M.Sc. Thesis

MULTIREGIONAL EVALUATION OF SM2RAIN SATELLITE BASED PRECIPITATION PRODUCT IN PAKISTAN

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ABSTRACT

Satellite precipitation products are being used at a global scale for rainfall estimation and mostly providing a reliable opportunity in in-situ data sparse region. Tropical Rainfall Measuring Mission version-07 (hereafter TRMM) and its successor Integrated Multi-Satellite Retrievals for Global Precipitation Measurement (hereafter IMERG) are currently used state-of-the-art satellite products and are based on ‘top to bottom’ approach. In addition to above products, SM2RAIN-ASCAT (hereafter SM2RAIN) is a novel satellite-based precipitation product which gives the rainfall estimates from the knowledge of soil moisture state and is based on ‘bottom to top’ approach. A comparative assessment of newly developed product e.g., SM2RAIN or a new version of the product is quite vital for algorithm developers and users. Hence, this research work was carried out to evaluate the accuracy and applicability of SM2RAIN, in comparison to in-situ data, TRMM, and IMERG in diverse regions of Pakistan. The current study consist of three main component i.e., climatic zoning using geo spatial analyst tool in GIS, evaluation of performance of selected products based on the performance metrics, and to check whether the performance metrics are statistically significant or not. Moreover, the comparative analysis was performed on temporal scale (daily and monthly) and seasonal scale (spring, autumn, summary, and winter) using five performance metrics namely, root mean square error, correlation coefficient, false alarm ratio, the probability of detection, and critical success index.

Using 30 years data of mean annual temperature, the Pakistan was divided into four different climatic zones. Based on precipitation data of various stations from each zone, the comparative results showed that (1)-SM2RAIN is a better rainfall estimation product and it gave promising rainfall estimates in the dry region of

Pakistan, however, less effective in hilly and mountainous terrain having high rainfall intensity, (2)- SM2RAIN provides more satisfactory estimates in winter and autumn seasons, while relative poor in the summer season when most parts of Pakistan observe heavy rainfall due to monsoon, (3)- SM2RAIN performs better in terms of rainfall detection in all considered cases i.e., different zones and temporal scales, (4)- Wilcoxon Signed rank sum test resulted that there is a statistical significant difference between the SM2RAIN and all selected satellite products in terms of POD and FAR with a p value less than α, except CSI, (5)- The overall performance of SM2RAIN is very convincing and it was concluded that SM2RAIN can also be a feasible satellite product for most of the areas of Pakistan. It is noteworthy here to mention that this could be the preliminary assessment of SM2RAIN in diverse climatic zones of Pakistan.

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I am highly indebted and grateful to our creator and the Lord of the universe, ALLAH Almighty, who granted me with the best of health and courage to undertake this responsibility and complete it in the best feasible way in minimum time. Without ALLAH's help and love of our Holy Prophet Hazrat Muhammad (Peace be upon Him) with us, this was never possible for an ordinary person like me.

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Engr. Muhammad Ehtsham

DEDICATION

Dedicated to thousands of people who lost their lives

due to extreme hydrological events.

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Chapter I
INTRODUCTION

1.1 GENERAL

The precise measurement of precipitation at fine spatiotemporal resolution is probably the most important subject to be discussed for a better understanding of the hydrological cycle, and for improving climatic, meteorological and hydrological applications. Conventionally, rain gauges have been considered as an authentic and accurate source of rainfall estimates (Villarini et al. 2008). In many parts of the world especially in developing countries, accurate estimation of rainfall at regional and temporal scale is considered a challenging task as the hydrometric networking is sparse and due to sparseness rain gauges are subjected to spatial representativeness problems (Kidd et al. 2017). In addition to limited spatial coverage, the short length of the record and missing information are also hindering the adequate rainfall analysis.

As an alternatives weather radars and the satellites based precipitation products are offering a variety of rainfall estimates at different spatial and temporal scales. Weather radars can offer a spatial measure of precipitation and are currently being used by the Pakistan meteorological department for rainfall measurement. Weather radars have their own shortcomings e.g. rainfall estimates obtained from radars are sometimes imprecise due to complex atmospheric regimes, variations in the height of the radar beam, beam blocking, and variations in the reflectivity-rainfall rate relationships (Jameson and Kostinski 2002). Furthermore, weather radars are very expensive and require technical experts, so they are sparse in developing countries.

To overcome the aforementioned shortcomings of ground-based precipitation measurement networks, satellite-based precipitation products are used as an alternative source. Moreover, compared with weather radar, the possibility of estimating global and near-real-time rainfall from satellite measurements is highly appealing. A numerous number of high-resolution satellite-based precipitation products have been developed in the recent past which are functioning and providing precipitation estimates on different temporal and spatial scales. Some of the most widely used products are TRMM multi-satellite precipitation analysis products (TMPA) 3B42-V6 and 3B42-V7 (Huffman et al. 2007), the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT)'s Multi-sensor Precipitation Estimate (MPE) (Heinemann and Kerényi 2003; Heinemann et al. 2002), the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIAN) (Hsu et al. 1997), the Climate Prediction Center Morphing technique, (CMORPH) (Joyce et al. 2004; Joyce and Xie 2011), Integrated Multi-satellite Retrievals for GPM (IMERG) products (Huffman et al. 2015a; Huffman et al. 2015b), the European Centre for Medium-Range Weather Forecasts (ECMWF)'s Era-Interim product (Dee et al. 2011; Palmer et al. 1990) and the Climate Hazards Group Infrared Precipitation with Station (CHIRPS) (Funk et al. 2015). The inherent shortcoming of all satellite-based precipitation products is that they are indirect estimates of rainfall. It is therefore essential to evaluate their accuracy by comparing against gauge observations before application (Chen et al. 2013). Recent studies indicate that there is no satellite-based product whose performance is consistent in different climatic and geographic regions. Accuracy and reliability of each satellite product vary in the different climatic and geographic region (Hirpa et al. 2010; Tan et al. 2015; Thiemig et al. 2012). Therefore, evaluation of the specific satellite-based rainfall products over different climatic and geographic regions is very important.

Recently, (Brocca et al. 2013) developed a new approach to estimate rainfall from the knowledge of soil moisture state and its variation in time through an algorithm called SM2RAIN by inversion of the soil-water balance equation. SM2RAIN estimates rainfall by using in situ soil moisture measurements and satellite-based soil moisture estimates. There are two versions of SM2RAIN product available, SM2RAIN ASCAT and SM2RAIN CCI. This approach has given promising estimates of accumulated rainfall amounts when tested against in situ data and single-sensor soil moisture products, (Brocca et al. 2015; Chiaravalloti et al. 2018; Ciabatta et al. 2016; Ciabatta et al. 2015; Paredes-Trejo et al. 2018) tested the applicability of SM2RAIN and resulted that it can provide promising rainfall estimates at the regional scale. However, still to be evaluated at the different diverse region of the world like Pakistan. A detailed study investigating the suitability of the SM2RAIN product for Pakistan, its range of applicability, its limitations and its comparison with other satellite-based precipitation products is still needed.

1.2 PROBLEM STATEMENT

Accurate estimation of rainfall at regional and temporal scale is of utmost importance especially in a country like Pakistan which involves complex atmospheric and topographic regions and has faced many extreme hydrological events (floods and droughts) in past. In Pakistan accurate estimation of rainfall at regional and temporal scale is considered a challenging task as the hydrometric networking is sparse. In addition to limited spatial coverage, the short length of the record and missing information are also hindering the adequate rainfall analysis. Weathers radars are also being used by Pakistan metrological department for accurate rainfall estimation but these are very expensive and require high maintenance and operational cost so, there is a limited number of weather radars which are being used. Rainfall estimation by satellite based precipitation products is very economical. However, it is essential to assess the accuracy and reliability of satellite based precipitation product in different regions because they are regional based i.e. if one product is better for one type of climatic zone probably it will not be as much effective in another type of climatic zone. Accuracy of precipitation products is greatly hindered by rainfall intensity, topographical condition, mean annual temperature and mean elevation form sea level. It is also observed that accuracy of a specific product changes in different seasons for a specific region. A large number of studies have been done in Pakistan in recent past to validate and assess different satellite products. SM2RAIN is a most advanced satellite product which estimates the rainfall from satellite soil moisture data and it is not assessed until now in Pakistan.

As precipitation is greatly varying in time and space and its approximation is challenging both with ground data (rain gauges and radar) and satellite observations. The problem is even more difficult under composite topographic conditions, compact vegetation zones and coastal counties.

Hence, the aim of this study is to address the following question; is it feasible to use the SM2RAIN satellite based product over challenging diverse regions as in Pakistan? What is the impact of time aggregation, season and topography on the accuracy and applicability of SM2RAIN product in Pakistan? How SM2RAIN performs when comparative comparison with two other state of the art satellite products is done?

1.3 OBJECTIVES

There are two main objectives of this research work as follow:

a) Climatic zoning of study area using Geo-Spatial Analysis in GIS.

b) Evaluation of the SM2RAIN Product, its comparative assessment with other satellite based rainfall products and to check whether the different performance matrices are statistically significant or not.

1.4 SCOPE

For the study, data was the major constraint. Ground based Gauge data starting from 1st January 2014 to 31st December 2017 was collected from Pakistan Metrological Department.

1.5 UTILIZATION OF RESEARCH RESULTS

i) Results may suggest the compatibility of the SM2RAIN product for Pakistan, it will increase the accuracy of estimation of rainfall.

ii) The rainfall estimates obtained from SM2RAIN will also be considered for the correction of observed rainfall data obtained from rain gauges.

iii) SM2RAIN is completely independent from other existing state-of-the-art precipitation products, therefore will offer an additional long term dataset that can be used for independently evaluating these global-scale precipitation products.

Chapter II
LITERATURE REVIEW

Satellite based precipitation products have become an attractive source of rainfall estimates over the last two decades and have been extensively used in research and hydrological applications around the globe. However, it is necessary to assess the effectiveness of each satellite product for a specific region before application. A large number of studies have been made globally for the assessment of different satellite products in different regions at different spatial and temporal resolutions.

Owusu et al., (2016) in their study evaluated satellite rainfall estimates in the Pra Basin of Ghana. This study assessed the accuracy of three satellite rainfall products; CMORPH, TMPA 3B42 and TMPA 3B42RT in the Pra basin of Ghana. The evaluation was done by adopting the point-to-pixel method by comparison of 0.25°x 0.25° satellite grids to gauged rainfall based on gauge locations and analyzed statistically using bias and percent bias (pBias), correlation coefficient, as the performance verification methods. Seven ground based gauge stations with continuous (no missing) data for the period of 2003-2008 was for the analysis. The analysis was based on four timescales i.e., daily, monthly, annual and seasonal. Results of this study depicted a strong correlation between the TMPA products and the gauged data on all four timescales. A huge overestimation was observed in the estimates of CMORPH at all selected gauge locations. It was concluded that TMPA 3B42 is the best product amongst the three.

Sharifi et al., (2016) did a study for the assessment GPM-IMERG and Other Precipitation Products against Gauge Data under Different Topographic and Climatic Conditions in Iran and concluded that IMERG gives better results in terms of Critical Success Index (CSI), False Alarm Ratio (FAR) and for detection of rainfall events on the basis of Probability of Detection (POD), in the regions with orographic and stratiform precipitation.

Brocca et al., (2013) in their study introduced a new method for rainfall estimation through soil moisture observations. A simple analytical relationship for estimating the accumulated rainfall from the knowledge of SM time series was obtained by inversion of the soil water balance equation. Satellite soil moisture and in situ soil moisture observations from three different points in France, Italy and Spain were used to assess the accuracy of the suggested approach in different climatic zones. The results of this study depicted that the proposed approach is able to reproduce daily rainfall estimates when in situ soil moisture observations are used (R = Correlation Coefficient was nearly equal to 0.9).

Brocca et al., (2014) made a study and in which they estimated global rainfall from satellite soil moisture data by considering soil as a natural rain gauge. Three different satellite SM data sets from the Advanced SCATterometer (ASCAT), the Advanced Microwave Scanning Radiometer (AMSR-E), and the Microwave Imaging Radiometer with Aperture Synthesis were used to obtain the new daily global rainfall products. The "First Guess Daily" product of the Global Precipitation Climatology Centre (GPCC) was employed as main benchmark in the validation period 2010–2011 for determining the continuous and categorical performance of the SM-derived rainfall products by considering the 5 day accumulated values. The real-time version of the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis product, i.e., the TRMM-3B42RT, was adopted as a state-of-the-art satellite rainfall product. The SM-derived rainfall products showed good Pearson correlation values (R) with the GPCC data set, mainly in areas where SM retrievals are found to be accurate.

Brocca et al., (2015) made a study for the evaluation of the SM2RAIN algorithm in this study they did Rainfall estimation from in situ soil moisture observations at several sites in Europe. Results depicted that the SM2RAIN algorithm show good performance both in the real data and synthetic experiments, thus providing a new independent source of data to improve precipitation estimation and thereby improve meteorological, hydrological and climatic studies.

Ciabatta et al., (2018) in their study introduced a new global long-term rainfall data set derived from European Space Agency Climate Change Initiative (ESA CCI) soil moisture data. The quality of the SM2RAIN-CCI rainfall data set was assessed by its comparison with two state-of-the-art rainfall satellite products, the Climate Prediction Center Morphing Technique (CMORPH) and the Tropical Measurement Mission Multi-satellite Precipitation Analysis 3B42 real-time product (TMPA 3B42RT), and one modeled data set (ERA-Interim). A quality check was carried out on a global scale at 1◦ of spatial resolution and 5 days of temporal resolution by comparing these products with the gauge-based Global Precipitation Climatology Centre Full Data Daily (GPCC-FDD) product. SM2RAIN-CCI depicted comparatively good results in terms of different performance metrics during the evaluation period, correlation coefficient (median value > 0.56), bias (median value < −14.44 %) and root mean square difference (median value < 10.34 mm). The validation was carried out at original resolution which was 0.25◦ over Europe, Australia and five other regions worldwide to evaluate the capacity of the data set to correctly estimate the rainfall events under diverse climatic regimes.

Chiaravalloti et al., (2018) did a study for the evaluation of GPM and SM2RAIN-ASCAT rainfall products over complex terrain in southern Italy. In this study the evaluation of the different satellite products was carried out at different rainfall time accumulation i.e. from 0.5 to 24 hours for a period of 2 years starting from 10th March 2015 to 31st December 2016. Results of this study depicted that the different factors affect the products quality, especially topographic complexity seems to play the most vital role, particularly for SM2RAIN-ASCAT, similar behavior was observed for IMERG as well. Overall results of this research work depicted that the selected satellite products agree reasonably well with observation keeping in view the challenging features of the region. The combination of SM2RAIN-ASCAT and IMERG provides a solution to overcome their deficiencies and to estimate the rainfall with a higher efficiency.

