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REVIEW

Literature Review on Stochastic Modeling of Wet and Dry Spells

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ABSTRACT

With increasing concerns about climate change and its profound implications for water resources, stochastic modeling of wet and dry spells has emerged as a critical domain within hydrology and climatology, providing insight into the temporal patterns of precipitation and drought occurrences. This review of the literature synthesizes recent advances in the modeling of wet and dry spells using stochastic methods, focusing on publications from 2000 to 2024. The review examines various modeling approaches, including Markov chain models, mixed probability models, non-homogeneous models, and time series approaches. Key findings indicate that Markov chain models are effective in simulating the sequential occurrence of wet and dry spells, with higher-order variants addressing issues of overdispersion. Mixed probability models excel at representing heterogeneity and extremes in precipitation data, especially in regions with distinct wet and dry seasons. Non-homogeneous models are valuable for understanding the temporal dynamics and irregularities of dry spells, revealing significant shifts in their frequency and duration over time. These can be complemented by time-series methods to highlight long-term trends and seasonal variations. The review underscores the importance of regional specificity in modeling approaches to accurately capture local climatic and geographical variability. Recommendations for future research include the integration of hybrid models that combine the strengths of various approaches to improve predictive precision, focusing on the impacts of climate change, and conducting cross-regional comparisons to generalize findings and enhance the robustness of the models.

Keywords: Stochastic modeling; Wet spells; Dry spells; Markov chain; Mixed probability models; Non-homogeneous

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models; Time series; Climate change; Precipitation

1. Introduction

The study of wet and dry spells is of paramount importance, particularly due to the strong link between the trends of these spell characteristics and the occurrence of extreme weather phenomena, including floods and landslides [1–3]. By identifying changes in the duration, frequency, and intensity of these spells, researchers can uncover vital clues about the evolving nature of our climate and provide valuable information to forecast future climatic phenomena [4, 5]. Understanding these patterns not only enriches the scientific knowledge base but also plays a crucial role in developing policies and practices aimed at reducing the impact of climate-related hazards on communities worldwide [6, 7].

The evolution of stochastic modeling techniques has been significantly shaped by key studies that established the foundation for current methodologies. Gabriel and Neumann [8] were pioneers in applying Markov Chains to hydrology, modeling daily rainfall occurrences, and revealing crucial insights into the independence of rainy days across different months. Katz [9] further advanced this approach by developing a probabilistic model that generalized the Markov chain method, enabling a more detailed analysis of daily precipitation sequences. Wilks [10] later expanded the scope of stochastic models in atmospheric sciences, integrating complex temporal and spatial dynamics, which have become essential in modern weather and climate predictions. These foundational contributions have collectively influenced the development and refinement of stochastic modeling in meteorology.

Recent studies highlight the increasing frequency and intensity of extreme events due to climate change. For instance. The 2023 IPCC report emphasizes that human-induced global warming has led to unprecedented changes in weather patterns, significantly impacting wet and dry spells [11]. In India, extreme rainfall and prolonged dry spells have become more frequent, posing severe challenges for agriculture and infrastructure [12]. Similarly, in California, the occurrence of severe droughts followed by intense rainfall has led to a cycle of dry conditions and flash floods, causing widespread damage and disruption [13]. These examples underscore the urgent need for accurate modeling of wet and dry spells to mitigate the adverse effects of climate change.

Wet and dry spells, characterized by consecutive days of precipitation or lack thereof, directly influence agricultural productivity [14]. Accurate modeling of these phenomena is vital for developing strategies to plan for agricultural activities. For instance, in sub-Saharan Africa, changes in the timing and duration of wet and dry spells have had significant impacts on crop yields, necessitating the adaptation of farming practices to new climatic realities [15]. To address the complexity and variability inherent in wet and dry spells, advanced analytical methods are needed. These methods must be capable of capturing the daily transitions between wet and dry states and accounting for the spatial and temporal heterogeneity of precipitation patterns. Among the various approaches available, Markov chain (MC) models have been extensively employed due to their ability to simulate the sequential occurrence of wet and dry spells and provide detailed insights into the persistence and transition probabilities of precipitation events [16, 17].

Recent research has further refined these models to better predict climate variability. For example, studies have utilized regional climate models to project changes in precipitation extremes and their impact on infrastructure [18]. In Canada, the investigation of spatial and temporal dynamics in wet and dry spells has revealed significant contributions to climate-related hazards, emphasizing the need for adaptive measures [17].

Despite the extensive body of research on wet and dry spells, there remains a lack of comprehensive review articles that systematically synthesize the diverse modeling approaches developed for these phenomena. This review aims to fill this gap by providing a critical analysis of various modeling techniques, identifying their strengths and weaknesses, and highlighting promising avenues for future research.

This article makes a significant contribution to the field by reviewing recent studies on the modeling of wet and dry spells using stochastic models across various geographic locations from 2000 to 2024. The structure of the review is as follows: Section 2 details the methodology and criteria employed for selecting the studies included in this review, as well as the methods used for data collection and analysis. Section 3 presents a synthesis of the key findings from the reviewed literature, organized by the different modeling approaches. Section 4 offers an analysis of the implications of these findings, discusses the strengths and limitations of the various models, and identifies current research gaps. Finally, Section 5 summarizes the main conclusions, addresses the limitations of this review, and suggests potential directions for future research.

2. Methodology

This article conducts an in-depth review of relevant literature on stochastic models for wet and dry spells. The review focused on studies employing various stochastic modeling approaches, including MC models, mixed probability models, non-homogeneous models, and time series approaches. To ensure the inclusion of both current and significant research, the review considered articles published between 2000 and 2024 in peer-reviewed scientific journals, international conferences, and relevant technical reports. Notably, one preprint that has not yet undergone peer review was included due to its high relevance to the topic. Google Scholar was used as the primary database to collect papers published during this period. The search was conducted using keywords such as "stochastic modeling of wet and dry spells" "Markov chains," "mixed probability models," "non-homogeneous models," and "time series." This search yielded a total of 48 papers that were included in the review. **Figure 1** illustrates the distribution of the reviewed studies by year. Studies that did not directly focus on the modeling of wet and dry spells using stochastic models were excluded from the review. Additionally, non-peer-reviewed articles and publications in languages other than English were not considered.

3. Results

The study of wet and dry spells requires a comprehensive approach, that integrates various statistical and stochastic models to capture their temporal and spatial dynamics. In this section, we present the findings from our extensive review, with a focus on evaluating the effectiveness and limitations of different modeling techniques. The subsections that follow will explore a range of methodologies, from traditional MC models to more advanced mixed probability models, non-homogeneous models, and time series approaches. Each subsection will highlight the specific applications, strengths, and challenges associated with these models in representing the complex behavior of wet and dry spells across diverse climatic regions.

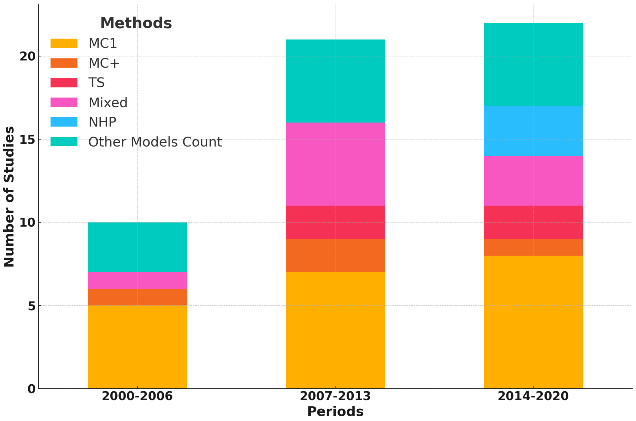

Figure 1. Trends of Studies by Method Over Three Periods (2000–2006), (2007–2013) and (2014–2020).

3.1 Markov chain models

One of the primary challenges in modeling wet and dry spells is the day-to-day variability in precipitation. which complicates the development of models that can reliably predict short-term weather patterns. MC models, particularly first-order and higher-order variants, have been extensively employed for their ability to simulate the sequential occurrence of wet and dry spells. These models can capture the daily transitions between wet and dry states. However, the inherent simplicity of first-order models often necessitates the use of higher-order models or additional modifications to address issues such as overdispersion. These enhancements help improve the accuracy of the simulations by better capturing the complexities of day-to-day variability in precipitation.

Wet spells

Studies using first-order Markov chains have demonstrated their effectiveness in predicting short-term rainfall. For example,[19] investigated the temporal and spatial variations in the occurrence of dry and rainy days by employing a first-order stationary MC to model daily precipitation patterns. This model showed high efficiency in predicting daily precipitation occurrences, with performance metrics including RMSE: 14.1568, NSE: 0.9973, RSR: 0.0149, and PBIAS: −1.7650, indicating strong predictive capability. However, the study highlighted the need for increased attention to the Amazon-Cerrado Biome (Ecotone) areas, where a higher frequency of consecutive drought days was observed. To address this, higher-order Markov chains are recommended to improve accuracy in these regions. Furthermore, The study found that the probabilities of transitions favoring rainfall were higher near the Atlantic Ocean, whereas transitions leading to drought were more prevalent in the Cerrado biome, underscoring the spatial variability in precipitation patterns across different geographic regions.

