65	0.43	0.80	0.81	0.71	0.57	0.63	0.95	0.61
2008	0.06	0.55	0.09	0.30	0.62	0.07	0.53	0.09	0.08	0.09	0.08	0.04	0.16	0.09	0.05
2009	0.56	0.92	0.91	0.78	0.85	0.91	0.85	0.86	0.83	0.85	0.79	0.67	0.73	0.78	0.75
2010	0.77	0.80	0.77	0.68	0.47	0.83	0.70	0.70	0.56	0.66	0.79	0.71	0.40	0.64	0.64
2011	0.44	0.62	0.63	0.47	0.05	0.45	0.47	0.09	0.08	0.09	0.08	0.67	0.32	0.79	0.55
2012	0.06	0.61	0.69	0.73	0.73	0.76	0.93	0.76	0.53	0.73	0.54	0.91	0.77	0.87	0.79
2013	0.06	0.04	0.09	0.07	0.41	0.07	0.08	0.64	0.47	0.48	0.08	0.19	0.05	0.50	0.36
2014	0.73	0.61	0.76	0.66	0.42	0.85	0.59	0.34	0.08	0.77	0.74	0.47	0.53	0.24	0.86
2015	0.52	0.75	0.71	0.70	0.05	0.92	0.81	0.75	0.08	0.09	0.85	0.90	0.60	0.68	0.92
2016	0.06	0.68	0.09	0.07	0.55	0.34	0.08	0.52	0.08	0.31	0.08	0.04	0.64	0.09	0.50
2017	0.85	0.87	0.75	0.56	0.83	0.87	0.92	0.65	0.39	0.65	0.84	0.87	0.05	0.09	0.71

Table 5.6 Indices and historic drought years

Year	DM prob-ability	Dry spell	Pan India major droughts (Samra 2004)	Pan India major droughts (Kaur)	Pan India severe drought (Kaur)	Year	DM prob-ability	Dry spell	VCI	Pan India major droughts (Sarma 2004)	Pan India major droughts (Kaur)	Pan India severe drought (Kaur)
1974	Yes	Yes	Yes	Yes		1996			-			
1975						1997			-			
1976						1998			-			
1977						1999			-			
1978						2000			-			
1979	Yes	Yes	Yes	Yes	Yes	2001	Yes	Yes				
1980	Yes	Yes				2002	Yes	Yes	Yes	Yes	Yes	
1981		Yes				2003				-		
1982	Yes		Yes	Yes		2004			Yes	-		
1983						2005	Yes	Yes	Yes	-		
1984						2006	Yes			-		
1985		Yes	Yes			2007				-		
1986	Yes	Yes	Yes			2008				-		
1987	Yes	Yes	Yes	Yes	Yes	2009				-	Yes	Yes
1988						2010				-		
1989						2011				-	-	-
1990						2012	Yes			-	-	-
1991	Yes	Yes				2013				-	-	-
1992						2014			Yes	-	-	-
1993						2015	Yes	Yes		-	-	-
1994						2016				-	-	-
1995						2017				-	-	-

Table 5.7 Dry spell weeks' count

Year	Jamwa Ramgarh	Amber	Chomu	Bairath	Thanagaji	Bassi	Kotputli	Phulera	Sanganer	Neem Ka Thana	Srimadhopur	Alwar	Rajgarh	Dausa	Kanota
1974	5	6	3	5	6	7	7	8	4	7	6	4	4	6	3
1975	2	2	2	4	2	1	2	7	1	2	1	1	1	1	1
1976	2	2	3	2	3	1	5	4	2	2	2	2	3	2	2
1977	3	3	2	3	3	2	2	2	2	2	1	3	2	3	7
1978	2	2	2	3	2	2	2	2	2	2	1	2	2	1	2

1979	7	7	7	6	7	7	10	6	7	5	7	6	7	7	7
1980	6	5	6	6	3	5	3	7	7	6	5	3	3	3	5
1981	4	6	5	3	4	6	6	8	6	5	6	6	4	4	6
1982	4	4	5	4	4	4	5	3	4	5	4	5	3	3	4
1983	3	3	2	3	2	4	4	4	3	4	3	2	2	1	3
1984	3	3	5	2	2	11	3	4	3	3	2	3	3	3	2
1985	5	5	5	6	6	6	4	5	5	4	5	4	4	3	5
1986	5	4	5	4	7	8	5	3	5	4	5	5	4	8	5
1987	9	3	4	4	10	9	5	2	7	6	7	9	6	6	7
1988	2	3	5	3	3	6	2	2	3	3	3	2	6	4	2
1989	2	3	3	3	3	4	9	4	4	4	2	4	2	4	3
1990	4	4	3	3	1	1	2	2	3	4	3	3	4	3	2
1991	5	5	5	5	8	4	5	3	3	5	4	5	5	4	5
1992	4	4	3	5	3	4	3	5	4	3	2	1	2	1	2
1993	4	3	6	3	3	3	3	4	3	3	3	3	3	4	4
1994	2	1	1	1	1	1	3	1	2	3	4	1	2	2	2
1995	5	4	4	2	3	2	5	2	2	2	2	5	5	4	2
1996	2	2	1	2	2	1	1	2	2	3	3	2	1	2	2
1997	3	3	3	2	2	1	1	3	2	5	1	1	1	1	3
1998	3	3	5	3	2	4	3	4	3	5	3	3	3	2	2
1999	3	3	4	3	3	3	5	4	6	5	5	3	5	5	4
2000	2	3	3	3	1	4	3	4	3	5	4	2	4	3	4
2001	5	6	5	5	6	5	5	6	5	5	6	3	5	5	3
2002	4	7	7	6	6	5	12	12	6	5	14	7	4	8	7
2003	1	2	2	1	1	1	1	1	2	2	3	4	1	2	2
2004	2	2	6	7	7	3	6	3	3	4	4	3	7	5	4
2005	7	7	7	2	6	5	5	4	8	6	3	4	7	4	6
2006	4	2	7	4	4	4	3	2	2	4	4	3	4	4	3
2007	2	2	6	2	4	3	2	5	2	2	6	2	2	2	1
2008	2	4	4	3	2	4	3	4	3	3	3	3	2	2	2
2009	2	3	5	3	2	2	2	3	2	3	5	2	2	5	3
2010	2	3	2	3	3	3	3	3	2	3	2	3	2	3	2
2011	1	2	1	2	4	3	4	1	2	1	2	1	1	2	3
2012	3	3	3	3	3	3	4	4	4	3	8	3	1	3	4
2013	3	3	4	3	3	3	3	3	3	4	3	4	4	3	3
2014	3	3	2	3	3	5	2	3	4	1	3	2	6	3	3
2015	5	5	4	4	5	7	4	5	7	5	6	5	4	6	4
2016	2	2	2	2	2	2	4	2	2	3	2	3	2	2	2
2017	7	7	2	4	4	3	3	3	3	6	2	3	3	2	8

Table 5.8 Dry spell probability (non exceedance)

Year	Jamwa Ramgarh	Amber	Chomu	Bairath	Thanagaji	Bassi	Kotputli	Phulera	Sanganer	Neem Ka Thana	Srimadhopur	Alwar	Rajgarh	Dausa	Kanota
1974	0.82	0.92	0.36	0.87	0.88	0.90	0.91	0.96	0.65	0.96	0.85	0.71	0.70	0.91	0.43
1975	0.18	0.13	0.14	0.70	0.20	0.05	0.17	0.93	0.02	0.10	0.04	0.03	0.04	0.04	0.02
1976	0.18	0.13	0.36	0.15	0.43	0.05	0.74	0.60	0.16	0.10	0.19	0.23	0.49	0.22	0.18
1977	0.43	0.39	0.14	0.43	0.43	0.21	0.17	0.17	0.16	0.10	0.04	0.49	0.24	0.47	0.96
1978	0.18	0.13	0.14	0.43	0.20	0.21	0.17	0.17	0.16	0.10	0.04	0.23	0.24	0.04	0.18
1979	0.96	0.97	0.93	0.95	0.93	0.90	0.99	0.86	0.96	0.80	0.91	0.93	0.96	0.96	0.96
1980	0.91	0.83	0.87	0.95	0.43	0.73	0.38	0.93	0.96	0.91	0.75	0.49	0.49	0.47	0.82
1981	0.66	0.92	0.76	0.43	0.64	0.83	0.85	0.96	0.91	0.80	0.85	0.93	0.70	0.68	0.91
1982	0.66	0.65	0.76	0.70	0.64	0.59	0.74	0.39	0.65	0.80	0.60	0.86	0.49	0.47	0.66
1983	0.43	0.39	0.14	0.43	0.20	0.59	0.58	0.60	0.41	0.60	0.40	0.23	0.24	0.04	0.43
1984	0.43	0.39	0.76	0.15	0.20	0.99	0.38	0.60	0.41	0.34	0.19	0.49	0.49	0.47	0.18
1985	0.82	0.83	0.76	0.95	0.88	0.83	0.58	0.76	0.82	0.60	0.75	0.71	0.70	0.47	0.82
1986	0.82	0.65	0.76	0.70	0.93	0.94	0.74	0.39	0.82	0.60	0.75	0.86	0.70	0.98	0.82
1987	0.99	0.39	0.59	0.70	0.99	0.97	0.74	0.17	0.96	0.91	0.91	0.99	0.91	0.91	0.96
1988	0.18	0.39	0.76	0.43	0.43	0.83	0.17	0.17	0.41	0.34	0.40	0.23	0.91	0.68	0.18
1989	0.18	0.39	0.36	0.43	0.43	0.59	0.98	0.60	0.65	0.60	0.19	0.71	0.24	0.68	0.43
1990	0.66	0.65	0.36	0.43	0.04	0.05	0.17	0.17	0.41	0.60	0.40	0.49	0.70	0.47	0.18
1991	0.82	0.83	0.76	0.87	0.97	0.59	0.74	0.39	0.41	0.80	0.60	0.86	0.83	0.68	0.82
1992	0.66	0.65	0.36	0.87	0.43	0.59	0.38	0.76	0.65	0.34	0.19	0.03	0.24	0.04	0.18
1993	0.66	0.39	0.87	0.43	0.43	0.41	0.38	0.60	0.41	0.34	0.40	0.49	0.49	0.68	0.66
1994	0.18	0.01	0.02	0.01	0.04	0.05	0.38	0.03	0.16	0.34	0.60	0.03	0.24	0.22	0.18
1995	0.82	0.65	0.59	0.15	0.43	0.21	0.74	0.17	0.16	0.10	0.19	0.86	0.83	0.68	0.18
1996	0.18	0.13	0.02	0.15	0.20	0.05	0.03	0.17	0.16	0.34	0.40	0.23	0.04	0.22	0.18
1997	0.43	0.39	0.36	0.15	0.20	0.05	0.03	0.39	0.16	0.80	0.04	0.03	0.04	0.04	0.43
1998	0.43	0.39	0.76	0.43	0.20	0.59	0.38	0.60	0.41	0.80	0.40	0.49	0.49	0.22	0.18
1999	0.43	0.39	0.59	0.43	0.43	0.41	0.74	0.60	0.91	0.80	0.75	0.49	0.83	0.83	0.66
2000	0.18	0.39	0.36	0.43	0.04	0.59	0.38	0.60	0.41	0.80	0.60	0.23	0.70	0.47	0.66

2001	0.82	0.92	0.76	0.87	0.88	0.73	0.74	0.86	0.82	0.80	0.85	0.49	0.83	0.83	0.43
2002	0.66	0.97	0.93	0.95	0.88	0.73	1.00	1.00	0.91	0.80	1.00	0.97	0.70	0.98	0.96
2003	0.02	0.13	0.14	0.01	0.04	0.05	0.03	0.03	0.16	0.10	0.40	0.71	0.04	0.22	0.18
2004	0.18	0.13	0.87	0.98	0.93	0.41	0.85	0.39	0.41	0.60	0.60	0.49	0.96	0.83	0.66
2005	0.96	0.97	0.93	0.15	0.88	0.73	0.74	0.60	0.98	0.91	0.40	0.71	0.96	0.68	0.91
2006	0.66	0.13	0.93	0.70	0.64	0.59	0.38	0.17	0.16	0.60	0.60	0.49	0.70	0.68	0.43
2007	0.18	0.13	0.87	0.15	0.64	0.41	0.17	0.76	0.16	0.10	0.85	0.23	0.24	0.22	0.02
2008	0.18	0.65	0.59	0.43	0.20	0.59	0.38	0.60	0.41	0.34	0.40	0.49	0.24	0.22	0.18
2009	0.18	0.39	0.76	0.43	0.20	0.21	0.17	0.39	0.16	0.34	0.75	0.23	0.24	0.83	0.43
2010	0.18	0.39	0.14	0.43	0.43	0.41	0.38	0.39	0.16	0.34	0.19	0.49	0.24	0.47	0.18
2011	0.02	0.13	0.02	0.15	0.64	0.41	0.58	0.03	0.16	0.01	0.19	0.03	0.04	0.22	0.43
2012	0.43	0.39	0.36	0.43	0.43	0.41	0.58	0.60	0.65	0.34	0.95	0.49	0.04	0.47	0.66
2013	0.43	0.39	0.59	0.43	0.43	0.41	0.38	0.39	0.41	0.60	0.40	0.71	0.70	0.47	0.43
2014	0.43	0.39	0.14	0.43	0.43	0.73	0.17	0.39	0.65	0.01	0.40	0.23	0.91	0.47	0.43
2015	0.82	0.83	0.59	0.70	0.78	0.90	0.58	0.76	0.96	0.80	0.85	0.86	0.70	0.91	0.66
2016	0.18	0.13	0.14	0.15	0.20	0.21	0.58	0.17	0.16	0.34	0.19	0.49	0.24	0.22	0.18
2017	0.96	0.97	0.14	0.70	0.64	0.41	0.38	0.39	0.41	0.91	0.19	0.49	0.49	0.22	0.98

Table 5.9 Yearly water balance for irrigation scenarios

Location & Soil Type / Water balance component	Site B: FAO subsoil O1				Site B: Silt Loam				Site F:Sandy Loam			
	In mm		In % of precipitation		In mm		In % of precipitation		In mm		In % of precipitation	
Irrigation scenario	I6	I2	I6	I2	I6	I2	I6	I2	I6	I2	I6	I2
ET Kharif	340	340	53%	53%	333	333	52%	52%	338	338	52%	52%
ET Rabi	274	142	42%	22%	273	141	42%	22%	259	127	40%	20%
GW Recharge from Rainfall	299	300	46%	46%	308	308	48%	48%	301	302	47%	47%
Blue water (Rabi)	261	104	41%	16%	261	104	41%	16%	259	104	40%	16%
Green water (Rabi)	12	38	2%	6%	11	37	2%	6%	0	23	0%	4%
P	645	645	-	-	645	645	-	-	645	645	-	-