Trejo et al. (2018) did a comprehensive study for the evaluation of SM2RAIN and state-of-the-art satellite rainfall products over north-eastern Brazil. Comparisons were made at daily and 5-day temporal resolution, 0.25◦ spatial resolution, for the period of 1998 to 2015. The continuous metrics upon which the satellite products were evaluated were pearson correlation coefficient, root mean square error, mean absolute error and percent bias. The results of this study depicted that In terms of detection of rainfall events, SM2RAIN shows good performance. This study suggests that the efficiency and accuracy of SM2RAIN product is greatly reduced in very dry or very wet climates. Overall results of this study highlight the feasibility of SM2RAIN in poorly gauged regions in the semiarid region of north-eastern Brazil.

Prakash et al., (2019) made a study for performance evaluation of SM2RAIN-CCI , CHIRPS, MSWEP and TMPA precipitation products across India. In this study mean monthly rainfall estimates obtained from SM2RAIN-CCI, CHIRPS, TMPA and MSWEP WERE compared with Indian metrological department's gauge-based data. The evaluation was carried out for central India, west coast and northeast India for the period starting from 01st January 1998 to 31st December 2015.

Chapter III
METHODOLOGY

3.1 STUDY AREA

Pakistan (Figure 3.1) is a developing country located between 23.5◦N–37◦N (latitude) and 61◦E–77◦E (longitude), covering 796,096 km^2 geographical area with an elevation ranges from 0 m to 8611 m. It is characterized by a dominant arid climate, 24% of the total country's area is cultivated, and approximately 80% of this cultivated area is irrigated. Pakistan has a diverse landscape which ranges from coastline alongside the Arabian Sea in the south, snow peaked mountains in the north and deserts and plain area in the central region. There is a notable change of mean annual rainfall in different regions of the country due to the diverse climatic regimes, mean annual rainfall ranges from 1500 mm in the north to 300 mm in the south. To measure the rainfall Pakistan metrological Department's ground-based hydrometric networking is installed that is characterized by no or inadequate density and generally is inadequate for accurate estimates of hydrologic parameters.

3.2 METHODOLOGY

The study was carried out for the evaluation of SM2RAIN satellite product and its comparison with two state of the art satellite products namely TRMM and IMERG. Ground based gauge data was collected from Pakistan metrological department. The rainfall estimates derived from the three select products were compared with gauge upon the different performance metrics which include root mean square error, correlation coefficient, false alarm ratio, probability of detection and critical success index. Figure 3.2 is showing the flow chart which was adopted to achieve the specific objectives.

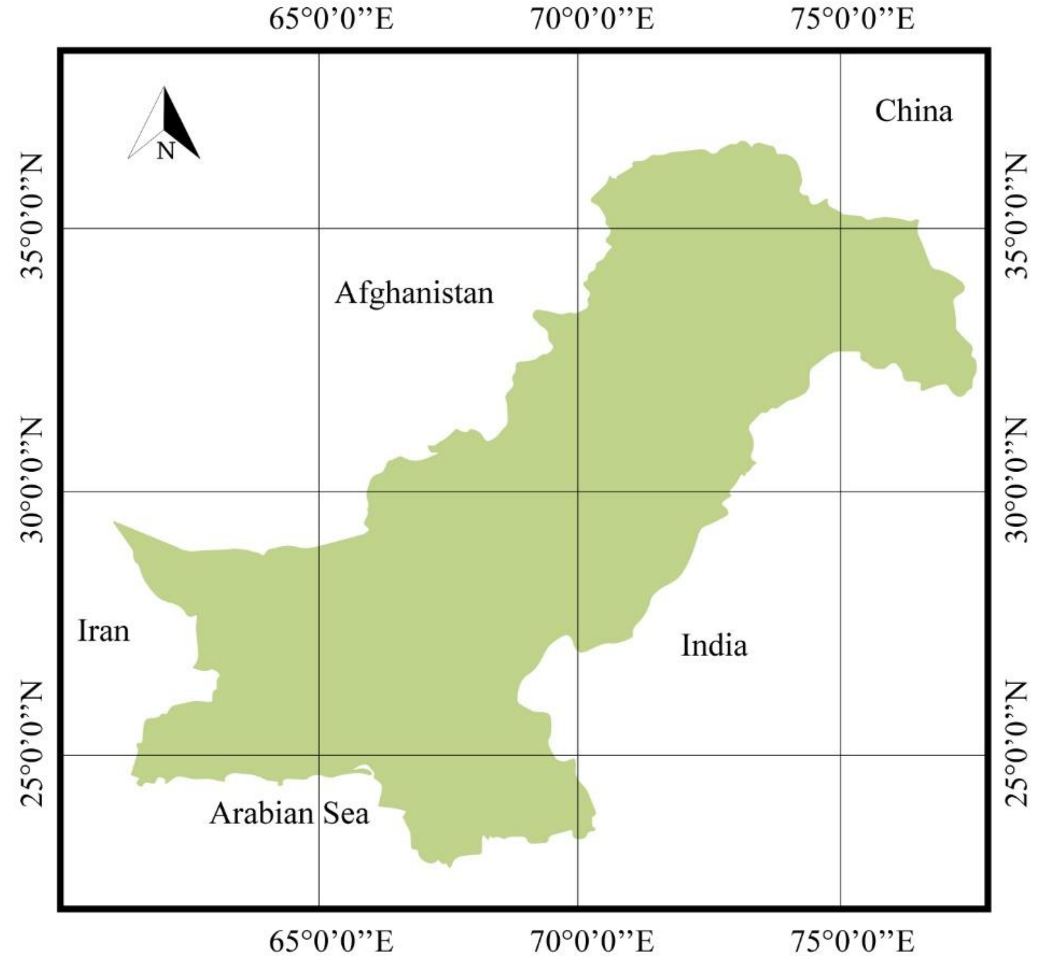


Figure 3.1 Study Area, Pakistan.

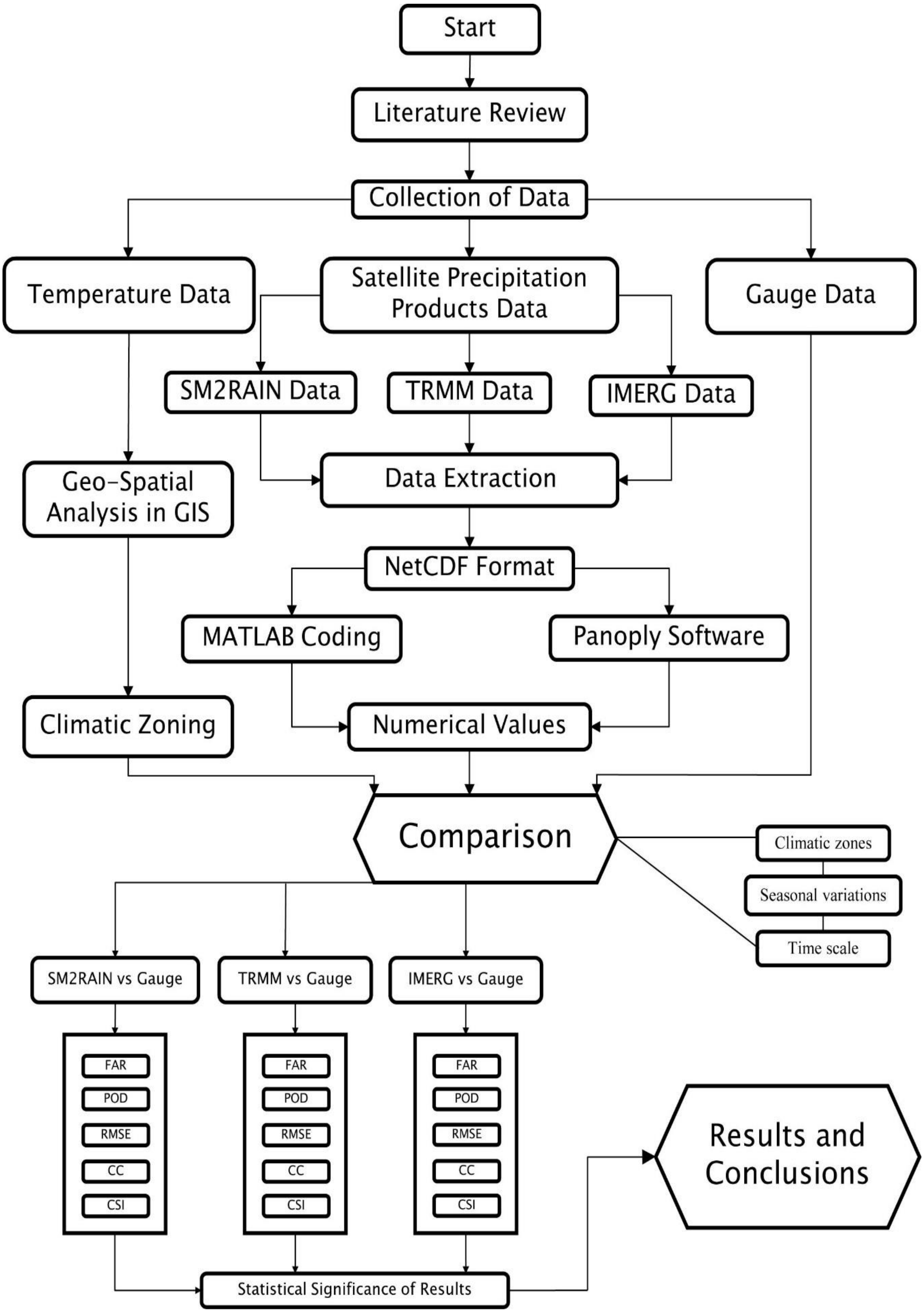


Figure 3.2 Flow Chart to achieve the specific objectives.

3.2.1 Rainfall Datasets

3.2.1.1 Ground-Based Dataset

Pakistan has diverse climatic regimes (i.e. extremely warm in summer and cold in winter season), intensity of climatic extremes vary in different regions. Due to diverse climatic regimes, the change in intensity of precipitation also varies in different regions. To monitor the rainfall, Pakistan metrological department is recording the rainfall and temperature since the existence of Pakistan. I selected various rain gauges (total of thirty-three (33)) from the whole study area by ensuring the quality and continuity (no missing) of rainfall data, selected rain gauges can be seen in (Figure 3.3).

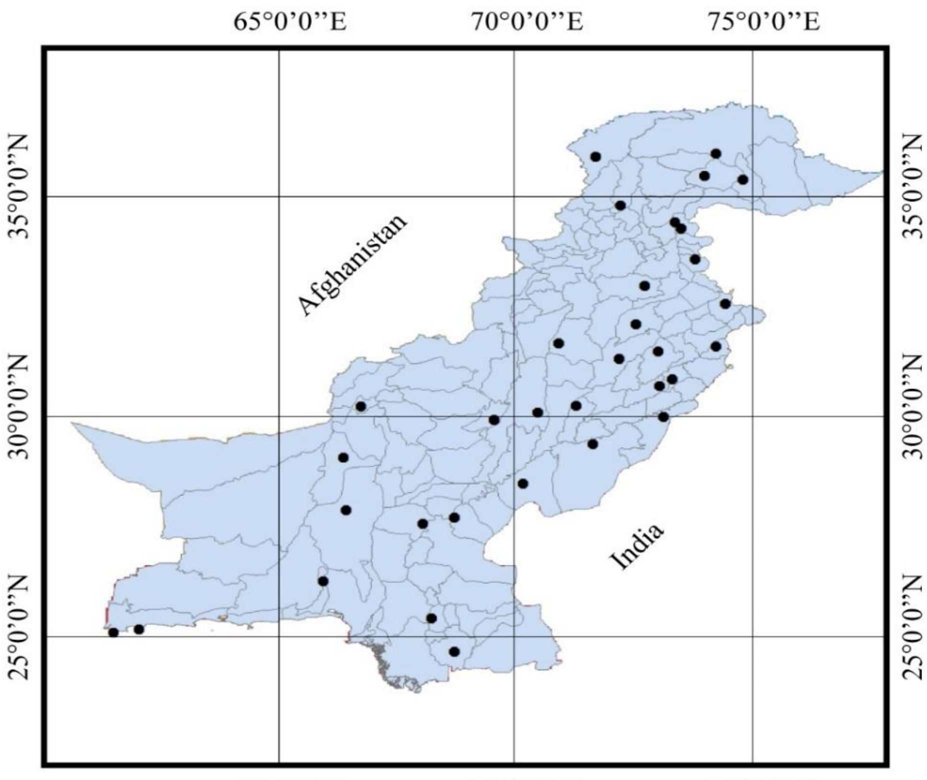


Figure 3.3 Spatial representation of selected rain gauges across the study area.

3.2.1.2 SM2RAIN ASCAT Dataset

The SM2RAIN-ASCAT is a global scale satellite precipitation product, recently developed from Advanced SCATteromete (ASCAT) soil moisture data by using SM2RAIN algorithm (Brocca et al., 2013). SM2RAIN algorithm used a novel approach for precipitation estimation from satellite that is based on a 'bottom to top' approach (using soil moisture for rainfall estimation) compared to the 'top to down' approach of TRMM and successor products. In this research work, SM2RAIN-ASCAT with a spatial resolution of 0.125◦×0.125◦ and temporal resolution of 1 day is used. The newly developed product of SM2RAIN i.e., SM2RAIN-ASCAT (hereafter SM2RAIN) is freely available for 12-year (2007-2018) at a global scale at https://zenodo.org/record/2591215.

3.2.1.3 TRMM-TMPA 3B42-V7 Dataset

The TRMM-TMPA 3B42-V7 (hereafter TRMM), Multi-satellite Precipitation Analysis (TMPA) (Huffman et al., 2007) product was launched with the aim to provide approximately global (-180◦-50◦, 180◦50◦) estimates of rainfall on a temporal resolution of 3 hours, daily accumulated and monthly. TRMM combines IR radar with four Passive microwave sensors named Precipitation Radar, Advanced Microwave Scanning Radiometer, Microwave Imager, and Special Sensor Imager. Rainfall Data is freely available at disc.gsfc.nasa.gov for temporal coverage of 01/01/1998 to present. In current study Rainfall estimates obtained from TRMM-TMPA 3B42-V7 were used, with a spatial resolution of 0.25◦×0.25◦ and temporal resolution of 1 day.

