Chapter 25
Rainfall Variability Assessment—A Case Study of Rokel-Seli River Basin in Sierra Leone

Saramadie Thorlu-Bangura, Mitthan Lal Kansal, and Surendra Kumar Chandniha

Abstract Rainfall is a most important factor for climate study. It is depending on various factors of hydrological cycle. Actual projection of rainfall pattern is quite difficult due to involvement of uncertainty with respect to space and time. Hence, it is very difficult to access actual occurrence of rainfall in daily basis. For climate study various agencies are developed number of climate data base as per long term historical hydro-meteorological data sets. Using these climatic data base, one can project the rainfall patters under particular uncertainty bands and understand the rainfall variability at particular space. Understanding the trend and variability of rainfall is also important to determine the supplemental water requirements for crops as well as water resources planning during their critical water deficit periods. The aim of this study is to investigate the past variation of rainfall and to identify the trend over Rokel-Seli river basin in Sierra Leone for a period of 45 years (1961–2005) of rainfall data. Rokel-Seli river basin is importance to the country's economy as it supplies water to the Bumbuna hydroelectric power scheme as well as water for the agriculture, fisheries, mining and transportation and for ecological purposes. The long-term trend has been detected using the Mann Kendell (MK) and Modified Mann Kendall (MKK) test(s) for historical time series in terms of monthly, seasonal and annual basis. Further, shift change point has been detected for break point identification using SNHT and MWP test(s). Moreover, rainfall has been projected till

S. Thorlu-Bangura
Ministry of Water Resources, Freetown, Sierra Leone
e-mail: thorlubangura@gmail.com

S. Thorlu-Bangura · M. L. Kansal (✉)
Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, India
e-mail: mlk@wr.iitr.ac.in

S. K. Chandniha
Department of Soil and Water Engineering, Indira Gandhi Krishi Vishwavidyalaya, Raipur, Chhattisgarh, India
e-mail: chandniha.surendra@gmail.com

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2050s under different climate scenarios with various CMIP5 emission conditions, i.e., RCP-2.6, RCP-4.5 and RCP-8.5. Project rainfall and its trends can be useful for future prospective of agriculture and water resources planning and mitigations under consideration of Climate change.

25.1 Introduction

Rainfall variability assessment is quite important for determining the water availability and requirement for a catchment which can influence water use and allocation. Precipitation is most important factor which influences the living beings directly and indirectly. However, precipitation play key role in hydrological cycle (Prabhakar et al. 2019). The overall hydrology is initiated with precipitation and is regulate hydrology, vegetation and water bodies, and it is also significant for agricultural production (King et al. 2014). The occurrence and variability of precipitation influences to a large extent which crops can grow in different areas/regions throughout the world (Silberstein et al. 2012). A good knowledge of rainfall variability is relevant to help optimize farm production in a sustainable manner (Gajbhiye et al. 2015).

The Rokel-Seli river basin is of critical importance to the country's economy as it supplies water to the Bumbuna hydroelectric power scheme as well as water for agriculture, fisheries, mining and transportation and for ecological purposes. As per future prospective, quantum of water availability from precipitation is also quite important (Zhao et al. 2008). Hence, allocation of water for irrigation, industrial and domestic use is also very important and interlinked with hydrological cycle. Understanding the trend and variability of precipitation is also necessary to determine the supplemental water requirements of crops during their critical growth periods (Liu and Lin 2004). The response of hydrologic circulation to climate and land use changes is important in studying the historical, present, and future evolution of aquatic ecosystems.

The present study highlights the rainfall variability over the Rokel-Seli River Basin in Sierra Leone. The adopted analysis provides key information of basin's water availability and hence this work offers benchmark information that can be used to increase the capacity of long-range water resource planning and management, land use planning, agricultural water development and conservation, and industrial water use over the next several decades at basin level. Climate change impacts the rainfall distribution all around the world. The variation in rainfall distribution would alter the storage, recharge surface runoff and soil moisture (Masafu et al. 2016). Moreover, the rainfall variation can increase or decrease the discharge and water availability to a river basin. Increased variation in the intensity and frequency of precipitation is one of the major impacts of climate change (Anandhi et al. 2008).

25.2 Description of Study Area

The Rokel-Seli River, which is the largest river in Sierra Leone is 356 km (221 miles) in length and has a width varying from 6.4 to 16.1 km (4–10 miles). It stretches across the entire northern region before joining the Atlantic Ocean. It has a basin area of 10,699 km^2 which infringes four major districts (Koinadugu, Bombali, Tonkolili and Port Loko districts) having 31% (2,159,119) of the total country population (7,075,641) of Sierra Leone. Location map of study area is shown in Fig. 25.1.

This basin is characterized by a heterogeneous forest-savanna mosaic and experiences a humid tropical climate with annual rainfall averaging 2435 mm and mean monthly temperature of 27.78 °C. Elevation difference is about 956 m and varies from 19 to 975 m. There are two main seasons: rainy season (May–October) and dry season (November–April). There are several small traditional villages in the area with rice cultivation in wet depressions and harvesting of non-timber forest products such as oil palm nuts. Between the upstream and downstream, lots of mining and agricultural activities are taking place such that the rainfall pattern within this area varies considerably.