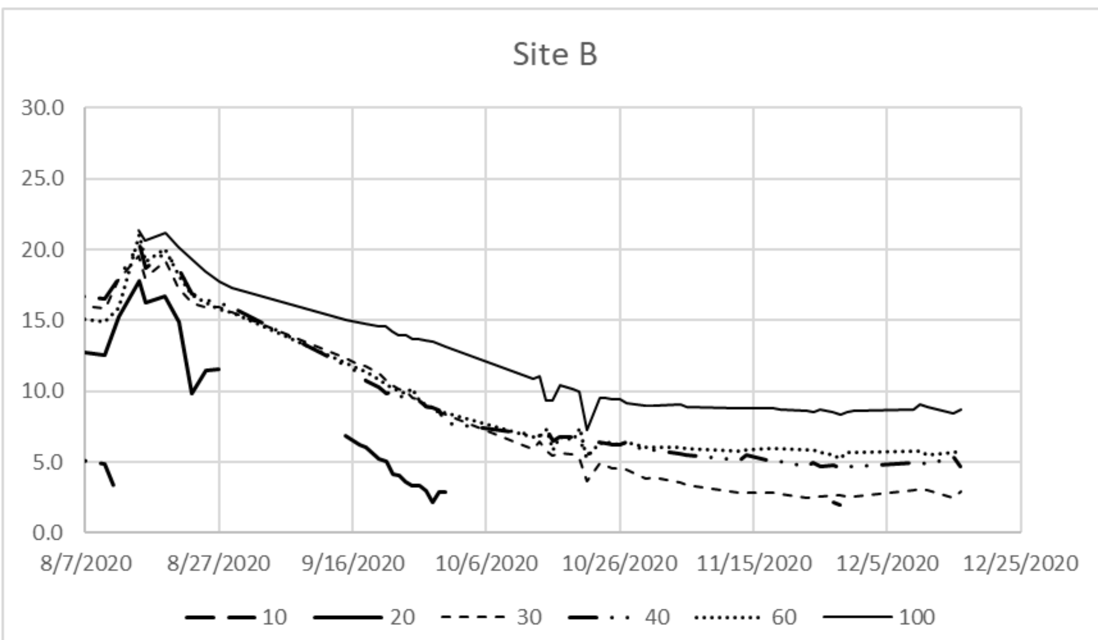


Figure 5.3: Soil moisture site B

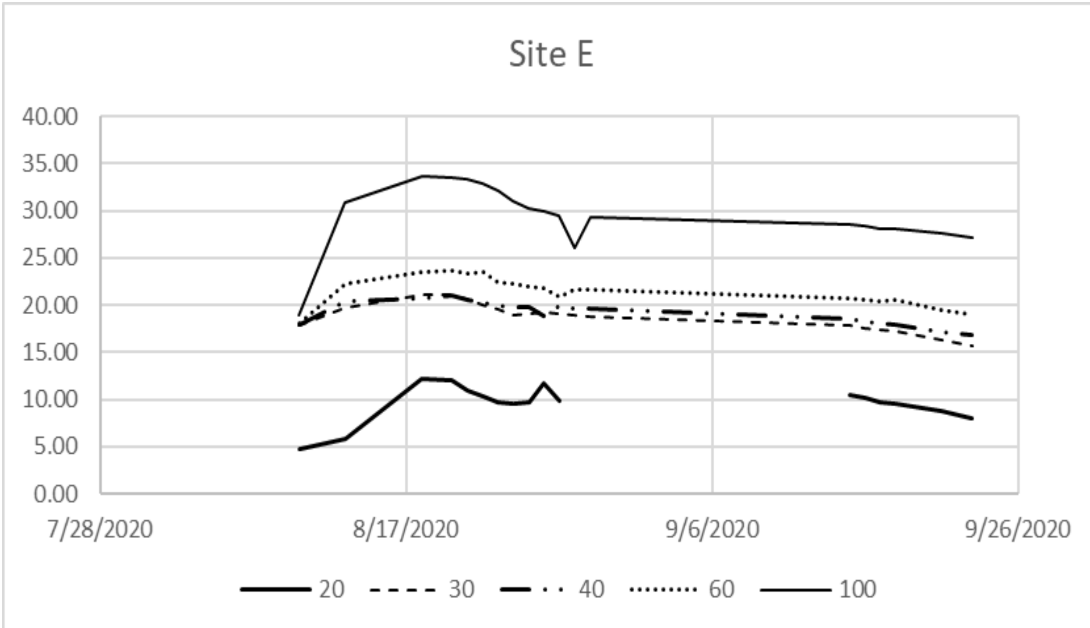


Figure 5.4: Soil moisture site E

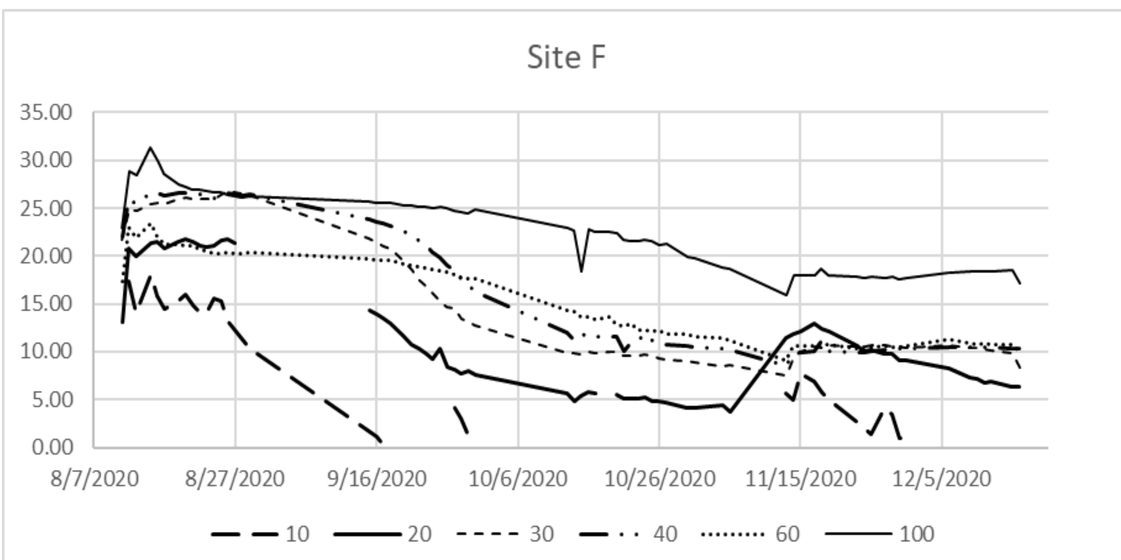


Figure 5.5: Soil moisture site F

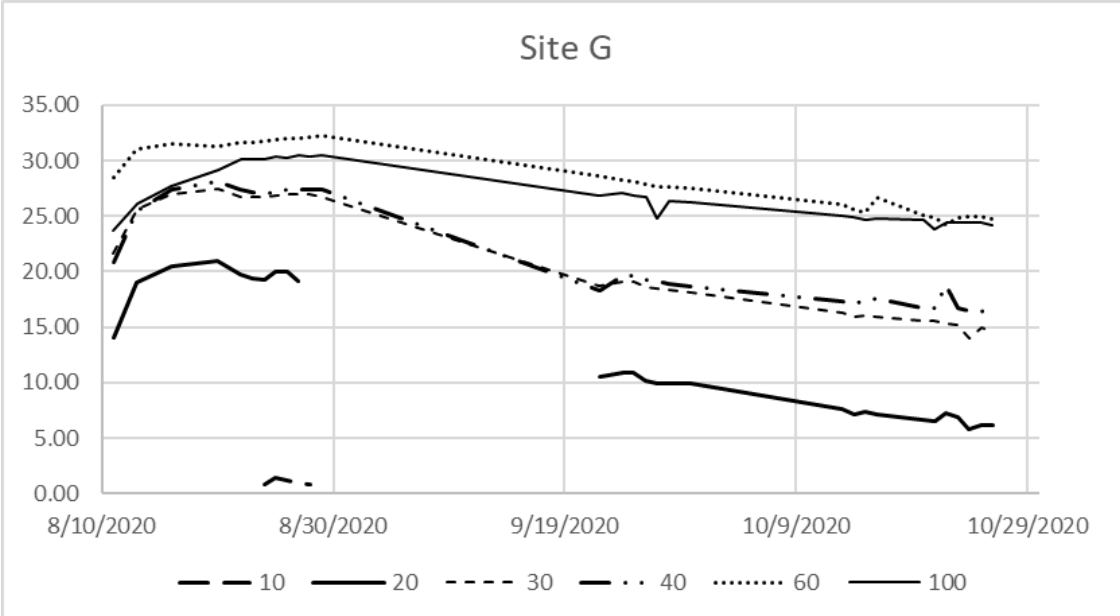


Figure 5.6: Soil moisture site G

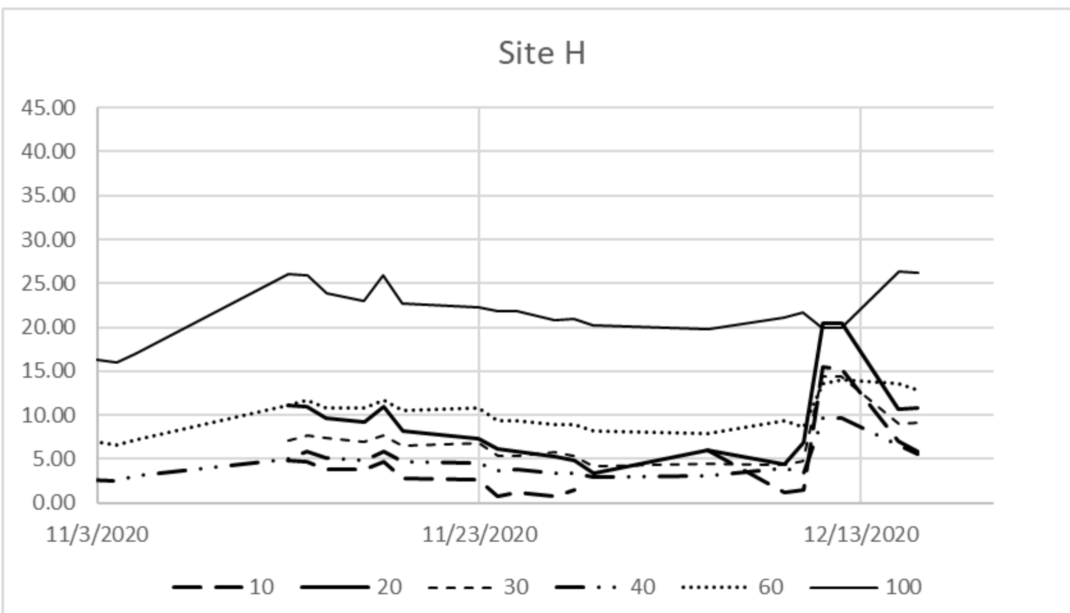


Figure 5.7: Soil moisture site H

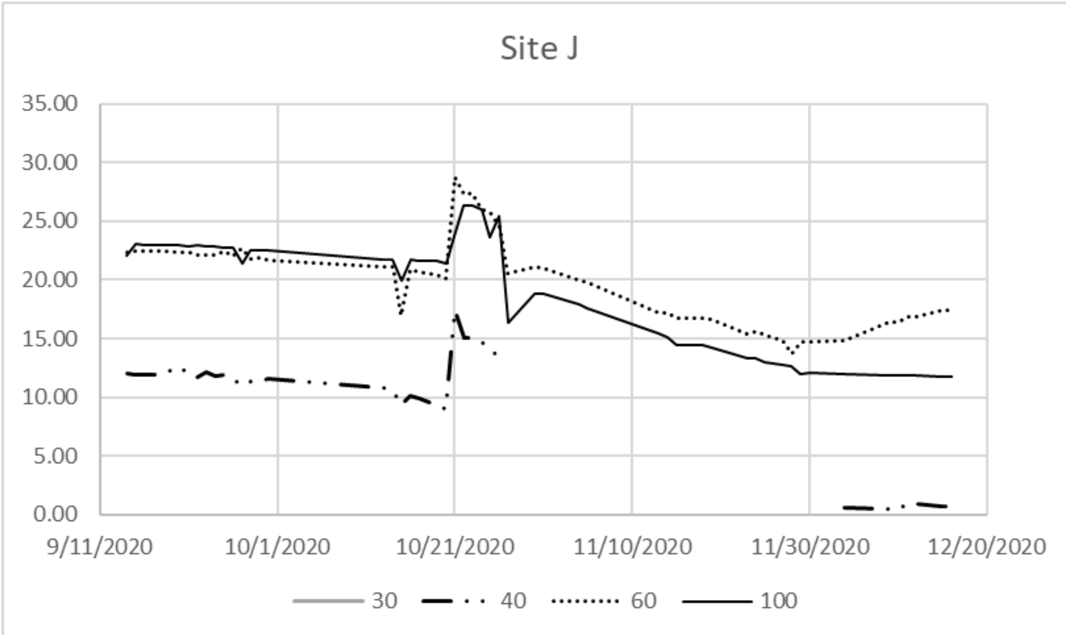


Figure 5.8: Soil moisture site J

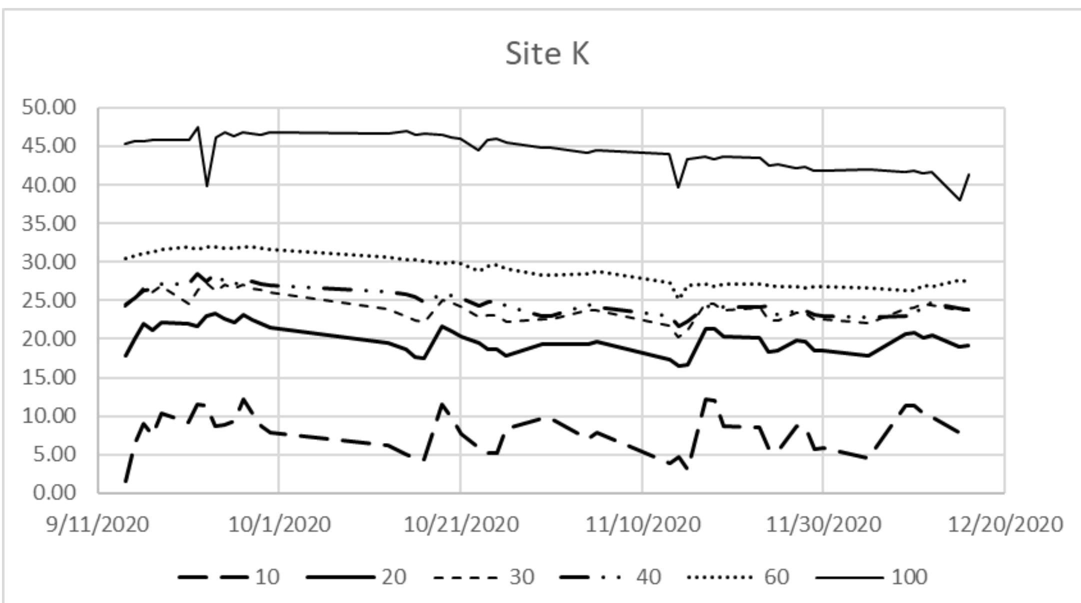


Figure 5.9: Soil moisture site K

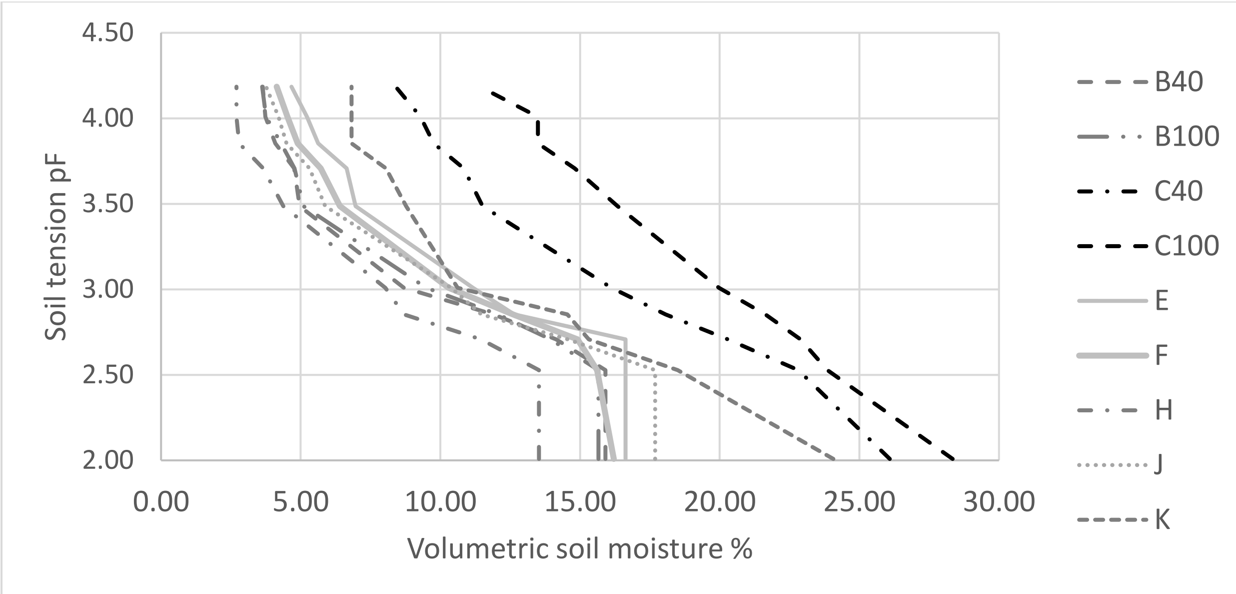


Figure 5.10: Soil moisture characteristics curves

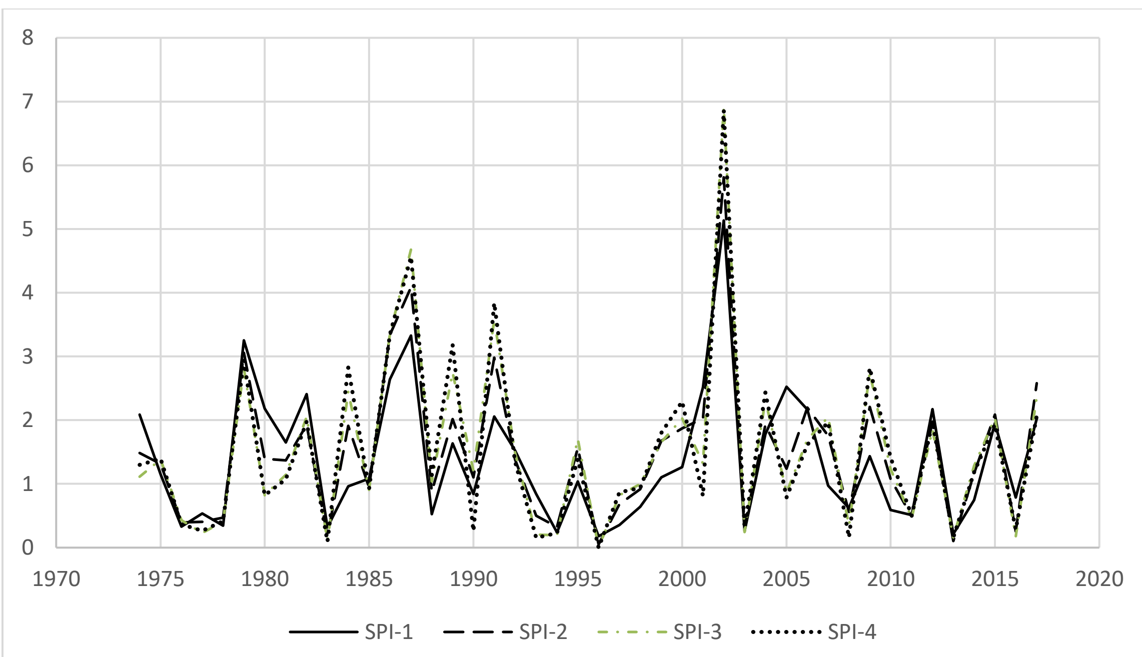


Figure 5.11: Average drought magnitude SPI-1 to SPI-4

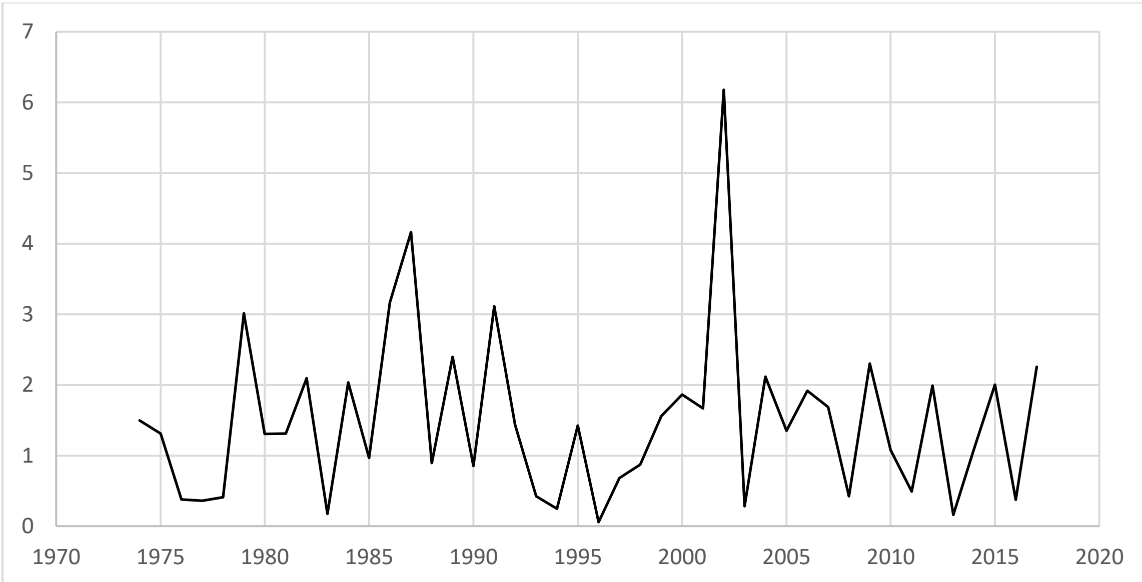


Figure 5.12: Average drought magnitude

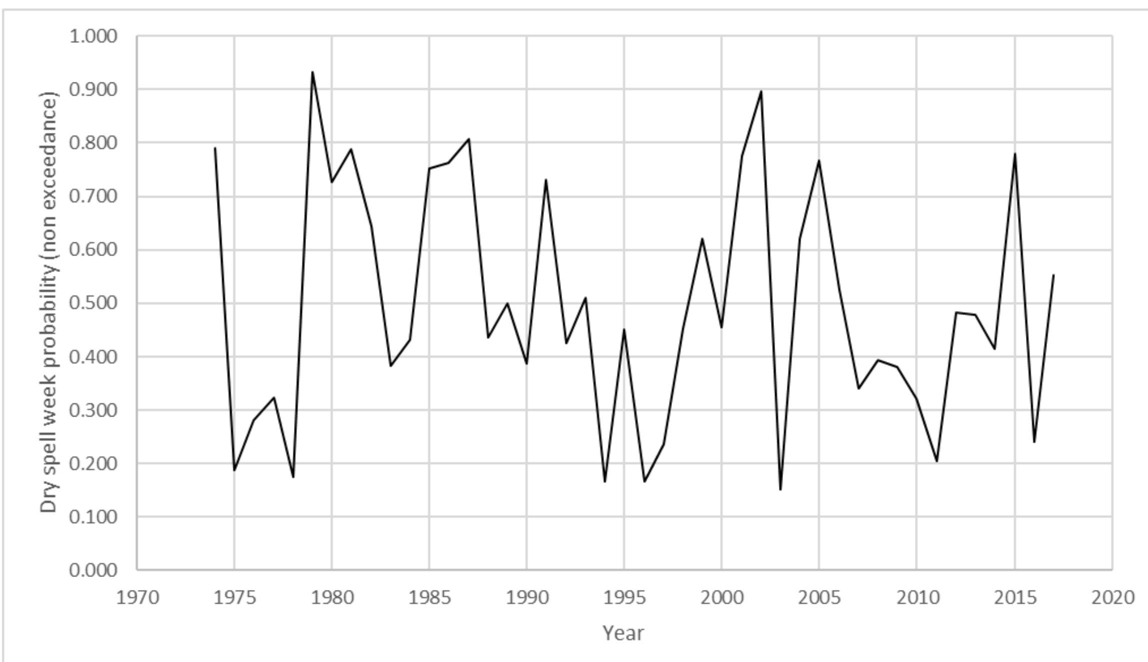


Figure 5.13: Yearly average dry spell week probability (non-exceedance)

