A COMPARATIVE STUDY OF THREE MODELS FOR THE DISTRIBUTION OF WET AND DRY SPELLS IN THE MAHANADI DELTA

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ABSTRACT: This paper makes a comparative study of three models namely, Markov Chain, Truncated Negative Binomial and Eggemberger-Polya probability models in order to identify the most appropriate one to represent the distribution of wet and dry spells during rainy season for the Mahanadi Delta region of Odisha. In judging the performance of a model, the minimum value of the Akaike's Information Criterion, and Chi-Squared and Kolmogorov-Sminov goodness of fit tests are used.
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1. INTRODUCTION

The wet and dry spells (or runs) are two main physical characteristics of the rainfall occurrences and the volume of rainfall in a geographical area depends heavily on the distribution of such spells. It is therefore important to investigate the pattern of occurrence of wet and dry spells scientifically through model-based analysis that consists of studying statistical properties of two common indicators – spell length and spell frequency. Such studies are very much essential for agricultural planning, water resource management and other sectors such as fisheries, health, ecology, environment etc. Several kind of stochastic models have been used to describe frequency distributions of spell lengths at spatial and temporal levels. The fitted probability distributions of spell lengths under the models are used to study the persistence properties of the wet and dry spells. Since the spell lengths govern the persistence properties of the daily precipitation process, it is desirable to use a criterion for selection of the best model among a series of competitive models fitted successfully to the observed datasets.

Anagnostopolou *et al.* (2003) compared performances of Negative Binomial and Markov Chain models to analyze spell frequencies in 20 stations in Greece using data from 1958 –1997. Studying rainfall data for six locations in Brazil, De Arruda and Pinto (1980) showed that for tropical regions, the Truncated Negative Binomial model is more suitable than Markov Chain model, nevertheless for wet spells the Eggemberger-Polya model provides a very good fit to the observed data of Uccle [Berger and Goossens (1983)]. By analyzing data for four locations in Italy, Giuseppe *et al*. (2005) confirmed that Truncated Negative Binomial and Eggemberger-Polya distributions were better fitted models to explain the dry spell frequencies. Of these two distributions, Truncated Negative Binomial is not suitable for very long dry spells which were considered as extreme events, but Eggemberger-Polya distribution was better fit for the longer dry spells. An analysis of daily rainfall data at Campina Grande from May to July during the period 1939-1972, Kamar and Rao (2004) indicated that the Eggenberger-Polya model provided good estimates of spell frequencies at the station than that from Logarithmic distribution. The studies of Lana *et al*. (2005) and Aghajani (2007) have also shown that compared to other models, Weibull model fitted well with the empirical frequency distributions of spell lengths for a number of selected stations. Deni *et al*. (2009) conducted a study at 14 selected rainfall stations in Peninsular Malaysia using rainfall data for the period 1975-2004 and found that a Mixed Log Series Geometric (MLG) distribution (proposed by the authors) was better than Mixed Log Series Poisson and Truncated Poisson distributions. This result was further strengthen by Deni and Jemain (2009) and Mahmud *et al.* (2011) as they observed that the MLG distribution had also a better fit than some other competing models for the rainfall data of the same study region during the periods 1975-2004 and 1975-2009 respectively at various locations.

The Mahanadi Delta, as is situated on the eastern coast of India, gets rainfall from the south-west monsoon with an average annual rainfall 1572 mm and the rainy day in a year ranging from 55 to 80 days. The most pre-dominant crop in this region is paddy covering about 95% of the total area under cultivation. As sufficient supplementary irrigation facilities are not available in the most parts, people mainly depend on autumn and winter paddy which are grown during monsoon season (June-September) and harvested during post-monsoon season (October and November). During monsoon season a large variety of vegetables are also grown here. Although the quantum of rainfall received by this river basin is fairly good, yet its irregular distribution and variation in time and space leads to heavy downpour or very low precipitation in some areas. Variability in rainfall is therefore a cause of great stress to the farming activities, crop production and crop yield as the agriculture is mostly rain fed. Hence, an appropriate modeling of the occurrence of the sequence of wet and dry days is therefore of crucial importance in planning agricultural activities and managing the associated water supply systems at various locations of the study domain.