Similarly, [20] conducted a study focused on modeling a 30-year daily rainfall time series in the Basque Country region of northern Spain. The researchers used MC models to analyze the temporal patterns of rainfall and assess the persistence of daily rain. By fitting theoretical probabilities to empirical data, they demonstrated that Markovian models effectively represent the distribution of wet spells in the region, showcasing the utility of these models in capturing local precipitation dynamics.

In another example, [21] evaluated the performance of various stochastic models in generating daily precipitation sequences across Canada for the period 1971–2000. By testing multiple models at 657 stations, the authors find that the simple Markov chain (SMC) model effectively reproduces the durations of dry and wet spells but suffers from an overdispersion problem, which reduces the interannual variability of monthly total precipitation. This issue is partially resolved by adding a separate model to simulate the number of wet days per year, called the modified Markov chain (MMC) model. This modified model adjusts the transition probability by separately simulating precipitation occurrences for each month using a beta distribution. Regarding the distribution of daily precipitation amounts, the mixed exponential distribution proves to be superior, especially during warmer months, while the gamma distribution is adequate for winter months. The authors conclude that the MMC model, coupled with a mixed exponential distribution, offers the best overall performance for simulating precipitation in Canada. This approach successfully reproduced critical statistics such as extreme daily precipitation, the lengths of dry and wet spells, and interannual variability, making it a robust tool for understanding and predicting precipitation patterns across diverse climatic regions.

In India, [22] focused on assessing the probabilities of floods in the northeastern parts of the country during the southwest monsoon season.The researchers used a first-order MC model to calculate the probabilities of having 2 and 3 consecutive wet weeks in selected areas. By identifying critical periods when the probability of wet spells is greater than 80%, the study aimed to raise awareness and facilitate planning for heavy rainfall events in these vulnerable areas.

[23] employed a second-order Markov Chain model to evaluate the spatial and temporal characteristics of wet spells in Greece over 40 years. Their study also assessed the Negative Binomial Distribution (NBD) alongside the Markov Chain model. Both models showed a good fit to the observed wet spells. Still, the second-order Markov Chain model provided better predictions for long-duration wet spells, particularly in regions with complex topography like Western Greece.

Dry spells

Several studies highlight the importance of MC models in understanding the temporal progression of dry spells. For instance, in the Iberian Peninsula, [24] employed the second-order Markov chain. The authors assess the persistence of dryness, a key indicator for drought, and early warning systems. Analyzing both observational data and climate model simulations, the Markovian characteristics of dry spells are likely to persist into the future, with an increase in longer dry spells and a decrease in shorter ones.

Similarly, [25] introduced a Markov-based framework to map dry spell lengths in Tanzania's Makanya catchment, correlating with spatial information like elevation and proximity to the sea. The method assessed the probability of crop failure by comparing dry spell lengths with critical durations based on soil and crop water requirements. A high spatial variability in dry spell occurrences is revealed with the identification of regions at risk of unsustainable rainfed agriculture.

The diversity in MC modeling techniques, from simple stochastic models by [26] to more complex Markov chains by [27] in Greece, illustrates the diverse nature of dry spell research. [28] conducted a detailed analysis of dry spells over the period 1951-1990. It focused on mapping the length and frequency of dry spells across 35 observatories, defining various rainfall thresholds (0.1, 1.0, and 10.0 mm) for dry spells. The authors concentrated specifically on longer dry spells, between 7 and 120 days. Many parts of Spain exhibited high mean and maximum lengths during these dry periods. Moreover, the study innovatively applied Markov chains up to the tenth order to model the duration of dry spells, specifically examining spells longer than 1, 2, or 3 months. Regional classification of Spain into three distinct zones is performed based on the predictability and characteristics of dry spells: the northern region with satisfactory Markovian adjustments; a central region where the models had a good overall fit but displayed inconsistencies for longer periods; and the southern region where the Markovian models proved to be inadequate, indicating that drought patterns in this area do not follow a predictable Markovian sequence. The study in[29] analyzes dry spells based on intensity, length, and timing during South Africa's mid-summer period. It finds varying intensities, durations, and frequencies of dry spells across the region, with no significant trend in their occurrence. The MC probabilities indicate a west-to-east decrease in dry spells.

[30] combined the Markov chain model with several other probability distribution functions, such as the Log Pearson type III and Gumbel distributions, to analyze rainfall and predict dry spells in Odisha, India. These distributions helped in forecasting the onset and withdrawal of monsoon seasons, and the occurrence of dry spells. The combined use of Markov chain models and these distributions allowed for better agricultural planning by providing more accurate predictions of dry spell duration and frequency.

Understanding the persistence of dryness, particularly as an indicator of drought, is crucial. MC models have proven valuable in this context, but their effectiveness can vary based on the region and the specific characteristics of the dry spells being studied. Previous research has shown that the persistence and duration of dry spells can differ greatly between regions, influenced by factors such as elevation, proximity to water bodies, and seasonal climatic variations.

Wet and dry spells

Several studies have employed Markov Chain models to analyze both wet and dry spells simultaneously, highlighting the model's versatility in understanding precipitation variability across different climates.

[31] applied a first-order Markov chain simulation model to predict both wet and dry spells in the semi-arid Kano Plains of Kenya. They used conditional probabilities and the Poisson distribution to simulate critical dry and wet spells. For wet spells, the model identified periods of 12 days during the long rainy season and 8 days during the short rainy season. Similarly, for dry spells, the model revealed critical periods of 14 days in the long rainy season and 12 days in the short rainy season. These findings are crucial for sustainable water and land management in regions highly dependent on precise predictions of wet and dry periods for agriculture and water resource planning. The combination of Markov Chain models with these probabilistic approaches enabled the researchers to simulate extreme weather events effectively, providing important data for decision-makers in the Kano Plains.

[32] conducted a comparative study on the distribution of wet and dry spells using data from the Kenitra station in Morocco, covering the period from 1967 to 2017. They applied first-order and second-order Markov Chain models along with the truncated negative binomial distribution to model both wet and dry durations. Using chi-square and Kolmogorov-Smirnov tests to assess model fit and the Akaike Information Criterion (AIC) to determine the most appropriate model, the study demonstrated that higher-order Markov chains, combined with truncated negative binomial models, were highly effective in representing wet and dry durations. This study also introduced an algorithm to investigate the distribution of the number of wet and dry days over a k-day period, showing strong consistency between the calculated and observed moments of these durations. The results highlight the flexibility of combining Markov Chains with other probability models for accurate precipitation prediction, particularly in regions with complex rainfall patterns, such as Kenitra.

[33] analyzed daily rainfall data from 1970 to 2013 at five stations in Santa Catarina using a first-order MC model. They assessed the statistical descriptors of the Markov model, the expected lengths of dry and wet spells, and the monthly count of dry and rainy days. The adherence of the data to the geometric distribution was verified using the Kolmogorov-Smirnov (KS) test. Their findings revealed seasonal and spatial variations in the Markov model descriptors and the durations of dry and rainy periods, influenced by factors

such as air masses and topography. Lages station, located in the Plateau of Santa Catarina, exhibited the highest P00 values, indicating more stable atmospheric conditions. No significant differences were observed between coastal and western stations during autumn and winter. The geometric distribution proved suitable for estimating the probabilities of dry and rainy days. This study stands out for its comprehensive approach, utilizing various statistical descriptors and estimating the duration of dry and wet cycles and the number of rainy days. An MC probability model was explored by[34] to analyze the long-term frequency patterns of wet or dry weather spells during the primary rainy season in Dhera, located in the Central Rift Valley Region of Ethiopia. Using 24 years of weekly precipitation data from 1984 to 2010, the study found that the primary rainy season starts on the 26th week (June 25th to July 1st) and continues until the 40th week (October 1st to October 7th), lasting 105 days. The coefficients of variance for the weeks of onset and end are 69.4% and 99.2%, respectively. Initial and conditional probabilities exceed 50% during the 26th and 28th weeks at thresholds of 10 mm and 20 mm per week, suggesting land preparation for planting should occur during these weeks. Supplemental irrigation and moisture conservation practices are recommended during the 38th and 40th weeks for short-duration crops, and additional irrigation is necessary for crops exceeding 40 weeks, particularly with runoff water collection and soil erosion measures during the 28th and 33rd weeks.

A study by[35] applied an MC model to analyze the probability of rainfall and dry spell occurrences in Tanzania. Using daily datasets spanning from 1981 to 2019, the researchers identified a high probability of 8-day dry spells across all stations, ranging from 42.2% to 82.0% in October, November, and December. The study also highlighted the significant impact of climate change on the frequency and duration of dry spells.

Another investigation by[36] examined the projected changes in dry and wet spell probabilities in West Africa employing an MC model. Utilizing simulations from the CORDEX-Africa program, the study found an increase in the probability of dry days and a corresponding decrease in wet days under the anthropogenic forcing scenarios RCP4.5 and RCP8.5. Notably, the probability of consecutive dry days is expected to rise in the Central Sahel, Western Sahel, and Sudanian areas, while the Guinea Coast is projected to experience a decrease. These findings have significant implications for water management and risk reduction strategies in the energy and agricultural sectors.[37] introduced CON-SST-RAIN, a novel stochastic space-time rainfall generator developed for model-based urban drainage design and planning. This innovative model uses Markov chains to simulate sequences of dry and rainy days and employs stochastic storm transposition (SST) to create realistic rainfall fields from weather radar data. CON-SST-RAIN showed excellent performance in preserving extreme rain rates, including sub-hourly values, compared to observed rain gauge data. The model's capability to generate continuous area rainfall time series of arbitrary lengths makes it a valuable tool for urban planners and engineers involved in drainage and flood management. The study highlights the model's potential to improve urban infrastructure's resilience to extreme weather events.