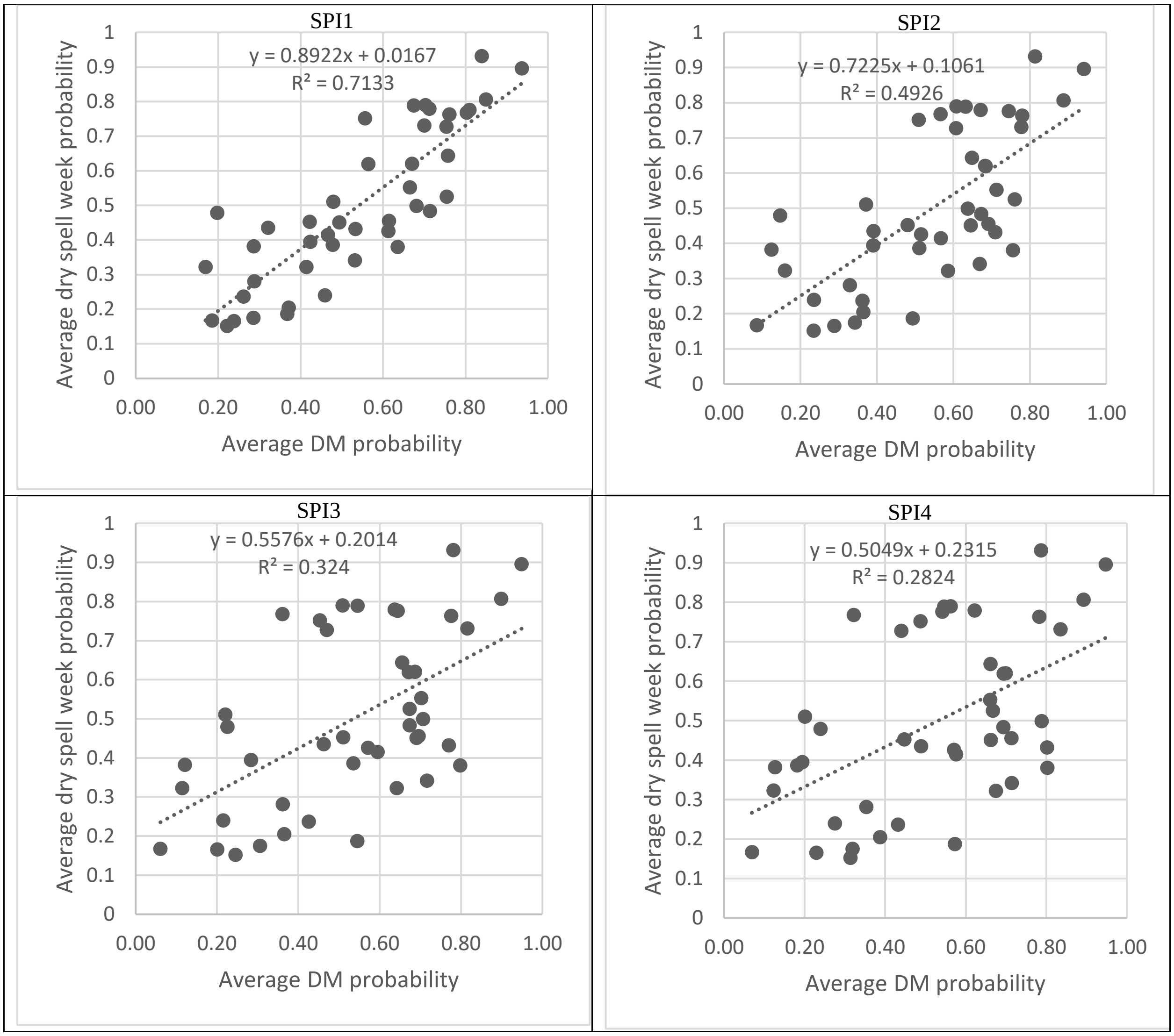
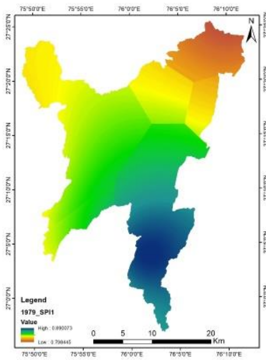
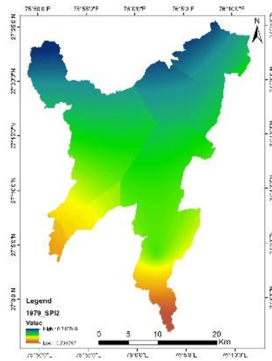
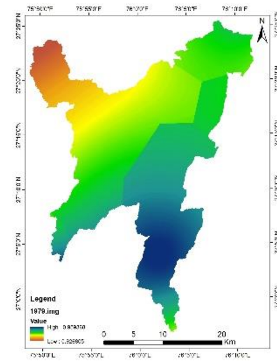
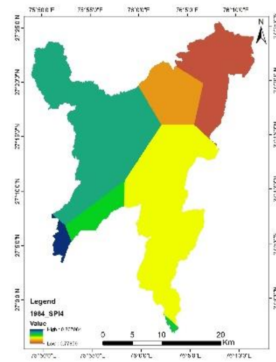
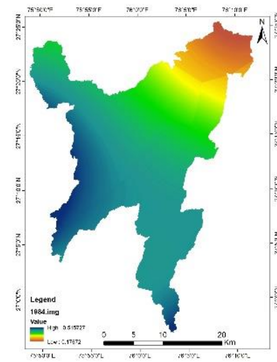
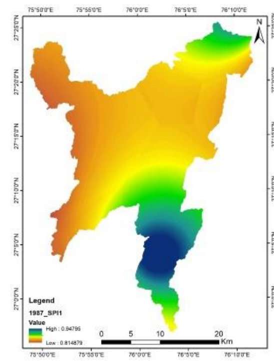
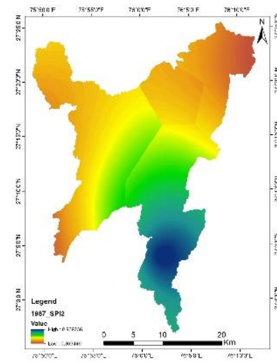
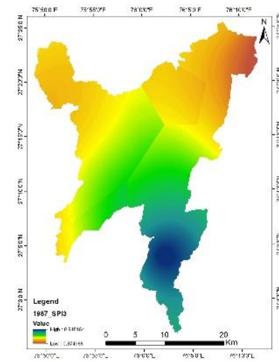
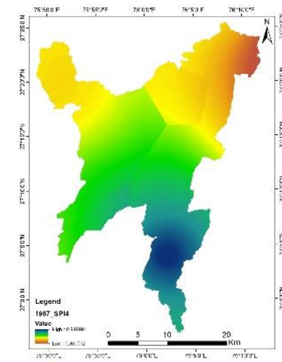
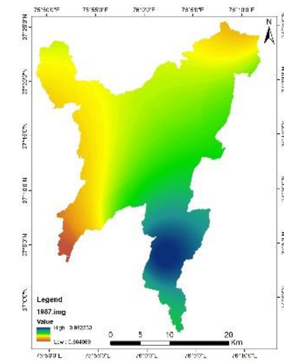
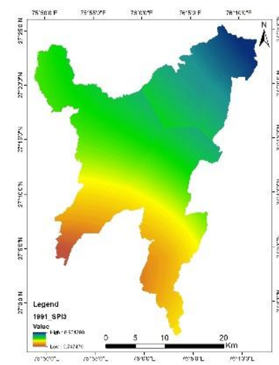
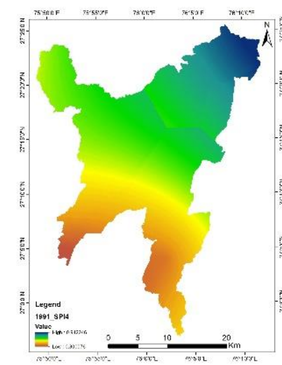
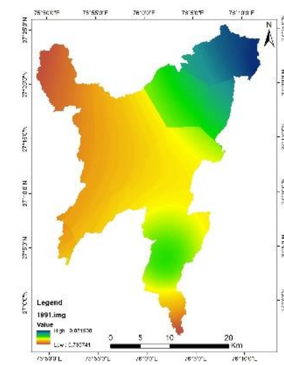
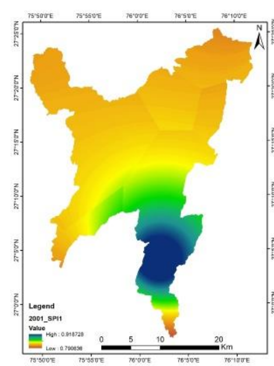
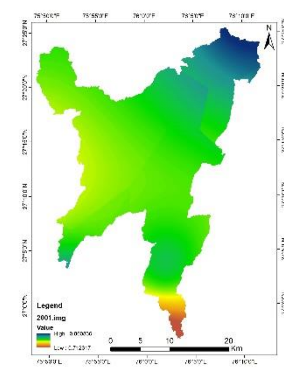


Figure 5.14: Relationship between average probability of DM and dry spell week

SPI1_Avg_DM_Probability	SPI2_Avg_DM_Probability	SPI3_Avg_DM_Probability	SPI4_Avg_DM_Probability	Avg_Dry Spell Week_Probability	Year
					1979
					1984

					1987
					1991
					2001

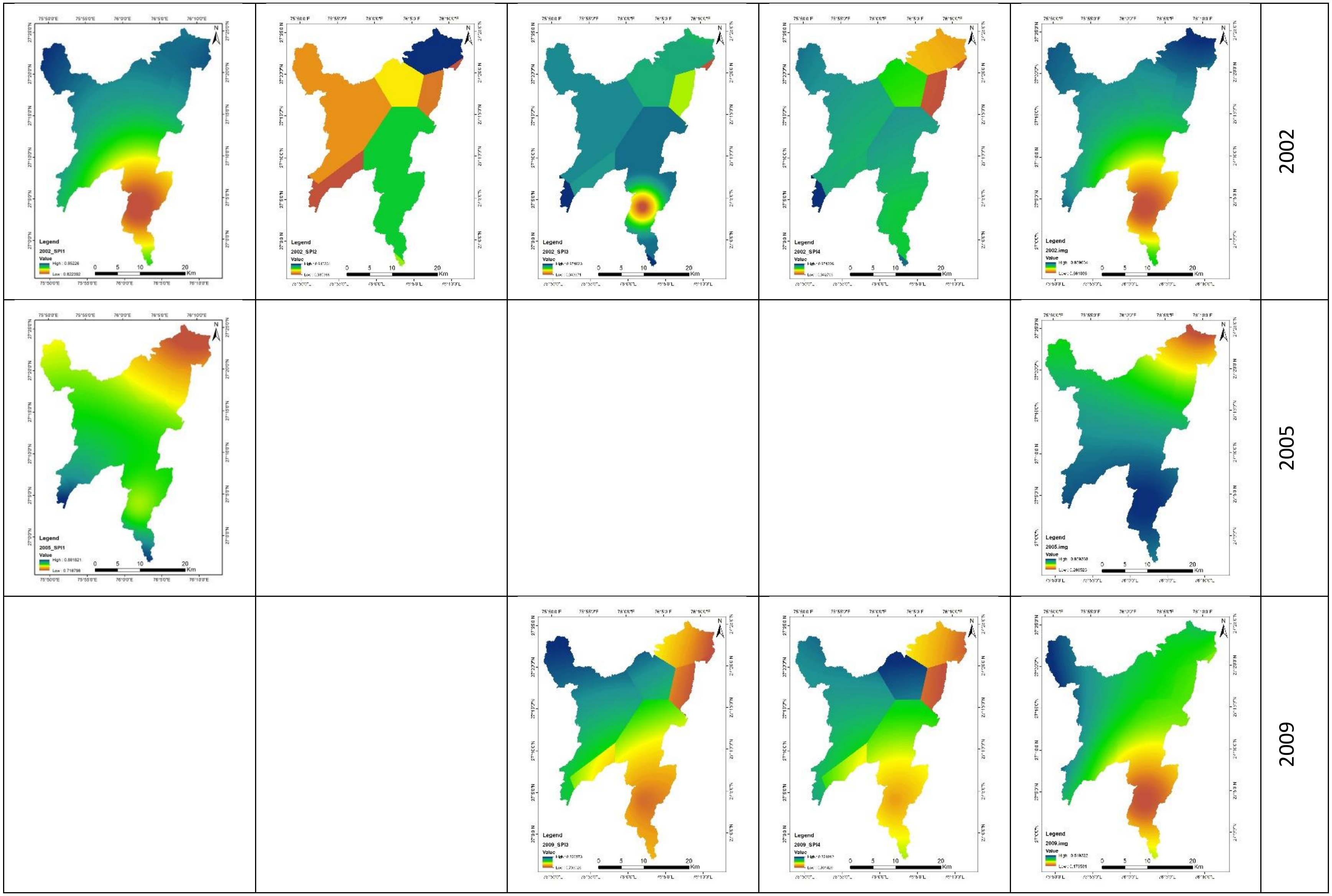


Figure 5.15: Average yearly DM probability >80% in SPI-1,2,3,4 and maximum dry spell weeks' probability