This paper undertakes a comparative study of three models *viz*., Markov Chain (MC), Truncated Negative Binomial (TNB) and Eggemberger-Polya (EP) probability models. The goal is to identify better one than others to fit empirical frequency distributions of the spell lengths for each considered rainfall station and for the study domain as a whole.

2. DATA AND METHODOLOGY

Source and Nature of Data: The present study utilizes data on daily rainfall amount of the four meteorological stations – Bhubaneswar, Cuttack, Paradip and Puri of the Mahanadi Delta region for 28 years (1982-2009). The relevant data were collected from the Meteorological Centre, Bhubaneswar, Odisha. We are restricted to the rainy season (June – October) only, because during this season our study site receives more than 85% of its total annual rainfall. The period considered for the study *i.e.,* from 1st June to 31st October also coincides with the growth season of the paddy crop, the major cash crop in the tract. A dry day (a rainy or wet day) has been defined as one with < 2.5 mm (≥ 2.5 mm) of rainfall according to the definition proposed by the Indian Meteorological Department. It may be pointed out here that in order to classify a day as wet or dry for the whole study region (Mahanadi Delta), we have considered the average rainfall of the four stations *i.e*., Bhubaneswar, Cuttack, Paradip and Puri for that day.

Markov Chain Probability Model

This model assumes that the occurrence of a wet or a dry day depends on the weather condition of the previous day. The parameters of this probability model are the two conditional probabilities p_o and $1-p_1$, where p_o is the probability of a wet day given that the previous day was dry, and $1-p_1$ is the probability of a dry day given that the previous day was wet *i.e.*, we have $p_1 = \Pr\{W/W\}$, $1-p_1 = \Pr\{D/W\}$, $p_0 = \Pr\{W/D\}$ and $1-p_0 = \Pr\{D/D\}$. Denoting wet spell length by X, the probability of a wet spell of length x is therefore given by

$$P(X=x) = (1-p_1)p_1^{x-1},\ x = 1, 2, \ldots\ldots \quad (1)$$

This means that the random variable X under the Markovian preconditions follows a geometric distribution. Similarly, if Y is the length of dry spell, the probability of a dry spell of length y is

$$P(Y=y) = p_0(1-p_0)^{y-1},\ y = 1, 2, \ldots\ldots \quad (2)$$

The maximum likelihood estimates of p_0 and p_1 are given by

$$\hat{p}_0 = \frac{n\{W/D\}}{n\{W/D\}+n\{D/D\}} \text{ and } \hat{p}_1 = \frac{n\{W/W\}}{n\{W/W\}+n\{D/W\}}, \quad (3)$$

where $n\{W/W\}$, $n\{D/W\}$, $n\{W/D\}$ and $n\{D/D\}$ are the observed frequencies of the respective conditional events [*cf*., Cox and Miller (1967)].

Truncated Negative Binomial Probability Model

For this model, the probability of occurrence of a wet spell of length x, in Fisher's (1941) notation, is given by

$$P(X=x) = \frac{g^k}{(1-g^k)(k-1)!} \cdot \frac{(k+x-1)!}{x!}(1-g)^x,\ x = 1, 2, \ldots\ldots \quad (4)$$

The values of g and k are calculated according to the method used by Brass (1958), where

$$g = \frac{\bar{x}}{s^2}\left(1-\frac{n_1}{n}\right) \quad (5)$$

and $$k = \left(\bar{x}g - \frac{n_1}{n}\right)/(1-g), \quad (6)$$

such that $\bar{x}$ and s^2 are respectively mean and variance of the length of wet spells, n_1 is the observed frequency corresponding to $x = 1$, and n is the total number of wet periods. Since, the calculated values of k are fractions, the factorials $(k + x - 1)!$ and $(k - 1)!$ can be computed using the Gamma-Function Table. However, for practical purposes, the transformed equation

$$P(X = x) = \frac{\prod_x (k+x-1)}{x!\,(1-g^k)} g^k (1-g)^x \quad (7)$$

can also be used. Results for the length of dry spell Y can be derived analogously.