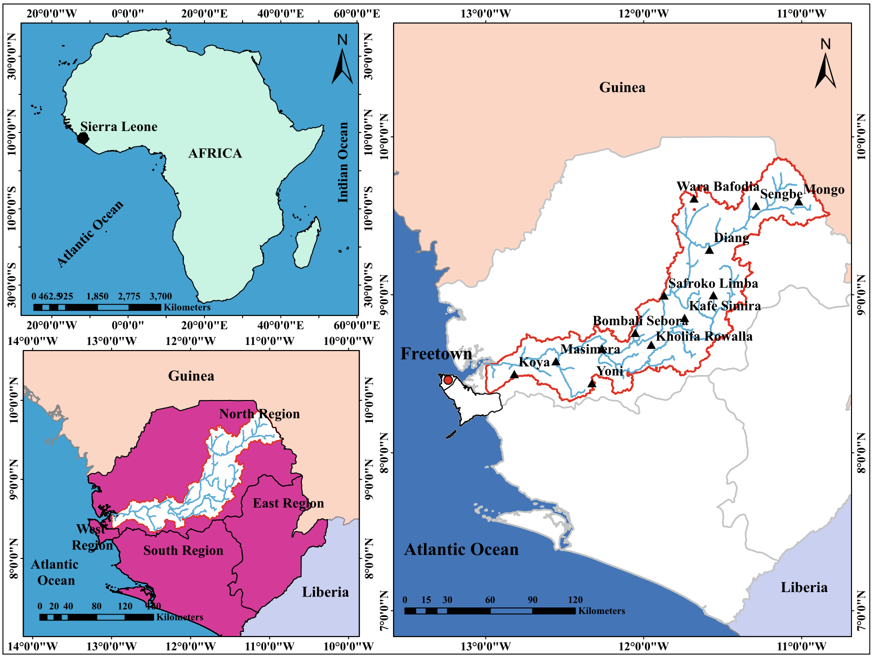

Fig. 25.1 Location map of study area

25.3 Methodology

25.3.1 Assessment of Rainfall Variability

In other to assess the rainfall variability, the rainfall data used for the thirteen (13) stations in the Rokel-Seli river basin from 1961 to 2005 (45 years) was obtained from the Sierra Leone water security website (https://www.salonewatersecurity.com/data) which was created to serve as a repository for hydrological (rainfall, surface water and groundwater) data. This was achieved by the Ministry of Water Resources, the lead government institution of Sierra Leone responsible for monitoring water resources in collaboration with multiple and diverse organizations re-established for hydrological monitoring activities. The extracted monthly, annual and seasonal rainfall data for the entire basin (station-wise) can be shown in Table 25.1.

The average annual rainfall for the basin was estimated as weighted rainfall. The area covered by each rain gauge station with their corresponding annual and seasonal rainfall values were computed to give the mean annual rainfall of RSRB as shown in Table 25.2.

The mean annual and seasonal depth of rainfall of Rokel-Seli river basin was estimated to be 2435, and 2190 and 245 mm in the wet season and dry Season respectively as illustrated in Fig. 25.2.

This means that 90% of the average annual rainfall occurs in the wet season with only 10% contribution of rainfall in the dry season on the basin. The assessment of rainfall variability is of crucial importance for stakeholders and policy makers to provide information for an improved water management. Table 25.3 gives the statistics relating to the variability of the annual and seasonal rainfall of Rokel-Seli river basin.

Considerable aerial variation exists in the annual rainfall on the basin with highest rainfall of magnitude 3589 mm annually and, 3336 and 715 in the wet and dry season respectively.

Based on the rainfall variability analysis carried out on the historical rainfall, it has been detected that the average annual rainfall over the basin was 2435 mm, varying from minimum rainfall of 895 mm to 3589 maximum rainfall. Most of the rainfall occurs during the wet season, contributing 90% of the annual rainfall over the basin ranging from minimum rainfall of 844 mm to 3336 mm maximum rainfall with average annual rainfall of 2190 mm which occurs during the months of May–October. The dry season which occurs between the periods of November to April has only a maximum rainfall of 715 mm contribute only 10% of annual rainfall on the basin with a minimum of 11 mm with mean annual rainfall of 245 mm (Table 25.3).

The coefficient of variation of the annual and seasonal rainfall varies between 14 and 52 with an average value of about 25. The coefficient of variation is least at stations of high rainfall and largest in regions of scanty rainfall as indicated in Fig. 25.3 at station Seng be (upstream) and station Yoni (downstream) for both annually and seasonally.

Table 25.1 Historical average monthly, annual and seasonal rainfall (mm) of RSRB for the period of 1961–2005

Station	J	F	M	A	M	J	J	A	S	O	N	D	Annual	Wet season	Dry season
Bombali	10	15	47	115	300	361	374	483	435	265	91	13	2507	2217	290
Diang	12	17	31	91	276	394	493	545	480	278	126	28	2772	2467	305
Kafe Simera	6	11	18	74	251	360	460	599	508	318	106	18	2729	2496	233
Kholifa Rowala	14	14	25	97	279	323	337	487	427	338	125	20	2486	2191	295
Koya	3	9	25	74	188	300	355	421	362	279	80	10	2106	1905	202
Malal Mara	5	7	17	72	310	361	449	550	483	268	91	14	2627	2421	206
Masimera	10	11	31	97	246	306	312	443	418	339	109	11	2333	2064	269
Mongo	9	8	21	76	203	284	312	406	363	221	62	9	1972	1787	185
SafrokoLimba	9	13	25	104	307	351	426	518	455	281	104	13	2605	2338	268
Sambaia	9	11	16	66	223	365	417	508	439	269	84	17	2425	2220	204
Sengbe	7	6	20	83	241	317	341	419	348	203	61	9	2054	1868	186
Warra Bafodia	7	9	20	92	257	310	356	454	437	364	150	17	2474	2179	295
Yoni	13	10	24	120	333	399	445	519	442	235	68	11	2618	2373	245
Average Rainfall	**9**	**11**	**25**	**89**	**263**	**341**	**390**	**488**	**431**	**281**	**97**	**15**	**2435**	**2194**	**245**
Standard Deviation	**3**	**3**	**8**	**17**	**43**	**37**	**61**	**58**	**49**	**48**	**27**	**5**	**256**	**232**	**45**

Table 25.2 Mean annual and seasonal weighted station rainfall (mm) of RSRB for the period of 1961–2005

Rain gauge station	Station area (km^2)	Weightage factor	Station reading of average rainfall			Weighted station rainfall		
			Annual	Wet season	Dry season	Annual	Wet season	Dry season
Bombali	499	0.043	2507	2217	290	109	96	13
Diang	1449	0.126	2772	2467	305	350	311	38
Kafe Simera	923	0.08	2729	2496	233	219	201	19
Kholifa Row	1427	0.124	2486	2191	295	309	272	37
Koya	843	0.073	2106	1905	202	155	140	15
Malal Mara	606	0.053	2627	2421	206	139	128	11
Masimera	763	0.066	2333	2064	269	155	137	18
Mongo	1141	0.099	1972	1787	185	196	178	18
SafrokoLimba	201	0.018	2605	2338	268	46	41	5
Sambaia	1494	0.13	2425	2220	204	315	289	27
Sengbe	710	0.062	2054	1868	186	127	115	12
Warra Bafodia	764	0.067	2474	2179	295	165	145	20
Yoni	661	0.058	2618	2373	245	151	137	14
Total	**11,481**	**1**				**2435**	**2190**	**245**

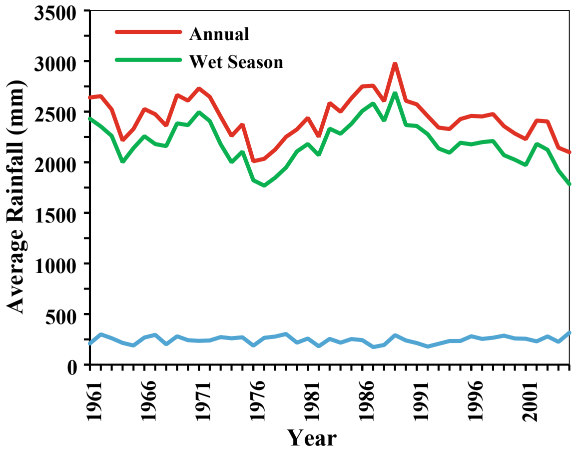

Fig. 25.2 Average annual and seasonal rainfall distribution over RSRB during 1961–2005