Figure 5.16 (a): Kharif season MOD13Q1 16-day NDVI

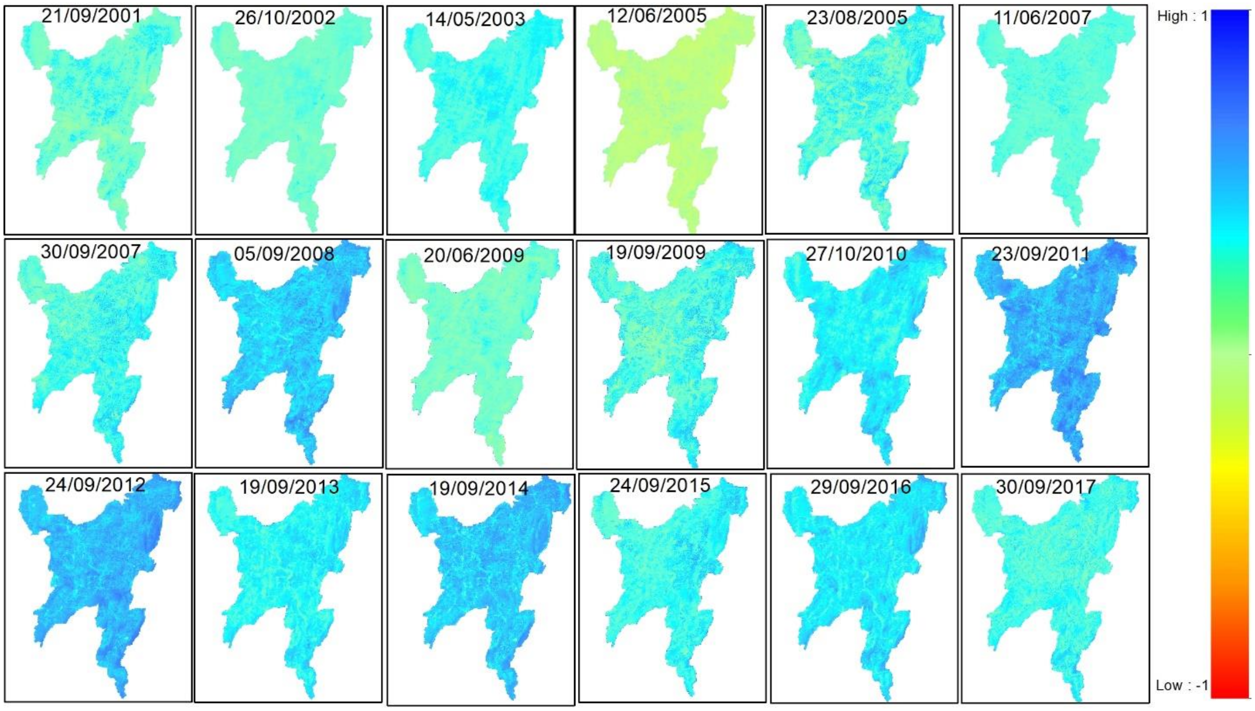


Figure 5.16 (b): Kharif season IRS_LISSIII NDVI

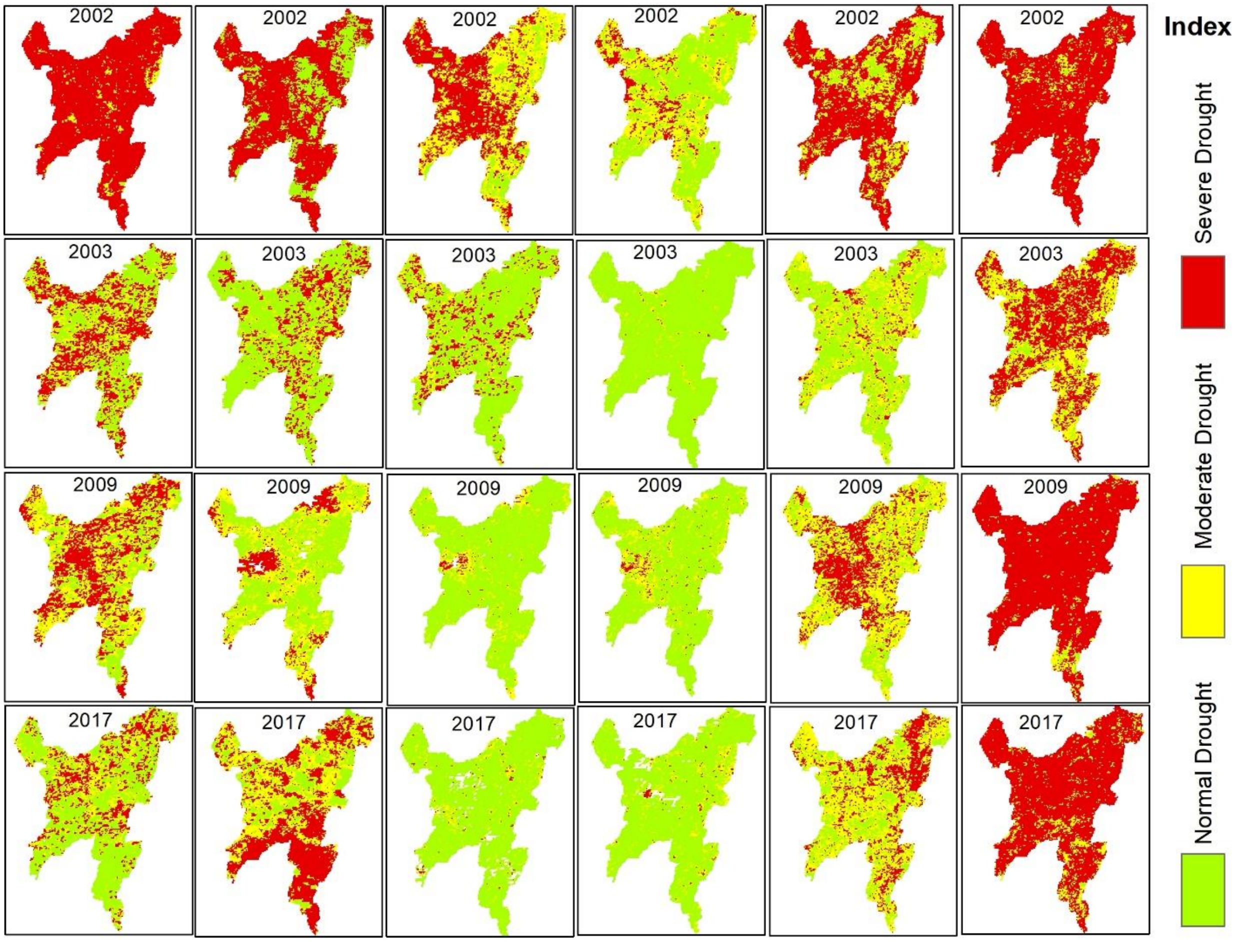


Figure 5.17 (a): Kharif season MOD13Q1 16-day VCI

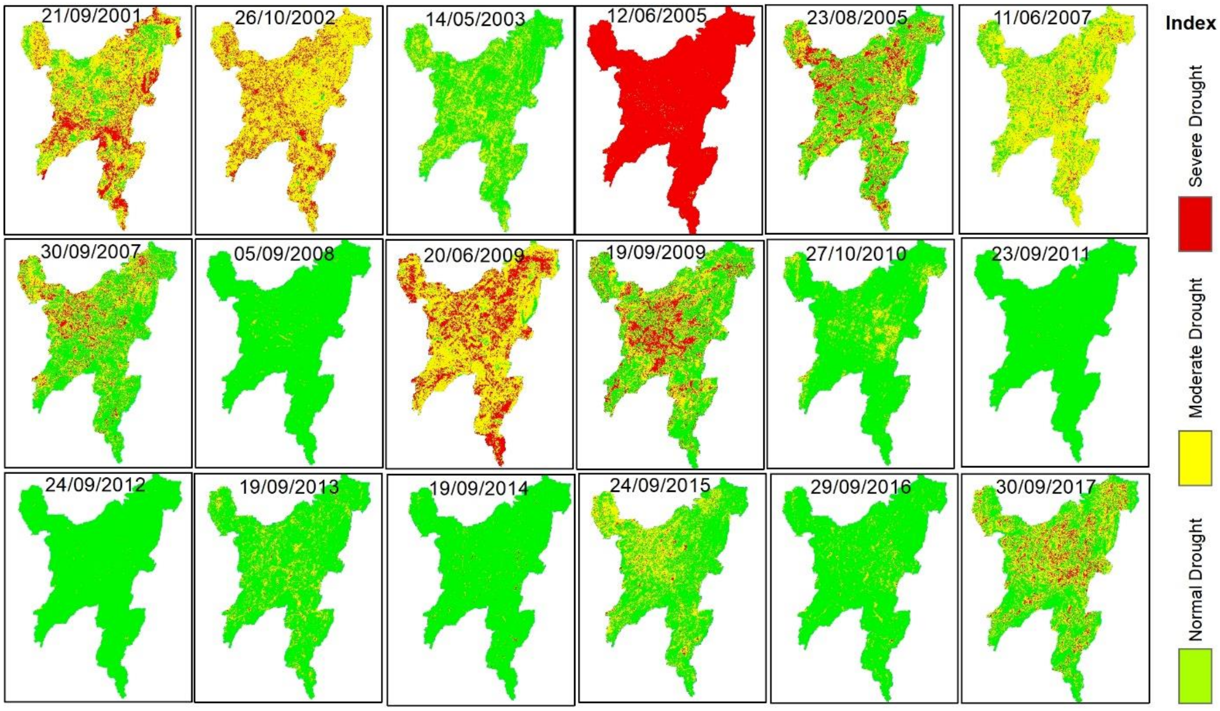


Figure 5.17 (b): Kharif season IRS_LISSIII VCI

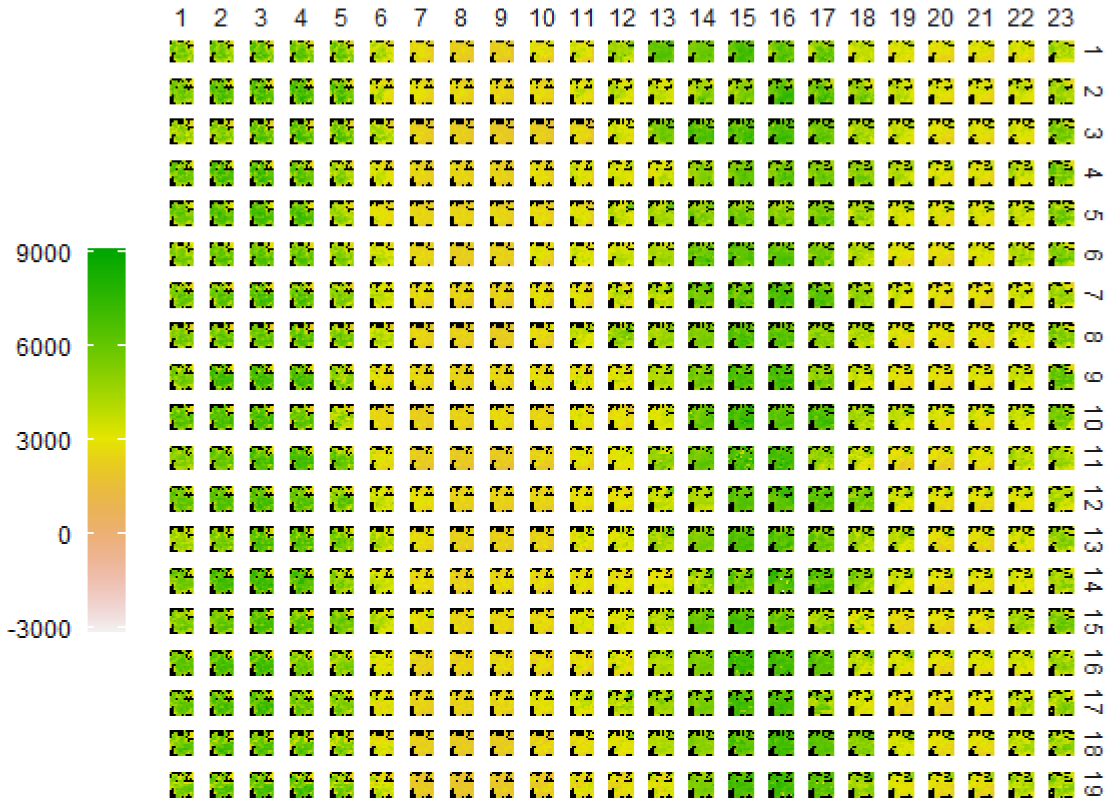


Figure 5.18 (a): Vegetation masked MOD13Q1 16-day NDVI

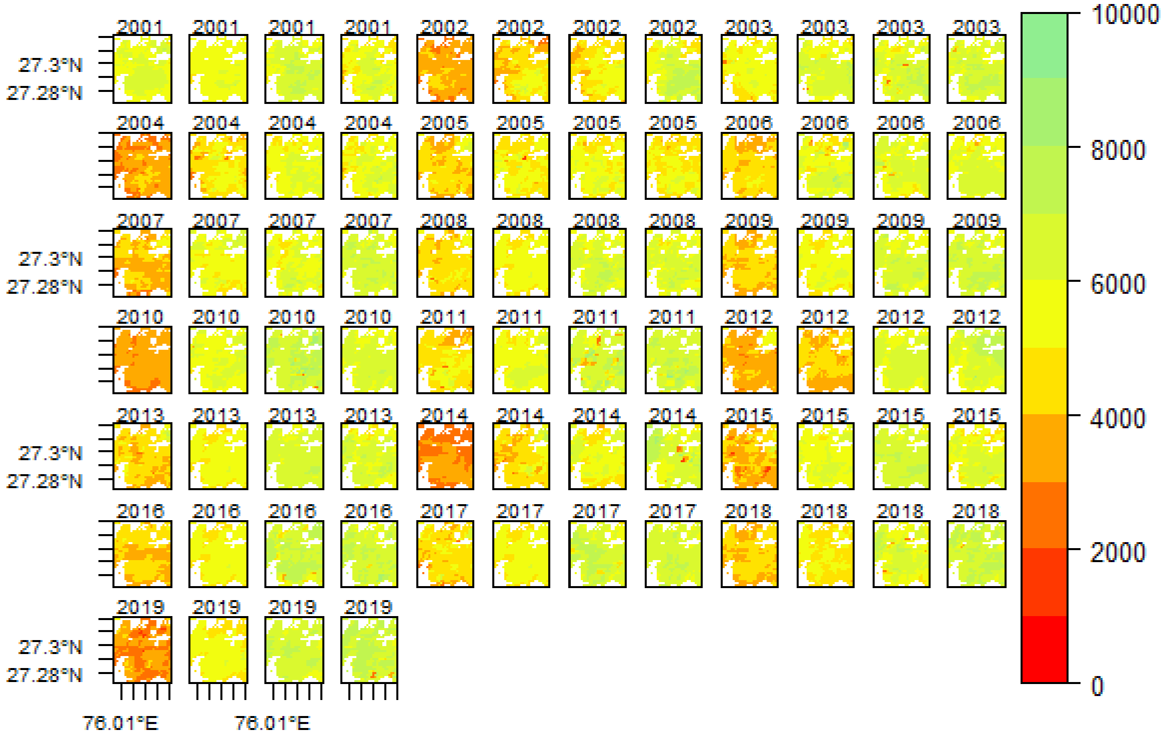


Figure 5.18 (b): Kharif season MOD13Q1 16-day NDVI

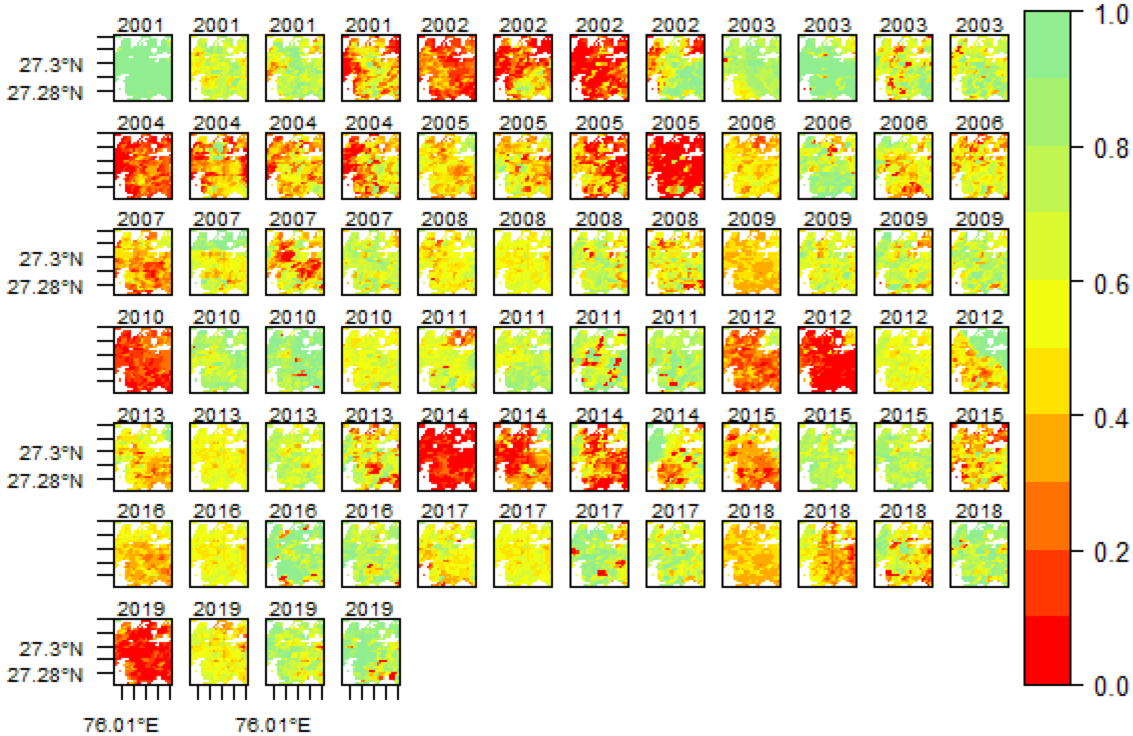


Figure 5.18 (c): Kharif season MOD13Q1 16-day VCI

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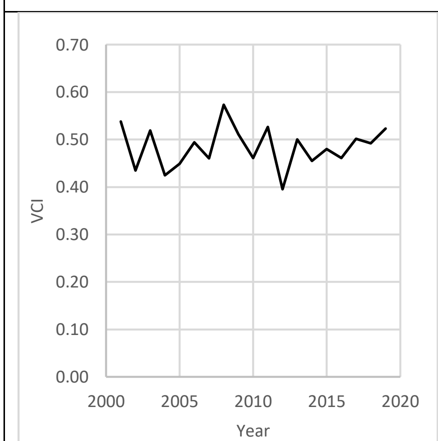
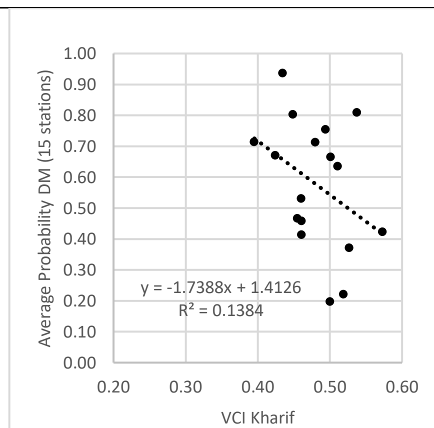
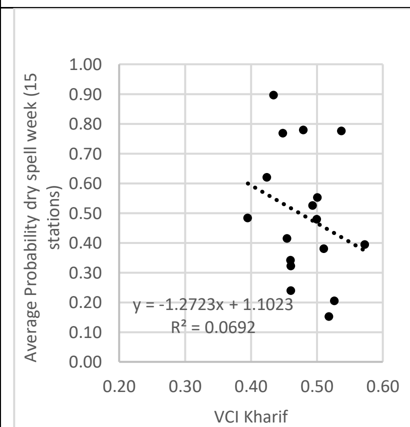
<tr><td>
</td><td>
</td><td>
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<tr><td colspan="3">Sample 1_MODIS</td></tr>
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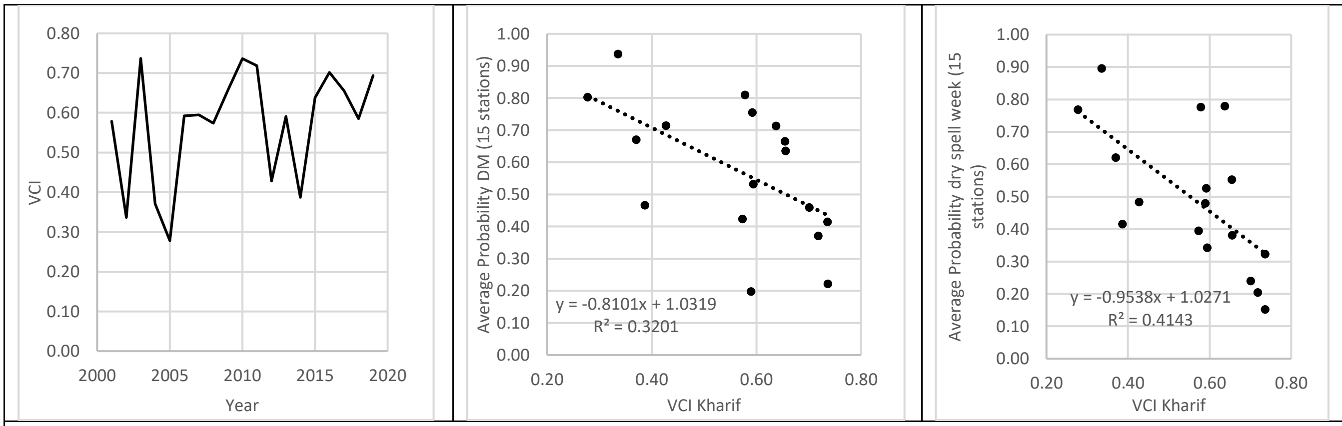