Eggemberger–Polya Probability Model

According to Berger and Goossens (1983), the probability of a wet spell of length x under this model is given by

$$P(X = x) = \frac{h+(x-2)d}{(x-1)(1+d)} P(x-1), x = 2, 3, \dots \dots \quad (8)$$

with $$P(x = 1) = (1 + d)^{-\frac{h}{d}}, \quad (9)$$

where $h = \bar{x} - 1$ and $f =$ frequency of x consecutive wet spells. The parameter d represents the degree of influence of an event on the following event and can be computed by

$$d = \frac{s^2}{h} - 1. \quad (10)$$

Results for the dry spell of length $Y = y$ can be derived analogously.

3. PERFORMANCE CRITERIA FOR MODEL IDENTIFICATION

Although graphical methods are useful for the model identification, here two principal criteria have been used – (i) Selection on the minimum value of the Akaike's Information Criterion (AIC) [Akaike (1974)], and (ii) Selection through the goodness-of-fit (GOF) tests based on Chi-Squared (CS) and Kolmogorov-Sminov (KS) statistics. The AIC is defined by

$$AIC = -2(maximum\ log\ likelihood) + 2\vartheta, \quad (11)$$

where ϑ is the number of free parameters in the model.

If a particular data set shows the minimum value of the AIC in respect of a model but does not show a significant fit based on either CS GOF test or KS GOF test or both, the next model with the minimum AIC value fulfilling the said testing requirements would be selected. For the CS test of GOF, the following test statistic is used:

$$\chi^2 = \sum_z \frac{(O_z - E_z)^2}{E_z}, \quad (12)$$

where O_z and E_z are respectively the observed and expected (predicted) frequencies corresponding to the spell length z (wet or dry). On the other hand, for the KS test of GOF, the test statistic defined by

$$\kappa = \max_z |OR_z - ER_z|, \quad (13)$$

is used, where OR_z and ER_z are respectively the observed and expected relative cumulative frequencies corresponding to the spell length z.

4. RESULTS, MODEL IDENTIFICATION AND DISCUSSIONS

Identification of a day as wet or dry according to the definition stated earlier gives occurrences of alternative sequences of wet and dry days *i.e.*, spells. From the observed wet and dry spells, frequency distributions of their lengths are constructed.

Table 1: Statistical Descriptors of Wet and Dry Spells

Characteristics	Station									
	Bhubaneswar		Cuttack		Paradip		Puri		Mahanadi Delta	
	Wet Spell	Dry Spell	Wet Spell	Dry Spell	Wet Spell	Dry Spell	Wet Spell	Dry Spell	Wet Spell	Dry Spell
Probability of Rainy Day	0.3945	0.6055	0.3849	0.6151	0.3562	0.6438	0.3445	0.6555	0.3700	0.6300
No. of Wet Spells	781	809	759	804	706	758	678	740	731	778
Mean of Spell Length	2.2	3.1	2.2	3.2	2.1	3.6	2.1	3.8	2.2	3.4
SD of Spell Length	1.7	3.3	1.6	3.4	1.5	3.7	1.5	3.6	1.6	3.5
CV of Spell Length	77.27	106.45	72.72	106.25	71.42	102.77	71.42	94.73	72.72	102.94
Maximum Spell Length	12	25	13	28	14	31	12	28	14	31

Tables1 shows some important statistical descriptors of the distributions of spell lengths including probabilities of wet and dry days calculated from the empirical data sets. As the chances of occurrence of a wet day are considerably less than those of a dry day, the descriptors such as number of spells, average spell length, standard deviation (SD) of spell length, and maximum spell length in case of wet spells are less than those of dry spells. It means that during the period under study, dry spells have longer length than wet spells and variability of the lengths of dry spells is also more than that of wet spells. It can also be seen that Paradip has the longest duration of wet spells with maximum of 14 days and the longest duration of dry spells with maximum of 31 days. From the results on the coefficient variation (CV) of spell lengths, it is also clear that distributions of wet spells are more consistent than those of dry spells for all metrological stations. However, the four stations appear to be more similar in respect of mean, SD, CV and maximum duration of wet spells than in respect of these measures of dry spells.