3.2.1.4 IMERG V.05 Dataset

The Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for Global Precipitation Measurement (GPM) (IMERG), is developed to include, merge, and inter-calibrate all precipitation infrared satellite (IR) along with microwave (MW) estimates, ground precipitation gauges, and all other precipitation estimators that were involved in TRMM satellite era. The IMERG is an extension of the sensor package compared to TRMM instruments and has a spatial-temporal resolution (0.1°×0.1°) that is much finer than that of the TMPA 3B42 (0.25°×0.25°) and is freely available at disc.gsfc.nasa.gov and accessible since March 2014 (Huffman et al. 2015a). IMERG Version.05 with nearly global scale (90◦N-90◦S×60◦N-60◦S) was recently launched by Global precipitation measurement with an aim to enhance the quality and continuity of satellite-based precipitation products at the global level. The precipitation estimates obtained from IMERG early run product, V5 (hereinafter IMERG), with a spatiotemporal resolution of 0.1◦/1day starting from 12/03/14 is used in this study.

3.2.2 Extraction of Satellite Data

Satellite rainfall estimates from SM2RAIN, TRMM and IMERG were downloaded in NetCDF file formats. Netcdf files can be opened in panoply software and one can observe the rainfall estimate of a specific day at a specific point i.e. latitude/longitude. However, it is a time taking job to observe the daily rainfall estimate of each point from the panoply and then recording these daily estimates in Microsoft excel. Hence, for extraction of rainfall data of specific points from Netcdf files MATLAB coding was used. Rainfall estimates from SM2RAIN were extracted from the file “ASCAT_SM2RAIN_0125_2007-2017_Pakistan.nc”. Following MATLAB code was used to extract the rainfall data of SM2RAIN from netcdf file.

```
“netTimes = ncread('ASCAT_SM2RAIN_0125_2007-2017_Pakistan.nc','Time');
netLatitudes = ncread('ASCAT_SM2RAIN_0125_2007-2017_Pakistan.nc','Latitude');
netLongitudes = ncread('ASCAT_SM2RAIN_0125_2007-2017_Pakistan.nc','Longitude');
netRainfall = ncread('ASCAT_SM2RAIN_0125_2007-2017_Pakistan.nc','Rainfall');
%%% Choose Between Giving Date as Input or Co-ordinates as Input %%%%%
inputGiven = 'both';  % Either 'date' or 'coord' or 'both'
%%% Specify Date Range %%%% Input Your Date Interval Here: 'dd-mon-year'
startDate = '1-jan-2007';
endDate  = '31-dec-2017';
%%%%%%%%%%%%%%%%%%%%%%%%%%%
startNum = daysact(startDate);  % Convert given input to no. of dayss since
endNum = daysact(endDate);      % 01-Jan-0000
k1 = find(netTimes==startNum,1); % find indices of relevant days in time matrix
k2 = find(netTimes==endNum,1);
%%% Specify Co-ordinates %%%%   Your Latitude- Longitude Co-ordiantes Here
inLong = 74.0796814;
inLat = 35.45450211;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Extract Data %%%
delete 'extractedData.xlsx'     % Delete Previous Output File
if strcmp(inputGiven,'date')    % Check Which Method Used
```

```
    dates = datetime(netTimes(k1:k2),'ConvertFrom','datenum','Format','defaultdate') ;
    rainf = netRainfall(k1:k2,:);
    coords = [];
    for i = 1:length(netLongitudes)
        coords = [coords strcat(string(netLatitudes(i)),'° ',string(netLongitudes(i)),'°')];
    end
    xlswrite('extractedData.xlsx',coords,1,'B1')
    xlswrite('extractedData.xlsx',string(dates),1,'A2')
    xlswrite('extractedData.xlsx',rainf,1,'B2')
elseif strcmp(inputGiven,'coord')
    dates = datetime(netTimes,'ConvertFrom','datenum','Format','defaultdate');
    for i = 1:length(netLongitudes)
        if round(netLatitudes(i),4) == round(inLat,4) && round(netLongitudes(i),4) ==
round(inLong,4)
            break
end
    rainf = netRainfall(:,i);
    coords = [strcat(string(netLatitudes(i)),'° ',string(netLongitudes(i)),'°')];
    xlswrite('extractedData.xlsx',string(coords),1,'B1')
    xlswrite('extractedData.xlsx',string(dates),1,'A2')
    xlswrite('extractedData.xlsx',rainf,1,'B2')
else
    dates = datetime(netTimes(k1:k2),'ConvertFrom','datenum','Format','defaultdate') ;
    for i = 1:length(netLongitudes)
```

```
        if round(netLatitudes(i),4) == round(inLat,4) && round(netLongitudes(i),4) ==
round(inLong,4)
            break
        end
    end
    rainf = netRainfall(k1:k2,i);
    coords = [strcat(string(netLatitudes(i)),'° ',string(netLongitudes(i)),'°')];
    xlswrite('extractedData.xlsx',string(coords),1,'B1')
    xlswrite('extractedData.xlsx',string(dates),1,'A2')
    xlswrite('extractedData.xlsx',rainf,1,'B2')
end”
```

Similarly, daily rainfall estimates were extracted from the IMERG and TRMM Netcdf files. It is noteworthy here to mention that the Netcdf files for each day were downloaded from the respective web sources of TRMM and IMERG. So, a different MATLAB code was applied to extract the data from the number of Netcdf files. Following MATLAB coding was applied to the Netcdf files of TRMM and IMERG to extract the data of desired points i.e. latitudes/longitudes.

```
“prompt = {'Enter Latitude :','Enter Longitude :'};
title = 'Input Co-ordinates';
dims = [1 50];
definput = {'30.05','66.95'};
coords = inputdlg(prompt,title,dims,definput);
inLong = str2double(coords{2});
```

```
inLat = str2double(coords{1});
dname = uigetdir('C:\');
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
folderDetailsNet = dir(strcat(dname,'\*.nc4'));
[~, reindex] = sort( str2double( regexp( {folderDetailsNet.name}, '\d+', 'match',
'once' )));
folderDetailsNet = folderDetailsNet(reindex);
fileNamesNet = extractfield(folderDetailsNet,'name');
fileNamesNet = fileNamesNet(:);
foldernameNet = folderDetailsNet.folder;
fileNo = length(fileNamesNet);
dates = cell(fileNo,1);
outdata = zeros(fileNo,1);
for file = 1:fileNo
   currentFile = strcat(foldernameNet,'\',fileNamesNet{file,1});
   ginfo = ncinfo(currentFile);
   dates{file} = datetime(ginfo.Attributes(1).Value);
   netLatitudes = ncread(currentFile,'lat');
   netLongitudes = ncread(currentFile,'lon');
   netPrec = ncread(currentFile,'HQprecipitation');
   for i = 1:length(netLatitudes)
      for j = 1:length(netLongitudes)
         a = abs(netLatitudes(i)-inLat) <
1e4*eps(min(abs(netLatitudes(i)),abs(inLat)));
```

```
        b=abs(netLongitudes(j)-inLong) <
1e4*eps(min(abs(netLongitudes(j)),abs(inLong)));
        if a && b
            outdata(file) = netPrec(i,j);
            break
end
dataFile = 'extractedDataAll.xlsx';
delete 'extractedDataAll.xlsx'     % Delete Previous Output File
coords = strcat(string(inLat),'° ',string(inLong),'°');
xlswrite(dataFile,cellstr(coords),1,'B1')
xlswrite(dataFile,string(dates),1,'A2')
xlswrite(dataFile,outdata,1,'B2')”
```

3.2.3 Climatic Zoning

Climatic zoning of study area was carried out in GIS by using geo spatial analyst tool. Mean annual temperature data of 60 stations of past 30 years across the study area was used for the climatic zoning. In geo spatial analyst tool, Kriging interpolation method was adopted for climatic zoning of Pakistan. The Kriging interpolation method is also known as Gaussian process regression in which the interpolated values are modeled by a Gaussian process governed by prior covariance. It uses complex mathematical formulas to estimate values at unknown points based on the values at known points.

In current study, temperature brakes of 3°C were chosen for climatic zoning keeping in view the number of rain gauges lying in the respective zones. The mean annual temperature lies in the range 15°C to 18°C in first, 18°C to 21°C in second, 21°C to 24°C in third and 24°C to 27°C in fourth climatic zone.

3.2.4 Evaluation of Precipitation Products

Satellite rainfall estimates from SM2RAIN, TRMM and IMERG were downloaded in NetCDF file format. Spatial-temporal resolution of SM2RAIN data was 0.125◦/1-Day, TRMM data was downloaded with 0.25◦/1-Day spatial-temporal resolution and IMERG data was downloaded with 0.1◦/1-Day spatial-temporal resolution. As the spatial resolutions of above-mentioned satellite rainfall products differ from each other, point-to-pixel method was adopted to match the spatial resolution of 0.25◦ for all three selected products. Aggregation method was adopted and areal weights were assigned to each grid cell respective to the area lying in the 0.25◦×0.25◦ grid. It was made sure that the latitude/longitude of selected rain gauge lies within the chosen pixel range of respective precipitation product. The rainfall estimates from SM2RAIN, TRMM, and IMERG were compared with the respective ground-based gauge observations for the period 12/03/2014 to 31/12/2017. To systematically assess the effectiveness of each satellite product, rainfall estimates were compared on the basis of different performance metrics, which include: (a) Root Mean Square Error (RMSE), (b) The correlation coefficient, (c) False alarm ratio (FAR), (d) The probability of detection (POD) and (e) The Critical success index (CSI).

RMSE was used to estimate the average absolute error, it shows how the values of satellite-based estimates differ from the gauge values and a satellite product with a minimum RMSE represents a more authentic source of rainfall estimates. CC is a measure of how strong the relationship is between two variables. CC was used to assess the relationship between gauge data and satellite data, the ideal value of CC is 1. FAR depicts the fraction of events which are incorrectly detected by satellite precipitation records. POD is the percent of events which are forecast, or simply it is the hit rate, the ideal value of POD is 1. CSI is also known as threat score or ratio of verification, it is the ratio of correctly recorded events to the total number of events i.e. correct + incorrect + miss, the ideal value of CSI is one. It noteworthy here to mention that 1 mm was chosen as the rain or no rain limit for this study.

Table 3.1 Formulas of performance metrics, their ranges, and ideal values.

Name	**Formula**	**Range**	**Perfect value**
Root Mean Square Error	$RMSE = \sqrt{\left[\frac{\sum_{i=1}^{N}\left(R_i^s - R_i^o\right)^2}{N}\right]}$	0 to ∞	0
Correlation Coefficient	$CC = \frac{\sum_{i=1}^{N}\left(R_i^s - R_{avg}^s\right)\left(R_i^o - R_{avg}^o\right)}{\sqrt{\sum_{i=1}^{N}\left(R_i^s - R_{avg}^s\right)^2}\sqrt{\sum_{i=1}^{N}\left(R_i^o - R_{avg}^o\right)^2}}$	+1 to −1	1
False Alarm Ratio	FAR=(F.A)/(H+ F.A)	0 to 1	0
Probability of Detection	POD=H/(H+ M)	0 to 1	1
Critical Success Index	CSI=H/T.E	0 to 1	1

Where N represents the total number of observations R_i^S represents daily rainfall estimate from precipitation product for the respective time step in millimeter. R_i^O

shows daily observed rainfall from gauge for the respective time step in millimeter. R^{S}_{avg} indicates Average of rainfall estimate from satellite based precipitation product. R^{o}_{avg} represents Average of observed rainfall values. F.A indicates Number of False Alarms i.e. when there is no precipitation recorded by gauge but satellite product records rainfall. H shows Number of Hits i.e. when rainfall is correctly recorded by satellite product. M represents Number of misses i.e. when the rainfall is not recorded by satellite product. T.E represents total number of events i.e. F.A + H + M.

3.2.5 Statistical Significance of Performance Metrics

The statistical significance of results was checked by applying Wilcoxon signed rank sum test, it was performed to check whether the different performance metrics are statistically significant or not. It is a non-parametric hypothesis test.

Wilcoxon signed rank sum was performed in XLSTAT by comparing the results of performance metrics of SM2RAIN with results of performance metrics of TRMM and IMERG at all selected stations.

Following are the Wilcoxon signed rank sum test interpretation:

- H_o: The two samples follow the same distribution.
- H_a: The distributions of the two samples are different.
- When the computed p-value will be greater than the significance level alpha=0.05, one cannot reject the null hypothesis H_o.

Chapter IV
RESULTS AND DISCUSSION

4.1 CLIMATIC ZONING

Based on 30 years collected data of the mean annual temperature of 60 stations across the study area, climatic zoning of Pakistan was done using GIS and was divided into four different climatic zones. Some salient characteristics of created zones are as follows; Zone 1 (Z-1) is in the extreme north of Pakistan, the climate is mild in the summer season and extremely cold in the winter season, the terrain is hilly and mountainous. Zone 2 (Z-2) is transition zone, the temperature is cold enough in winter but not to the extent of Z-1, weather in summer is mildly warm. Zone 3 (Z-3) is a bigger zone as compared to the first two zones, climate in Z-3 is hot in summer and Cold in winter, this zone comprises of different terrains from dry mountainous terrain in the west to the warm deserts in the center of region and plain semi-arid, arid terrain in the west part of zone. Zone 4 (Z-4) is the zone with the highest range of mean annual temperature. Therefore, for the better illustration of the performance of SM2RAIN in the different climatic zone, for the current study, I selected various rain gauges (total of thirty-three (33)) from all created four zones by ensuring the quality and continuity of rainfall data (Figure 4.1).

4.2 EVALUATION OF PRECIPITATION PRODUCTS

Evaluation of all three products was carried out for daily and monthly time scales. Moreover, seasonal analysis was also performed to check the efficiency of satellite products in different seasons.

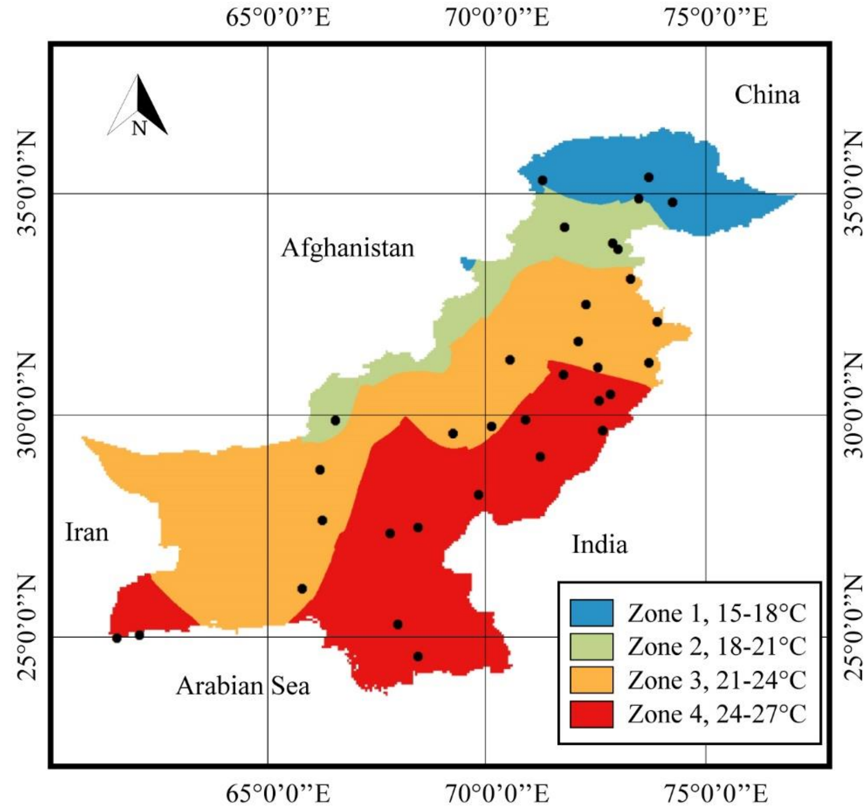


Figure 4.1 Climatic zones of study area and spatial representation of selected rain gauges in different zones.