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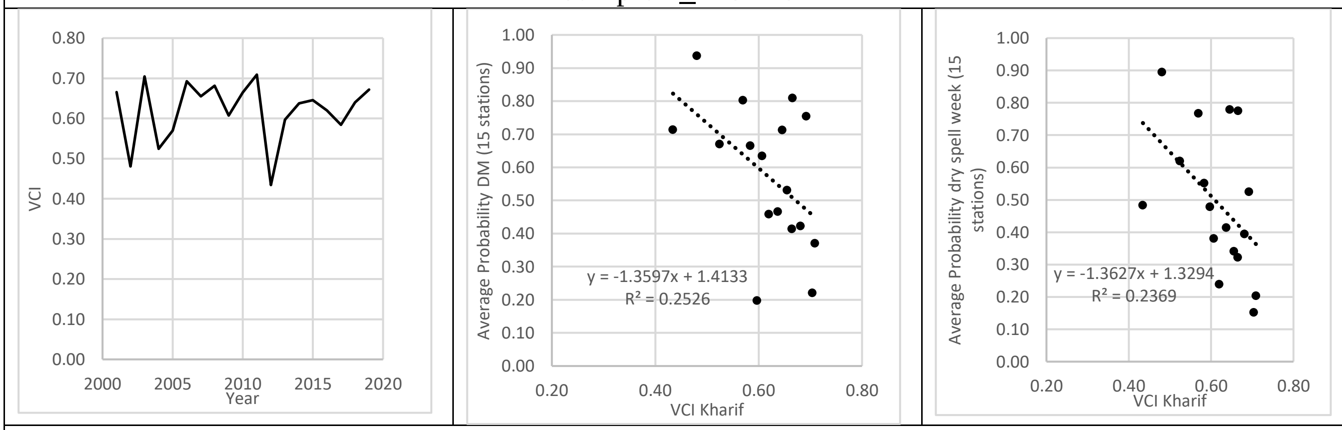
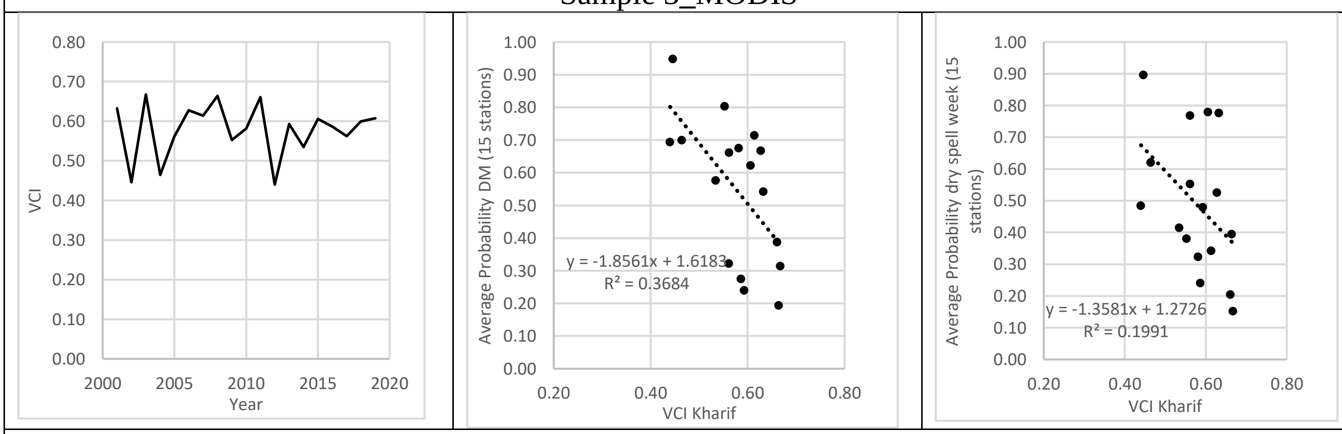
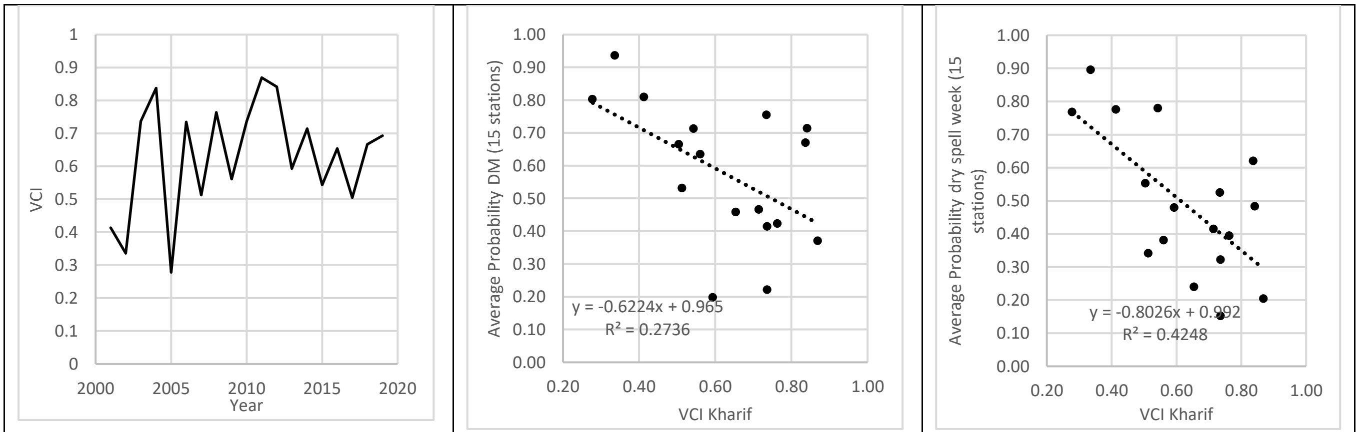


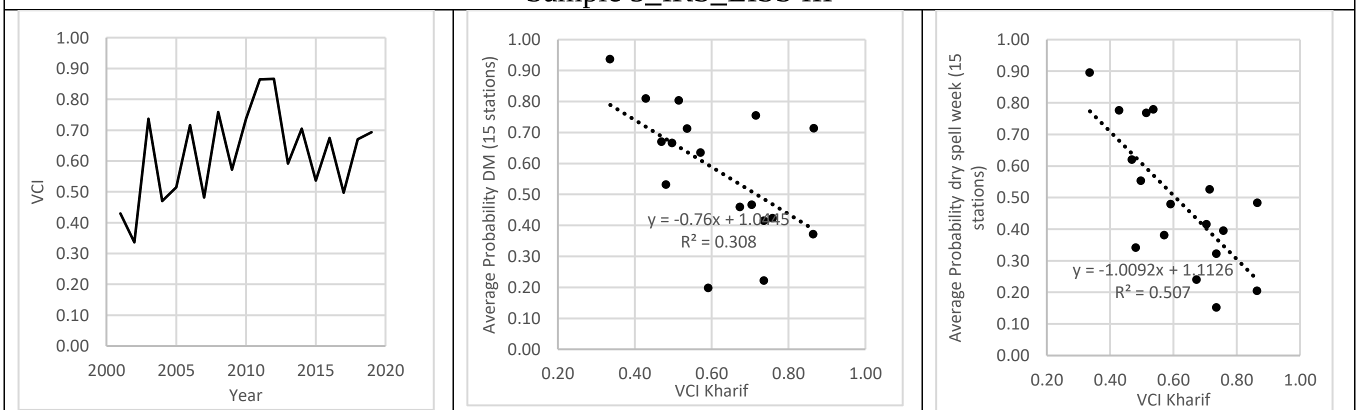
Sample 3_MODIS



Sample 4_MODIS



Sample 5_IRS_LISS III



Sample 6 _IRS_LISS III

Figure 5.19: VCI, Relation between VCI Kharif and average probability DM or average probability dry spell week

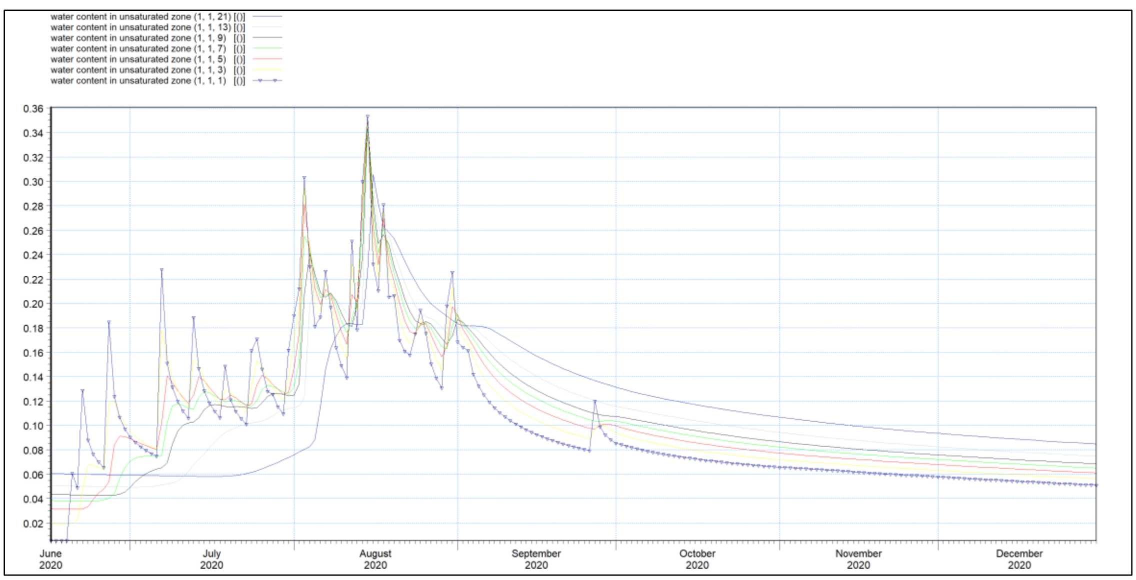
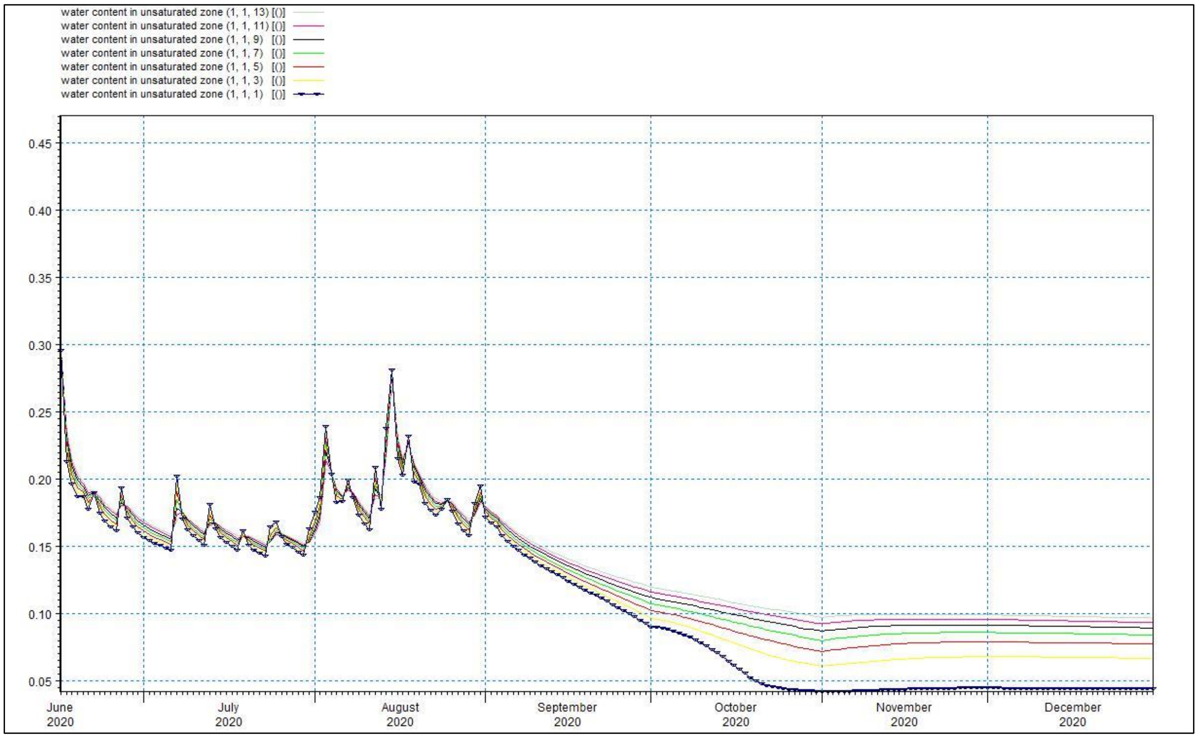
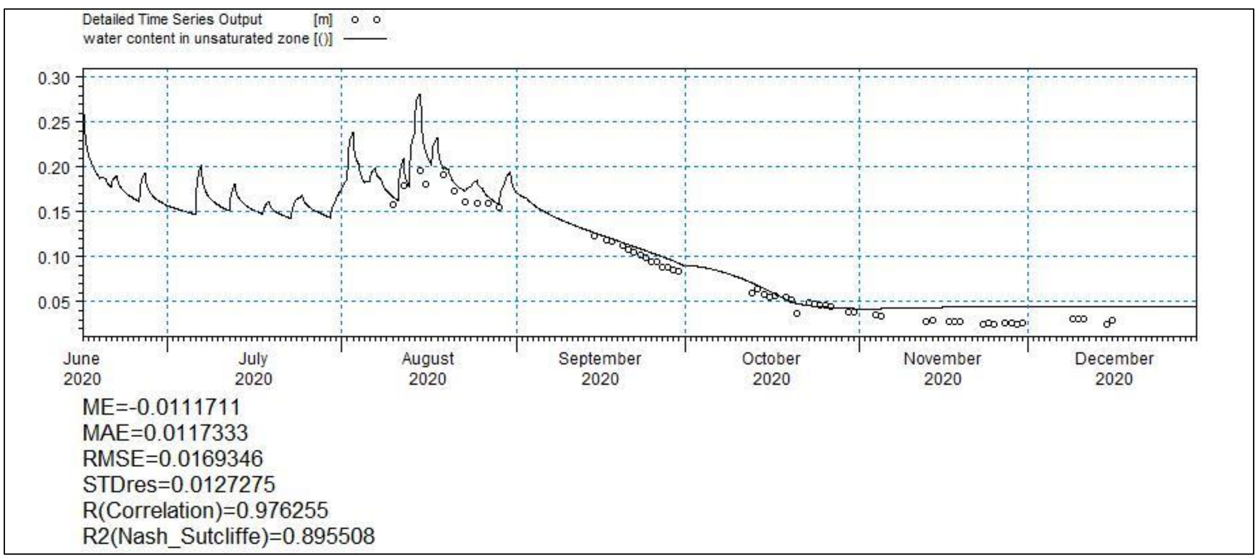


Figure 5.20: Unsaturated zone simulation for site B (FAO Subsoil O1)

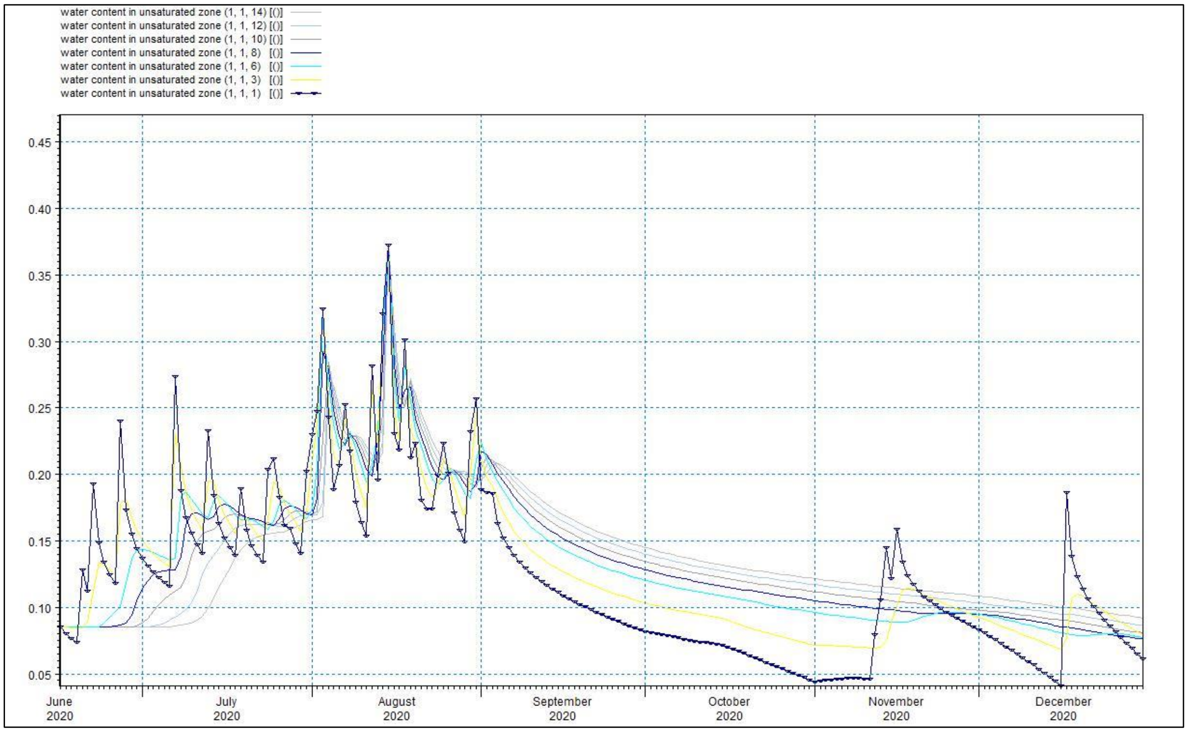


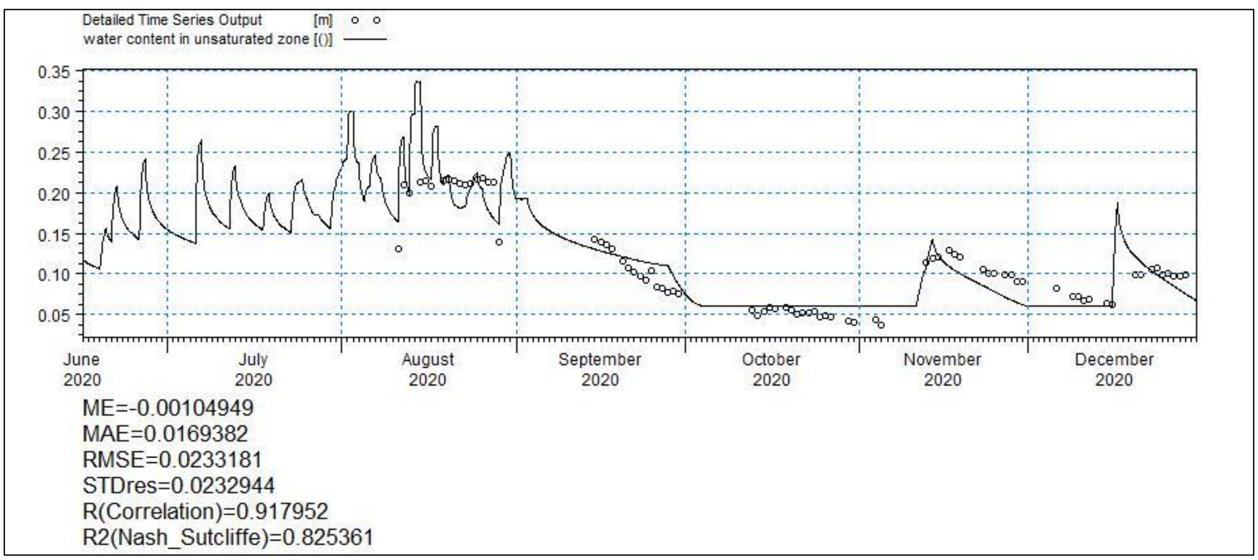


Simulation Statistics

Name	Data type	ME	MAE	RMSE	STDres	R (Correlation)	R2 (Nash_Sutcliffe)
Site B	water content in unsaturated zone	-0.011	0.0117	0.017	0.0127	0.97	0.89