All 153 days from the 1st June to the 31st October for 28 years are classified into four classes according to the occurrence of four conditional events W/W, D/W, W/D and D/D such that 1st June is classified on the consideration of the weather condition of the 31st May. After counting class frequencies for different classes, MC model parameter p_0 and p_1 are estimated by using (3). The estimated values of the parameters for TNB and EP models are also computed in the manner described in the previous section from the observed frequency distributions of the spell lengths.

Table 2: Observed and Expected Frequencies of Wet Spells for Four Metrological Stations

Spell Length (Days)	Metrological Station															
	Bhubaneswar				Cuttack				Paradip				Puri			
	O_z	E_z			O_z	E_z			O_z	E_z			O_z	E_z		
		MC	TNB	EP		MC	TNB	EP		MC	TNB	EP		MC	TNB	EP
1	384	348	372	359	355	337	350	343	324	316	324	324	318	315	313	307
2	148	193	185	189	163	187	186	188	170	175	179	179	157	169	173	176
3	103	107	99	103	113	104	101	103	105	96	96	96	91	90	92	94
4	71	59	54	57	63	58	55	56	56	53	51	51	63	48	48	49
5	36	33	30	32	26	32	30	31	29	29	27	27	23	26	25	25
6	20	18	17	18	20	18	17	17	11	16	14	14	15	14	13	13
7	5	10	10	10	10	10	9	9	3	9	7	7	6	8	7	7
8	6	6	6	6	4	6	5	5	1	5	4	4	3	4	3	3
9	5	3	3	3	1	3	3	3	4	3	2	2	0	2	2	2
10	1	2	2	2	2	2	2	2	1	2	1	1	0	1	1	1
11	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
12	1	1	1	1	1	1	0	1	0	1	0	0	1	0	0	0
13	0	0	1	0	1	0	0	0	0	0	0	0	-	-	-	-
14	0	0	0	0	-	-	-	-	1	0	0	0	-	-	-	-
15	0	0	0	0	-	-	-	-	-	-	-	-	-	-	-	-
Total	781	781	781	781	759	759	759	759	706	706	706	706	678	678	678	678

Observed frequencies (O_z) and corresponding expected frequencies (E_z) of the lengths of wet and dry spells according to the competing models – MC, TNB and EP models at each station are provided in Tables 2 and 3 respectively. However, the said frequencies for the Mahanadi Delta are given in Table 4.

In Tables 5 and 6, we present AIC values, and values of the CS and KS statistics in respect of the three comparable models for all rainfall stations and for the Mahanadi Delta. These values are computed on the basis of the equations (11), (12) and (13), and figures displayed in Tables 2, 3 and 4.

Table 3: Observed and Expected Frequencies Dry Spells for Four Metrological Stations

Spell Length (Days)	Metrological Station															
	Bhubaneswar				Cuttack				Paradip				Puri			
	O_z	E_z			O_z	E_z			O_z	E_z			O_z	E_z		
		MC	TNB	EP		MC	TNB	EP		MC	TNB	EP		MC	TNB	EP
1	318	236	325	350	290	223	304	338	246	190	253	271	209	181	211	217
2	159	167	158	144	179	161	157	143	155	142	145	137	136	137	141	138
3	117	118	95	87	108	116	97	88	96	107	95	90	120	103	99	97
4	64	84	62	59	63	84	65	60	73	80	66	63	62	78	72	71
5	40	60	43	42	48	61	46	43	44	60	48	46	51	59	53	53
6	27	42	31	30	27	44	33	31	36	45	35	35	38	45	40	39