The importance of the sequence of dry and wet periods in agricultural planning is further confirmed by[38], applying an MC probability model to Mayurbhanj based on 20 years of data (1997–2016) of weekly rainfall data. The monsoon season starts on the 24th week (June 11th to 17th) and continues until the 43rd week (October 22nd to 28th). Initial, conditional, and consecutive probability analyses reveal a high probability of wet weeks from the 24th to the 40th week. This indicates that summer plowing and initial seed bed preparations should begin between the 20th and 22nd weeks (May 14th to June 3rd), with sowing starting in the 23rd week (June 4th to 10th). During the rabi season, from the 46th to the 50th week, there is a 30% probability of a wet week, suggesting reduced precipitation reliability and the necessity for assured irrigation.

[39] employed a Markov model within the Google Earth Engine (GEE) cloud platform to assess long-term fluctuations in dry-wet spells across India. The study identified the monsoon season from the 23rd to the 39th standard meteorological week as particularly significant. The initial probabilities (IPs) of dry (Pd) and wet (Pw) spells intersect at the 50% probability level, showing significant spatiotemporal variation. The coefficient of variation is low (< 60%) in the initial probabilities of dry spells and high (> 60%) in wet spells in semi-arid and arid regions. Conversely, eastern, northern, and central regions show a high coefficient of variation (>

60%) in dry spells and a low coefficient of variation (< 40%) in wet spells. This study is relevant for long-term agricultural and water resource planning in the Indian subcontinent.

For multisite rainfall modeling,[40, 41] integrated Markov chains to enhance the understanding of the spatial-temporal distribution of rainfall, improving predictive accuracy. In India,[42] studied weekly rainfall patterns in Dharmapuri district, Tamil Nadu, classifying weeks with less than 20 mm of rainfall as dry and those with 20 mm or more as wet. There is a high probability (75–100%) of consecutive dry weeks during the first 32 weeks of the year, highlighting the need for efficient irrigation and moisture management. In contrast, there is a significant probability (43.8–68%) of consecutive wet weeks between the 37th and 45th weeks, suggesting opportunities for rainwater harvesting and the need to prevent soil erosion.

[43] explored the utility of higher-order Markov chain models for daily precipitation occurrence using long-term data from 831 weather stations in the continental United States. The study found discrepancies between the K-S test and the BIC in recommending model orders, often due to the distribution of rainy episodes rather than dry ones. The analysis concluded that models selected based on BIC might not accurately replicate the distributions of wet and dry spells at certain times of the year.

Additionally, the importance of selecting the appropriate MC order for generating daily precipitation series has been highlighted in a global study that evaluated model performance across different Köppen climate regimes. The study found that while first-order Markov chains generally performed well across various climates, higher-order models, particularly third-order, were necessary to accurately replicate dry spell distributions in tropical regions. This finding advocates for a more tailored approach in choosing MC orders, depending on the specific climate regime, to ensure an accurate representation of precipitation patterns[44].

The DHMC model, a sophisticated version of the MC model, is employed by[45] to evaluate the spatial and temporal variability of rainfall and the performance of a stochastic rainfall model in Bangladesh. The study assessed the variability of interannual rainfall using daily data from 1973 to 2012 for 18 sites. The DHMC model effectively explored probability distributions and auto-correlations of rainfall. The results showed significant interannual variability in rainfall amounts (standard deviation: 80-250 mm) and wet spell durations (standard deviation: 4-6 days) during the wet season (June to September) in eastern Bangladesh and higher variability in the dry season in the western region. The DHMC model preserved observed rainfall fluctuations across daily to multi-year time scales but slightly underestimated the auto-correlation of monthly rainfall amounts. Despite limitations, the DHMC is an effective stochastic rainfall simulator for Bangladesh's tropical monsoon climate.

Recent research conducted in West Africa has further expanded the application of MC models to project future changes in precipitation patterns under different climate change scenarios. Utilizing regional climate models from the CORDEX-Africa program, this study analyzed the impact of anthropogenic forcing on the probabilities of wet and dry spells. The findings revealed a significant increase in consecutive dry days, particularly in the Sahel region, along with a corresponding decrease in wet days, especially under the RCP8.5 scenario. These projections underscore the relevance of MC models in predicting climate-induced shifts in weather patterns, which are crucial for developing adaptive strategies in regions susceptible to extreme climatic conditions[46].

Each of these studies shows how flexible and useful MC models are for helping us understand and predict the future in a world where weather patterns are changing and becoming less predictable. These studies collectively demonstrate the adaptability and efficacy of MC models in modeling the length of wet and dry spells.

3.2 Mixed probability model

In addition to MC models, mixed probability models have shown promise in depicting the distribution of wet and dry spells. By combining different statistical distributions, these models can better capture the heterogeneity and extremes in precipitation data. They have been particularly effective in regions with distinct wet and dry seasons.

For instance,[47] conducted a detailed analysis of dry spells in the Segura Basin, a semiarid region in southeastern Spain. The study compared various probability distribution functions, including Burr, Dagum, generalized extreme value, and Wakeby distributions. The Wakeby distribution provided the best fit for the annual maximum dry spell series across all 29 weather stations, with a p-value of 0.9424 in the Kolmogorov-Smirnov test. The research highlighted the spatial variability in dry spells, with a noticeable northeast-southeast gradient of increasing dry spell durations. This mixed probability approach was critical in accurately representing the region's precipitation extremes.

[48] applied a similar approach to study dry spells over the Iberian Peninsula under present and future climate conditions. Their findings indicated that future climate scenarios would lead to a substantial increase in both the mean and maximum lengths of dry spells, particularly in southern regions. The flexibility of mixed probability models allowed the researchers to better capture the complexities of these changes, making the study highly relevant for managing future water resource challenges.

[49] focused on forecasting dry spells in Kenya and the Murray Darling Basin (MDB) of Australia. By using generalized linear models (GLM) and generalized additive models (GAM), the study was able to predict monthly dry spell durations at lead times of 1, 3, and 6 months. The mixed probability models successfully captured the increasing trends in dry spells across both regions, with probabilities of drought risk reaching 50% in Kenya and up to 77% in the MDB. The lognormal distribution proved to be the most appropriate for modeling dry spell lengths in these areas, demonstrating the effectiveness of mixed models in regions with significant agricultural dependence.

The efficacy of theoretical models like the mixed geometric distribution was demonstrated by [50] in Peninsular Malaysia. This study evaluated various probability models, including simple geometric, log series, and mixture models, to describe the distribution of wet spells. The analysis used daily rainfall data from 1977 to 2004 and observed frequency data for wet spells from the 1940s to 1976 across eight selected rainfall stations. The chi-square goodness of fit test was applied to select the best-fitting model for each station. The findings revealed that the mixed geometric distribution was the most successful model, effectively representing the distribution of wet spells for both periods and exhibiting good fits with all data sets. Additionally, geostatistical interpolators were used to create a spatial map of the theoretical persistence of daily rainfall patterns, visualizing the spatial variability of rainfall persistence across the region.

[51] employed mixed Poisson and mixed exponential distributions. Using information-theoretical entropy reasoning, the authors provided support for their proposed models, which can also be interpreted within the framework of the Bayesian approach. These advanced models offered better insights into the characteristics and distribution of wet spells.

A recent study conducted in the Chittagong Division of Bangladesh further validated the utility of mixed probability models in accurately modeling wet spells. This study meticulously evaluated various distributions and found that the log-normal distribution provided the best fit for wet spell data during the cool wet monsoon and cool dry monsoon seasons. In contrast, the geometric distribution exhibited a close fit for wet spells occurring during the hot humid summer. The robustness of these findings was ensured through the application of the Kolmogorov-Smirnov (KS) goodness-of-fit test, alongside the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) for model selection. These results underscore the importance of tailoring probability distributions to specific seasonal and regional climates to achieve more precise predictive capabilities [52].

[53] investigated the development of a discrete precipitation model capable of accurately simulating the duration of consecutive dry and wet periods at two specific stations, Szeged and Szombathely. The study focused on the precise representation of prolonged dry periods, which are prevalent in the climate of Central Europe, with a selected precipitation threshold of 0.1 mm. The findings revealed that mixed distributions are more appropriate for modeling wet and dry spells compared to the simple geometric distribution, which is particularly inadequate for long dry sequences. The use of a weighted sum of two geometric distributions and a combination of one geometric and one Poisson distribution provided a good fit for dry spells. However, only the latter combination is recommended for wet periods. The parameters of these distributions vary depending on both the season and the specific location being analyzed.