This analysis can be useful to detect the changes in the precipitation-streamflow relationship and quantifies the impact of precipitation to runoff (i.e. response of streamflow to climate change) in the basin. It was observed that two stations; one at the extreme upstream and the other at downstream gives highest values of coefficient of variation ranging between 30 and 52% for both annual and seasonal. This means,

Table 25.3 Average annual and seasonal rainfall Statistics of RSRB for the period of 1961–2005

Station	Annual					Wet season					Dry season				
	Min.	Max.	Mean	SD	%CV	Min.	Max.	Mean	SD	%CV	Min.	Max.	Mean	SD	%CV
Bombali Sebora	887	3855	2507	468	19	857	3245	2217	402	18	30	3245	290	142	49
Diang	1099	4082	2772	560	20	1075	3747	2467	557	23	24	512	305	94	31
Kafe Simira	849	3498	2729	444	16	835	3397	2496	448	18	14	564	233	104	45
Kholifa Rowalla	892	3274	2486	439	18	883	3042	2191	450	21	9	548	295	121	41
Koya	799	3447	2106	468	22	799	3369	1905	463	24	0	521	202	96	48
Malal Mara	940	3299	2627	365	14	927	3009	2421	332	14	13	509	206	91	44
Masimera	976	3354	2333	350	15	976	3076	2064	372	18	0	562	269	124	46
Mongo	745	3261	1972	431	22	741	3193	1787	424	24	4	450	185	95	52
SafrokoLimba	992	3426	2605	391	15	975	3090	2338	351	15	18	531	268	105	39
Sambaia	936	3514	2425	504	21	918	3163	2220	489	22	18	419	204	75	37
Sengbe	638	3579	2054	552	27	636	3422	1868	544	29	2	379	186	88	47
Warra Bafodia	940	3496	2474	464	19	928	3248	2179	434	20	12	568	295	118	40
Yoni	941	4569	2618	758	29	939	4369	2373	741	31	3	493	245	111	45
Rokel-Seli river basin	**895**	**3589**	**2435**	**256**	**11**	**884**	**3336**	**2190**	**232**	**11**	**11**	**715**	**245**	**45**	**18**

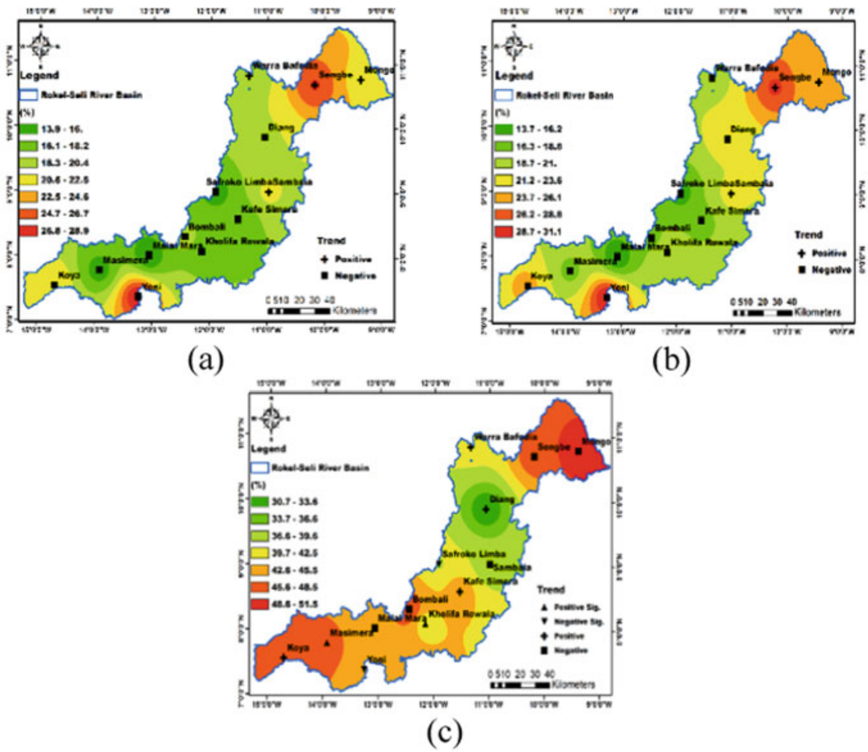

Fig. 25.3 Inter-annual variability of rainfall (%CV) for **a** annual, **b** wet and **c** dry season over RSRB during the period of 1961–2005

less rainfall occurs at those points on the basin during the period of 1961–2005. There is less variation in most part of the basin considering the middle part ranging between 13 and 16% noting that, much of the rainfall is being received at this point. The absolute variability of rainfall distribution was 256 and 232 annually and wet season for the entire basin (Table 25.3); noting that there is significant magnitude of deviation from their mean values of rainfall. However, the standard deviation for the dry season was found to be 45 depicting that, there is low dispersion or variability from the mean rainfall. Hence, there is little or no significant amount of rainfall in the dry season.

25.3.2 Rainfall Trend Analysis

Trend analyses of precipitation are useful to explore the impact of climate change on water resources. Thus, trend analyses of precipitation are required to facilitate more sustainable water planning and management. In this study, the long-term trend has been detected using the Mann–Kendall (MK) test for historical time series in terms of monthly, seasonally and annually.

25.3.2.1 Mann–Kendall Test (MKT)

The non-parametric Mann–Kendall test is commonly employed to detect monotonic trends in series of environmental data, climate data or hydrological data (Hamed and Rao 1998). The null hypothesis, H_0, is that the data come from a population with independent realizations and are identically distributed. The alternative hypothesis, H_A, is that the data follow a monotonic trend (Pohlert 2016). In this study the Mann–Kendall test (MKT) and the Modified Mann–Kendall test (MMKT) has been used to detect the rainfall trend during the period of 1961–2005 over RSRB. The Mann–Kendall test statistic S is calculated using the formula as follows:

$$S = \sum_{i=1}^{N=1} \cdot \sum_{j=i+1}^{N=1} \text{sgn}\left(x_j - x_i\right) \tag{25.1}$$

where x_j and x_i are the annual values in years j and i, j > i respectively, and N is the number of data points. The value of sgn $(x_j - x_i)$ is computed as follows:

$$\text{sgn}\left(x_j - x_i\right) = \begin{cases} 1 & if\ \left(x_j - x_i > 0\right) \\ 0 & if\ \left(x_j - x_i\right) = 0 \\ -1 & if\ \left(x_j - x_i\right) < 0 \end{cases} \tag{25.2}$$