7	20	30	23	23	29	32	24	23	19	34	26	26	31	34	30	30
8	12	21	17	17	12	23	18	18	22	25	20	20	14	25	22	23
9	9	15	13	13	3	17	14	13	19	19	15	15	24	19	17	17
10	7	11	10	10	10	12	10	10	11	14	12	12	15	14	13	13
11	5	8	7	8	8	9	8	8	5	11	9	9	10	11	10	10
12	4	5	6	6	7	6	6	6	5	8	7	7	5	8	8	8
13	9	4	4	5	2	5	5	5	3	6	6	6	5	6	6	6
14	4	3	3	3	3	3	4	4	6	4	4	4	2	5	4	4
15	3	2	3	3	1	2	3	3	2	3	4	4	5	4	3	3
16	1	1	2	2	3	2	2	2	4	3	3	3	7	3	3	3
17	4	1	2	2	1	1	2	2	2	2	2	2	0	2	2	2
18	0	1	1	1	4	1	2	2	2	1	2	2	0	2	2	2
19	1	0	1	1	0	1	1	1	2	1	1	1	0	1	1	1
20	1	0	1	1	0	1	1	1	2	1	1	1	2	1	1	1
21	0	0	1	1	0	0	1	1	0	1	1	1	1	1	1	1
22	0	0	1	1	0	0	1	1	0	1	1	1	1	1	1	1
23	0	0	0	0	2	0	0	1	2	0	1	1	0	0	0	0
24	2	0	0	0	2	0	0	0	0	0	1	1	1	0	0	0
25	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	-	-	-	-	1	0	0	0	0	0	0	0	0	0	0	0
27	-	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0
28	-	-	-	-	1	0	0	0	1	0	0	0	1	0	0	0
29	-	-	-	-	-	-	-	-	0	0	0	0	-	-	-	-
30	-	-	-	-	-	-	-	-	0	0	0	0	-	-	-	-
31	-	-	-	-	-	-	-	-	1	0	0	0	-	-	-	-
Total	809	809	809	809	804	804	804	804	758	758	758	758	740	740	740	740

As mentioned earlier, identification of the most appropriate probability model to describe the observed distributions of wet and dry spells is based on two criteria. First, the particular model should have the smallest value of AIC and secondly, it should have successful fit to the data validated by the GOF tests. On the basis of these selection criteria, we rank the models as 1, 2 and 3 according to their performance, and their ranks for various locations are also shown in Tables 5 and 6. A model is not ranked under a GOF test when it did not satisfy the test *i.e.*, failed to fulfill our second criterion.

Table 4: Observed and Expected Frequencies of Wet and Dry Spells for Mahanadi Delta

Wet Spell				Dry Spell									
Spell Length (Days)	□□	□□		Spell Length (Days)	□□	□□			Spell Length (Days	□□	□□		
		MC	TNB	EP		MC	TNB	EP			MC	TNB	EP
1	1381	1316	1360	1334	1	1063	824	1086	1063	17	9	6	7	9
2	638	724	721	730	2	629	606	607	629	18	7	4	6	7
3	412	398	387	396	3	441	445	391	441	19	6	3	5	6
4	253	219	209	214	4	262	327	268	262	20	6	2	4	6
5	114	120	113	115	5	183	241	190	183	21	0	2	3	0
6	66	66	61	62	6	128	177	138	128	22	0	1	2	0
7	24	36	33	33	7	99	130	102	99	23	6	1	2	6
8	14	20	18	18	8	60	96	76	60	24	0	1	1	0
9	10	11	10	10	9	55	70	58	55	25	0	1	1	0
10	4	6	5	5	10	43	52	44	43	26	0	1	1	0
11	3	3	3	3	11	28	38	34	28	27	0	0	1	0
12	3	2	2	2	12	21	28	26	21	28	4	0	1	4
13	1	1	1	1	13	19	21	20	19	29	0	0	1	0
14	1	1	1	1	14	15	15	15	15	30	0	0	0	0
15	0	1	0	0	15	11	11	12	11	31	1	0	0	1
Total	2924	2924	2924	2924	16	15	8	9	15	Total	3111	3111	3111	3111

Results in Table 5 reveal that MC model is the most appropriate model for fitting distributions of wet spells in all locations. The next appropriate model for Bhubaneswar and Puri is the TNB distribution, and for Cuttack, Pardip and Mahanadi Delta is the EP distribution. TNB model is emerged out as the most suitable model for describing dry spells in all locations, and EP as the next suitable model for Bhubaneswar, Paradip and Puri (Table 6). However, there is no choice for the second appropriate model for Cuttack and Mahanadi Delta in case of dry spells because of the non fulfillment of the second criterion.