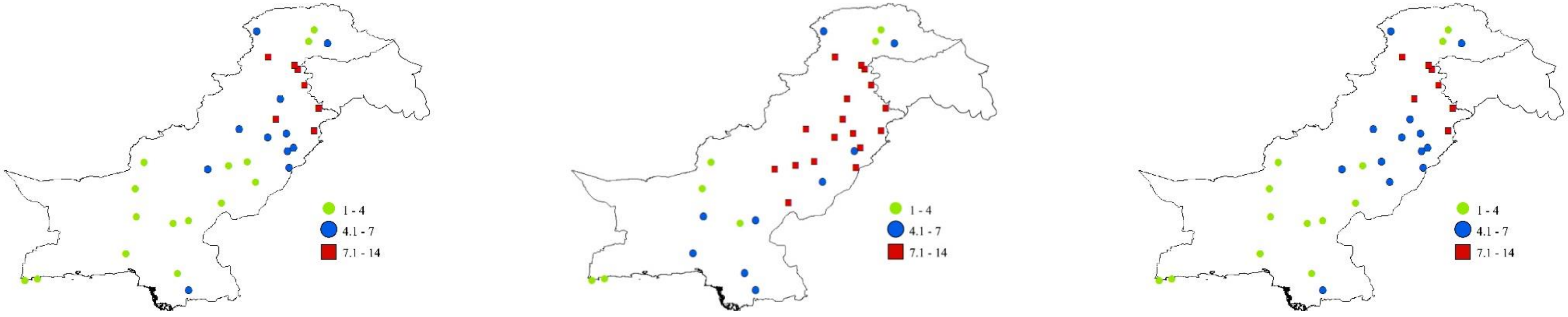
4.2.1 Spatial Variability of Performance Metrics of Satellite Products

In order to evaluate the spatial variability of performance associated with SM2RAIN, TRMM and IMERG, analysis at daily time scale was carried out for the period 12/03/2014 to 21/12/2017.

Values of different performance metrics at respective selected gauge stations for each satellite product are provided in Table (Appendix) and Figure 4.2. Figure 4.2 represents the spatial variability of RMSE, CC, FAR, POD and CSI for SM2RAIN, TRMM and IMERG at selected thirty-three (33) stations across the study area. The results revealed that SM2RAIN is the best performing product in terms of RMSE, as the values of RMSE associated with SM2RAIN at about 15 stations (out of 33) lie within minimum range (1-4mm), while the value of RMSE at 13 stations, and 7 stations for IMERG and TRMM respectively fall in minimum range. Similarly, CC of SM2RAIN at eight (8) stations lies in the highest range (0.33-0.55), while in case of TRMM, and IMERG, the numbers of stations are only one (1) and two (2) respectively. In addition to that, the number of stations at which the FAR values of SM2RAIN lie in the lowest range i.e. 0.008-0.14 is greater than the other two products. Similarly, based on POD, SM2RAIN resulted in better performance at a considerable number of stations compared to the other two products.

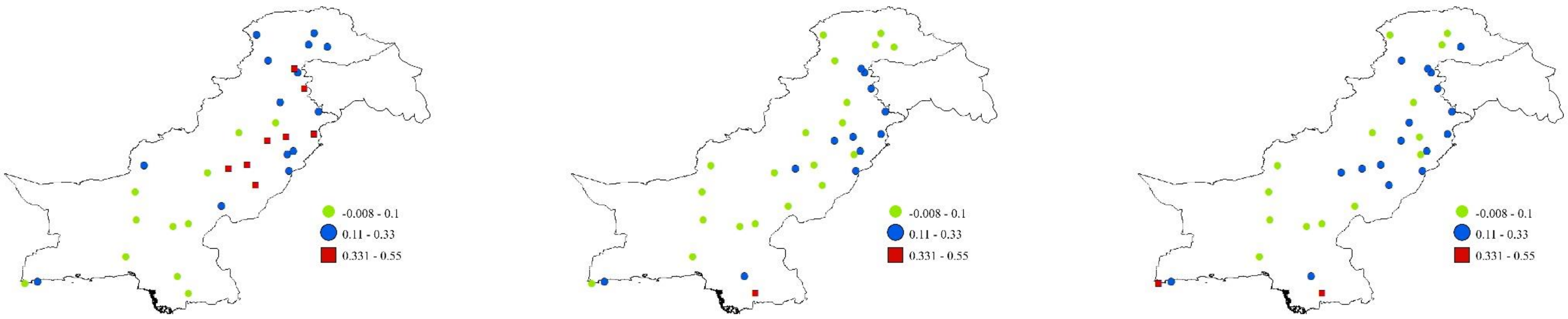
4.2.2 Zone-Based Performance Evaluation at Daily and Monthly Temporal Scale

Using resulted performance metrics at the selected thirty-three (33) stations of different zones, the zonal average performance was assessed by averaging the values of performance metrics of all stations in the individual zone. Zonal Averages of performance metrics at daily timescale are depicted in Table 4.1. Zonal averages of RMSE of SM2RAIN vary from 3.94 to 7.18, and it shows comparatively better results in all zones compared to IMERG and TRMM. Considering CC, FAR and specifically POD based performance evaluation, SM2RAIN outperformed the TRMM and IMERG in all 4 zones, IMERG and TRMM are ranked as second and third respectively in terms of CC. Whereas TRMM shows a slight difference from IMERG in case POD, while better performance in case FAR-based evaluation. In the case of CSI based evaluation of performance, the sequence of performance-based ranking remains constant in all four zones, SM2RAIN is best performing product in all four zones.



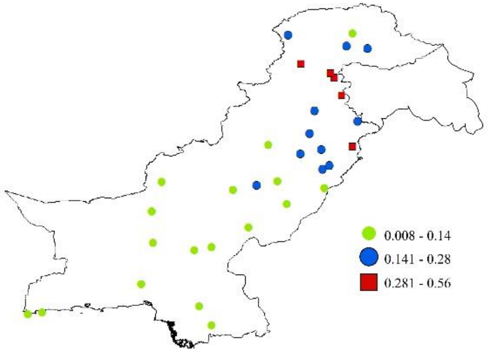
RMSE SM2RAIN RMSE TRMM RMSE IMERG

(a)

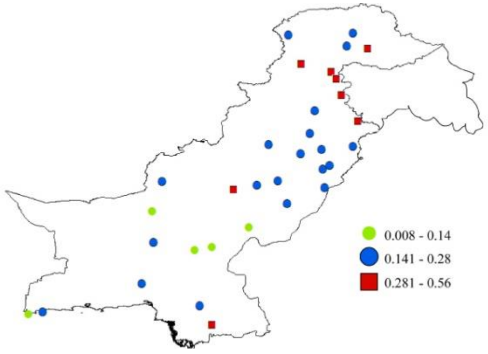


CC SM2RAIN CC TRMM CC IMERG

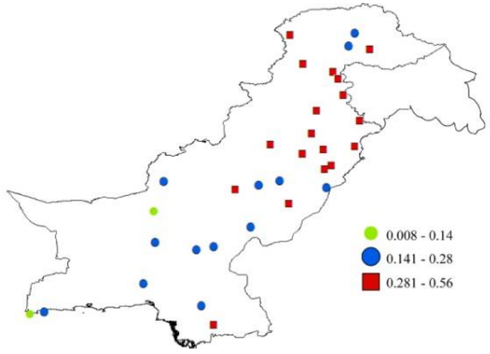
(b)



FAR SM2RAIN

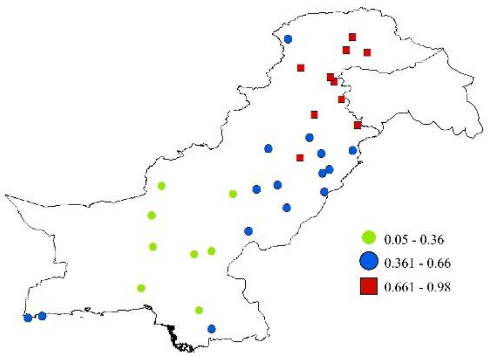


FAR TRMM

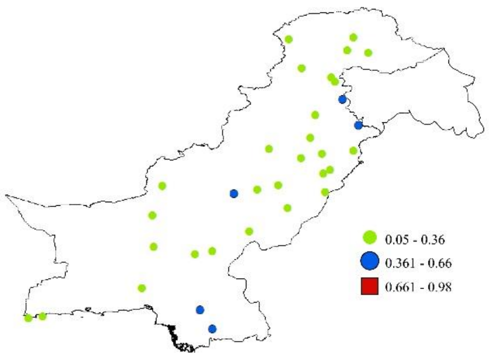


FAR IMERG

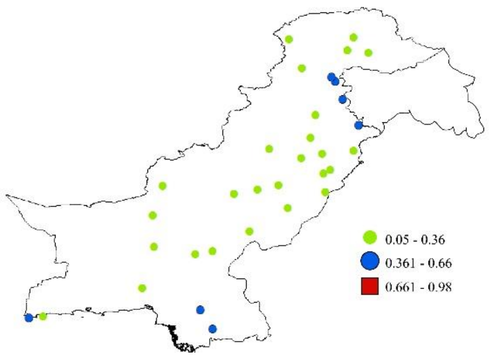
(c)



POD SM2RAIN

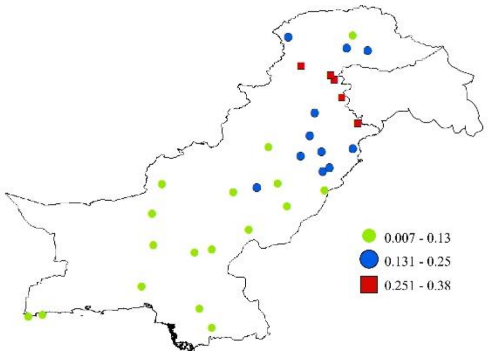


POD TRMM

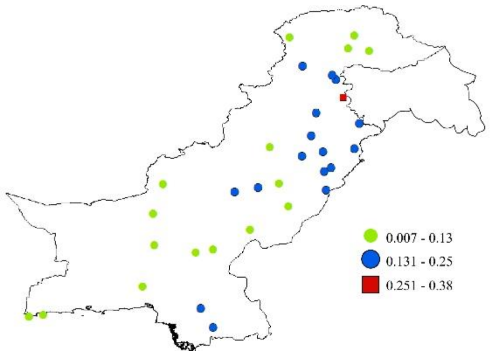


POD IMERG

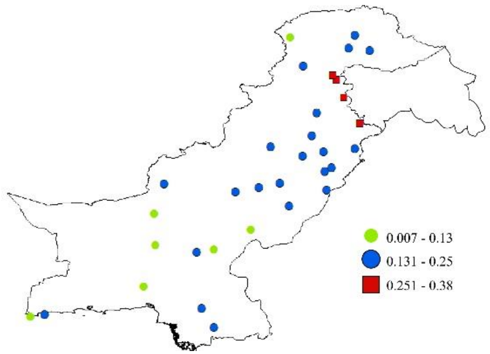
(d)



CSI SM2RAIN



CSI TRMM



CSI IMERG

(e)

Figure 4.2 Spatial Distribution of (a) root mean square error, (b) correlation coefficient, (c) false alarm ratio, (d) the probability of detection, and (e) critical success index for SM2RAIN, TRMM and IMERG.

Table 4.1 Zonal Averages of performance metrics of SM2RAIN, TRMM, and IMERG for 4 zones at daily timescale.

	RMSE (mm)			CC		
Zone	**SM2RAIN**	**TRMM**	**IMERG**	**SM2RAIN**	**TRMM**	**IMERG**
1	4.52	5.72	4.64	0.18	0.05	0.12
2	7.18	7.95	7.28	0.28	0.10	0.19
3	6.33	8.40	6.42	0.22	0.13	0.16
4	3.94	5.81	4.06	0.20	0.13	0.19

	FAR			POD		
Zone	**SM2RAIN**	**TRMM**	**IMERG**	**SM2RAIN**	**TRMM**	**IMERG**
1	0.16	0.23	0.34	0.73	0.10	0.21
2	0.31	0.35	0.42	0.63	0.28	0.33
3	0.18	0.26	0.32	0.46	0.30	0.29
4	0.11	0.19	0.24	0.47	0.27	0.31