These statistics represents the number of positive differences minus the number of negative differences for all the differences considered. For large samples ($N > 10$), the test is conducted using a normal approximation (Z statistics) with the mean and the variance as follows:

$$E[S] = 0 \tag{25.3}$$

$$Var(S) = \frac{1}{18}\left[\begin{array}{l} N(N-1)(2N+5) - \sum_{p=1}^{q} \cdot t_p\left(t_p - 1\right) \\ \left(2t_p + 5\right) \end{array}\right] \tag{25.4}$$

Here q is the number of tied (zero difference between compared values) groups, and t_p is the number of data.

values in the pth group. The values of S and VAR(S) are used to compute the test statistic Z as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if \ S(S) < 0 \end{cases} \tag{25.5}$$

The presence of a statistically significant trend is evaluated using the Z value. A positive value of Z indicates an upward trend and its negative value a downward trend.

25.3.2.2 Modify Mann–Kendall Test (MMKT)

The Modified Mann–Kendall test has been used for trend detection of autocorrelation series. Therefore, in this analysis the autocorrelation between the ranks of the observations 'pk' has been estimated after subtracting the non-parametric Sen's median slope from the slope.

$$\frac{n}{n^*} = 1 + \frac{2}{n(n-1)(n-2)} \times \sum_{p}^{q} (n-k)(n-k-1) \\ (n-k-2)p \tag{25.6}$$

Significant values of 'pk' have only been used for calculating the variance correction factor n/n* and it was calculated from the equation proposed by Hamed and Rao (1998).

where:

n represents the actual number of observations,

n* is represented as effective number of observations to account for the autocorrelation in the data and pk is the autocorrelation function for the ranks of the observations.

The corrected variance is then given as (Hamed and Rao 1998).

$$Var^*(S) = Var(S) \times \frac{n}{n^*} \tag{25.7}$$

where $Var(S)$ is from Eq. (25.4).

25.3.3 *Magnitude of Rainfall Trend (Theil Sen's Slope)*

Sen (1968) developed a non-parametric method to estimate the magnitude (slope) of the trend in a time series (Sen 1968). This method assumes a linear trend in the time series. In this method, the slope Qi of all data value pairs are calculated according to:

$$Qi = \frac{x_j - x_k}{j - k} \tag{25.8}$$

where j > k. If there are n values x_j in the time series we get as many as $N = \frac{n(n-1)}{2}$ slope estimates Qi. The Sen's estimator of the slope is the median of these N values of Qi. The N values of Qi are ranked from the smallest to the largest and the Sen's estimator as follows:

$$Q = \left(Q_{\left[\frac{n+1}{2}\right]}\right), \quad \text{if N is odd} \tag{25.9}$$

Or

$$Q = \frac{1}{2}\left(Q_{\frac{n}{2}} + Q_{\left[\frac{n+2}{2}\right]}\right), \quad \text{if N is even} \tag{25.10}$$

The two-sided test is carried out at 100 (1 − a) % of the confidence interval to obtain the true slope for the non-parametric test in the series. The positive or negative slope Q_i is obtained as upward (increasing) or downward (decreasing) trend. In the present study, the test was carried out at 5% significance level, therefore when Z value exceeds ±1.96 null hypotheses is rejected and show the existence of trend in the series as in Table 25.4.

The Z-statistics value was analyzed (Chandniha et al. 2017) as follows:

- $-1.96 < Z < 1.96$ = No Trend (Not significant)
- $Z > 1.96$ = Increase in trend (i.e. positively significant)
- $Z < -1.96$ = Decrease in trend (i.e. negatively significant).

The values of +Z and −Z indicates upward and downward trend respectively. The Z values of Mann–Kendall test accept the null hypotheses of no trend when;

$$\pm Z \leq Z_1 - x/2$$

where x is the level of significance at two tailed trend tests.

The Theil Sen's slope estimator is a robust method of robustly fitting a line of sample points in the plane by choosing the medians of the slope of all line through pairs of the points. It has been viewed as the most popular nonparametric analysis for determining a linear trend and therefore this can be illustrated by box plot in Fig. 25.4.

Table 25.4 The sen slope and Z-statistic values of annual and seasonal rainfall using MK and MMK for RSRB during 1961–2005

Station	MK			MMK			Sen Slope		
	Annual	Wet Season	Dry Season	Annual	Wet Season	Dry Season	Annual	Wet Season	Dry Season
Bombali	−0.323	−0.245	−0.440	−0.254	−0.245	−0.532	−2.034	−1.203	−0.530
Diang	−0.479	−0.773	0.851	−0.479	−0.773	0.851	−2.890	−4.057	0.736
Kafe Simera	−1.947	−2.299	0.382	−1.947	−**2.299**	0.448	−9.758	−11.090	0.457
Kholifa Rowala	−1.105	−1.575	2.827	−1.105	−1.873	*2.827*	−5.961	−9.484	4.009
Koya	−0.088	−0.303	1.458	−0.068	−0.269	1.458	−0.430	−1.367	1.550
Malal Mara	−0.303	−0.284	−0.225	−0.339	−0.284	−0.225	−0.990	−1.247	−0.272
Masimera	−0.538	−1.712	3.238	−0.628	−1.622	*3.533*	−2.032	−6.709	4.789
Mongo	0.264	0.812	−0.147	0.208	0.631	−0.180	1.666	3.715	−0.132
SafrokoLimba	−1.438	−1.145	−2.358	−1.252	−0.915	−**2.358**	−7.537	−4.661	−2.979
Sambaia	0.665	1.017	−1.800	0.842	1.336	−1.800	4.920	7.126	−1.647
Sengbe	1.301	1.301	−0.695	1.371	1.347	−0.779	6.591	6.928	−0.844
Warra Bafodia	0.127	−0.470	1.272	0.164	−0.372	1.272	0.267	−1.836	1.267
Yoni	−1.849	−1.477	−3.042	−1.399	−0.939	−**3.042**	−17.354	−12.920	−3.917

Italic values: Indicates the significant increasing trend during 1961–2005
Bold values: Indicates the significant decreasing trend during 1961–2005