In [54], various theoretical distributions were fitted to sequences of wet and dry days. This study aimed to fit seven types of theoretical distributions to wet and dry spell data for 10 principal rain gauge stations in Peninsular Malaysia. Using daily rainfall observations for the period 1971–2005, the sequences of wet and dry days were analyzed separately at each station. A chi-square goodness-of-fit test was employed to determine the best-fitting distribution for the observed data. The study found that a compound geometric distribution and the truncated negative binomial (TNB) distribution were the most frequently selected models to describe the characteristics of wet and dry spells, respectively. Additionally, the study identified the most suitable theoretical distribution for each rainfall station, which varied based on the location of the stations.

More complex mixed probability models were developed by[55] to characterize the distribution of dry (wet) spells. Daily rainfall data from 14 selected rainfall stations in Peninsular Malaysia for the periods of 1975 to 2004 was analyzed. The mixed probability models consist of a combination of the log series distribution with three other models: the Poisson distribution (MLPD), the truncated Poisson distribution (MLTPD), and the geometric distribution (MLGD). Furthermore, the MLSD and MGTPD distributions are also presented as alternative models. The results demonstrated that MLGD exhibited the best performance in representing the distribution of dry spells across the Peninsula.

Thirteen types of probability models with one to three parameters, including the geometric and log series distribution families, were developed by[56]. The study aimed to identify the most suitable probability models to describe the distribution of dry and wet spells at each of the 38 rainfall stations in Peninsular Malaysia from 1975 to 2004. Analyses were conducted on an annual basis and during the monsoon seasons. The modified log series (MLD) and compound geometric (CGD) distributions were identified as the best models for dry and wet spells, respectively, during the monsoon seasons. Across most stations on the peninsula, the MLTPD demonstrated the best performance in representing the observed distribution of both annual dry and wet spells.

In a later study,[57] assessed mixed probability models, including mixtures of log series, geometric, Poisson, and truncated distributions, alongside higher-order MC models (up to the tenth order). The models are tested using the KS goodness-of-fit test on data from twelve rainfall stations between 1975 and 2010. The findings indicate that the mixture log series and MLTPD effectively fit the distribution of weekly dry spells, while the mixture log series and MGTPD better describe wet spells. The study also reveals that higher-order MC models can outperform mixed probability models in certain cases but require a greater number of parameters. The MLTPD and MGTPD models are preferred for their balance between complexity and accuracy, successfully fitting most stations during both monsoon seasons and on an annual basis. These models are used to produce indices such as the mean and maximum lengths of spells and the frequency of short and long spells, providing valuable information for future climatic event predictions and water resource management.[58]'s article centered around identifying the most suitable mixed regression models for wet and dry spells along the southern coast of the Caspian Sea. Over 55 years, specifically from 1960 to 2015, a total of eight stations located along the southern coast of the Caspian Sea were used in this investigation. The region experiences frequent occurrences of one- and two-day wet spells. Moreover, the western part of the country experiences more wet spells lasting four days or longer compared to the east. The most effective probability distributions for wet spells include the two-parameter gamma, two-parameter normal log, two-parameter logistic log, four-parameter generalized gamma, generalized three-parameter gamma, two-parameter gamma, three-parameter gamma, and three-parameter logistic log. In addition, the dry spells in the region are more appropriately simulated by generalized Pareto, generalized logistics, and generalized extreme value distributions. The most appropriate generalized linear mixed (GLM) model for wet spells is the negative binomial log, log Poisson, log normal, and gamma logarithmic. Additionally, the log Poisson, log normal, and negative binomial (NB) distributions were adequate for modeling annual dry spells.

Another significant contribution by[59] investigated two distinct methods for modeling rainfall characteristics across Europe, focusing on the suitability of various probability distributions for wet spells. Their comprehensive analysis revealed that the geometric distribution often failed to adequately capture the frequencies of wet spells. To address this limitation, the researchers relaxed the assumptions of the renewal process, particularly by considering local seasonality, which resulted in improved performance. By fitting daily rainfall data from multiple stations across different climatic regions in Europe, they utilized the KS goodness-of-fit test along with the AIC and BIC to select the most appropriate models. Their findings underscore the importance of accounting for seasonal variations to accurately model wet spell frequencies, enhancing the predictive capabilities for different rainfall regimes across Europe.

3.3 Non-homogeneous model

Non-homogeneous Poisson models have also been employed to analyze the randomness and irregularity of dry spell occurrences. These models are particularly useful for assessing the impact of geographical features on dry spell durations. The application of Monte Carlo simulations in conjunction with these models has further improved the robustness of the predictions, highlighting significant shifts in dry spell frequencies and durations over time.

[60] used the non-homogeneous Poisson model to analyze long dry spells in Calabria, Italy, from 1981 to 2010. The findings reveal that the characteristics of long dry spells are closely related to geographical features such as elevation and latitude. The study concludes that the non-homogeneous Poisson model is effective in evaluating drought probabilities. Similarly, the non-homogeneous Poisson model is used to analyze the sequences of dry days at the Cosenza rain gauge in southern Italy. The model is employed by

[61] to compare the behavior of dry spells over two distinct 30-year periods (1951–1980 and 1981–2010). The authors utilized Monte Carlo simulations to assess the statistical significance of variations in the expected annual mean values of dry spells. The results indicate a significant rise in the occurrence probabilities of long dry spells in the latter period. In addition, the return periods for fixed long dry spells in the second period are substantially shorter than those in the first period, highlighting a noticeable shift towards more frequent and prolonged dry spells in recent decades. Recently, [62] reapplied the same model in Italy to analyze dry spells below specific rainfall thresholds. The study covers 60 years on four rain gauges in Calabria, examining dry spell behaviors over two 30-year periods (1951–1980 and 1981–2010). The Monte Carlo simulation technique is used to evaluate the statistical significance of changes in the mean durations of dry spells annually. The study discovers that the durations of dry spells have increased in the latter period across all thresholds. For example, at the Cassano station, there is a noted increase of about 10% in the maximum dry spell duration for a 5 mm threshold. Return periods for fixed long dry spells were also found to be lower in the second period, indicating an increasing trend in both the frequency and duration of dry spells over time.

3.4 Time series approaches

Various Time series approaches have been employed in different regions to understand the temporal dynamics and trends of dry spells and rainfall patterns. A study in Croatia using data from 25 meteorological stations from 1961 to 2000, revealed distinct climatological patterns in highlands, mainland, and coastal regions [63]. Dry spells were defined by daily precipitation thresholds of 0.1, 1, 5, and 10 mm, The highlands experienced shorter dry spells compared to the mainland, while the coastal region encountered longer dry spells. Positive trends in both mean and maximum dry spell durations were observed during winter and spring, with a negative trend in autumn across all thresholds. Notably, significant positive trends were found in the mean dry spell duration for the 5 and 10 mm thresholds during spring and the annual maximum dry spell duration with a 10 mm threshold. The Discrete Autoregressive Moving Average (DARMA(1,1)) model estimated the probabilities of dry spells lasting up to 20–30 days. Another study explored the suitability of the DARMA(1,1) model to simulate daily rainfall sequences in Malaysia, using daily monsoon rainfall data from Subang Airport [64]. The model accurately matched the autocorrelation function and the probability distributions of wet and dry run lengths. Two simulations tested the model's ability to handle long sequences of daily rainfall, demonstrating the model's effectiveness.

Further research examined the estimation of extreme daily rainfall during northeast and southwest Malaysian monsoons using a DARMA(1,1)-gamma model, which combined the DARMA(1,1) model with a two-parameter gamma distribution, [65]. This study estimated the return period of multiday rainfall and found that the model accurately estimated the return period of rainfall for both monsoon seasons at Subang Airport.

In Denmark and Australia, a new class of stochastic models for analyzing precipitation intermittency was introduced [66]. This approach combined two binary stochastic models: a one-parameter white noise model and either a first-order or a second-order autoregressive model, characterized by two and three parameters, respectively. The resulting second-order compound models consisted of three and four parameters, respectively. The study established formulas for these parameters and provided equations to evaluate the parameters of the foundational models based on those of the compound models. The analysis of daily binary precipitation time series from Copenhagen and Alice Springs demonstrated that these new models showed significant differences from traditional approaches, particularly in handling the skewed data resulting from intermittent precipitation processes. The models offered improved estimates for the cumulative distribution and return periods of wet and dry spell durations.

Recent research conducted in Austria has expanded the application of spatio-temporal models by employing a generalized additive model (GAM) to assess changes in precipitation patterns over the past 50 years. This study compared two 10-year periods (1973–1982 and 2013–2022) to examine shifts in monthly mean and maximum precipitation, as well as the maximum length of dry spells. The model utilized a non-stationary Matérn covariance function to account for Austria's mountainous terrain and an AR(1) process to capture temporal dependencies. The findings revealed significant changes in precipitation patterns, underscoring the importance of advanced spatio-temporal modeling in understanding the impacts of climate change, especially in geographically complex regions like the Alps. These results are crucial for supporting and extending existing climate change studies in the Alpine region, emphasizing the need for models that integrate both spatial and temporal dynamics [67]. A study focusing on the Cheliff-Zahrez basin in Algeria, an area prone to intense droughts that affect agriculture, analyzed data from 65 weather stations spanning 1960 to 2010 [68]. Various methods, including the Standardized Precipitation Index (SPI), MC models, the drought index, and time series modeling, were employed to characterize drought conditions. The SPI analysis revealed a low frequency of droughts in the 1960s but a notable increase in the 1990s, with SPI values declining to -2, indicating extremely dry conditions, across numerous sub-basins. The MC analysis suggested an increased probability of consecutive drought years in the southern subbasins. Transition probabilities from the Drought Index pointed to the southern and southwestern regions of the basin as the most susceptible to drought. Time series modeling, particularly the APARCH approach, was identified as the most effective for computing the SPI for different return periods, indicating SPI values lower than -1.5 (severely dry) in many subbasins for a 17-year return period. **Figure 2** illustrates the diversity of modeling approaches and their application across various regions, Underscoring the necessity for region-specific strategies in understanding and predicting wet and dry spells, different modeling approaches are employed to address the unique climatic challenges of various regions. In monsoonal climates like those in India and Brazil, where day-to-day variability in precipitation is significant, Markov Chain (MC) models, including both first-order (MC1) and higher-order variants (MC+), are extensively used to capture the sequential nature of wet and dry spells. These models are crucial for making informed agricultural and water resource management decisions.