	CSI		
Zone	**SM2RAIN**	**TRMM**	**IMERG**
1	0.15	0.07	0.14
2	0.28	0.18	0.23
3	0.21	0.16	0.18
4	0.19	0.13	0.15

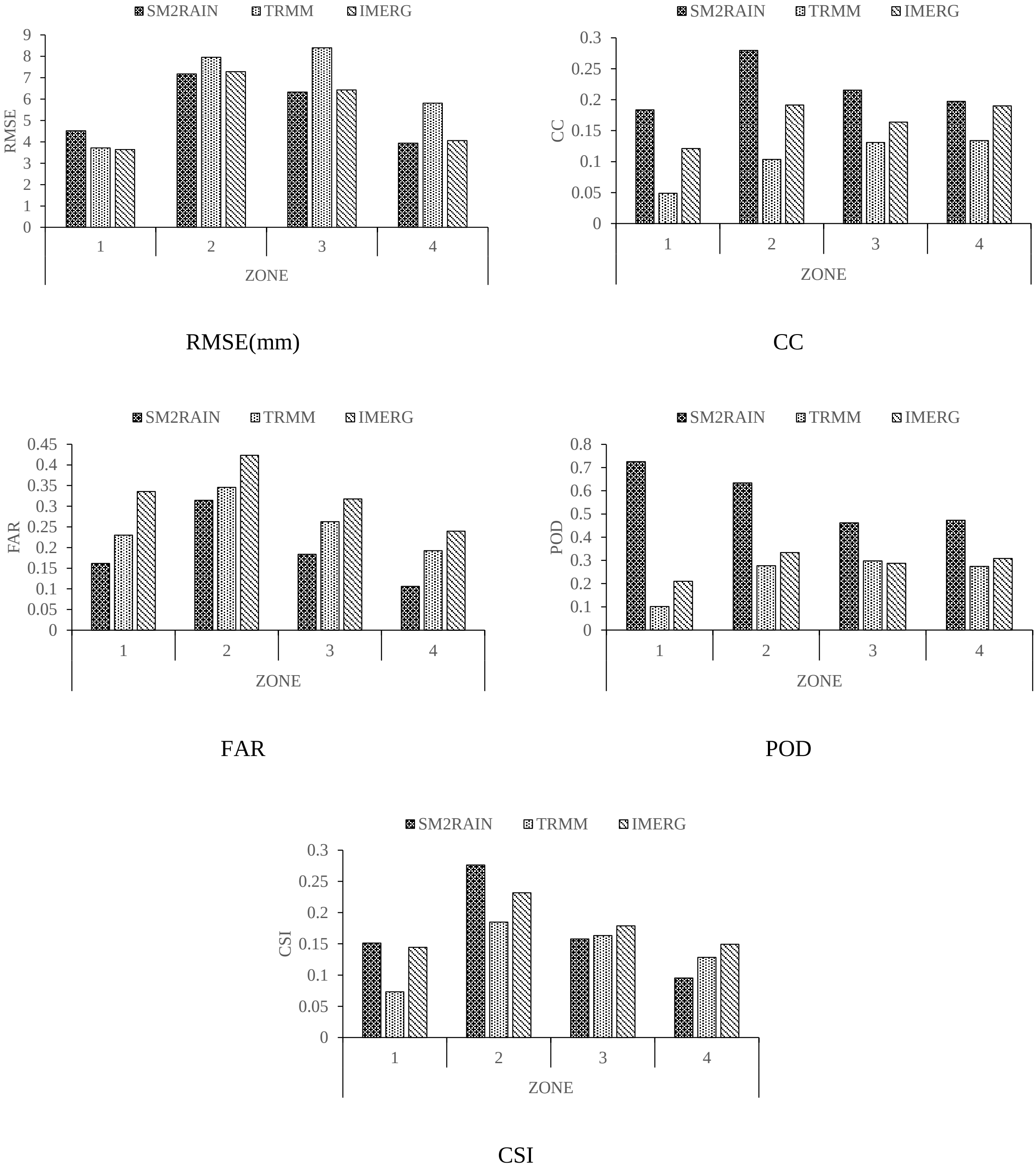


Figure 4.3 Bar charts of performance metrics obtained by comparing the daily rainfall estimates of satellite products with gauge data in all four zones.

Furthermore, to evaluate the performance at monthly time scale, the precipitation data at daily timescale are simply average to convert into monthly timescale. Bar charts of zonal averages of performance metrics in all four zones at monthly time scale are shown in Figure 4.4. It was resulted that RMSE of SM2RAIN is higher in zone 1. It is noteworthy here to mention that zone 1 is the zone with the highest altitude, humid climate, and mountainous and hilly terrain. RMSE of SM2RAIN is lowest in second, third and fourth zones. CC of SM2RAIN is better than TRMM in the first two zones and shows agreement with IMERG. However, in zone 3 and 4 CC of all three products is close to one another. SM2RAIN outperformed the other two products in terms of FAR in all four zones. POD of SM2RAIN is considerably better than other two products in first two zones and shows a strong agreement with TRMM in third and fourth zones while the performance of IMERG is weakest in third and fourth zones in terms of POD. CSI of SM2RAIN is significantly higher than the other two products in the first two zones. Moreover, there are slight variations in CSI of all three products in zone 3 and 4.

4.2.3 Performance Evaluation at Seasonal Scale

SM2RAIN TRMM and IMERG were also evaluated at seasonal scale i.e., winter (December -February), spring (March-May), summer (June-August) and autumn (September-November) at all 33 selected stations using daily rainfall estimates.

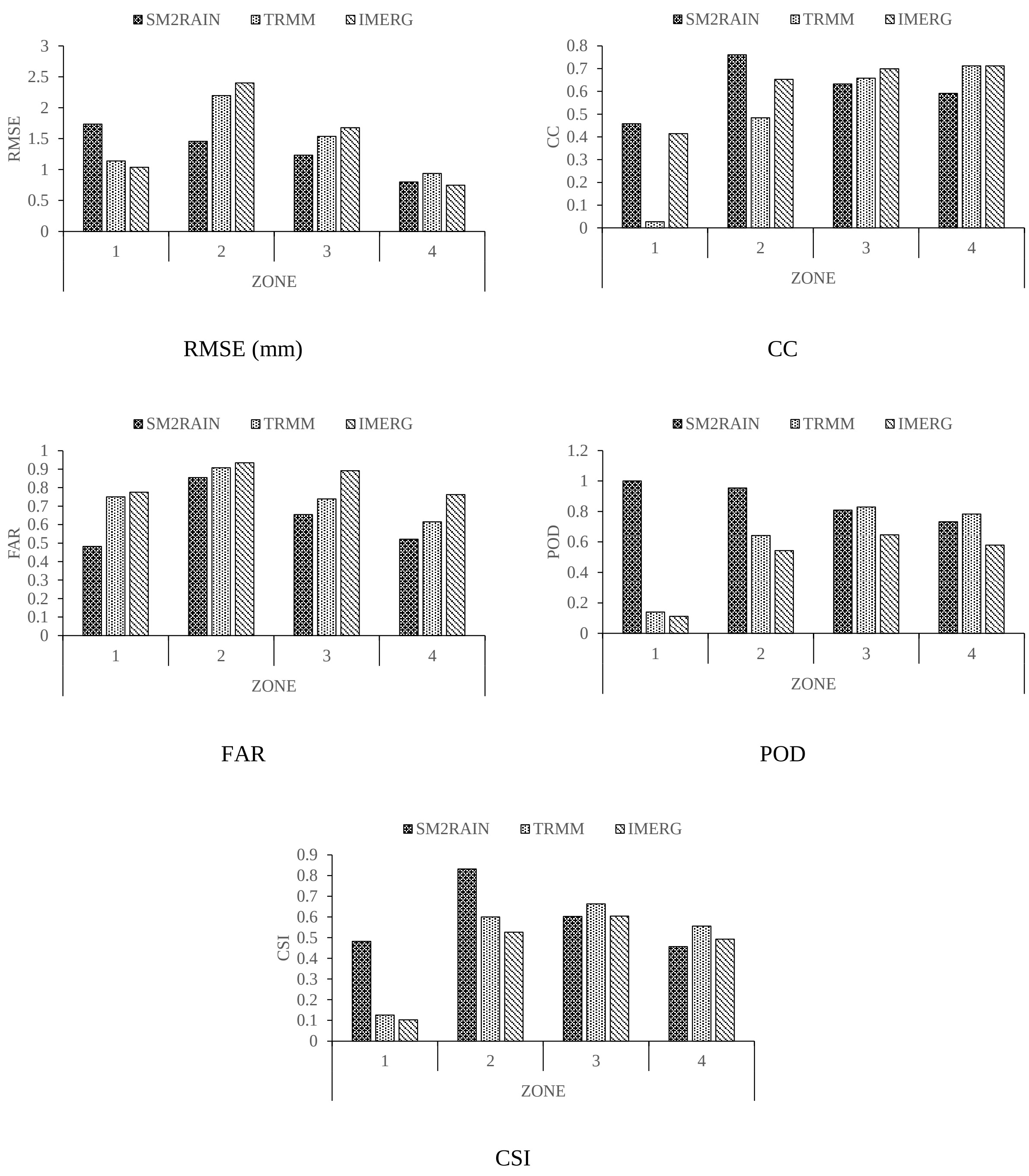
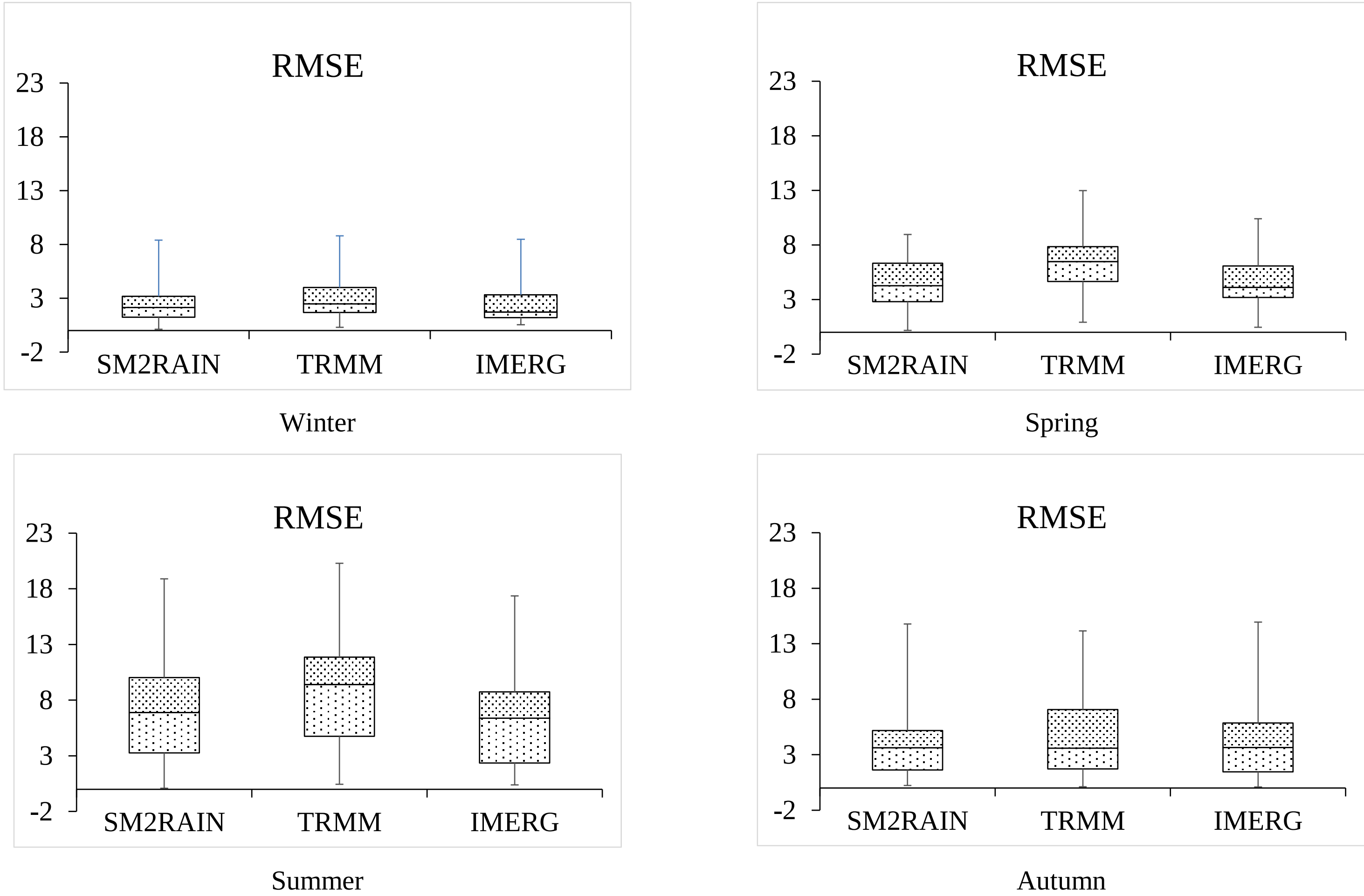


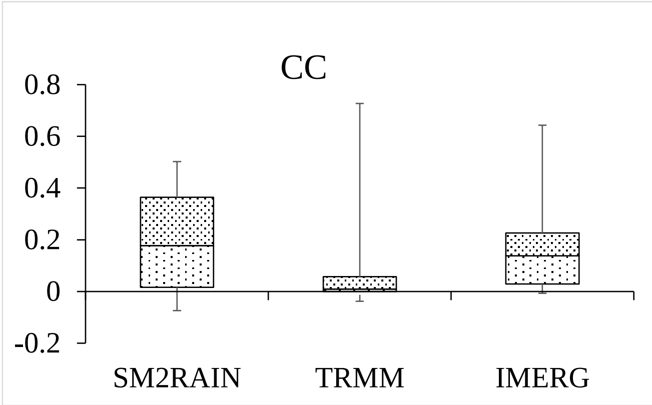
Figure 4.4 Bar charts of performance metrics obtained by comparing the monthly average rainfall estimates of satellite products with gauge data in all four zones.

Box plots are created to represent a graphical summary of performance metrics of each satellite product in different seasons. The center line that divides the two boxes depicts the median value, the middle box represents the range in which

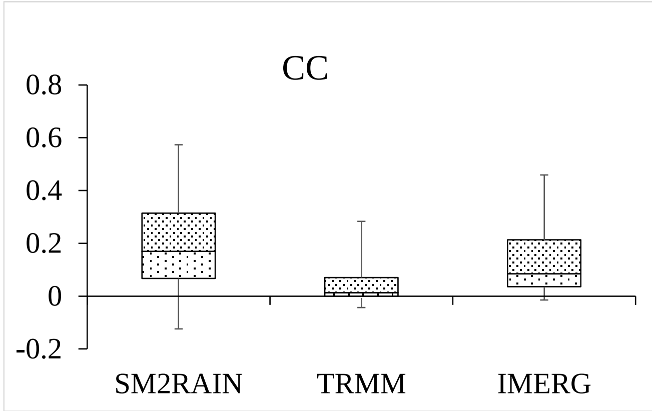
50% values lie and the lower and upper whiskers depict the values that are not in the middle 50% range. Box Plots of selected performance metrics obtained by comparing the daily rainfall estimates of satellite products with gauge data at seasonal scale are shown in Figure 8. Winter: There is a strong agreement between the mean value of RMSE of SM2RAIN and IMERG, while RMSE of TRMM is slightly higher than the other two in the winter season. CC, FAR and especially POD based evaluation for winter season revealed that SM2RAIN shows considerably better performance. However, in case of CSI based evaluation resulted in quite similar results in case of SM2RAIN and IMERG while TRMM performs poorly in terms of CSI as well in the winter season. During spring season: An agreement is observed between the RMSE of SM2RAIN and IMERG while CC of SM2RAIN is better than the other two products. FAR values of SM2RAIN and TRMM show an agreement in spring season while IMERG performs poorly in terms of FAR. POD of SM2RAIN is considerably better than the rest two. CSI of all three products has a slight difference in mean value in the spring season. Summer: IMERG performs slightly better than SM2RAIN and considerably better than TRMM in the summer season. Mean values of CC of all three products indicate a slight difference. SM2RAIN performs better than TRMM and IMERG in terms of FAR and POD. CSI of IMERG is better than rest two and SM2RAIN performs poorly as compared to the other two in terms of CSI in the summer season. Autumn: SM2RAIN and IMERG exhibit a strong agreement in terms of RMSE in the autumn season as well. SM2RAIN is ranked as best performing, IMERG as second and TRMM as poorly performed products in terms of CC in the autumn season. FAR and POD of SM2RAIN are considerably better than TRMM and IMERG, making it best performing product in terms of FAR and POD in the autumn season. Performance of SM2RAIN is poor as compared to the other two products in terms of CSI while the IMERG is best performing product in terms of CSI in the autumn season.