Comparison of the performance of three models visually with the help of graphs is also no way inferior to that of the numerical comparison. However, to save space, we display in Figure 1 the curves of the observed frequencies (OF) and expected frequencies (EF) of wet and dry spell lengths of the Mahanadi Delta. From this figure, it appears that the expected frequency curves of the MC and TNB models are respectively more close to the observed frequency curves of wet and dry spells than those of the other models. A similar visual finding has also been observed for other locations when the performance assessment of the models is made graphically.

Table 5: AIC and GOF Statistics Values, and Ranks of the Competing Models for Wet Spells

Station	Model	AIC Value	CS Statistic			KS Statistic		
			Calculated Value	5% Critical Value	Rank	Calculated Value	5% Critical Value	Rank
Bhubaneswar	MC	1038.639	19.944	15.507	-	0.0461	0.0487	1
	TNB	1039.368	17.530		-	0.0320		2
	EP	1039.446	17.438		-	0.0320		3
Cuttack	MC	1005.801	7.829	14.067	1	0.0237	0.0494	1
	TNB	1007.595	7.042		3	0.0237		3
	EP	1007.590	7.787		2	0.0171		2
Paradip	MC	911.403	7.683	12.592	1	0.0212	0.0512	1
	TNB	912.247	3.644		3	0.0128		3
	EP	912.213	3.644		2	0.0128		2
Puri	MC	872.901	7.622	14.067	1	0.0182	0.0522	1
	TNB	874.709	7.440		2	0.0177		2
	EP	875.018	7.723		3	0.0162		3
Mahanadi Delta	MC	958.167	25.674	21.026	-	0.0222	0.0252	1
	TNB	960.090	24.519		-	0.0212		3
	EP	960.034	24.615		-	0.0161		2

Table 6: AIC and GOF Statistics Values, and Ranks of the Competing Models for Dry Spells

Station	Model	AIC Value	CS Statistic			KS Statistic		
			Calculated Value	5% Critical Value	Rank	Calculated Value	5% Critical Value	Rank
Bhubaneswar	MC	1384.662	69.368	19.675	-	0.1014	0.0478	-
	TNB	1360.874	12.046		1	0.0222		1
	EP	1364.971	21.731		-	0.0396		2
Cuttack	MC	1402.214	55.965	21.026	-	0.1057	0.0480	-
	TNB	1383.134	18.247		1	0.0236		1
	EP	1389.599	33.488		-	0.0597		-
Paradip	MC	1411.664	38.219	21.026	-	0.0910	0.0494	-
	TNB	1398.993	7.582		1	0.0145		1
	EP	1401.091	12.358		2	0.0330		2
Puri	MC	1421.725	20.475	22.362	3	0.0595	0.0500	-
	TNB	1420.015	13.862		1	0.0189		1
	EP	1420.383	15.278		2	0.0176		2
Mahanadi Delta	MC	1403.572	165.271	30.144	-	0.0842	0.0244	-
	TNB	1385.794	20.464		1	0.0157		1
	EP	1384.870	40.750		-	0.0296		-