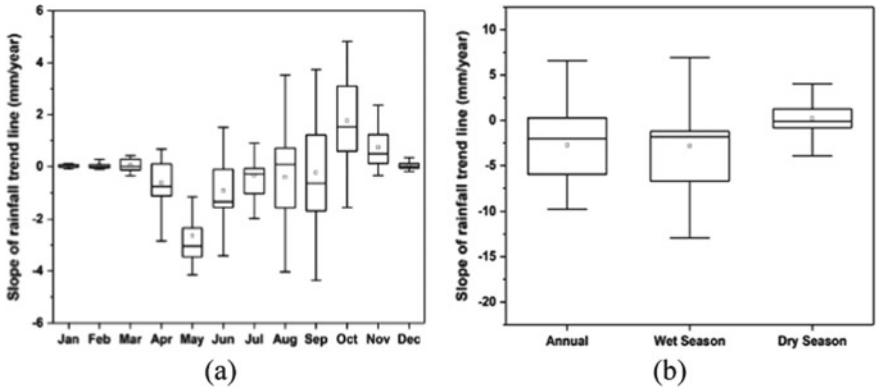

Fig. 25.4 **a** Box plot of the Theil-Sen slopes for annual and seasonal rainfall time series of RSRB. **b** Box plot of the Theil-Sen slopes for monthly rainfall time series

25.3.4 Homogeneity Test in the Times Series (1961–2005)

Application of homogenization on climatic time series preserve the climatic signal and reduce the impact of non-climatic factors in the time series. Therefore, it is important to address these factors in order to develop homogenized records for studying climate change. Change-point analysis examines climate data discontinuities and it directly addresses the question of where the change in the mean value of the observations is likely to have occurred.

Homogeneity in trends was tested using the Standard Normal Homogeneity Test (SNHT) to obtain the homogeneous and heterogeneous trend in the data time series with significance level of 5%. Change point (*P* values) has been computed using 10,000 Monte Carlo simulations base on Mann–Whitney-Pettit (MWP) Test and SNHT (Alexanderson 1986; Alexandersson and Moberg 1997).

The test interpretation, H_0: stands for the homogeneous series and *Ha*: there is a date at which there is change in the data as shown in Table 25.5. As the computed p-value is greater than the significance level alpha = 0.05, one cannot reject the null hypothesis H_0.

Trend analysis was done applying MK and MMK tests and Sen's slope on monthly, annual and seasonal rainfall data for all stations in the basin. The MK and MMK statistics at 5% significance level are shown in Table 25.4. Among all the 13 stations in the basin, 3 stations show a negatively significant trend in wet and dry season and just 2 stations show positively significant trend in the dry season. From the Z-statistics value, there is not any significant annual trend in all stations, although 9 stations show negative trend and 4 shows positive trend annually during the period of 1961–2005.

Monthly and annual trends are shown in Fig. 25.4 using the box plot of Theil-Sen's slope method for the Rokel-Seli River basin. The box central line represents median, upper and lower lines represent the 75th and 25th percentile, respectively. Also, the

Table 25.5 The MWP test and SNHT test for RSRB (1961–2005)

Station	Pettitt's test			SNHT test		
	P-value	Year	Trend	*P*-value	Year	Trend
Bombali	0.594	1972	Ho	0.736	1972	Ho
Diang	0.875	1998	Ho	0.740	2003	Ho
Kafe Simera	0.118	1973	Ho	0.232	2002	Ho
Kholifa Rowala	0.448	1993	Ho	0.589	1998	Ho
Koya	0.342	1973	Ho	0.159	1972	Ho
Malal Mara	0.667	1980	Ho	0.913	1980	Ho
Masimera	0.178	1991	Ho	0.644	1991	Ho
Mongo	0.267	1972	Ho	0.157	1972	Ho
SafrokoLimba	0.136	1967	Ho	0.044	1998	Ho
Sambaia	0.189	1967	Ho	0.060	1967	Ho
Sengbe	0.059	1982	Ho	0.253	1973	Ho
Warra Bafodia	0.546	1973	Ho	0.599	1973	Ho
Yoni	0.063	1992	Ho	0.098	1992	Ho

upper and lower lines represent the maximum and minimum values of rainfall slopes. Based on the analysis, the dry season shows a positive slope and similarly all the months found in the dry season (November–April) also shows positive slope in the monthly box plot. This denotes that, during periods of high rainfall the Theil-Sen's slope will show negative trend and vis-à-vis during low rainfall. Using MWP and SNHT tests in identifying homogeneity in the data series (Prabhakar et al. 2018), results in Table 25.5 shows that there was no shift change point detected in the data series for the period of 1961 and 2005. Hence all P-values shows Ho (Null Hypothesis) trend (i.e. all data in the series are homogenous during the time series) (Yusof and Kane 2013).

25.3.5 Rainfall Projections

Rainfall projections are necessary in determining the water balance and future water allocation in the basin. Thus, evaluating the future variation of hydrologic cycle and water resources has special significance for regional planning and water resources management. It helps in the assessment of the future impact of climate change over the basin which affects changes in the hydrologic cycle of the basin. Global Climate Models (GCMs) are the fundamental tools that provide future projections of climate variables in the changing ecosystem. Therefore, studies dealing with the climate change impact assessment at catchment scale require downscaling of GCM projections to an appropriate scale to represent the catchment heterogeneity (Silberstein et al. 2012). Various statistical and dynamic downscaling methods have been adopted in the past to downscale large scale atmospheric variables from the GCMs to a regional scale or to a finer scale representative of a catchment (Silberstein et al. 2012; Anandhi et al. 2008). For the purpose of this study, statistical downscaling method has been applied.

25.3.5.1 Statistical Downscaling Method (SDSM)

Statistical downscaling method was applied for downscaling the monthly rainfall of RSRB for future rainfall projections using traditional downscaling regression-based approach (Chandniha and Kansal 2016); Multiple-Linear Regression (MLR). The general formula of MLR is written as:

$$Y^{MLR} = \alpha + \sum_{i=1}^{n} \beta_i X_i + \varepsilon \tag{25.11}$$

where, Y^{MLR} is the estimated predictand (rainfall), α is the intercept; β is the regression coefficients, X_i is the predictor (26 parameters and ε is the error term. Regression coefficients at 95% confidence level were estimated with Durbin-Watson technique for residuals estimation. SPSS (Ver. 24) was applied for model fit, correlation values, coefficient of determination, descriptive statistics etc.