RMSE
23
18
13
8
3
-2
SM2RAIN
TRMM
IMERG
Winter
Spring
Summer
Autumn

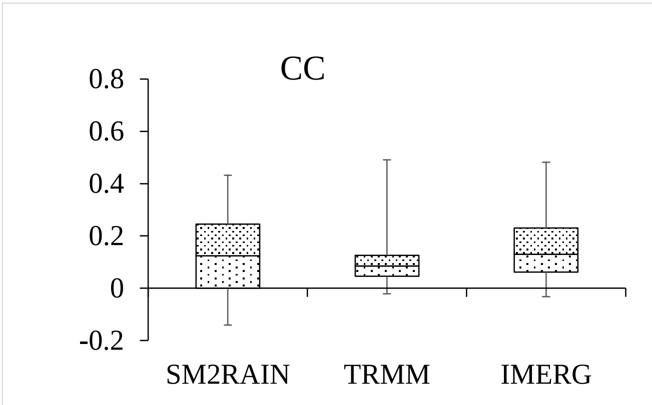
(a)



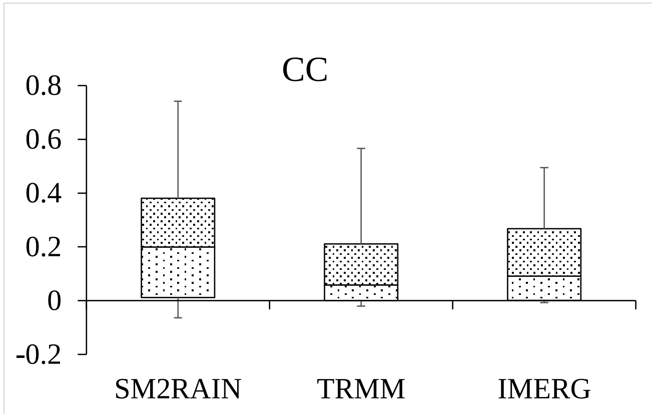
Winter



Spring

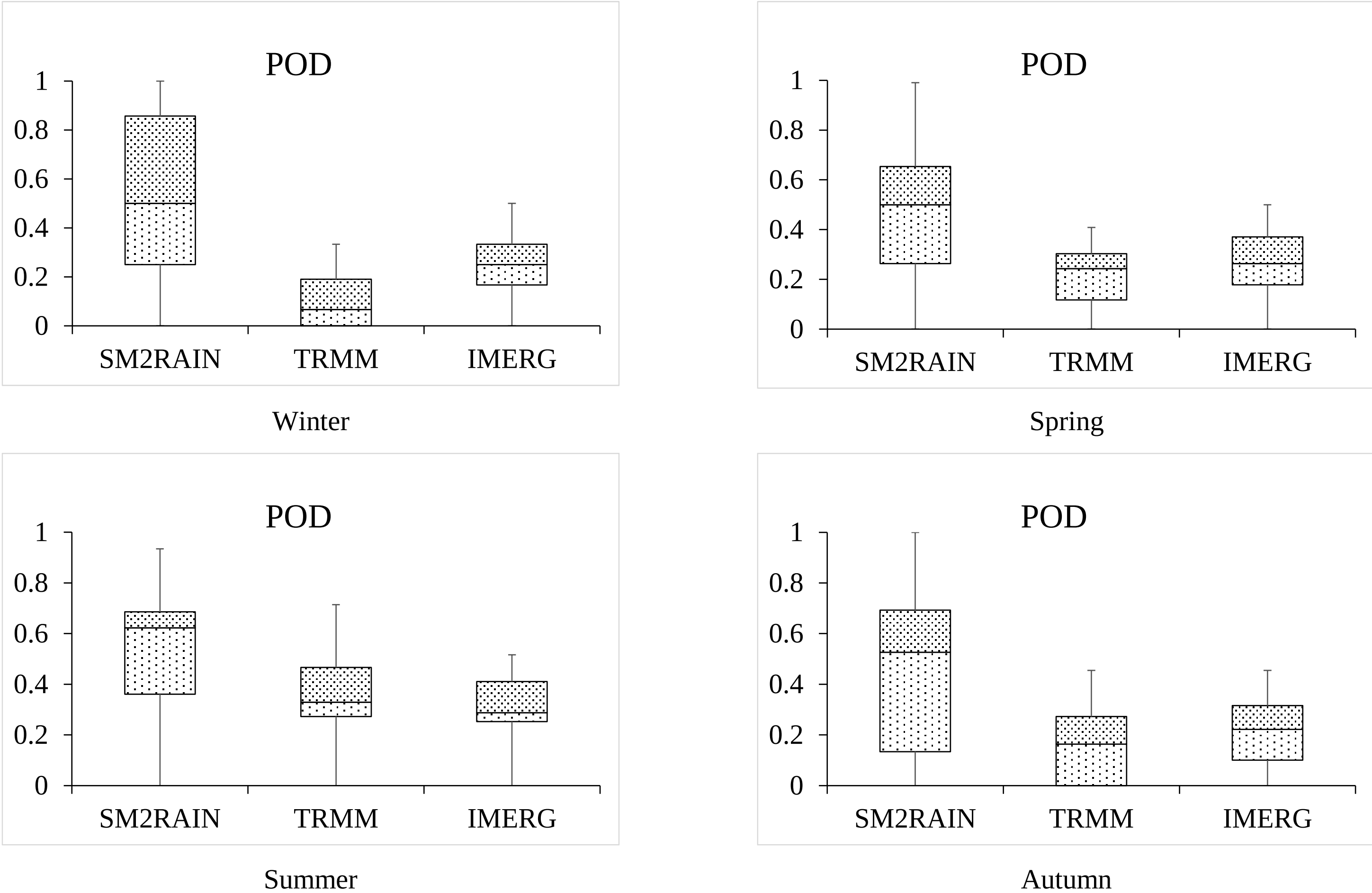


Summer

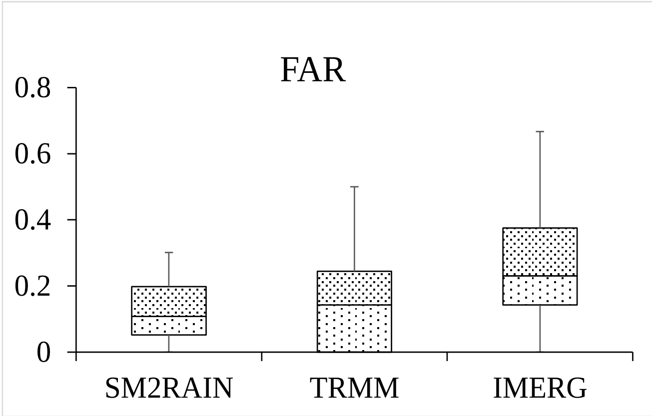


Autumn

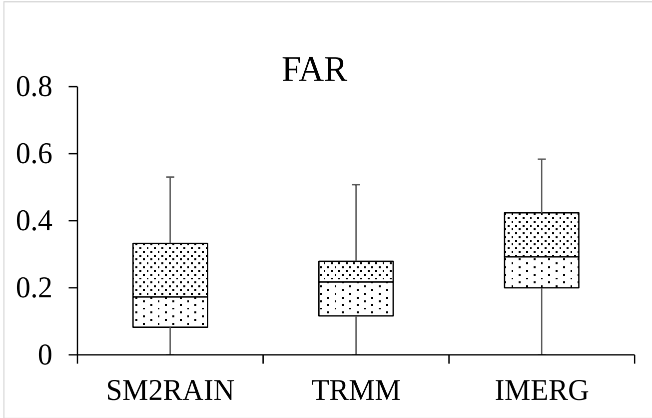
(b)


POD
1
0.8
0.6
0.4
0.2
0
SM2RAIN
TRMM
IMERG
Winter
Spring
Summer
Autumn

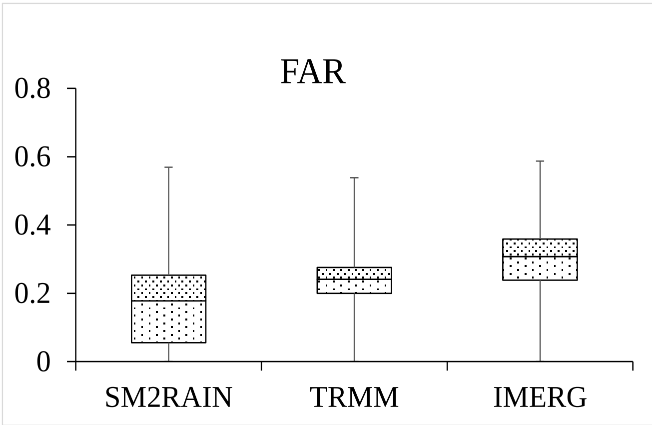
(c)



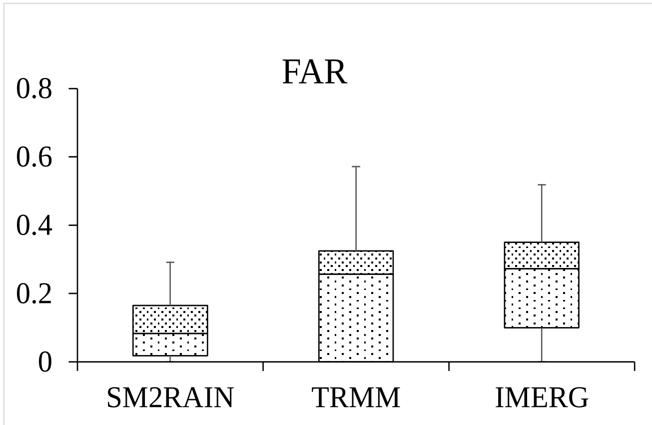
Winter



Spring

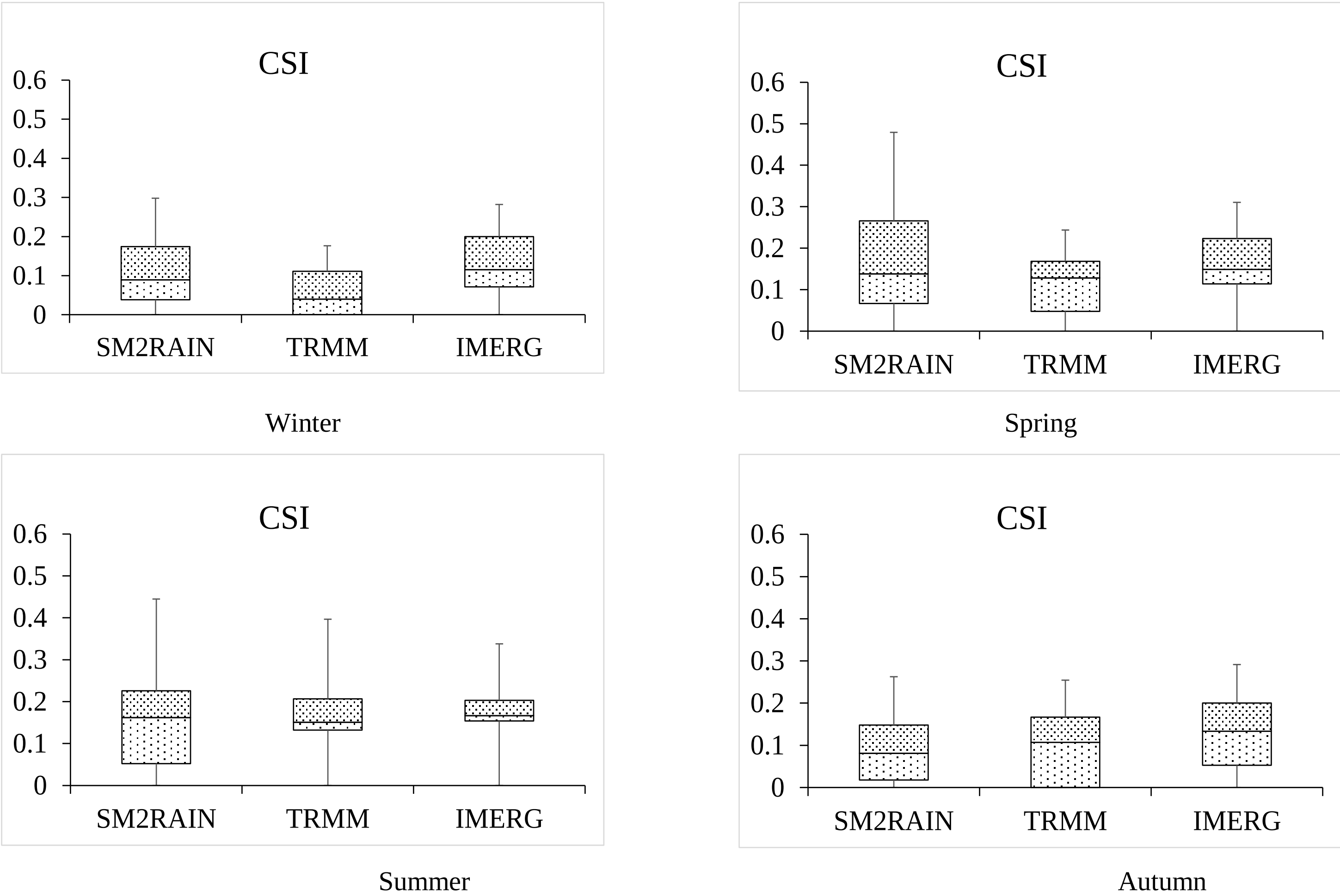


Summer



Autumn

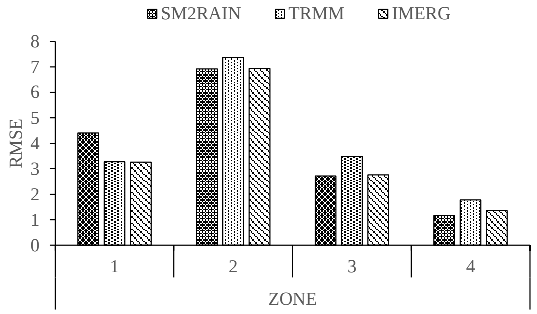
(d)



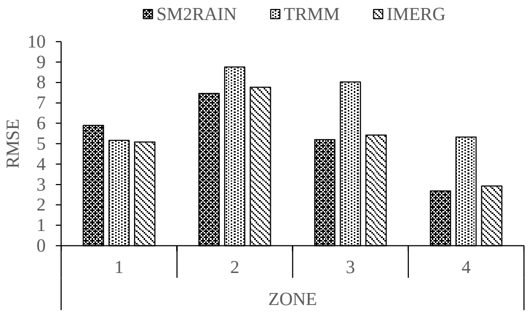
(e)

Figure 4.5 Boxplots of the (a) Root Mean Square Error, (b) Correlation Coefficient, (c) Probability of Detection, (d) False Alarm Ration, and (e) Critical Success Index of SM2RAIN, TRMM and IMERG for different seasons.