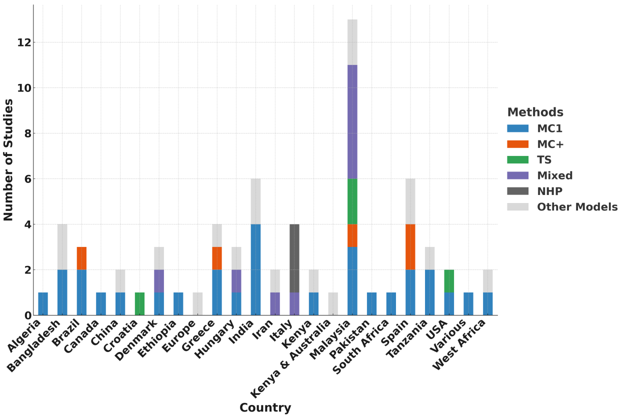

Figure 2. Distribution of Studies by Method for Each Country.

Conversely, in regions with distinct wet and dry seasons, such as Pakistan and Malaysia, mixed probability models excel in representing extremes and heterogeneity in precipitation data. This capability is vital for mitigating the impacts of seasonal floods and droughts. Time series approaches are particularly effective in countries like Canada and Tanzania, where analyzing long-term trends and seasonal patterns is essential for predicting future climate scenarios and informing agricultural planning.

In drought-prone areas such as Italy and Kenya, nonhomogeneous Poisson models are particularly useful. These models account for the irregularity and randomness of dry spells, providing critical insights for water resource management. The application of other specialized models across diverse regions, including Spain, the USA, and various parts of Africa, further highlights the need for tailored approaches that address the specific climatic and geographical challenges unique to each area. This comprehensive overview underscores the prevalence and effectiveness of different stochastic models in addressing the complexities of wet and dry spells under diverse climatic conditions.

4. Discussion

As summarized in **Appendix A**, the reviewed studies demonstrate the effectiveness and versatility of different modeling approaches for wet and dry spells. The strengths and weaknesses of these various modeling approaches are summarized in **Table 1**. MC models have been extensively used to simulate the sequential occurrence of wet and dry spells, effectively capturing daily transitions between these states. Higher-order variants of these models address complexities such as overdispersion. For example, [19, 20] successfully used these models to predict daily precipitation and persistence patterns, while [18] highlighted their limitations and the need for higher-order models for better accuracy.

Recent studies from 2024, including [35–37], further extended the application of MC models. [35] analyzed rainfall and dry spell probabilities in Tanzania, finding a high probability of 8-day dry spells and emphasizing the significant impact of climate change. Similarly, [36] examined projected changes in dry and wet spell probabilities in West Africa, noting an increase in dry days and a decrease in wet days under climate change scenarios. [37] introduced CON-SST-RAIN, an innovative stochastic space-time rainfall generator designed for urban drainage planning. This model integrates Markov chains with stochastic storm transposition to create realistic rainfall fields, thereby enhancing the resilience of urban infrastructure.

These recent studies also offer a forward-looking perspective on the applicability of Markov Chain (MC) models in predicting future climatic scenarios, particularly under varying climate change projections. For example, research on West Africa using MC models projected significant shifts in the probabilities of dry and wet days, with an increased frequency of consecutive dry days in the Sahel region under the RCP8.5 scenario [46]. This finding underscores the relevance of MC models for historical analysis and anticipating future climate adaptation needs. It challenges the models to incorporate more adaptive approaches to fully capture the complexity of evolving climate dynamics.

To significantly enhance the predictive accuracy and applicability of these models, the integration of various stochastic modeling approaches is highly advantageous. By combining the unique strengths of each method, a more comprehensive understanding of wet and dry spells across diverse climatic conditions can be achieved. Merging the sequential prediction capabilities of MC models with the distributional flexibility of Mixed Probability Models can improve simulations of both the occurrence and intensity of wet and dry spells. This hybrid approach offers a more accurate representation of extreme events and the inherent variability in precipitation data, especially in regions characterized by distinct wet and dry seasons. Additionally, integrating Non-Homogeneous Poisson models, which account for temporal variability, with Time Series methods that capture long-term trends and seasonality, can enhance the ability to predict irregular and random dry spells. This combined approach is particularly valuable in regions with complex topography, where both spatial and temporal variability play a significant role. Furthermore, incorporating climate change scenarios, such as those provided by the IPCC, into these integrated models is essential for simulating the potential impacts of varying levels of greenhouse gas emissions on the frequency and duration of wet and dry spells. This integrated approach is critical for accurately anticipating future climate dynamics and developing effective adaptation strategies.

Mixed probability models have shown promise in representing the distribution of wet and dry spells by combining different statistical distributions. These models are particularly effective in regions with distinct wet and dry seasons, capturing heterogeneity and extremes in precipitation data. [50] and [51] demonstrated the effectiveness of mixed geometric and mixed Poisson distributions. Recent studies by [59] further validated the utility of mixed probability models, emphasizing the importance of considering local seasonality and using rigorous model selection criteria like the KS goodness-of-fit test, AIC, and BIC.

The recent research in Bangladesh underscores the importance of selecting appropriate probability distributions for mixed models, particularly in regions with distinct climatic seasons. The findings from Bangladesh, where the log-normal distribution was identified as the most fitting for certain seasonal wet spells, challenge the application of more generalized models. This study highlights the necessity of tailoring stochastic models to specific regional climatic conditions to improve their predictive accuracy [52].

Non-homogeneous Poisson models and time series ap-

Table 1. Strengths and Weaknesses of Various Modeling Approaches.

Modeling	Strengths	Weaknesses
Markov Chain Models	• Capture the sequential nature of wet and dry spells [19–21]. • Provide insights into the persistence and transition probabilities of precipitation events [22, 24, 25]. • Simpler to implement and interpret [26–28]. • Can be applied to various time scales [29, 33].	• Often require higher-order models to accurately represent complex patterns [43, 45]. • May struggle to capture long-range dependencies and non-linear relationships [39–41]. • Assumption of stationarity may not hold in all cases [38, 42].
Mixed Probability Models	• Flexible in representing the heterogeneity and extremes in precipitation data [50, 51, 53]. • Can capture the distribution of wet and dry spells more accurately than simple models [54, 55]. • Useful for regions with distinct wet and dry seasons [56, 57].	• Can be more complex to implement and interpret than MC models [58, 59]. • Requires careful selection of appropriate probability distributions [50, 51]. • May not be suitable for all types of precipitation data [54, 56].
Non-Homogeneous Models	• Can account for the temporal variability in the occurrence of wet and dry spells [55]. • Can incorporate geographical features, improving the accuracy of predictions in different regions [57]. • Improved risk assessment by analyzing the irregularity and randomness of dry spells [56].	• Complexity in implementation [60]. • Require extensive and high-quality data to accurately capture temporal and spatial variability [61]. • Results can be more challenging to interpret [62].
Time Series Approaches	• Excel in identifying and analyzing long-term trends and seasonal patterns in precipitation data [63]. • Provide accurate short-term and long-term forecasts by capturing temporal dependencies in the data [65]. • Can be adapted to various types of data and are useful for both historical analysis and future predictions [66].	• Require a large amount of historical data [68]. • Often complex and computationally intensive to implement [64]. • Sensitivity to Changes [63].

proaches offer valuable insights into the temporal dynamics and trends of dry spells, assessing the randomness and irregularity of their occurrences over extended periods. Studies by [60, 63] employed these models to reveal significant spatial and temporal variability in dry spells. Spatial variability further complicates the modeling of wet and dry spells. Different regions experience varying frequencies and durations of wet and dry spells, influenced by local geographical and climatic conditions. Studies have demonstrated that while some regions may exhibit long and frequent wet spells, others may experience shorter and less predictable patterns. This spatial heterogeneity necessitates the use of region-specific models. For instance, in-depth regional assessments using daily rainfall data have highlighted significant differences in wet spell characteristics across different geographic areas, requiring tailored modeling approaches to accurately capture these patterns.