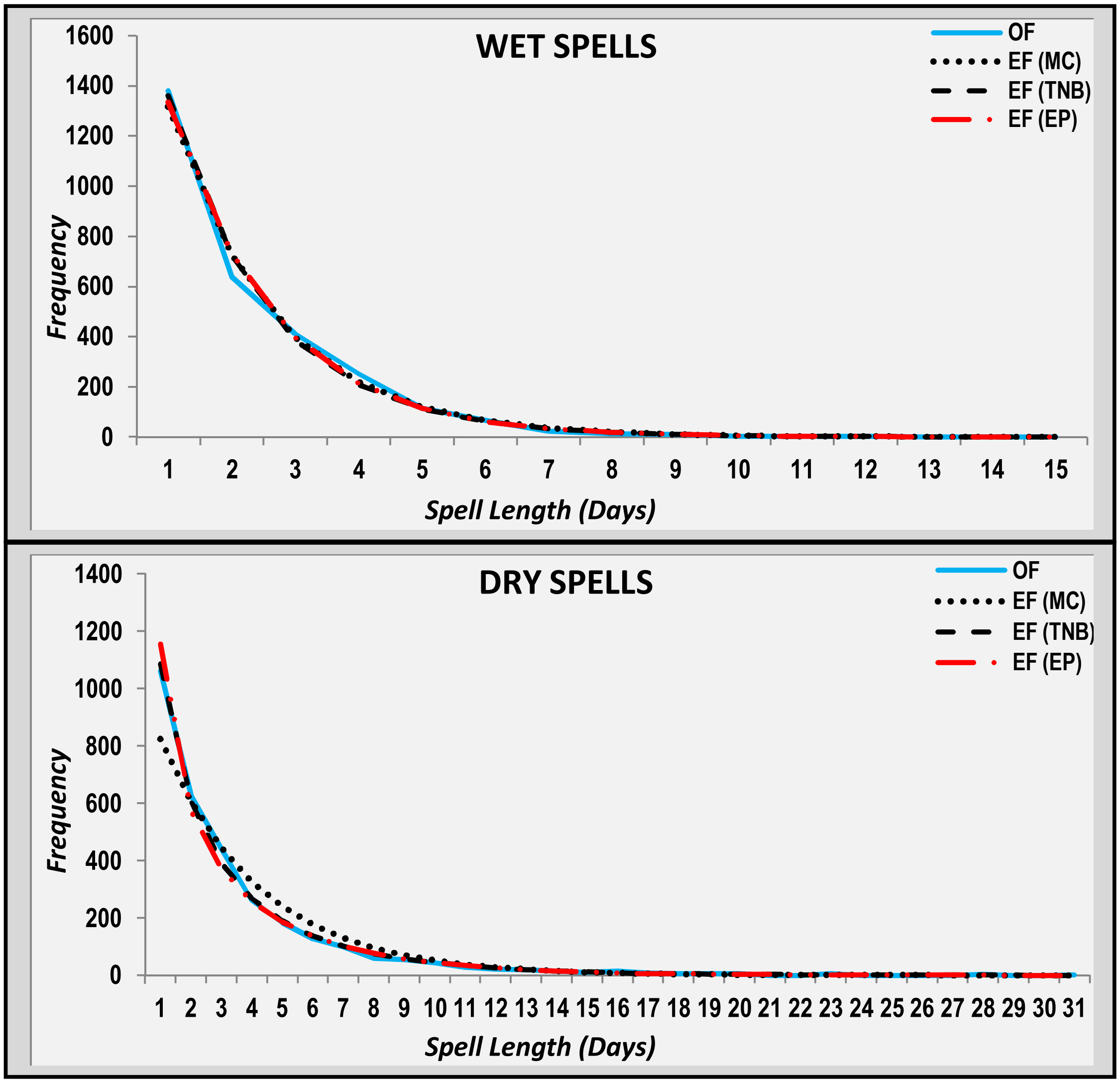

Figure 1: Observed and Expected Frequencies of Wet and Dry Spells for Mahanadi Delta

5. CONCLUSIONS

Our theoretical as well as graphical findings in this study clearly indicate that the distributions of wet and dry spells of the Mahanadi Delta can successfully be represented by means of the MC and TNB models respectively. This result is of course interesting as a single model can be exploited to analyze wet or dry spells of the entire study domain. It was possible due to the homogeneous characteristics of four stations in respect of the statistical descriptors provided in Table 1.

Although MC model has been widely used for defining probable occurrences of wet and dry spells, its failure in the present context in replicating dry spell lengths is somehow questionable. One of the probable reasons may be due to the fact that during the study period dry spells persist for longer period in comparison to wet spells and therefore the adequacy of the first order MC model for computing probabilities may not be satisfactory for long sequences, especially for prolonged dry spells when different meteorological forces are in operation. However, our analysis has proved that MC model is inferior to TNB model for dry spell description for the Mahanadi Delta. But, we must consider that the simplicity of interpretation of probabilities in Markov-based geometric model is apparently not matched in the TNB model as the former needs one parameter and the latter needs two parameters. Moreover, TNB is a higher order model and its superiority may not be really surprising.

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