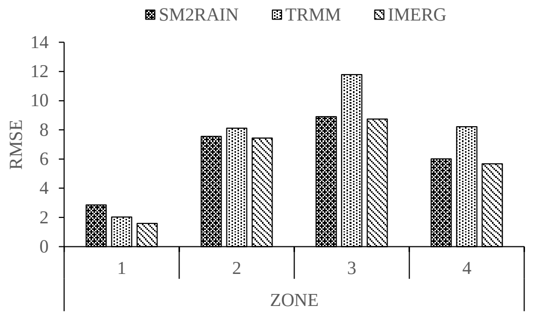
All three selected satellite products were evaluated at seasonal scale i.e., winter (December-February), spring (March-May), summer (June-August) and autumn (September-November) at all 33 selected stations using daily rainfall estimates situating in different climatic zones. Figure 4.6 is depicting bar charts of zonal averages of all selected performance metrics in different seasons.



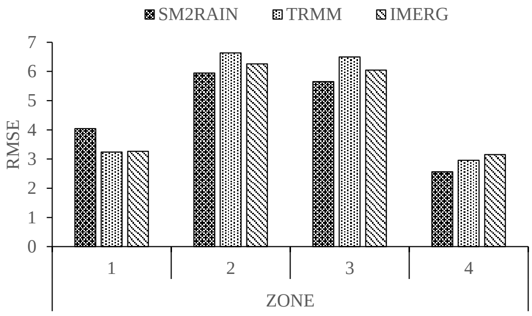
(a) Winter



(b) Spring

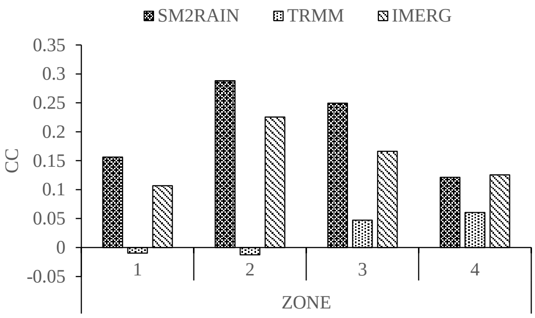


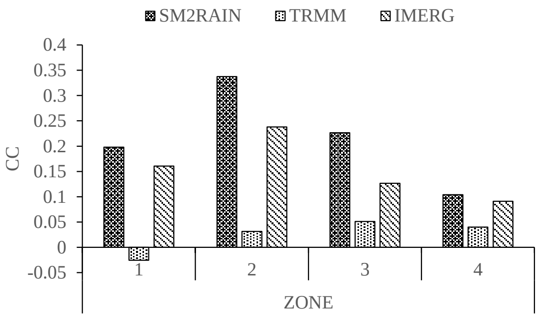
(c) Summer



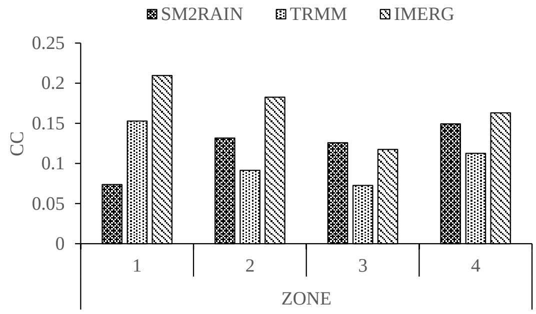
(d) Autumn

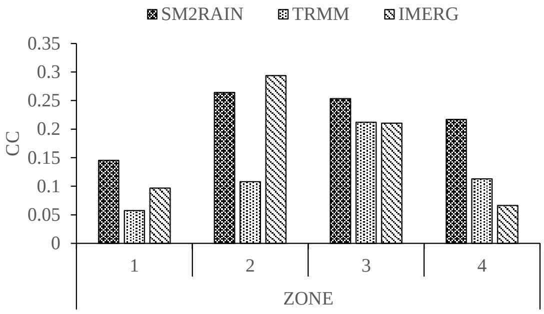
Figure 4.6 Bar Charts of Zonal Averages of RMSE in (a) winter, (b) spring, (c) summer, and (d) autumn seasons.





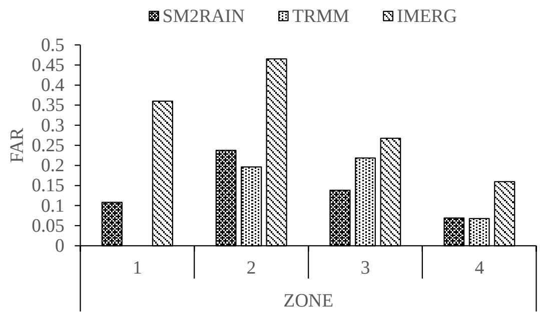
(a) Winter (b) Spring

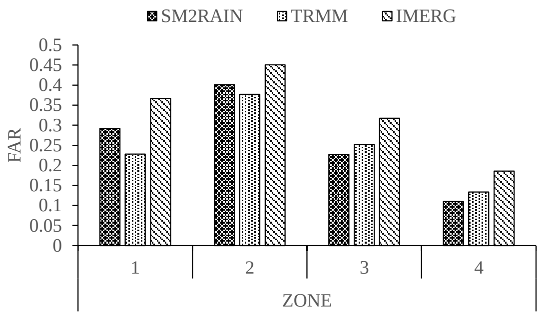




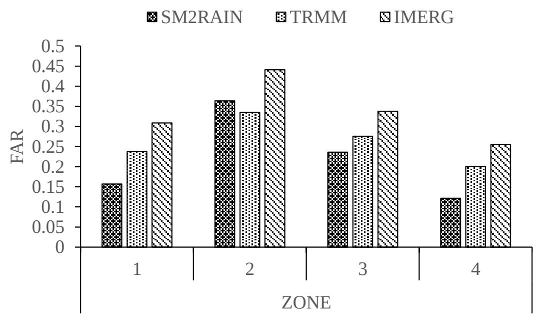
(c) Summer (d) Autumn

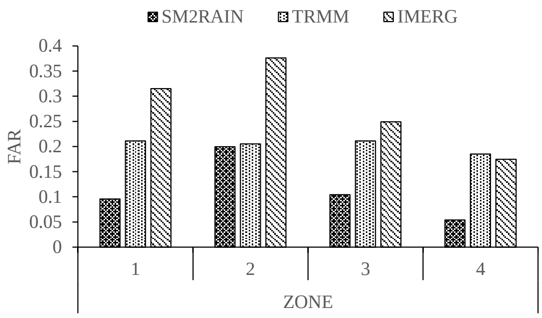
Figure 4.7 Bar Charts of Zonal Averages of CC in (a) winter, (b) spring, (c) summer, and (d) autumn seasons.





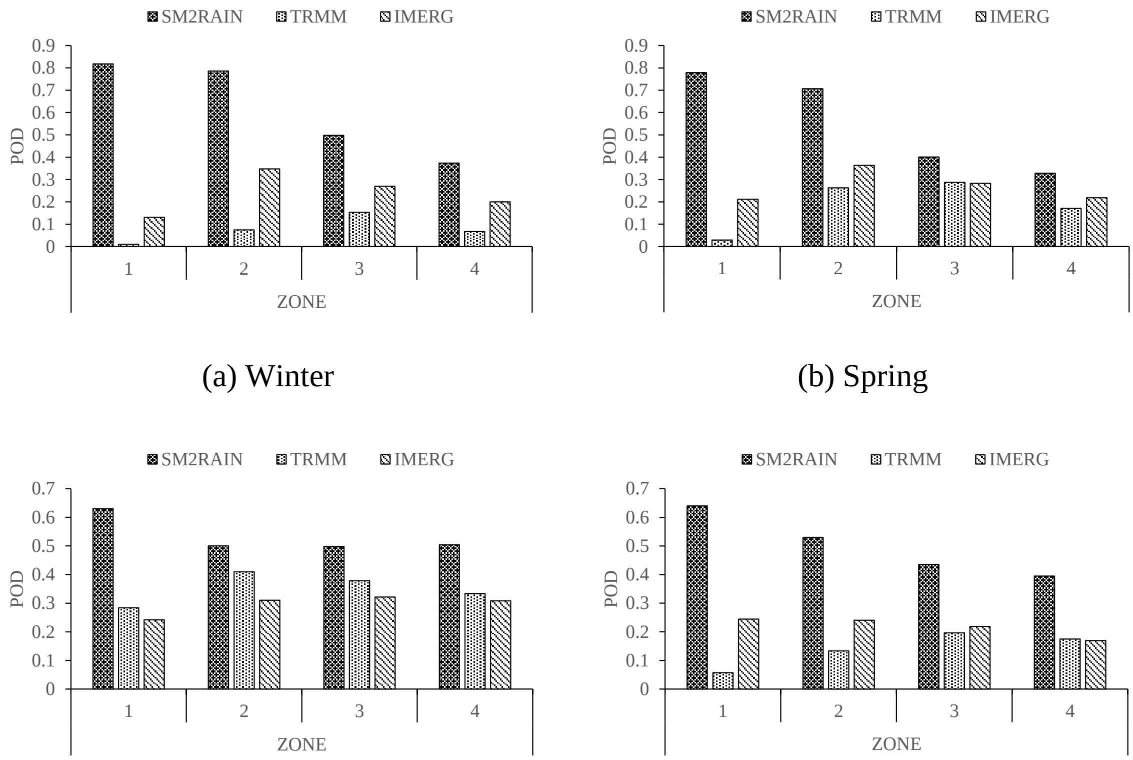
(a) Winter (b) Spring





(c) Summer (d) Autumn

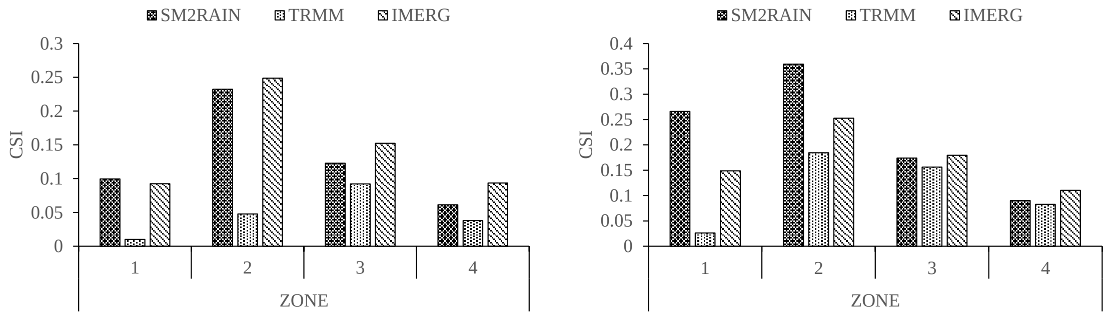
Figure 4.8 Bar Charts of Zonal Averages of FAR in (a) winter, (b) spring, (c) summer, and (d) autumn seasons.



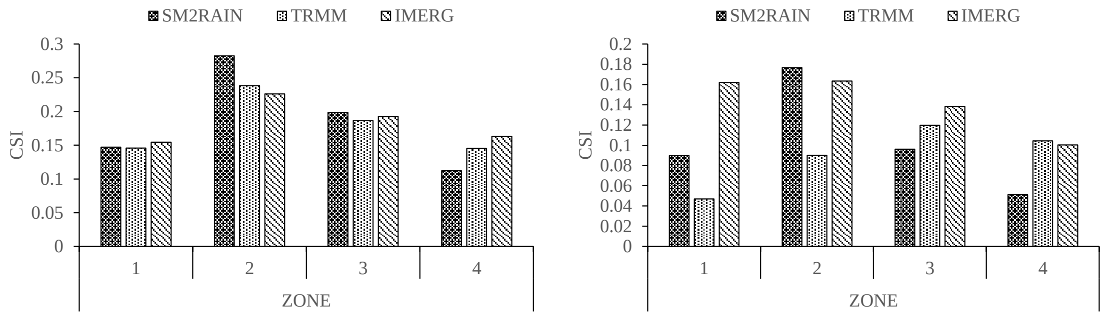
(a) Winter (b) Spring

(c) Summer (d) Autumn

Figure 4.9 Bar Charts of Zonal Averages of POD in (a) winter, (b) spring, (c) summer and, (d) autumn seasons.



(a) Winter (b) Spring



(c) Summer (d) Autumn

Figure 4.10 Bar Charts of Zonal Averages of CSI in (a) winter, (b) spring, (c) summer and, (d) autumn seasons.

4.3 STATISTICAL SIGNIFICANCE OF RESULTS

Wilcoxon Signed rank sum test resulted that there is a statistical significant difference between the SM2RAIN and all selected satellite products in terms of POD and FAR with a p value less than α, except CSI (Table 4.2). Moreover, in case of RMSE and CC, SM2RAIN and IMERG provided insignificant difference.

Table 4.2 Results of Wilcoxon Signed rank sum test.