The findings of[37] highlight the potential for integrating spatial modeling techniques, which can significantly enhance predictive capabilities for urban infrastructure planning. The recent study on precipitation and dry spells in Austria underscores the importance of incorporating spatio-temporal variability into stochastic models, especially in regions with complex topography. The application of a non-stationary Matérn covariance function to account for Austria's mountainous terrain highlights the need for models that can accurately capture localized impacts of global climate trends, challenging traditional modeling approaches that might overlook such intricacies [67].

Moreover, a global study on selecting appropriate Markov Chain (MC) orders across different Köppen climate regimes questions the traditional reliance on first-order models, particularly in tropical regions. In these regions, higher-order MC models were found to more accurately reproduce dry spell distributions. This study advocates for a more tailored approach in choosing MC orders to ensure that stochastic models are optimally suited to the specific climatic characteristics of each region [44].

As climate patterns become increasingly variable due to climate change, refining stochastic models like Markov Chains and Mixed Probability Models is essential. Incorporating future climate scenarios, such as those provided by the IPCC, into these models enables the simulation of potential impacts of varying greenhouse gas emissions on the frequency and duration of wet and dry spells. For instance, a study in Iran demonstrated that warmer wet spells have significantly altered precipitation patterns in snow-dominated regions, highlighting the necessity of including temperature as a variable in stochastic models [69].

In North-Eastern North America, projected changes indicate an increase in the frequency and intensity of wet spells, particularly during winter, which poses significant hydrological risks[70]. Similarly, studies in Pakistan using stochastic projections have revealed a decrease in annual precipitation but an increase in the intensity of wet days under various climate scenarios[71]. In Northwest North America, the frequency and intensity of lagged compound events—rapid transitions between wet and dry spells—are expected to rise, complicating water resource management and disaster mitigation strategies[72]. Research on East Asian river basins also suggests that future changes in wet and dry spells will likely exacerbate flood risks in low-latitude regions while increasing drought risks in high-latitude areas[73].

The increasing frequency and intensity of hydroclimatic swings between dry and wet spells across North America, as shown in a large ensemble study using the Canadian Regional Climate Model, further underscores the need for enhanced water resource management and adaptation strategies. This study identifies hotspots in Northern Central America and parts of the United States, such as California, where intensified transitions between dry and wet extremes are expected to pose severe environmental and socio-economic challenges[74]. Additionally, the Mediterranean Basin, already recognized as a climate change hotspot, is projected to experience a significant increase in the number, duration, and spatial extent of extreme dry spells during the wet season, potentially leading to severe socio-economic impacts[75]. These advancements not only enhance the relevance of stochastic models to current global challenges but also provide practical tools for predicting and mitigating the impacts of climate change on water resources and socio-economic systems. The outcomes from this review have significant theoretical and practical implications. Theoretically, the successful application of MC and mixed probability models underscores their robustness and adaptability in climatological research, enhancing our understanding of precipitation patterns and their underlying mechanisms. Practically, the insights gained from these studies can inform water resource management, agricultural planning, and disaster preparedness. Identifying high-probability wet and dry spells can guide irrigation practices, crop selection, and planting schedules, ultimately improving agricultural productivity and resilience. Additionally, understanding the spatial and temporal variability of wet and dry spells can aid in designing infrastructure that can better withstand weather extremes, thereby mitigating the impacts of climate change on urban planning and development.

This review acknowledges some limitations. The focus on peer-reviewed journals and major databases may have introduced publication bias, as studies with non-significant results are less likely to be published. Additionally, the review predominantly covered studies published in English, potentially excluding valuable research in other languages. The variability in regional contexts and climatic conditions across the reviewed studies poses challenges in generalizing the findings universally. Despite these limitations, this review provides a comprehensive overview of the current state of research on wet and dry spell modeling, highlighting key advancements, challenges, and future directions in this critical area of climatological research. Future research should focus on integrating hybrid models, improving data quality and availability, and conducting cross-regional comparisons to enhance the generalizability of findings. The impact of climate change on precipitation patterns should remain a central consideration in the development of new stochastic models.

5. Conclusions

This literature review has highlighted several key findings in the modeling of wet and dry spells. MC models are highly effective in capturing the sequential occurrence and persistence of wet and dry spells. Higher-order Markov chains, in particular, provide improved accuracy in predicting these patterns. Mixed probability models excel in representing the heterogeneity and extremes in precipitation data, especially in regions with distinct wet and dry seasons. They complement MC models by offering a more nuanced representation of spell distributions. Non-homogeneous and Time series models are valuable for understanding the temporal dynamics and irregularities of dry spells. They provide insights into long-term trends and variability, aiding in more robust predictions. The effectiveness of models varies significantly across different regions, emphasizing the need for region-specific approaches to accurately capture local climatic and geographical variability.

Based on the findings of this review, several directions for future research are suggested. Future studies should explore the integration of MC models with other approaches to leverage the strengths of each approach. Research should focus on the impacts of climate change on the frequency and duration of wet and dry spells, employing advanced models to predict future scenarios. Improving the quality and availability of high-resolution precipitation data will enhance model accuracy and reliability. Comparative studies across different regions can provide insights into the generalizability of models and help distinguish between universal and region-specific patterns.

Author Contributions

Mounia EL Hafyani: Conceptualization and design, data collection and processing, analysis of results, writing of the manuscript. Khalid EL Himdi: Supervision, methodological advice, critical revision.

Conflict of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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References

[1] Beniston, M., 2004. Climatic change and its impacts: an overview focusing on Switzerland. DOI: https://doi.org/10.1007/1-4020-2346-4

[2] Coulibaly, P., Dibike, Y.B., 2004. Downscaling of global climate model outputs for flood frequency analysis in the Saguenay river system, Final Project Report prepared for the Canadian Climate Change Action Fund, Environment Canada, Hamilton, Ontario, Canada.

[3] Pichard, G., Arnaud-Fassetta, G., Moron, V., et al., 2017. Hydro-climatology of the lower Rhône valley: historical flood reconstruction (ad 1300–2000) based on documentary and instrumental sources. Hydrological Sciences Journal. 62(11), 1772–1795. DOI: https://doi.org/10.1080/02626667.2017.1349314

[4] Chu, P.-S., Chen, H., 2005. Interannual and interdecadal rainfall variations in the Hawaiian islands. Journal of Climate. 18(22), 4796–4813. DOI: https://doi.org/10.1175/JCLI3578.1

[5] Philandras, C., Nastos, P., Kapsomenakis, J., et al., 2011. Long term precipitation trends and variability within the Mediterranean region. Natural Hazards and Earth System Sciences. 11(12), 3235–3250. DOI: https://doi.org/10.5194/nhess-11-3235-2011

[6] Field, C.B., Barros, V.R., 2014. Climate change 2014–Impacts, adaptation and vulnerability: Regional aspects. Cambridge University Press. DOI: https://doi.org/10.1017/CBO9781107415386

[7] Barnes, C.S., 2018. Impact of climate change on pollen and respiratory disease. Current allergy and asthma reports. 18, 1–11. DOI: 10.1007/s11882-018-0813-7

[8] Gabriel, K.R., Neumann, J., 1962. A Markov chain model for daily rainfall occurrence at Tel Aviv. Quarterly Journal of the Royal Meteorological Society. 88(375), 90–95. DOI: https://doi.org/10.1002/qj.49708837511

[9] Katz, R.W., 1977. Precipitation as a chain-dependent process. Journal of Applied Meteorology (1962–1982). 671-676. DOI: https://doi.org/10.1175/1520-0450(1977)016<0671:PAACDP>2.0.CO;2

[10] Wilks, D.S., 2011. Statistical methods in the atmospheric sciences (3rd ed.). Academic Press.

[11] Setzer, J., Higham, C., 2023. Global trends in climate change litigation: 2023 snapshot. DOI: https://doi.org/10.21953/lse.9t1vm73ug29o

[12] Vaidyanathan, G., 2023. How India is battling deadly rain storms as climate change bites. DOI: https://doi.org/10.1038/d41586-023-00341-5

[13] Diffenbaugh, N.S., Swain, D.L., Touma, D., 2015. Anthropogenic warming has increased drought risk in California. Proceedings of the National Academy of Sciences. 112(13), 3931–3936. DOI: https://doi.org/10.1073/pnas.142238511

[14] Gabriel, J., Quemada, M., 2011. Replacing bare fallow with cover crops in a maize cropping system: yield, n uptake, and fertilizer fate. European Journal of agronomy. 34(3), 133–143. DOI: https://doi.org/10.1016/j.eja.2010.11.006

[15] Masih, I., Maskey, S., Mussa, F., et al., 2014. A review of droughts on the African continent: a geospatial and long-term perspective. Hydrology and earth system sciences. 18(9), 3635–3649. DOI: https://doi.org/10.5194/hess-18-3635-2014

[16] Wilks, D.S., 2011. Statistical methods in the atmospheric sciences. Academic Press. DOI: https://doi.org/10.1016/C2017-0-03921-6

[17] Yang, Y., Gan, T.Y., Tan, X., 2021. Recent changing characteristics of dry and wet spells in Canada. Climatic Change. 165(3), 42. DOI: https://doi.org/10.1007/s10584-021-03046-8

[18] Elshorbagy, A., Lindenas, K., Azinfar, H., 2018. Risk-based quantification of the impact of climate change on storm water infrastructure. Water Science. 32(1), 102–114. DOI: https://doi.org/10.1016/j.wsj.2017.12.003

[19] Progenio, M.F., Blanco, C.J.C., Santana, L.R., 2023. Stochastic modeling of the daily precipitation occurrence in the Tocantins-Araguaia hydrographic region, amazon, brazil. International Journal of Hydrology Science and Technology. 15(4), 390–420. DOI: https://doi.org/10.1504/IJHST.2023.131180

[20] Fdez-Arroyabe Hernaez, P., Martin-Vide, J., 2012. Regionalization of the probability of wet spells and rainfall persistence in the Basque country (northern Spain). International Journal of Climatology. 32(12), 1909–1920. DOI: https://doi.org/10.1002/joc.2405

[21] Wan, H., Zhang, X., Barrow, E.M., 2005. Stochastic modeling of daily precipitation for Canada. Atmosphere-Ocean. 43(1), 23–32. DOI: https://doi.org/10.3137/ao.430102

[22] Gore, P., Chavan, A., 2013. Probabilities of wet spells over north eastern India leading to flood condition. MAUSAM. 64(3), 475–480.