Figure 5.21: Unsaturated zone simulation for site B





Simulation Statistics

Name	Data type	ME	MAE	RMSE	STDres	R(Correlation)	R2(Nash_Sutcliffe)
Site F	water content in unsaturated zone	-0.001	0.017	0.023	0.023	0.92	0.82

Figure 5.22: Unsaturated zone simulation for site F

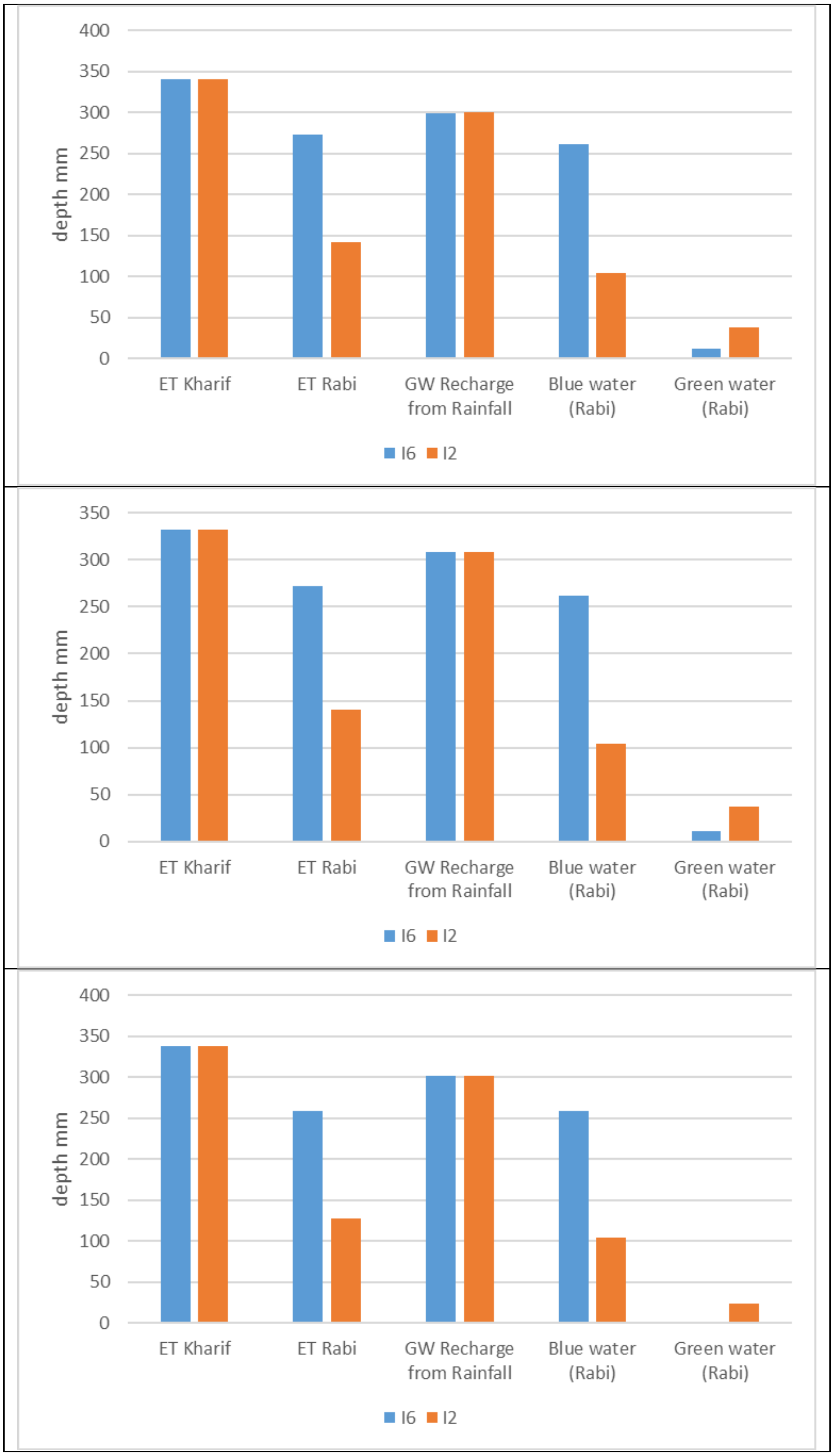


Figure 5.23: Scenario yearly water balance in mm

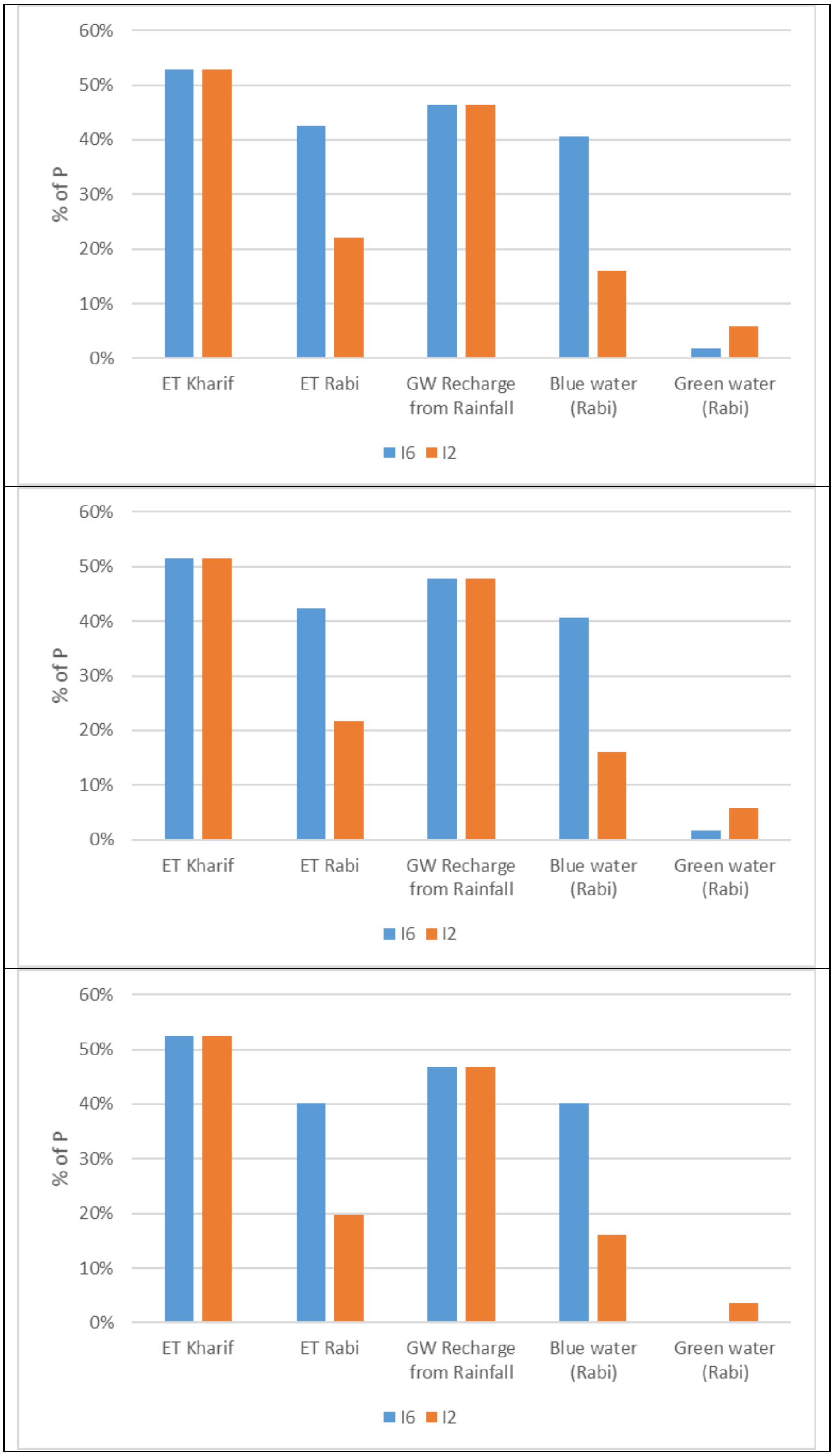


Figure 5.24: Scenario water balance in % of precipitation

Regionalizing drought indices

The different combinations of clusters are formed and forcefully divided into 2, 3 and 4 classes as shown in Figure 5.25 (a-g). On the basis of these combinations we found that cluster distribution of the variables is almost of similar type and pattern. The various combinations of clusters are spatially and statistically correlate with the drought magnitude and found that the whole region is in hydrologically similar catchment. So we can say regionality may not be the reason of drought like situation in that area.