Products	**Alpha**	**p-value**	**p-value < alpha or p-value > alpha**	**Accepted Hypothesis**	**Risk to reject Ho**
RMSE SM2RAIN VS TRMM	0.05	< 0.0001	p-value < alpha	Ha	0.01%
RMSE SM2RAIN VS IMERG	0.05	0.8302	p-value > alpha	**Ho**	83.02%
CC SM2RAIN VS TRMM	0.05	0.0040	p-value < alpha	Ha	0.40%
CC SM2RAIN VS IMERG	0.05	0.1118	p-value > alpha	**Ho**	11.18%
POD SM2RAIN VS TRMM	0.05	< 0.0001	p-value < alpha	Ha	0.01%
POD SM2RAIN VS IMERG	0.05	< 0.0001	p-value < alpha	Ha	0.01%
FAR SM2RAIN VS TRMM	0.05	< 0.0001	p-value < alpha	Ha	0.01%
FAR SM2RAIN VS IMERG	0.05	< 0.0001	p-value < alpha	Ha	0.01%
CSI SM2RAIN VS TRMM	0.05	0.5317	p-value > alpha	**Ho**	53.17%
CSI SM2RAIN VS IMERG	0.05	0.05	p-value < alpha	**Ho**	5%

4.4 DISCUSSION

Satellite-based precipitation products are considered as a modern tool for rainfall estimation, but the accuracy and reliability of satellite based products is inconsistent in different regions of the world. The accuracy and reliability are greatly dependent upon the climatic and geographic condition of that specific region. Hence, this study used different performance metrics to evaluate the accuracy and reliability of SM2RAIN in diverse regions of Pakistan. The performance of SM2RAIN was assessed by comparative analysis with in-situ observations and comparing the results with two state of the art precipitation products namely TRMM and IMERG. In general, the overall results (Figures 5-13) revealed that SM2RAIN could be a useful addition in satellite precipitation products family.

The performance evaluation on daily time scale resulted that SM2RAIN performs relatively better in all four diverse regions of Pakistan even though the spatial pattern of the performance metrics is different. The performance was much better in the arid and semiarid region, while in a humid region slightly low performance was observed. It may be because the high rainfall intensity (Chiaravalloti et al. 2018) in the humid region as SM2RAIN performance vary with the intensity of rainfall. It was noted that its performance is comparatively better in moderate rainfall intensity region, while low in case of the northern area of Pakistan. Performance of SM2RAIN is slightly lower in northern areas of Pakistan i.e., zones 1 and 2, evidently due to high topographic complexity, high altitude, hilly and mountainous terrain, and higher rainfall frequency as also resulted by (Paredes-Trejo et al. 2018). The overall performance of SM2RAIN is acceptable in all zones.

When considering the monthly time scale, the accuracy of TRMM and IMERG remarkably increased in most of the zones. The results concurred with the previous research (Ullah et al. 2019) which provides the evidence that with time aggregation the performance of IMERG significantly increases. The performance of SM2RAIN in terms of RMSE is found to be acceptable and there is considerable agreement with the other two products, especially with IMERG, similar results were derived by (Chiaravalloti et al. 2018). Higher RMSE of SM2RAIN in zone 1 is apparently due to hilly and mountainous terrain, high altitude and greater humidity index as compared to other zones. However, while considering other performance metrics e.g., FAR and POD, SM2RAIN was better in descriptive statistics compared to other product.

SM2RAIN provide better estimates in winter and autumn season, while relative poor in the summer season in which most parts of Pakistan observe higher temperature and heavy rainfall due to monsoon and soil moisture data is erroneous due to effect of higher air temperature and humidity (Brocca et al. 2015). Hence, it is evident that the performance of SM2RAIN is significantly affected by the rainfall intensity and it provides low performance in case of high-intensity rainfall irrespective of the region.

Chapter V
CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Rainfall is the most important input variable for many applications is hydrology, thus the accurate estimation of rainfall is of utmost importance in almost all parts of the world. Satellite-based products are providing the rainfall estimates at a better spatial coverage than the ground-based techniques. SM2RAIN is an advanced rainfall estimation technique, which gives the daily accumulated rainfall estimates by using the microwave-based satellite soil moisture observations derived from the Advanced SCATterometer (ASCAT). This study was launched to evaluate the performance of SM2RAIN in different regions of Pakistan, for this purpose the daily rainfall data from SM2RAIN was compared with gauge data of five performance metrics. Moreover, in order to compare the accuracy of SM2RAIN with other satellite-based products two states of the art rainfall products i.e., TRMM and IMERG were selected. The analysis was performed on daily rainfall estimates, monthly average rainfall and on a seasonal scale. Keeping in view the analysis results following conclusions could be drawn:

1. SM2RAIN-ASCAT could be best alternate satellite-based rainfall product.

2. The analysis on daily rainfall estimates depicts that SM2RAIN shows the weakest performance in very humid, mountainous and high altitude areas.

3. Performance of SM2RAIN for daily rainfall estimates is comparatively better than other products in dry areas.

4. SM2RAIN performs better than other satellite-based products in terms of rainfall detection in all considered cases i.e., different zones and temporal scales

5. The seasonal analysis shows that the SM2RAIN gives most accurate rainfall estimates in winter and autumn season, the performance of SM2RAIN in summer season is comparatively poor than other two products.

6. The overall performance of SM2RAIN was better than IMERG and TRMM, IMERG ranked as second while the TRMM showed the poorest performance.

7. This study reveals that in future SM2RAIN can be used as an effective tool for rainfall estimation in poorly gauged areas of Pakistan especially in zone 3 and zone 4, which are dry areas. Performance of SM2RAIN can be enhanced by merging its rainfall estimates with other state-of-the-art satellite products or by applying ensemble algorithm.

5.2 RECOMMENDATIONS

- This study recommends a new rainfall estimation product for poorly gauged areas of Pakistan.

- Performance of SM2RAIN can be further increased by merging its rainfall estimates with rainfall estimates of other state of the art satellite products.

- The results of this study suggested that SM2RAIN is a competitive satellite product thus its hydrological evaluation should be carried out by rainfall runoff modelling.

- Many other satellite based rainfall products are available globally, some of them are similar to SM2RAIN and estimate the rainfall by using satellite soil moisture data, evaluation of these products should be carried out in Pakistan. There is no doubt that future of rainfall estimation by satellite soil moisture based rainfall products is bright in whole world.

- The results of this study are very appealing and author is convinced to recommend water resources engineers and hydrologists to consider the satellite soil moisture based rainfall products in their research projects.

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APPENDIX

Table 1. RMSE of SM2RAIN, TRMM and IMERG at 33 selected stations.

RMSE				
Sr. No.	**STATION**	**SM2RAIN**	**TRMM**	**IMERG**
1	Astore	4.69	4.50	4.36
2	Badin	5.30	6.28	4.73
3	BahawalNagar	4.84	7.47	5.05
4	BahawalPur	3.91	6.71	4.11
5	Barkhan	5.72	7.88	5.27
6	Bhakar	6.59	7.30	5.10
7	Chakwal	7.09	10.22	7.75
8	Chilas	3.72	3.23	3.12
9	Chitral	5.63	4.93	4.86
10	D.G. Khan	3.31	7.91	3.97
11	Faisalabad	5.24	7.36	6.07
12	Garhi Dupatta	8.99	9.95	9.34
13	Gilgit	4.04	2.21	2.20
14	Gwadar	1.60	2.35	1.79
15	Hyderabad	3.76	5.58	3.73
16	Jhang	6.54	8.58	7.08
17	Jiwani	1.80	2.11	1.94
18	Kalat	2.07	2.46	1.83
19	Khuzdar	3.04	4.57	3.32
20	Kotli	9.95	12.93	11.71

21	Lahore	9.07	10.53	9.51
22	Larkana	1.95	3.56	1.95
23	Lasbella	2.51	5.90	2.80
24	Multan	3.99	7.18	4.82
25	Muzaffarabad	9.02	10.11	9.50
26	Okara	6.68	7.84	6.51
27	Quetta	2.88	3.18	2.74
28	Rahim Yar Khan	2.97	7.22	3.29
29	Rohri	2.22	4.22	2.22
30	Sahiwal	5.64	6.42	5.55
31	Saidu Sharif	7.84	8.57	7.55
32	Sargodha	8.11	9.97	6.94
33	Sialkot	13.24	13.76	12.84

Table 2. CC of SM2RAIN, TRMM and IMERG at 33 selected stations.

CC				
Sr. No.	**STATION**	**SM2RAIN**	**TRMM**	**IMERG**
1	Astore	0.15	0.08	0.22
2	Badin	0.08	0.42	0.41
3	BahawalNagar	0.31	0.15	0.24
4	BahawalPur	0.34	0.09	0.19
5	Barkhan	0.04	0.12	0.17
6	Bhakar	0.12	0.13	0.11
7	Chakwal	0.32	0.06	0.12
8	Chilas	0.30	0.03	0.09
9	Chitral	0.14	0.06	0.13
10	D.G. Khan	0.42	0.14	0.28
11	Faisalabad	0.45	0.17	0.12
12	Garhi Dupatta	0.34	0.17	0.21
13	Gilgit	0.15	0.02	0.04
14	Gwadar	0.20	0.27	0.29
15	Hyderabad	0.01	0.17	0.20
16	Jhang	0.35	0.16	0.15
17	Jiwani	0.11	0.06	0.35
18	Kalat	-0.02	-0.01	0.06
19	Khuzdar	-0.07	0.03	0.00

20	Kotli	0.54	0.17	0.24
21	Lahore	0.39	0.29	0.28
22	Larkana	0.00	0.05	0.04
23	Lasbella	0.01	0.11	0.11
24	Multan	0.40	0.09	0.18
25	Muzaffarabad	0.36	0.14	0.27
26	Okara	0.30	0.14	0.19
27	Quetta	0.14	0.09	0.10
28	Rahim Yar Khan	0.25	0.01	0.06
29	Rohri	0.01	0.12	0.11
30	Sahiwal	0.18	0.02	0.08
31	Saidu Sharif	0.28	0.02	0.19
32	Sargodha	0.10	0.07	0.21
33	Sialkot	0.29	0.27	0.26

Table 3. FAR of SM2RAIN, TRMM and IMERG at 33 selected stations.

FAR				
Sr. No.	**STATION**	**SM2RAIN**	**TRMM**	**IMERG**
1	Astore	0.18	0.32	0.47
2	Badin	0.11	0.34	0.30
3	BahawalNagar	0.13	0.21	0.27
4	BahawalPur	0.12	0.18	0.30
5	Barkhan	0.13	0.33	0.35
6	Bhakar	0.13	0.21	0.30
7	Chakwal	0.25	0.28	0.35
8	Chilas	0.18	0.16	0.25
9	Chitral	0.15	0.22	0.35
10	D.G. Khan	0.26	0.27	0.26
11	Faisalabad	0.25	0.27	0.33
12	Garhi Dupatta	0.42	0.43	0.52
13	Gilgit	0.13	0.22	0.28
14	Gwadar	0.05	0.20	0.19
15	Hyderabad	0.04	0.26	0.23
16	Jhang	0.25	0.24	0.29
17	Jiwani	0.03	0.08	0.08
18	Kalat	0.01	0.05	0.08
19	Khuzdar	0.01	0.19	0.19

20	Kotli	0.37	0.45	0.55
21	Lahore	0.30	0.28	0.40
22	Larkana	0.06	0.11	0.22
23	Lasbella	0.05	0.18	0.15
24	Multan	0.12	0.19	0.26
25	Muzaffarabad	0.43	0.47	0.52
26	Okara	0.17	0.24	0.29
27	Quetta	0.07	0.16	0.28
28	Rahim Yar Khan	0.10	0.13	0.19
29	Rohri	0.03	0.11	0.17
30	Sahiwal	0.17	0.22	0.32
31	Saidu Sharif	0.33	0.32	0.38
32	Sargodha	0.17	0.28	0.36
33	Sialkot	0.28	0.36	0.50

Table 4. POD of SM2RAIN, TRMM and IMERG at 33 selected stations.

POD				
Sr. No.	**STATION**	**SM2RAIN**	**TRMM**	**IMERG**
1	Astore	0.98	0.11	0.26
2	Badin	0.47	0.49	0.44
3	BahawalNagar	0.57	0.27	0.26
4	BahawalPur	0.44	0.25	0.26
5	Barkhan	0.33	0.38	0.28
6	Bhakar	0.42	0.23	0.33
7	Chakwal	0.76	0.35	0.31
8	Chilas	0.67	0.13	0.25
9	Chitral	0.51	0.06	0.12
10	D.G. Khan	0.51	0.32	0.24
11	Faisalabad	0.66	0.29	0.29
12	Garhi Dupatta	0.77	0.36	0.40
13	Gilgit	0.75	0.10	0.21
14	Gwadar	0.53	0.20	0.33
15	Hyderabad	0.26	0.59	0.41
16	Jhang	0.71	0.31	0.24
17	Jiwani	0.44	0.11	0.44
18	Kalat	0.13	0.13	0.21
19	Khuzdar	0.05	0.24	0.15

20	Kotli	0.69	0.39	0.39
21	Lahore	0.61	0.25	0.31
22	Larkana	0.34	0.17	0.27
23	Lasbella	0.22	0.29	0.20
24	Multan	0.50	0.22	0.24
25	Muzaffarabad	0.75	0.33	0.37
26	Okara	0.54	0.29	0.27
27	Quetta	0.30	0.15	0.24
28	Rahim Yar Khan	0.51	0.22	0.29
29	Rohri	0.22	0.19	0.22
30	Sahiwal	0.61	0.25	0.32
31	Saidu Sharif	0.72	0.27	0.32
32	Sargodha	0.43	0.31	0.30
33	Sialkot	0.74	0.39	0.44

Table 5. CSI of SM2RAIN, TRMM and IMERG at 33 selected stations.

CSI				
Sr. No.	**STATION**	**SM2RAIN**	**TRMM**	**IMERG**
1	Astore	0.18	0.09	0.20
2	Badin	0.10	0.25	0.22
3	BahawalNagar	0.12	0.13	0.15
4	BahawalPur	0.11	0.12	0.16
5	Barkhan	0.10	0.21	0.18
6	Bhakar	0.11	0.12	0.19
7	Chakwal	0.23	0.18	0.20
8	Chilas	0.17	0.08	0.14
9	Chitral	0.13	0.05	0.10
10	D.G. Khan	0.21	0.17	0.14
11	Faisalabad	0.22	0.16	0.18
12	Garhi Dupatta	0.38	0.24	0.29
13	Gilgit	0.12	0.07	0.13
14	Gwadar	0.05	0.11	0.14
15	Hyderabad	0.04	0.22	0.17
16	Jhang	0.22	0.16	0.15
17	Jiwani	0.02	0.05	0.07
18	Kalat	0.01	0.04	0.06
19	Khuzdar	0.01	0.12	0.09

20	Kotli	0.32	0.26	0.29
21	Lahore	0.25	0.15	0.21
22	Larkana	0.05	0.07	0.14
23	Lasbella	0.04	0.13	0.09
24	Multan	0.11	0.11	0.14
25	Muzaffarabad	0.38	0.24	0.28
26	Okara	0.15	0.15	0.16
27	Quetta	0.06	0.09	0.15
28	Rahim Yar Khan	0.09	0.09	0.13
29	Rohri	0.03	0.08	0.11
30	Sahiwal	0.16	0.13	0.19
31	Saidu Sharif	0.29	0.17	0.21
32	Sargodha	0.14	0.18	0.20
33	Sialkot	0.26	0.23	0.30