[23] Tolika, K., Maheras, P., 2005. Spatial and temporal characteristics of wet spells in Greece. Theoretical and Applied Climatology. 81, 71–85. DOI: https://doi.org/10.1007/s00704-004-0089-9

[24] Lopez-Franca, N., Sanchez, E., Losada, T., et al., 2015. Markovian characteristics of dry spells over the Iberian peninsula under present and future conditions using escena ensemble of regional climate models. Climate Dynamics. 45, 661–677. DOI: https://doi.org/10.1007/s00382-014-2280-8

[25] Fischer, B., Mul, M., Savenije, H., 2013. Determining spatial variability of dry spells: a Markov-based method, applied to the makanya catchment, tanzania. Hydrology and Earth System Sciences. 17(6), 2161–2170. DOI: https://doi.org/10.5194/hess-17-2161-2013

[26] Sadiq, N., 2014. Stochastic modelling of the daily rainfall frequency and amount. Arabian Journal for Science and Engineering. 39, 5691–5702. DOI: https://doi.org/10.1007/s13369-014-1132-5

[27] Anagnostopoulou, C., Maheras, P., Karacostas, T., et al., 2003. Spatial and temporal analysis of dry spells in Greece. Theoretical and Applied Climatology. 74, 77–91. DOI: 10.1007/s00704-002-0713-5

[28] Martin-Vide, J., Gomez, L., 1999. Regionalization of peninsular Spain based on the length of dry spells. International Journal of Climatology: A Journal of the Royal Meteorological Society. 19(5), 537–555. DOI: https://doi.org/10.1002/(SICI)1097-0088(199904)19:5<537::AID-JOC371>3.0.CO;2-X

[29] Mengistu, M., Olivier, C., Botai, J.O., et al., 2021. Spatial and temporal analysis of the mid-summer dry spells for the summer rainfall region of South Africa. Water SA. 47(1), 76–87. DOI: http://dx.doi.org/10.17159/wsa/2021.v47.i1.9447

[30] Mandal, K., Padhi, J., Kumar, A., et al., 2015. Analyses of rainfall using probability distribution and Markov chain models for crop planning in daspalla region in Odisha, India. Theoretical and Applied Climatology. 121, 517–528. DOI: https://doi.org/10.1007/s00704-014-1259-z

[31] Ochola, W., Kerkides, P., 2003. A markov chain simulation model for predicting critical wet and dry spells in kenya: analyzing rainfall events in the Kano plains. Irrigation and Drainage: The journal of the International Commission on Irrigation and Drainage. 52(4), 327–342. DOI: https://doi.org/10.1002/ird.94

[32] El Hafyani, M., El Himdi, K., 2022. A comparative study of geometric and exponential Laws in modelling the distribution of daily precipitation durations. In IOP Conference Series: Earth and Environmental Science (Vol. 1006, No. 1, p. 012005). IOP Publishing.

[33] Back, A.J., Miguel, L.P., 2017. Analysis of the stochastic model of the Markov chain on daily rainfall occurrence in the state of Santa Catarina, brazil. Management of Environmental Quality: An International Journal. 28(1), 2–16. DOI: https://doi.org/10.1108/MEQ-07-2015-0135

[34] Admasu, W., Tadesse, K., Yemenu, F., et al., 2014. Markov chain analysis of dry, wet weeks and statistical analysis of weekly rainfall for agricultural planning at Dhera, central rift valley region of Ethiopia. African Journal of Agricultural Research. 9(29), 2205–2213. DOI: https://doi.org/10.5897/AJAR2014.8664

[35] Magang, D., Ojara, M., Lou, Y., 2024. Dry spells and probability of rainfall occurrence over Tanzania, east Africa. Agrotechnology. 13, 360. DOI: https://doi.org/10.35248/2168-9881.24.13.360

[36] Basse, J., Camara, M., Diba, I., et al., 2024. Projected changes in dry and wet spells over west Africa using Markov chain approach. DOI:10.20944/preprints202405.1295.v1

[37] Andersen, C.B., Wright, D.B., Thorndahl, S., 2024. Con-sst-rain: Continuous stochastic space-time rainfall generation based on Markov chains and transposition of weather radar data. Journal of Hydrology. 637, 131385. DOI: https://doi.org/10.1016/j.jhydrol.2024.131385

[38] Ray, M., Biswasi, S., Sahoo, K., et al., 2018. A Markov chain approach for wet and dry spell and probability analysis. International Journal of Current Microbiology and Applied Sciences. 6, 1005–1013.

[39] Choudhury, I., Bhattachrya, B., 2023. Assessing the long-term fluctuations in dry-wet spells over Indian

region using Markov model in gee cloud platform. Journal of Agrometeorology. 25(2), 247–254. DOI: https://doi.org/10.54386/jam.v25i2.2184

[40] Gao, C., Guan, X., Booij, M.J., et al., 2021. A new framework for a multi-site stochastic daily rainfall model: Coupling a univariate Markov chain model with a multi-site rainfall event model. Journal of Hydrology. 598, 126478. DOI: https://doi.org/10.1016/j.jhydrol.2021.126478

[41] Gao, C., Booij, M.J., Xu, Y.-P., 2020. Development and hydrometeorological evaluation of a new stochastic daily rainfall model: Coupling Markov chain with rainfall event model. Journal of Hydrology. 589, 125337. DOI: https://doi.org/10.1016/j.jhydrol.2020.125337

[42] Nagarajan, K., 2022. Weekly rainfall analysis using the Markov chain model in the dharmapuri region of Tamil Nadu. Journal of Applied and Natural Science. 14(SI), 213–219. DOI: https://doi.org/10.31018/jans.v14iSI.3611

[43] Schoof, J., Pryor, S., 2008. On the proper order of Markov chain model for daily precipitation occurrence in the contiguous united states. Journal of Applied Meteorology and Climatology. 47(9), 2477–2486. DOI: https://doi.org/10.1175/2008JAMC1840.1

[44] Wilson Kemsley, S., Osborn, T., Dorling, S., et al., 2021. Selecting Markov chain orders for generating daily precipitation series across different Köppen climate regimes. International Journal of Climatology. 41(14), 6223–6237. DOI: https://doi.org/10.1002/joc.7175

[45] Chowdhury, A.K., Kar, K.K., Shahid, S., et al., 2019. Evaluation of spatio-temporal rainfall variability and performance of a stochastic rainfall model in Bangladesh. International Journal of Climatology. 39(11), 4256–4273. DOI: https://doi.org/10.1002/joc.6071

[46] Basse, J., Camara, M., Diba, I., et al., 2024. Projected Changes in Dry and Wet Spells over West Africa Using Markov Chain Approach. Preprints. 2024051295. DOI: https://doi.org/10.20944/preprints202405.1295.v1

[47] Perez-Sanchez, J., Senent-Aparicio, J., 2018. Analysis of meteorological droughts and dry spells in semiarid regions: a comparative analysis of probability distribution functions in the Segura basin (SE Spain). Theoretical and Applied Climatology. 133(3), 1061–1074. DOI: https://doi.org/10.1007/s00704-017-2239-x

[48] Sánchez, E., Domínguez, M., Romera, R., et al., 2011. Regional modeling of dry spells over the Iberian peninsula for present climate and climate change conditions: A letter. Climatic Change. 107, 625–634. DOI: https://doi.org/10.1007/s10584-011-0114-9

[49] Muita, R.R., 2013. Probabilistic forecasting of dry spells in Kenya and Australia, Doctoral dissertation, University of Sydney.

[50] Deni, S.M., Suhaila, J., Jemian, A.A., 2008. Probability models for wet spells in Peninsular Malaysia during the periods of 1940s-1976 & 1977-2004. Journal of Quality Measurement and Analysis JQMA. 4(1), 167–178.