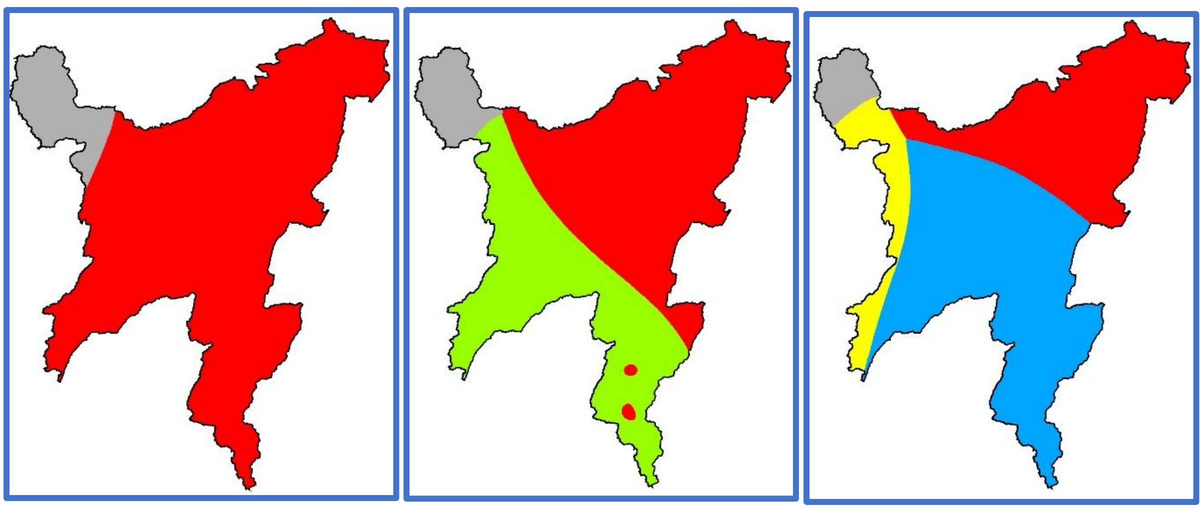


Figure 5.25 (a): Clusters of monsoon months and annual rainfall

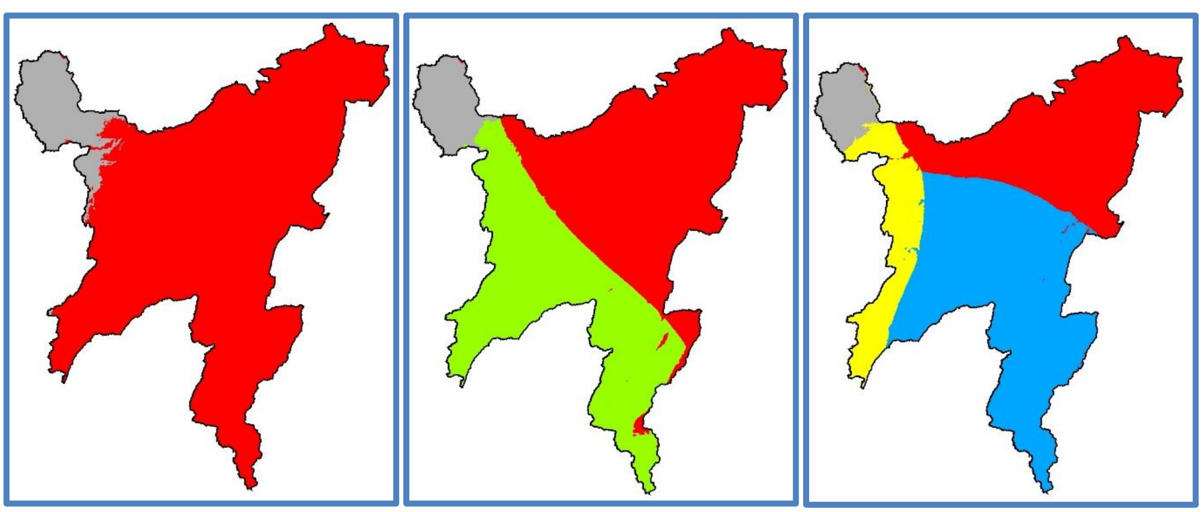


Figure 5.25 (b): Clusters of monsoon months' rainfall and elevation

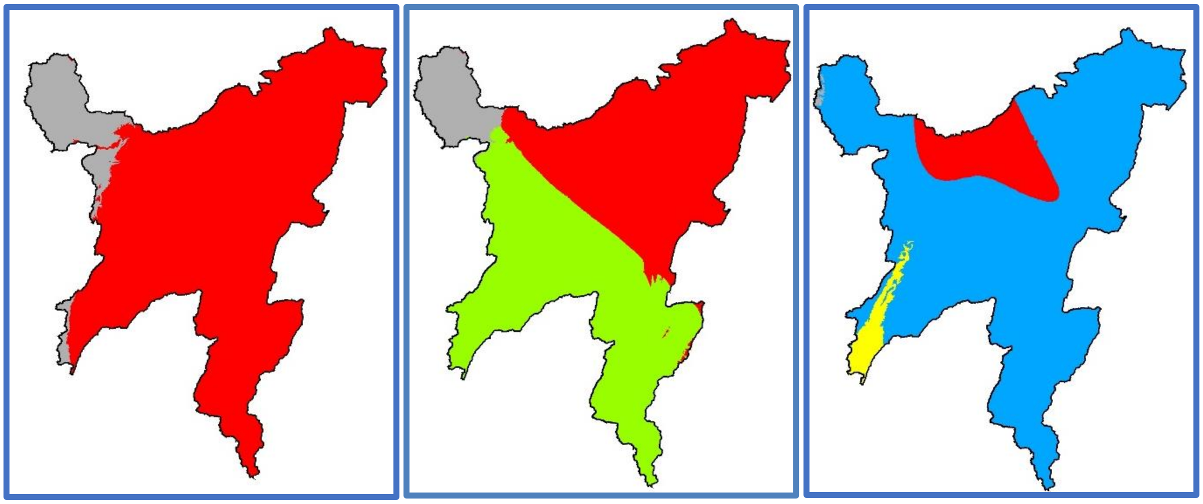


Figure 5.25 (c): Clusters of monsoon months' rainfall, elevation and location

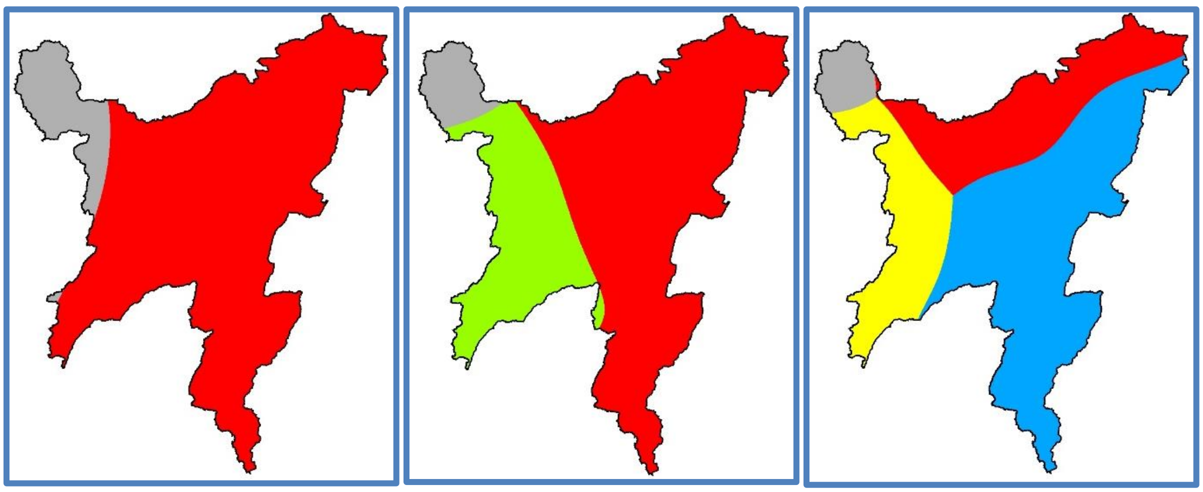


Figure 5.25 (d): Clusters of monsoon months' rainfall and temperature

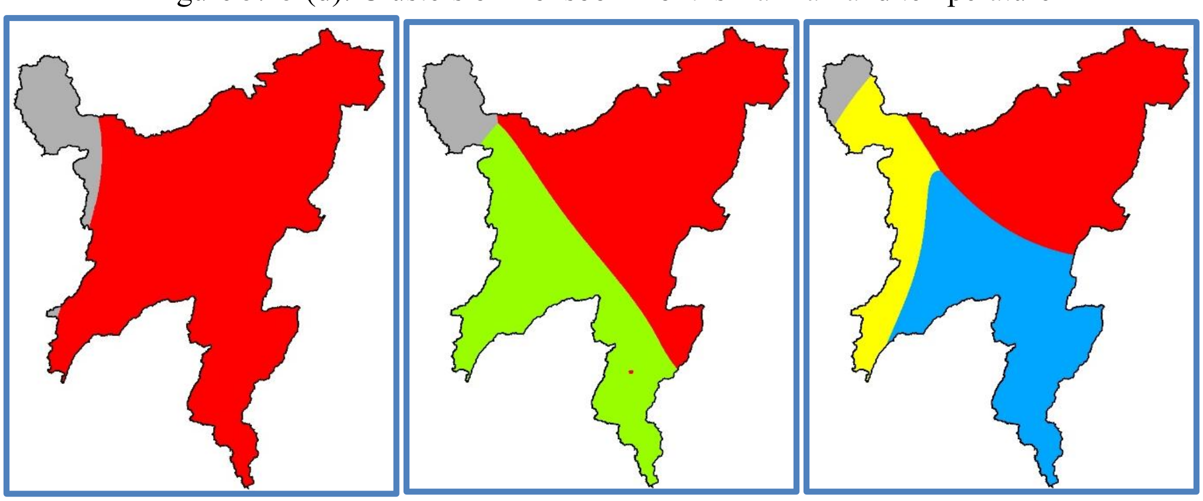


Figure 5.25 (e): Clusters of annual rainfall and temperature

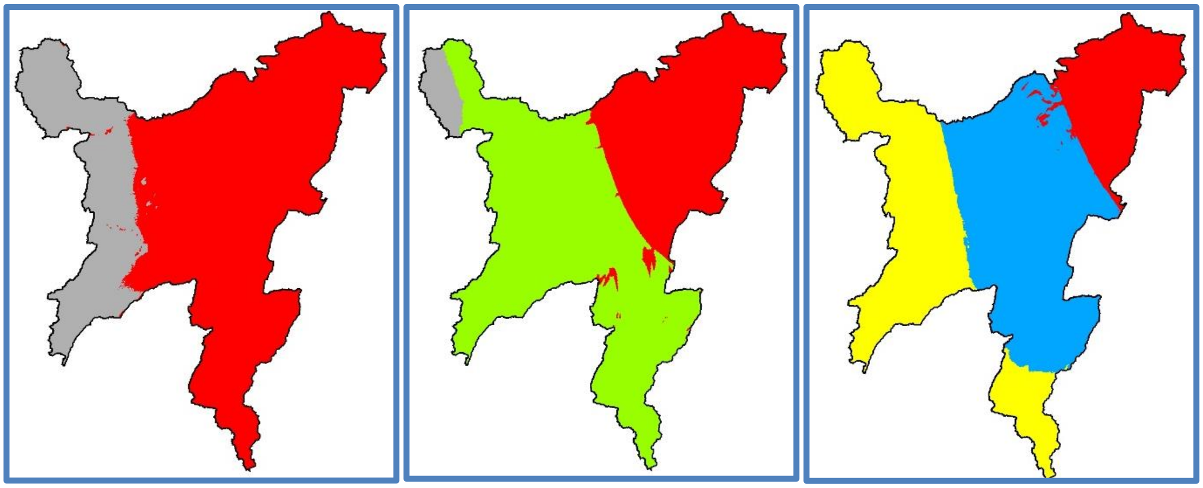


Figure 5.25 (f): Clusters of monsoon months' rainfall, temperature and elevation

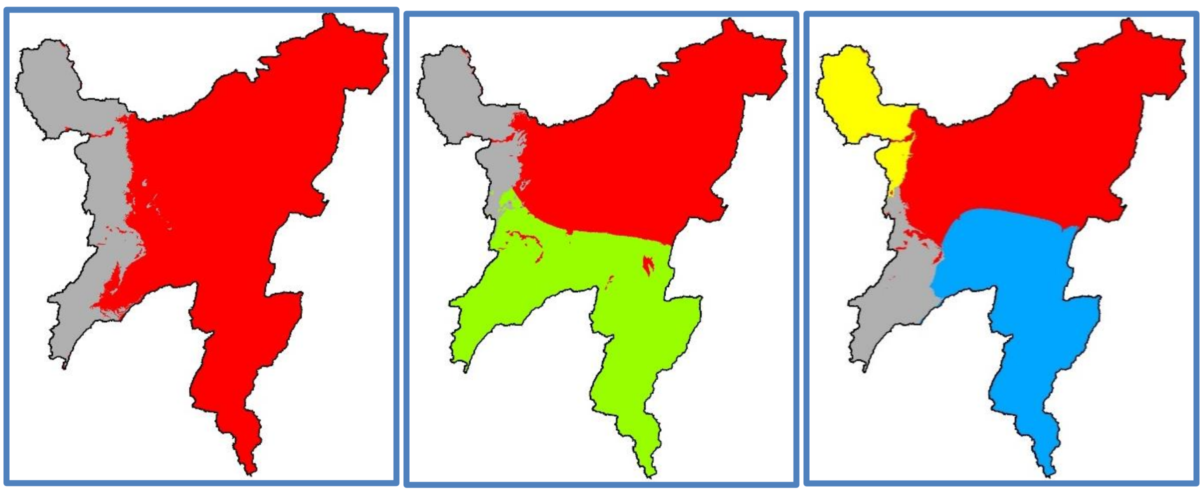


Figure 5.25 (g): Clusters of monsoon months' rainfall, temperature, elevation and location

Catchment modeling

In integrated modeling we initially, assigned the zero value for manning's roughness coefficient means no overland flow.Then the simulation results were nearly similar as that for model with only groundwater simulation model. Additionally, SZ exchange with river was simulated at the cells nearby river network. The value was of order of 0.05 cumec. SZ drainage from point is zero. Nearly up to 4 m flood depth occurred in few cells. Depths were more in northeast pediment area. In two inland depressions maximum flooding depth was 5- 20 m. The SZ elevation contours were smooth. Groundwater level declines up to 1 m in simulation period at few locations. Yearly fluctuation is up to 0.5 m. Quick changes were seen in at a grid in Jamwa Ramgarh, which indicated inundation in the cell. At the outlet maximum simulated discharge was nearly 240 cumec and occurred in 1981. Peak discharge in 1985 was nearly 120 cumec. In very few cell flooding occurred up to 4 m, which may be due to definition of local depression in the model setup. The minimum depth of water table at the end of simulation was nearly up to the ground level. In some of the inland basins groundwater mounds can be clearly seen. Contribution of baseflow to the river was higher than the drainage flow.

To set the initial conditions (such as groundwater level stabilization, water movement between saturated and unsaturated zones etc.) for model calibration Initially, the model was run as hot start for period June 1,1974 to Dec 31, 1985. Boundary condition for the model is fixed head and zero-flux has been assigned. The zero-flux boundary condition is assigned to the entire catchment except for the outlet, which has assigned a fixed head boundary condition. Constant 2 hr time step have been used for simulation of different flow characteristics and hydrological modelling components (channel flow, overland flow, ET and unsaturated flow and saturated flow) in MIKE SHE. To evaluate the performance of model at calibration/validation stages, used statistical indices, like, mean absolute error (MAE), correlation coefficient (r), Nash–Sutcliffe efficiency (NSE) etc. The parameters of MIKE SHE model, for simulating stream flows at outlet, have been calibrated and validated for periods, 1974–1983 and 1984–2005, respectively. Initial values of the model parameters were chosen on the basis of existing conditions in the catchment, available information in literature and modelling perception. The model calibration has been carried out using auto-calibration technique, i.e., AUTOCAL tool of DHI package (Madsen 2003). It is a population evolution based algorithm, i.e., shuffle complex evolution algorithm, in which probabilistic Latin hypercube sampling technique is used for calibration of optimal parameters. The balance optimal values of the model parameters were selected on the basis of relationship between observed and simulated discharge. In Table 5.10, the calibrated value of C_{int} = 0.05 mm, indicates that a maximum 0.05 mm water would be retained in the interception storage (on vegetation). In unsaturated zone, θ_s for different-2 soil varies from 0.41 to 0.47 indicates maximum water available in the root zone for evapotranspiration and percolation, whereas θ_{fc} = 0.11, 0.12 & 0.29 indicates the maximum water content available in the root zone to meet the vegetative evapotranspiration requirements, θ_{wp} = 0.05 & 0.06 specifies the limit of water content in unsaturated zone up to which the plants can extract the moisture from the soil without wilting, K_s varies between 0.2×10^{-3} to 1.17×10^{-6} m/s indicate high to low hydraulic conductivity of soil in the catchment due to dominant agriculture land and large variation of soils properties in the unsaturated zone. For saturated zone, the calibrated values of horizontal hydraulic conductivity K_{xx} is 5.2×10^{-5} m/s and vertical hydraulic conductivity K_{yy} is 9.3×10^{-6} m/s indicates the presence of low permeable alternate bed layers like clay and bare rocks in the major part of the catchment.

Table 5.10: Calibrated parameters

Component	Parameters	Unit	Range	Initial value	Calibrated value
ET zone					
Vegetation	Leaf Area Index (LAI) (average based on land use)	-	5.00	5.00*	-
	Root Depth (RD) (average based on land use)	mm	1000	1000*	-
	C_{int}	mm	0.01 - 0.1	0.01	0.05
Surface zone and stream channel					
Channel roughness	Manning's *n*	$m^{-1/3}$ s	0.04 – 0.06	0.04	0.05
Storage	Detention storage (D_s)	mm	0.00 - 50.00	5.0	0, 20 & 50
Unsaturated zone					
Soil	Moisture content at saturation (θ_s)	-	0.35 - 0.60	0.35	0.41, 0.44 & 0.47
	Moisture content at field capacity (θ_{fc})	-	0.10 - 0.40	0.10	0.11, 0.12 & 0.29
	Moisture content at wilting point (θ_{wp})	-	0.01 – 1.0	0.01	0.05 & 0.06
	Saturated hydraulic conductivity (K_s)	m/s	1×10^{-6} - 1×10^{-3}	1×10^{-3}	0.2×10^{-4}, 1.17×10^{-6}
Saturated zone					
Hydro-geological layer (33–200 m below ground level (bgl))	Horizontal hydraulic conductivity (*Kxx*)	m/s	1×10^{-7} - 1×10^{-3}	1×10^{-4}	5.2×10^{-5}
	Vertical hydraulic conductivity (*Kyy*)	m/s	1×10^{-8} - 1×10^{-5}	1×10^{-8}	9.3×10^{-6}
	Specific yield (*Sy*)	-	0.1 – 0.3	0.1	0.2
	Storage coefficient (*Sc*)	-	.00001 - .0001	.00001	.0001

**Parameters were estimated based on existing physiography of the catchment.*

The model parameters are calibrated by varying their ranges from -50 to +50%. These parameters are quantified on the basis of generated flow data. The simulated flow was compared with observed flow for stipulated period at Ramgarh dam site for achieving the optimal values. In this study coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE), was applied to the simulated result to analyze the predictability of the simulated discharge. During calibration R^2 0.8 and NSE -0.68 was achieved as shown in Figure 26. In validation all the efficiency criteria (R^2 0.65 & NSE -0.74). Nash coefficient is poor being negative and is due to over estimation of the volume. So further modeling and observation were required to satisfying the modeling needs as shown in Figure 27. The water balance of the catchment are given in Figure 28, and its will be indicates that most of the water of the catchment are loss in form evapotranspiration (ET). The results of the model are illustrating that model is highly capable for simulating hydrological balances.

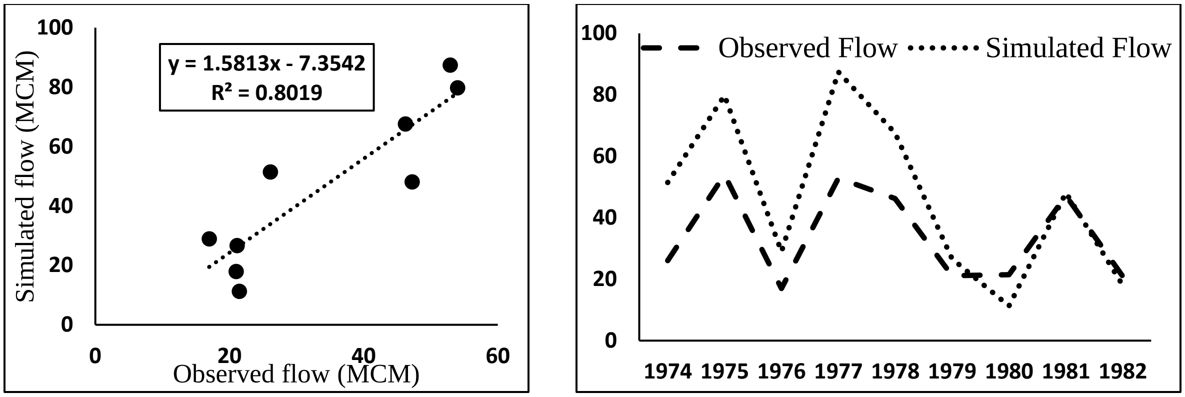


Figure 5.26: Relation between observed and simulated flow at calibration stage

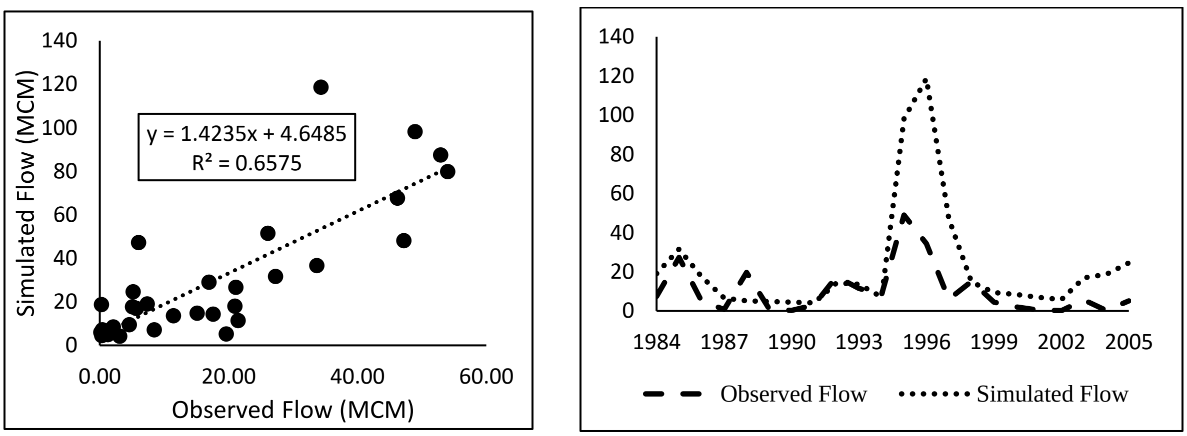


Figure 5.27: Relation between observed and simulated flow at validation stage

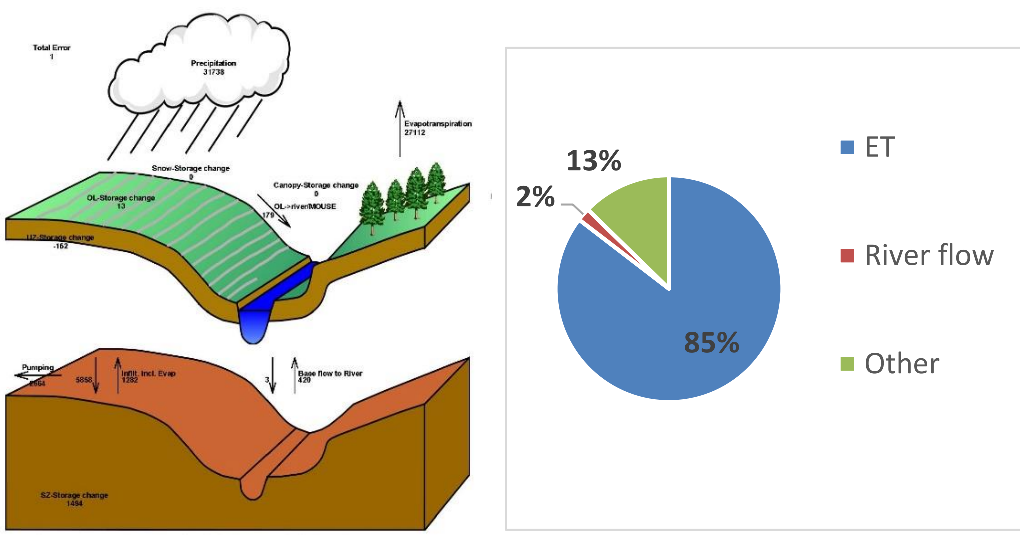


Figure 5.28: Water balance of the catchment

6.0 CONCLUSIONS

In this study rainfall trend has been evaluated on monthly (Monsoon months) and annual scale using non-parametric statistical tools namely Mann-Kendall (MK) and Sen's slope estimator for the period 1980 to 2017 (38 years). The study revealed both non-significant increasing and decreasing trends (at 95% confidence interval) at annual as well as monthly scale. Sen's Slope is also indicating increasing and decreasing magnitude of the slope in correspondence with the Mann-Kendall test values. However, Amber station showed significant increasing trend in month of June. The results indicate that there is no major impact of rainfall pattern in study area and also reveals that it may not be the reason of dryness of Jamwa Ramgarh dam.

In Jamwa Ramgarh catchment, soil moisture profiles at point scale were investigated for agriculture land. For agriculture land located in the floodplain area, the soil moisture variation was more uniform for different depths. At other locations non- uniform or nearly constant soil moisture were observed. Thus, more investigation will be necessary for understanding the soil moisture variations in the agricultural area in the basin. Through soil moisture simulation for a site the groundwater recharge, Kharif and Rabi season evapotranspiration and blue and green water could be estimated. The double cropping pattern with current flood irrigation practice was found to be non-sustainable. This will require reduction in the irrigation delta in the catchment. Drought magnitude and dry spell indices were found to be suitable in identification of major meteorological drought events. Vegetation condition index was found to have poor correlation with meteorological drought indices. Thus, further investigation will be needed to understand response of present cropping pattern and Kharif season supplementary irrigation practices, if any, in the catchment to occurrence of meteorological drought. It is also observed that the various combinations of clusters were found to be spatially and statistically correlated with the drought magnitude indicating hydrologically similarity. Moreover, the catchment is under the hydrometerological subzone 1b, hence regionality may not be the cause of drought like situation in the area. The Mike suite was calibrated and valdated to simulate the discharge for the catchment considering different efficiency criteria namely coefficient of determination (R2) and Nash-Sutcliffe efficiency (NSE) to analyze the predictability of the simulated discharge. The model is over estimated the discharge volume.

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Appendix A: Supplementary results

Table A.1 Field visits

S No	Dates	Activities	Remark
	26- 29 December 2018	• Visited Ramgarh Dam catchment area, Water Resources Department, Jaipur	
	12- 17 February 2019	• Visited various state and central govt. offices located in Jaipur and collect the data and information related to water resources structures, rainfall & GWL data etc.	
	3- 7 September 2019	• Visited 6 water resources structures, Department of Agronomy, RARI (institute under Agriculture University, Jobner)	
	14- 18 January 2020	• Visited KVK, Chomu • Installed profile probe tube at Gopalgarh (B) and Charanwas Gajja (C), measured soil moisture	
	9- 15 August 2020	• Measured soil moisture (profile probe) at five place. • Installed profile probe tubes at Mamtori Kalan (E), Maru ki Dhani (G, H) and Roda Nadi (F). • Collected undisturbed and disturbed soil samples at Mamtori Kalan (E), Maru Ki Dhani (H), Gopalgarh (B) and disturbed samples at Roda Nadi (F) • Installed raingauge at Roda Nadi.	No field work due to flood in Jaipur city on 14 August 2020 leading to road block.
	13- 15 September 2020	• Installed profile probe tube, measured soil moisture and collected undisturbed and disturbed soil samples at Gopalgarh (J) and Kanwarpura- Harchandpura (K)	
	26- 28 October 2020	• Changed location of profile probe tube at Gopalgarh (J) • Measured soil moisture (profile probe) at Gopalgarh (J), Roda Nadi (F) • Collected soil samples for moisture measurement	
	3-7 December 2020	• Collected soil samples for moisture measurement and measures moisture using TDR at Gopalgarh (J), Roda Nadi (F), Maru Ki Dhani (H), Mamtori Kalan (E), Kanwarpura (K) • Measured tubewell discharge at Gopalgarh (J), Roda Nadi (F), Maru Ki Dhani (H), Kanwarpura (K) • Removed profile probe tube at Mamtori kalan (K)	
	1-5 January 2021	• Collected soil samples for moisture measurement at Gopalgarh (J), Maru Ki Dhani (H) and Kanwarpura (K) • Measured moisture and removed tubes at Gopalgarh (B, J), Roda Nadi (F), Maru Ki Dhani (H) and Kanwarpura (K) • Measured sprinkler application rate at Gopalgarh (J) • Visited Revenue Board, Ajmer for crop statistics information	At Revenue Board district level information are available.