The following steps were used to carry out the methodology for rainfall projections:

1. Perform consistency check of observed monthly rainfall (Predictand) using Hydrognomon (Ver. 4) for the period of 1961–2005
2. Transfer National Centre of Environmental Predictions (NCEP)and Global Circulation Models (GCM) predictors for the study area from Canadian Centre for Climate Modeling and Analysis (CanESM2) https://www.climate-scenarios.canada.cac corresponding to Representative Concentration Pathways (RCP2.6, RCP4.5 and RCP8.5) emission scenarios and then convert the predictors from daily to monthly basis taking average of each predictor over the month.
3. Identify calibration period (from 1961 to 1990) and validation period (from 1991 to 2005) for the calibration and validation of the model
4. Develop the empirical relationship between historical rainfall (predictand) and the 26 predictors using MLR technique on calibration period data
5. Using expert opinion based on scatter plot, partial correlation, correlation etc. the most suitable predictors were identified
6. Rainfall (predictand) were estimated during the validation period using the selected predictors and compared with the observed values
7. The probable error in the observed and the estimated values were calculated and bias correction was applied to correct the predicated values
8. The important indicators of the goodness of regression were checked by the following parameter; Nash-Sutcliffe Error Estimate (NS-EE), Coefficient of

Correlation (CC), Normalized Mean Square Error (NMSE), and the Root Mean Square Error (RMSE)

9. The suggested series of NCEP Corresponding to RCP2.6, RCP4.5 and RCP8.5 scenarios and the selected predictors were used to generate the future series of the predictand for the periods of 2020s and 2050s.

In applying the above methodology for the future projection of rainfall over Rokel-Seli river Basin the daily observed predictor data of atmospheric variables derived from NCEP 2.80° (latitude) × 2.80° (longitude) grid-scale for 45 years (1961–2005) were obtained from CanESM2. The data was extracted between latitude 8.90° N to 9.30° N and longitude −11.98° W to −11.5° W (BOX_125X_36Y). The Representative Concentration Pathways (RCP2.6, 4.5 8.5) emission scenarios were also downloaded from CanESM2. Full descriptions of NCEP variables (predictors) are elaborated in the Table 25.6.

The Geostrophic air flow velocity, Vorticity, Zonal velocity component, Meridional velocity, Divergence and Wind direction are variables derived using the geostrophic approximation at different atmospheric levels.

The vorticity measures the rotation of the air, Zonal velocity component is the velocity component along a line of latitude (i.e. east–west), Meridional velocity component is the velocity component along a line of longitude (i.e. north–south), Divergence relates to the stretching and outflow of air from the base of an anticyclone. Wind direction variable is the only variable which is not normalized. The same parameters are considered in comparing the results based on MLR method.

The MLR equations derived for each rainfall station can be given as follows:

Bombali: $207.1 + 24.3X_{15} - 9.8X_{19} + 30.3X_{20} + 169.3X_{22}$

Diang: $253.6 + 45X_7 + 68.4X_{11} + 103.3X_{22} + 39.5X_{23} + 45.4X_{24} - 45.4X_{25}$

Kafe Simera: $236.5 + 29.4X_{15} - 0.5X_{19} + 18.4X_{20} + 215.7X_{22}$

Kholifa Rowala: $226.4 + 29.4X_7 + 41.8X_{11} + 69.1X_{22} + 41.5X_{23} + 30.2X_{25}$

Koya: $182.1 + 13.8X_{15} - 0.3X_{19} + 18.7X_{20} + 164.2X_{22}$

Malal Mara: $210.5 + 42.8X_{15} + 12.9X_{19} + 35.3X_{20} + 183.1X_{22}$

Masimera: $213.2 + 22.8X_7 + 40X_{11} + 64.7X_{22} + 39.9X_{23} + 32.8X_{25}$

Mongo: $162.1 + 25X_{15} - 1.5X_{19} + 24.4X_{20} + 142.3X_{22}$

SafrokoLimba: $244.6 + 68.8X_{11} + 56.8X_{22} + 52.3X_{23} + 25.1X_{24} + 29X_{25}$

Sambaia: $223.8 + 25.6X_7 + 22.1X_{11} + 184.9X_{22} - 0.9X_{23} - 13.7X_{25}$

Sengbe: $162.2 + 25.1X_{15} + 2.9X_{19} + 36.8X_{20} + 137.9X_{22}$

Warra Bafodia: $227.1 + 16.5X_7 + 25.6X_{11} + 100.6X_{22} + 26.9X_{23} + 37X_{25}$

Yoni: $199.4 + 56.4X_{15} - 13.6X_{19} + 41.8X_{20} + 158.3X_{22}$

Table 25.6 Variables and description of NCEP and GCM predictors (26 variables)

S. No.	Variable	Description	Unit
1	ncepmslpgl	Mean sea level pressure	Pa
2	ncepp1_fgl	Geostrophic air flow velocity	m/s
3	ncepp1_ugl	ZonaL velocity component	m/s
4	ncepp1_vgl	Meridional velocity component	m/s
5	ncepp1_zgl	Vorticity	m/s
6	ncepp1thgl	Wind direction	m/s
7	ncepp1zhgl	Divergence	m/s
8	ncepp5_fgl	Geostrophic air flow velocity	m/s
9	ncepp5_ugl	ZonaL velocity component	m/s
10	ncepp5_vgl	Meridional velocity component	m/s
11	ncepp5_zgl	Vorticity	m/s
12	ncepp5thgl	Wind direction	m/s
13	ncepp5zhgl	Divergence	m/s
14	ncepp8_fgl	Geostrophic air flow velocity	m/s
15	ncepp8_ugl	ZonaL velocity component	m/s
16	ncepp8_vgl	Meridional velocity component	m/s
17	ncepp8_zgl	Vorticity	m/s
18	ncepp8thgl	Wind direction	
19	ncepp8zhgl	Divergence	m/s
20	ncepp500gl	500 hPa geopotential height	m
21	ncepp850gl	850 hPa geopotential height	m
22	nceprcpgl	Near surface relative humidity	%
23	nceps500gl	Specific humidity at 500 hPa height	kg/kg
24	nceps850gl	Specific humidity at 850 hPa height	kg/kg
25	ncepshumgl	Near surface specific humidity	kg/kg
26	nceptempgl	Mean temperature at 2 m	K

Where, X_7 = Divergence; X_{11} = vorticity; X_{15} = Zonal velocity component; X_{19} = Divergence; X_{20} = 850 hPa geopotential height; X_{22} = near surface relative humidity; X_{23} = Specific humidity at 500 hPa height; X_{24} = specific humidity at 850 hPa height; X_{25} = near surface specific humidity.

25.3.6 Calibration and Validation

The daily observed predictor data obtained from NCEP reanalysis, normalized over the period of 1961–1990 and hence this period was selected for calibration, while the validation period was selected from 1991 to 2005 to normalize the calibration and validation model. Observed and estimated rainfall during calibration and validation period is shown in Fig. 25.5 and scatter plot of both cases are represented in Fig. 25.6. The important parameters or indicators of the goodness of the regression for each of the stations during the calibration and validation periods are also shown in Table 25.7.

During the calibration and validation periods the average monthly values were calculated for both observed and the estimated rainfall as in Table 25.8.