[51] Korolev, V.Y., Gorshenin, A.K., Gulev, S.K., et al., 2017. Statistical analysis of precipitation events. arXiv preprint arXiv:1705.11055. DOI: https://doi.org/10.48550/arXiv.1705.11055

[52] Ghosh, S., Das, L.C., Ahmed, R., et al., 2024. Exploring optimal probability distribution for consecutive wet spells in Chittagong Division, Bangladesh. American Journal of Mathematics and Statistics. 14(1), 9–15. DOI: https://doi.org/10.5923/j.ajms.20241401.02

[53] Dobi-Wantuch, I., Mika, J., Szeidl, L., 2000. Modelling wet and dry spells with mixture distributions. Meteorology and Atmospheric Physics. 73(3-4), 245–256. DOI: https://doi.org/10.1007/s007030050076

[54] Deni, S.M., Jemain, A.A., Ibrahim, K., 2008. The spatial distribution of wet and dry spells over Peninsular Malaysia. Theoretical and Applied Climatology. 94, 163–173. DOI: https://doi.org/10.1007/s00704-007-0355-8

[55] Deni, S.M., Jemain, A.A., Ibrahim, K., 2009. Mixed probability models for dry and wet spells. Statistical Methodology. 6(3), 290–303. DOI: https://doi.org/10.1016/j.stamet.2008.11.001

[56] Deni, S.M., Jemain, A.A., Ibrahim, K., 2010. The best probability models for dry and wet spells in Peninsular Malaysia during monsoon seasons. International Journal of Climatology. 30(8), 1194–1205. DOI: https://doi.org/10.1002/joc.1972

[57] Deni, S.M., Jemain, A.A., 2012. Comparison between mixed probability models and Markov chain models for weekly dry and wet spells in Peninsular Malaysia, in Proceedings of the World Congress on Engineering, Vol. 1.

[58] Roshani, M., Saligheh, M., Alijani, B., et al., 2020. Best probability model and generalized linear mixed model of wet and dry spells of the southern coast of the Caspian Sea. Geographic Space. 20(69), 17–37.

[59] Baiamonte, G., Agnese, C., Cammalleri, C., et al., 2024. Applying different methods to model dry and wet spells at daily scale in a large range of rainfall regimes across Europe. Advances in Statistical Climatology, Meteorology and Oceanography. 10(1), 51–67. DOI: https://doi.org/10.48550/arXiv.2402.02016

[60] Sirangelo, B., Caloiero, T., Coscarelli, R., et al., 2017. Stochastic analysis of long dry spells in Calabria (southern Italy). Theoretical and Applied Climatology. 127, 711–724.

[61] Sirangelo, B., Caloiero, T., Coscarelli, R., et al., 2015. A stochastic model for the analysis of the temporal change of dry spells. Stochastic Environmental Research and Risk Assessment. 29, 143–155. DOI: https://doi.org/10.1007/s00704-015-1662-0

[62] Sirangelo, B., Caloiero, T., Coscarelli, R., et al., 2019.

A stochastic approach for the analysis of long dry spells with different threshold values in southern Italy. Water. 11(10), 2026. DOI: https://doi.org/10.1007/s00477-014-0904-5

[63] Cindric, K., Pasaric, Z., Gajic-Capka, M., 2010. Spatial and temporal analysis of dry spells in Croatia. Theoretical and Applied Climatology. 102, 171–184. DOI: https://doi.org/10.1007/s00704-010-0250-6

[64] Muhammad, N.S., Julien, P.Y., 2015. Multiday rainfall simulations for Malaysian monsoons, in ISFRAM 2014: Proceedings of the International Symposium on Flood Research and Management, Springer, pp. 111–120. DOI: https://doi.org/10.1007/978-981-287-365-1_10

[65] Muhammad, N.S., Julien, P.Y., Salas, J.D., 2016. Probability structure and return period of multiday monsoon rainfall. Journal of Hydrologic Engineering. 21(1), 04015048. DOI: https://doi.org/10.1061/(ASCE)HE.1943-5584.0001253

[66] Wiuff, R., 2020. Analysis and modeling of precipitation intermittency by compound Markov-darma models. Water Resources Research. 56(2), e2019WR025522. DOI: https://doi.org/10.1029/2019WR025522

[67] Perchtold, C., Buckwar, E., 2024. Climate change in Austria: Precipitation and dry spells over 50 years. DOI: https://doi.org/10.48550/arXiv.2408.11497

[68] Habibi, B., Meddi, M., Torfs, P.J., et al., 2018. Characterization and prediction of meteorological drought using stochastic models in the semi-arid Cheliff–Zahrez basin (Algeria). Journal of Hydrology: Regional Studies. 16, 15–31. DOI: https://doi.org/10.1016/j.ejrh.2018.02.005

[69] Motamedi, A., Gohari, A., Haghighi, A.T., 2023. Three-decade assessment of dry and wet spells change across Iran, a fingerprint of climate change. Scientific Reports. 13, 2888. DOI: https://doi.org/10.1038/s41598-023-30040-0

[70] Vaittinada Ayar, P., Mailhot, A., 2021. Evolution of Dry and Wet Spells Under Climate Change Over North-Eastern North America. Journal of Geophysical Research: Atmospheres, 126(5), e2020JD033740. DOI: https://doi.org/10.1029/2020JD033740

[71] Nabeel, A., Athar, H., 2020. Stochastic projection of precipitation and wet and dry spells over Pakistan using IPCC AR5 based AOGCMs. Atmospheric Research. 234, 104742. DOI: https://doi.org/10.1016/j.atmosres.2019.104742

[72] Rezvani, R., Na, W., Najafi, M.R., 2023. Lagged compound dry and wet spells in Northwest North America under 1.5° C–4° C global warming levels. Atmospheric Research. 290, 106799. DOI: https://doi.org/10.1016/j.atmosres.2023.106799

[73] Huang, L., Du, H., Dang, Y., et al., 2023. Observed and projected changes in wet and dry spells for the major river basins in East Asia. International Journal of Climatology. 43(12), 5369–5386. DOI: https://doi.org/10.1002/joc.8151

[74] Na, W., Najafi, M.R., 2024. Rising risks of hydroclimatic swings: A large ensemble study of dry and wet spell transitions in North America. Global and Planetary Change. 238, 104476. DOI: https://doi.org/10.1016/j.gloplacha.2024.104476

[75] Raymond, F., Ullmann, A., Tramblay, Y., et al., 2019. Evolution of Mediterranean extreme dry spells during the wet season under climate change. Regional Environmental Change. 19, 2339-2351. DOI: https://doi.org/10.1007/s10113-019-01526-3

Appendix A

Table A1. Summary of studies on the distribution of wet and dry spells using various models—Part1.

Study	Country	Data period	MC1	MC+	TS	Mixed	NHP	Other models
[19]	Brazil	-	✓	✓				
[39]	India	Long term	✓					GoogleEarth
[29]	South	Mid-summer	✓					
[40]	Various	Various terms	✓					
[58]	Iran	1960–2015				✓		NB, GLM
[66]	Denmark	Australia				✓		
[62]	Italy	1951–1980,					✓	

Table A1 continued

Study	Country	Data period	MC1	MC+	TS	Mixed	NHP	Other models
[45]	Bangladesh	1973–2012	✓					DHMC
[47]	Spain	20 years						Burr, Dagum,
[38]	India	1997–2016	✓					
[33]	Brazil	Seasonal data	✓					
[60]	Italy	1981–2010					✓	
[51]	Various	Long term				✓		
[68]	Algeria	1960–2010	✓		✓			
[65]	Malaysia	-			✓			Gamma
[61]	Italy	1951–1980					✓	
[64]	Malaysia	-			✓			

Table A2. Summary of studies on the distribution of wet and dry spells using various models—Part2.

Study	Country	Data period	MC1	MC+	TS	Mixed	NHP	Other models
[34]	Ethiopia	1984-2010	✓					
[49]	Kenya & Australia	-						Lognormal, GLM, GAM
[25]	Tanzania	-	✓					Spatial Analysis
[22]	India	Monsoon season	✓					
[48]	Spain	-						Weibull
[63]	Croatia	1961–2000			✓			
[56]	Malaysia	1975–2004				✓		
[55]	Malaysia	1975–2004				✓		
[43]	USA	Long term	✓ ✓	✓				
[50]	Malaysia	1977–2004	✓			✓		
[23]	Greece	1958–1997		✓				NBD
[21]	Canada	1971–2000	✓					
[31]	Kenya	Critical periods	✓					Poisson
[20]	Spain (Basque Country)	1965–1994	✓	✓				
[24]	Spain (Iberian Peninsula)	Observations (1989–2007), Simulations (1970–2000, 2021–2050)	✓	✓				

Table A3. Summary of studies on the distribution of wet and dry spells using various models—Part3.

Study	Country	Data period	MC1	MC+	TS	Mixed	NHP	Other models
[42]	India	1980–2019	✓					
[27]	Greece	1958–1997	✓	✓				
[26]	Pakistan	1981–2010	✓					
[57]	Malaysia	1975–2010	✓	✓		✓		Poisson
[30]	India	1995–2010	✓					Log Pearson type III and Gumbel
[53]	Hungary	1951–1995	✓			✓		Poisson
[54]	Malaysia	1971–2005	✓			✓		TNB
[41]	China	Not specified	✓					SDRM-MCREM
[35]	Tanzania	1981–2019	✓					
[59]	Europe	-						Lerch distribution (DM and IM)
[36]	West	-	✓					CORDEX-Africa regional climate models
[37]	Denmark	Multi-year records	✓					Stochastic Storm Transposition (SST)
[32]	Morocco	1967–2017	✓	✓				TNB