Table A.2 Investigation sites

S. No.	Code	Description	Rabi 2019-20		Kharif 2020- 21		Kharif 2020- 21		Rabi 2020-21		Location	Remark
			Crop	Irrigation	Crop	Irrigation	Crop	Irrigation	Crop	Irrigation		
1	B	Gopalgarh (Field 1)	Wheat	Sprinkler	Fallow	-	Fallow	-				
2	C	Charanwas Gajja (Field 1)	Wheat	Flood								
	D	Charanwas Gajja (Field 1)	-	-								
3	E	Mamtori Kalan			Pearl millet	Dry land						
4	F	Roda nadi			Fallow	-			Wheat	Flood		
5	G	Maru Ki Dhani (Field 1)			Pearl millet	Dry land						Gravelly soil
6	H	Maru Ki Dhani (Field 2)			Fallow	-	Carrot	Sprinkler				
7	J	Gopalgarh (Field 2)					Carrot	Sprinkler				
8	K	Kanwarpura-Harchandpura					Tomato	Drip				

Table A.3 Soil tests

S No	Tests	Location	Remark
Undisturbed sampling (B and C in February 2020, B, E, F, H on 9-15 August 2020, J, K on 13- 15 September 2020)			
	Sites	20, 60, 80 cm: B, E, H, J, K	
	Permeability (ICW Lab Permeameter- Constant head method)	20, 60, 80 cm: Sites B, H, K 60, 80 cm: Site J	Fast running samples: Site E (20, 60, 80 cm), Site J (20 cm) Least permeable: Site K Test not carried out at site B (first sampling), C
	Bulk density	20, 60, 80 cm: Sites B, H, J, K ___: Site B, C	
Disturbed sampling			
	Sites	40, 100 cm: B, C Composite 20- 100 cm: E, F, H, J, K	
	Soil Water Pressure & Moisture Content Relationship (Pressure plate apparatus)		
	Soil texture (Sieve, Master Sizer)		

Table A.4 Soil moisture profile probe observation

S. No.	Code	Description	Observation periods	Frequency
1	B	Gopalgarh (Field 1)	January- February, August- December 2020	January- February: One observation each month August- December: 15 days each month
2	C	Charanwas Gajja (Field 1)	January- February 2020	
	D	Charanwas Gajja (Field 1)	February 2020	
3	E	Mamtori Kalan	August- October 2020	
4	F	Roda nadi	August- December 2020	
5	G	Maru Ki Dhani (Field 1)	August- October 2020	
6	H	Maru Ki Dhani (Field 2)	October- December 2020	
7	J	Gopalgarh (Field 2)	October- December 2020	
8	K	Kanwarpura- Harchandpura	October- December 2020	

Table A.5 Soil texture

Soil Water Laboratory						
Ground Water Hydrology Division						
National Institute of Hydrology, Roorkee						
S.No.	Site Code	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Soil Type
1	Gopalgarh- B (40 cm)	0.00	39.70	51.80	8.50	Silt Loam
2	Gopalgarh- B (100 cm)	0.00	55.09	40.79	4.12	Sandy Loam
3	Charanwas Gajja- C (40 cm)	0.47	33.48	61.43	4.62	Silt Loam
4	Charanwas Gajja- C (100 cm)	0.03	21.11	69.84	9.03	Silt Loam
5	Mamtori Kalan- E (20-100 cm)	0.00	63.07	32.22	4.71	Sandy Loam
6	Roda Nadi-F (20-100 cm)	0.61	48.04	45.45	5.90	Sandy Loam
7	Maaru Ki Dhani-H (20-100 cm)	0.00	70.17	29.71	0.12	Loamy Sand
8	Gopalgarh-J (20-100 cm)	0.00	30.85	61.59	7.56	Silt Loam
9	Kanwarpura-Harchandpura-K (20-100 cm)	0.10	44.18	51.75	3.98	Silt Loam

Table A.6 Soil reports

ICW LAB PERMEAMETER EXPERIMENT BY CONSTANT HEAD METHOD SAMPLE ANALYSED BY: N K LAKHERA & C S CHOWHAN TECH GR.I													
Experiment during 02/09/2020 to 11/09/2020 (Sampling done 9-15 August 2020 field visit)													
Ring Number or Sample Code	Depth of sample in cm	Weight of empty ring in grams	Weight of moist soil with ring in grams	Weight of saturated soil with ring in grams	Weight of oven dried soil with ring in grams	percentage moisture content	Sat. Density (grams/cm^3)	Dry Density (grams/cm^3)	Bulk Density (grams/cm3)	q(i) in cm3/minute	h(i) in mm	cons.	Permeability (m/day)
1A	20	97.00	264.10	290.61	246.76	11.579	1.933	1.495	1.668	1.450	23.5	37.38764	2.3069
Maaru Ki Dhani H													
2A	60	99.73	282.00	300.10	259.05	14.405	2.000	1.590	1.819	0.047	21.5	37.38764	0.0810
Maaru Ki Dhani H													
3A	80	95.05	293.59	300.79	263.03	18.193	2.054	1.677	1.982	0.010	29.5	37.38764	0.0127
Maaru Ki Dhani H													
4A	20	95.36	271.16	291.30	251.52	12.577	1.956	1.559	1.755	0.350	23.5	37.38764	0.5568
Gopalgarh B													
5A	60	96.54	266.08	292.50	248.69	11.430	1.956	1.519	1.692	1.000	27.0	37.38764	1.3847
Gopalgarh B													
6A	80	98.79	266.70	298.17	254.36	7.932	1.990	1.553	1.676	1.000	25.0	37.38764	1.4955
Gopalgarh B													
7A	20	95.56	277.61	295.32	258.08	12.017	1.994	1.622	1.817	50.000	20.5	37.38764	91.1894
Mamtori Kalan E												Fast Running Rejected	
8A	60	95.59	286.91	300.00	262.76	14.446	2.040	1.669	1.910	90.000	9.0	37.38764	373.8764
Mamtori Kalan E												Fast Running Rejected	
9(1D)	80	58.69	253.49	264.64	228.81	14.507	2.056	1.698	1.945	74.000	13.5	37.38764	204.9396

Mamtori Kalan E												Fast Running Rejected	

Table A.7 Soil moisture, bulk density and permeability

ICW LAB PERMEAMETER EXPERIMENT BY CONSTANT HEAD METHOD SAMPLE ANALYSED BY: N K LAKHERA, C S CHOWHAN TECH GR.I & Rajat Agarwal 'RA'													
Experiment during 17/09/2020 to 30/09/2020 (Sampling done 13-15 September2020 field visit)													
Ring Number or Sample Code	Depth of sample in cm	Weight of empty ring in grams	Weight of moist soil with ring in grams	Weight of saturated soil with ring in grams	Weight of oven dried soil with ring in grams	percentage moisture content	Sat. Density (grams/cm^3)	Dry Density (grams/cm^3)	Bulk Density (grams/cm3)	q(i) in cm3/minute	h(i) in mm	cons.	Permeability (m/day)
10A/J	20	94.93	282.41	303.59	262.45	11.915	2.083	1.672	1.871	111.000	8.5	37.38764	488.2385
Gopalgarh J												Fast running Rejected	
11A/J	60	95.00	282.66	304.40	261.75	12.540	2.090	1.665	1.873	0.275	22.5	37.38764	0.4570
Gopalgarh J													
12A/J	80	95.82	288.63	309.25	266.80	12.768	2.130	1.707	1.925	0.113	24.5	37.38764	0.1724
Gopalgarh J													
13A/K	20	95.65	303.70	317.22	277.96	14.119	2.212	1.820	2.077	0.020	25.5	37.38764	0.0293
Harchandpura K													
14A/K	60	95.73	308.09	319.25	278.62	16.114	2.231	1.826	2.120	0.040	25.5	37.38764	0.0586
Kanwarpura-Harchandpura K													
*15A/K	80	99.68	310.59	317.99	279.85	17.062	2.179	1.798	2.105	nil	least Perm.		< 0.0293
Kanwarpura-Harchandpura K		Sample *15A/K is least permeable											

Table A.8 Soil water pressure and moisture relationship

SOIL WATER LABORATORY NIH ROORKEE

Soil Water Pressure & Moisture Content Relationship (Average MC at Dfferent Pressures)

Data arranged on : 05/11/2020 for Indent E.S.No.- dated 17/08/2020,16/09/2020, P.I.- Mr. D.S.Rathore, Sc-'F'

Analysed by :N.K.Lakhera & C.S.Chowhan, Tech.Gr.I

Sr. No.	Sample Code	Pressure>	in bars>	0.10	0.33	0.50	0.70	1.00	3.00	5.00	7.00	10.00	15.00
			in H(cm)>	00101.98	00336.53	00509.90	00713.16	01019.80	03059.40	05099.00	07138.60	10198.00	15297.00
		(Depth in cm) Place											
1	B	(40 CM) GOPALGARH		12.47	15.91	14.14	11.90	8.70	4.96	4.77	4.09	3.73	3.64
2	B	(100 CM) GOPALGARH		12.65	15.66	13.95	12.06	9.50	5.10	4.78	4.30	3.76	3.62
3	C	(40 CM) CHARANWAS GAJJA		26.09	22.82	20.30	18.06	16.13	11.51	10.84	9.76	9.29	8.40
4	C	(100 CM) CHARANWAS GAJJA		28.34	23.86	22.89	21.64	19.98	16.34	14.81	13.49	14.68	11.42
5	E	(20-100 CM) MAMTORI KALAN		16.15	16.63	17.11	12.64	11.17	6.97	6.65	5.63	5.23	4.67
6	F	(20-100 CM) RODA NADI		16.21	15.61	14.91	12.60	10.30	6.40	5.72	4.89	4.53	4.14
7	H	(20-100 CM) MAARU KI DHANI		12.86	13.53	11.46	8.69	8.03	4.38	3.66	2.80	2.70	2.87
8	J	(20-100 CM) GOPALGARH		16.43	17.69	14.57	11.47	10.39	5.88	5.32	4.49	4.21	3.76
9	K	(20-100 CM) Kanwarpura-HARCHANDPURA		24.07	18.50	15.31	14.55	10.62	8.77	8.05	6.82	7.56	7.47

Table A.9 Bulk density and volumetric soil moisture

Location (Sampling date)	Depth cm	Bulk density gm/cu cm	Volumetric soil moisture %	Permeability m/day
Gopalgarh B (February 2020)	10	1.61	13.53	
Gopalgarh B	40	1.55	14.13	
Gopalgarh B	80	1.42	12.93	
Charanwas Gajja C (February 2020)	10	1.45	26.69	
Charanwas Gajja C	40	1.58	32.25	
Charanwas Gajja C	80	1.76	35.93	
Maru Ki Dhani H (9-15 August 2020)	20	1.67	19.31	2.3069
Maru Ki Dhani H	60	1.82	26.21	0.0810
Maru Ki Dhani H	80	1.98	36.06	0.0127
Gopalgarh B (9-15 August 2020)	20	1.75	22.07	0.5568
Gopalgarh B	60	1.69	19.34	1.3847
Gopalgarh B	80	1.68	13.30	1.4955
Mamtori Kalan E (9-15 August 2020)	20	1.82	21.84	-
Mamtori Kalan E	60	1.91	27.59	-
Mamtori Kalan E	80	1.94	28.21	-
Gopalgarh J (13- 15 September 2020)	20	1.871	34.16	-
Gopalgarh J	60	1.873	35.92	0.4570
Gopalgarh J	80	1.925	0.00	0.1724
Kanwarpura- Harchandpura K (13- 15 September 2020)	20	2.077	0.00	0.0293
Kanwarpura- Harchandpura K	60	2.120	0.00	0.0586
Kanwarpura- Harchandpura K	80	2.105	0.00	< 0.0293

Table A.10 Soil moisture measurement through gravimetric method and TDR (3-7 December 2020)

S No	Site	Volumetric soil moisture			Remark
		Gravimetric method	TDR	Difference	
1	Maaru Ki Dhani H	17.7	12	-5.71	
2	Maaru Ki Dhani H	8.7	8.4	-0.31	
3	Mamtori Kalan H	10.1	9.8	-0.34	
4	Roda Nadi F	13.9	14.9	1.03	
5	Gopalgarh J	23.8	23.6	-0.24	
6	Gopalgarh J	22.2	17.8	-4.42	
7	Gopalgarh J	19.6	17.4	-2.24	
8	Kawarpura K	22.8	32.2	9.38	
9	Kawarpura K	23.0	15.6	-7.36	Nearby field (recently sown)
				-1.14	

Table A11: Assessed Mean Annual Surface and Ground Water Availability (including inter-State share of Rajasthan) (Source: Report, 2014)

S. No.	Basin	Mean Annual Virgin Water Yield within Rajasthan, Mm^3	Imported water to Rajasthan as per inter-State Share, Mm^3				Mean Annual Groundwater Resources, Mm^3			
			Received at Rajasthan Border for Agriculture Use	Conveyance Losses upto Rajasthan Border	Reserved for Non-Agriculture Use	Total	Dynamic		Static	
							Fresh	Saline	Fresh	Saline
1	Shekhawati	562.85				0.00	433.35	22.70	1196.66	130.77
2	Ruparail	641.38	18.42	0.97		19.39	302.18	49.07	472.79	107.89
3	Banganga	754.83	32.08	1.69		33.77	525.76	147.19	813.57	280.35
4	Gambhir	700.89				0.00	428.21	29.78	478.18	56.82
5	Parbati	427.18				0.00	128.50	0.00	103.69	0.00
6	Sabi	348.09				0.00	429.89	6.93	698.56	13.69
7	Banas	5097.26				0.00	2282.73	107.65	1808.90	90.42
8	Chambal	8702.14	3387.00			3387.00	1999.54	26.33	953.39	22.09
9	Mahi	3720.25	699.62			699.62	604.88	0.00	108.82	0.00

10	Sabarmati	732.52				0.00	62.98	10.93	11.81	4.09
11	Luni	2269.92	562.34	21.83	131.25	715.42	1493.18	488.99	10884.72	4041.33
12	West Banas	222.14				0.00	69.63	4.26	7.44	0.89
13	Sukli	137.61				0.00	51.68	0.00	6.06	0.00
14	Other Nallahs of Jalore	51.42	165.33	6.42		171.75	115.28	0.00	705.82	0.00
15	Ghaggar	19.54	2,587.41 *	693.80	1267.00	14205.07	239.44	446.69	484.60	1120.90
16	Outside Basin	990.60	9656.86				1446.61	2281.47	14179.17	23856.27
State Total		25378.62	17109.06	724.71	1398.25	19232.02	10613.84	3621.99	32914.18	29725.51

** Including 489.07 Mm^3 of Ghaggar flood water.*

Table A12: Brief Details of Basins of Rajasthan (including inter-State share of Rajasthan) (Source: Report, 2014)

S.No.	Basin	Sub-Basins	Location	Basin falls in District	Area Covered (Km^2)	Avearge Annual Rainfall	Avearge Annual Temperature in °C	
							Max	Min
1	Shekhawati	Dohan, Kantli and Mendha	North-eastern part	Ajmer, Alwar, Churu, Jaipur, Jhunjhunu, Nagaur and Sikar	9,750.88	489.60	45.38	2.83
2	Ruparail	-	North-eastern part	Alwar and Bharatpur	4,033.66	626.10	45.94	3.02
3	Banganga	-	Eastern part	Alwar, Bharatpur, Dausa, Jaipur, Karauli, Sawai Madhopur and Sikar	8,583.34	640.60	45.87	3.46
4	Gambhir	-	Eastern part	Bharatpur, Dausa, Dhaulpur, Karauli and Sawai Madhopur	4,693.52	643.60	46.35	3.74
5	Parbati	-	Eastern part	Bharatpur, Karauli and Dhaulpur	1,887.07	648.40	46.81	3.74
6	Sabi	-	North-eastern part	Alwar, Jaipur and Sikar	4523.67	627.60	45.8	2.45
7	Banas	Banas, Berach, Dain, Gudia, Kalisil, Khari, Kothari, Mashi, Morel, Sodra	South-eastern part	Ajmer, Bhilwara, Bundi, Chittaurgarh, Dausa, Jaipur, Karauli, Pratapgarh, Rajsamand, Sawai Madhopur, Tonk and Udaipur	47,060.27	588.80	44.89	3.79

8	Chambal	Chakan, Chambal Downstream, Chambal Upstream, Kalisindh, Kunu, Mej and Parwati	South-eastern part	Baran, Bhilwara, Bundi, Chittaurgarh, Dhaulpur, Jhalawar, Karauli, Kota, Pratapgarh, Sawai Madhopur and Tonk	31,242.50	784.90	45.88	5.11
9	Mahi	Anas, Bhadar, Jakham, Mahi, Moran and Som	Southern part	Banswara, Chittaurgarh, Dungarpur, Pratapgarh and Udaipur	16,610.63	753.10	44.36	5.10
10	Sabarmati	Sabarmati, Sei, Vatrak and Wakal	Southern part	Dungarpur, Pali, Sirohi and Udaipur	4,130.12	684.40	42.59	1.98
11	Luni	Bandi, Bandi-Hemawas, Guhiya, Jawai, Jojri, Khari, Khari-Hemawas, Luni, Mithari, Sagi, Sukri and Sukri-Sayala	Central and south-western part	Ajmer, Barmer, Bhilwara, Jaisalmer, Jalore, Jodhpur, Nagaur, Pali, Rajsamand, Sirohi and Udaipur.	69,302.11	388.20	44.84	3.48
12	West Banas	-	Southern part of the western Rajasthan	Pali, Sirohi and Udaipur	1,831.34	817.60	39.03	-0.89
13	Sukli	-	Southern part of the western Rajasthan	Sirohi	990.44	948.50	37.67	-1.70
14	Other Nallahs of Jalore	-	Southern part of the western Rajasthan	Jalore and Sirohi	1,900.27	590.70	42.40	1.70
15	Ghaggar	-	Northern part	Ganganagar and Hanumangarh	5,201.51	221.70	46.59	1.53
16	Outside Basin	Sub1, Sub2, Sub3, Sub4, Sub5, Sub6 and Fragmented area	Western part	Barmer, Bikaner, Churu, Ganganagar, Hanumangarh, Jaisalmer, Jhunjhunu, Jodhpur, Nagaur and Sikar	130,522.48	286.10	46.20	2.43