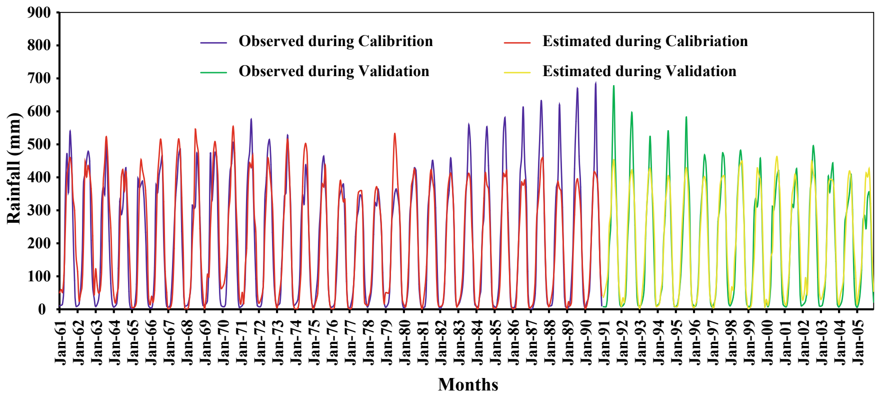

Fig. 25.5 Observed and estimated monthly rainfall during calibration and validation periods

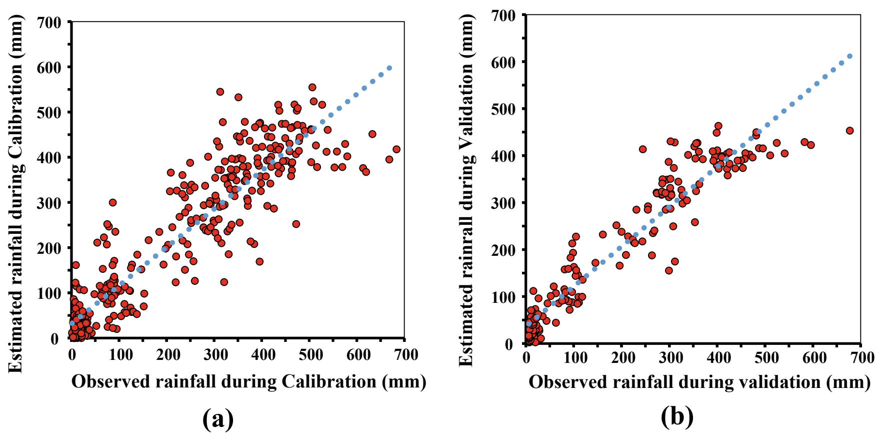

Fig. 25.6 Scattered plot between observed and estimated rainfall during **a** calibration and **b** validation

Table 25.7 Important indicators of accuracy of results during calibration and validation for rainfall time series at the various stations of Rokel-Seli River Basin

Station	NCEP	Calibration/Validation	RMSE (mm)	NMSE	NASH	CC
Bombali	1961–1990	Calibration	115.43	0.16	0.65	0.81
	1991–2005	Validation	104.45	0.24	0.72	0.86
Diang	1961–1990	Calibration	136.27	0.13	0.71	0.81
	1991–2005	Validation	129.56	0.30	0.70	0.84
Kafe Simera	1961–1990	Calibration	130.53	0.19	0.67	0.84
	1991–2005	Validation	126.55	0.32	0.71	0.85
Kholifa Rowalla	1961–1990	Calibration	114.72	0.15	0.69	0.82
	1991–2005	Validation	88.25	0.20	0.74	0.86
Koya	1961–1990	Calibration	103.99	0.10	0.75	0.82
	1991–2005	Validation	91.14	0.27	0.71	0.85
Malal Mara	1961–1990	Calibration	120.20	0.16	0.70	0.84
	1991–2005	Validation	127.17	0.33	0.70	0.85
Masimera	1961–1990	Calibration	104.99	0.14	0.70	0.83
	1991–2005	Validation	76.45	0.17	0.77	0.88
Mongo	1961–1990	Calibration	96.72	0.10	0.76	0.82
	1991–2005	Validation	93.99	0.31	0.70	0.84
SafrokoLimba	1961–1990	Calibration	114.40	0.11	0.76	0.83
	1991–2005	Validation	89.71	0.19	0.79	0.90
Sambaia	1961–1990	Calibration	112.68	0.11	0.79	0.84
	1991–2005	Validation	98.33	0.25	0.76	0.87
Sengbe	1961–1990	Calibration	120.60	0.35	0.58	0.77
	1991–2005	Validation	93.93	0.30	0.65	0.82
Wara Bafodia	1961–1990	Calibration	114.83	0.18	0.60	0.81
	1991–2005	Validation	87.93	0.18	0.79	0.89
Yoni	1961–1990	Calibration	159.08	0.32	0.58	0.78
	1991–2005	Validation	114.49	0.31	0.60	0.82

The equations derived after SDSM base on MLR approach during calibration and validation periods are applied for future projections under Couple Model Inter-comparison phase-5(CMIP5) emission scenarios; RCP 2.6 RCP 4.5 and RCP 8.5 which are used in this study.

For the purpose of this work, the projected rainfall has been categorized in various time step as; past (1961–2005), 2020s (2011–2040) and 2050s (2041–2070) scenarios as tabulated in Table 25.9.

Further, climate change scenarios also help the future planning of various activities which are associated with water and dependent with rainfall over the catchment.

Table 25.8 Calibration and validation values of monthly average rainfall of Rokel-Seli River Basin

Rainfall (mm)	(OBS/NCEP)	Monthly												R^2	Annual			
		J	F	M	A	M	J	J	A	S	O	N	D		Min	Max	Average	SD
Calibration	Observed	8	11	24	93	277	354	401	496	431	275	93	15	0.848	1962	2820	2477	271
	Estimated	20	21	34	87	210	352	428	433	414	296	143	36		1966	2926	2474	289
Validation	Observed	11	12	26	81	233	315	370	473	430	293	104	15	0.905	1893	2798	2363	267
	Estimated	17	28	48	104	211	325	404	420	395	304	145	42		2048	2852	2444	255

Table 25.9 Past and future rainfall statistics under RCP2.6, RCP4.5 and RCP8.5 of RSRB

Projection scenarios		Past and predicted monthly average rainfall (mm)											
		J	F	M	A	M	J	J	A	S	O	N	D
RCP-2.6	Past	9	11	25	89	263	341	390	488	431	281	97	15
	2020s	23	16	36	143	284	373	433	458	435	233	131	20
	2050s	15	18	30	144	288	385	451	460	339	251	143	20
RCP-4.5	Past	9	11	25	89	263	341	390	488	431	281	97	15
	2020s	16	19	37	122	269	362	420	454	389	279	115	26
	2050s	29	23	45	145	292	379	443	434	410	309	118	17
RCP-8.5	Past	9	11	25	89	263	341	390	488	431	281	97	15
	2020s	30	25	31	145	287	372	439	461	408	306	108	18
	2050s	29	26	30	135	292	379	443	434	410	309	114	21

Projection scenarios		Annual Rainfall (mm)			
		Min.	Max.	Average	SD
RCP-2.6	Past	1972	2772	2435	182
	2020s	1967	3250	2744	173
	2050s	1928	3270	2545	172
RCP-4.5	Past	1972	2772	2435	182
	2020s	2725	3907	2508	171
	2050s	2602	4568	2645	174
RCP-8.5	Past	1972	2772	2435	182
	2020s	2450	5946	2630	177
	2050s	2524	5175	2623	175

The forecasted rainfall is expected to help the policy makers and the stakeholders for making effective water resources planning.

It can also be observed that, the MLR model fits between the observed and estimated monthly average rainfall during the calibration and validation periods with a coefficient of determination of 0.848 and 0.905 respectively as indicated in Table 25.8. Applying the recommended MLR model, average annual rainfall estimated for the period of 1961–1990 was 2474 mm as compared to the observed rainfall of 2477 mm. Similarly, the estimated average rainfall during 1990–2005 was 2444 mm compared to 2363 mm as observed rainfall. The projected mean annual rainfall for the periods of 2020s and 2050s according to CMIP5 emission scenarios are; 2744 and 2545 mm (RCP 2.6), 2508 and 2645 mm (RCP 4.5) and 2630 and 2623 mm (RCP8.5) as against observed rainfall of 2435 mm. The overall forecasted rainfall (taking the average of all 3 scenarios) for 2020s is 2627 mm and for 2050s is 2604 mm as compared to the observed value of 2435 mm. As projected for the average rainfall over Rokel-Seli River Basin, the expected rainfall to occur in 2020s and 2050s is about 7–8% higher than the observed rainfall during the periods of 1961–2005.

25.3.7 Dependable Annual Rainfall of Rokel-Seli River Basin

It is very important to know the annual rainfall dependability in planning water resources over the basin in order to obtain the relationship between the magnitude of the event and its probability of exceedance. Hence the 75% or 95% dependable annual rainfall are of utmost concern to identify the minimum water availability.

Therefore, in this study, the dependable annual rainfall has been estimated for the past (1961–2005) and future time series of 2020s (2011–2041) and 2050s (2041–2070) as shown in Table 25.10 and Fig. 25.7.

The 95% dependable rainfall for the past, 2020s and 2050s were estimated as 2034 mm, 2320 mm and 2462 mm respectively. This justifies the values of minimum average rainfall that occurred in the basin and which could be expected in 2020s and 2050s. Hence these values are very useful for future water resources development and management on the basin.

Table 25.10 Dependable annual rainfall of RSRB for past (1961–2005), 2020s (2011–2040) and 2050s (2041–2070)

Percentage dependability	Dependable rainfall (mm)		
	Past	2020s	2050s
5	2749	2751	2815
50	2451	2551	2588
75	2284	2507	2529
90	2125	2412	2499
95	2034	2320	2462

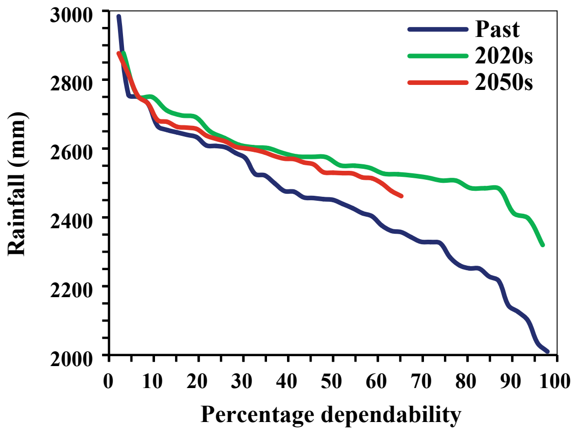

Fig. 25.7 Rainfall dependable curves for past (1961–2005), 2020s (2011–2040) and 2050s (2041–2070)

25.4 Conclusions

The rainfall over Rokel-Seli river basin varies considerably from the upstream and downstream showing high value of coefficient of variation annually and seasonally. Thus, the high values of CV at these stations shows that less rainfall occurs at these parts of the basin and high rainfall occurring most part at mid of the basin with average rainfall of 2435 mm. The non-parametric (MK and MMK) tests were used to detect rainfall trends over the basin during the period of (1961–2005). The accuracy of MMK test in terms of significance level was more precise than MK test at the same level of significance, showing only 3 stations having negatively significant trend and two stations with positively significant trends in the wet and dry seasons. No significant trends were identified annually.

The Sen's slope magnitude varies between −17.354 and 6.951 mm/year annually in the basin (1961–2005), therefore the seasonal slopes were mostly negative for the wet season and positive for the dry season. The Mann–Whitney–Pettitt and SNHT tests were used to identify possible break points in precipitation during the 45 year period. However, from the results of the study, it can be concluded that there was no shift change point in the data series. Hence the rainfall data was homogenous for all throughout the time series for the period of 1961–2005.

Rainfall projections has been carried out in the basin for the periods of 2020s and 2050s. The average annual rainfall projected in the 2020s (2011–2040) is 2627 mm and for 2050s (2041–2017) is 2604 mm as compared to the observed value of 2435 mm. This means that there would be increase in rainfall of about 7–8% unto 2050s due to climate change. The observed dependable annual rainfall at 95% is 2034 mm and the projected dependable rainfall at 95% dependability in 2020s and 2050s is 2320 mm and 2462 mm respectively. It is very important to know the dependable rainfall in planning water resources over the basin to identify the minimum water available for various water requirement, also to determine the projected minimum rainfall which could be used for future water resources management.

The present study highlights the rainfall variability over the Rokel-Seli River Basin in Sierra Leone. The adopted analysis provides key information of basin's water availability and hence this work offers benchmark information that can be used to increase the capacity of long-range water resource planning and management, land use planning, agricultural water development and conservation, and industrial water use over the next several decades at basin level. The results of the study also help in the assessment of the future impact of climate change over the basin which affects changes in the hydrologic cycle of the basin. Also, this study can be used as a guide to simulate rainfall variability over other basins in Sierra Leone to determine the water balance within those basins. Project rainfall and its trends can be useful for future prospective of agriculture and water resources planning and mitigations under consideration of Climate change.

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