Chapter 8 P20

SUSTAINABILITY CONCEPT TO EVALUATE PERFORMANCE OF RAINFALL TIME SERIES

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1. INTRODUCTION

Climate change has emerged as the single most-pressing problem globally, and accordingly, the same has received increasing attention across the world [4]. The rainfall and temperature are two most important climatic variables clearly evidencing the occurrence of the climate change. Rainfall is particularly more susceptible to the impacts of climate change as the changing rainfall patterns may ultimately lead to extreme hydrological events, i.e. floods/droughts in different regions [60]. In rainfed agriculture in semi-arid and arid regions, variability of the rainfall due to climate vulnerability significantly affects the spatial and temporal water availability [13]. It is also revealed from the literature that number of studies exploring spatial and temporal variability of the rainfall time series at different time scales is currently increasing [5, 7, 14, 20, 39, 50]. Understanding spatial and temporal variability of the rainfall is further important for the arid lands, which are spreading over 61 million km^2 worldwide (46% of the global area) [16].

In the arid lands, the water deficit scenario is quite common due to relatively less occurrence of rainfall and its low magnitudes. The arid lands in India, extending over 50.8 million ha (15.8% of the country's geographical area) [46, 48], can be further sub-divided into hot arid and cold arid zones. A large portion of the hot arid zone in the country, i.e. 32 million ha, exists in western Rajasthan consisting of 62% of country's hot arid zone, and another 19.6% of country's total arid land is situated in Gujarat [28].

Time series modelling is considered as a comprehensive technique for exploring temporal patterns of hydrologic time series through identification/determination of all important time series characteristics, i.e. normality, stationarity, homogeneity, presence/absence of trend and persistence [1, 37, 38, 39, 56]. From the statistical perspective, the term homogeneity determines whether or not the entire data in the time series belong to one population, and if true, the time series should have a time-invariant mean. The non-homogeneity may be introduced in the time series due to anthropogenic factor when a change occurs in the method of data collection and/or due to natural factors when the environment, in which data collection is done, is changed [17]. The term stationarity determines whether the statistical parameters of the time series, i.e. mean, standard deviation, etc. computed from different samples change only due to sampling variations or due to any other reason. Presence of trend in a time series is observed when a significant relation is found between the observations and time as revealed from the values of correlation coefficient. Trends in hydrologic time series are incurred due to natural as well as anthropogenic activities [56]. The term persistence reflects the tendency for the magnitude of an event (or data) to be dependent on the magnitude of the previous event(s) or data.

Sustainability index (SI) is another useful tool that can be used to evaluate performance of the hydrologic time series based on reliability-resilience-vulnerability approach. The SI makes it possible to evaluate and compare hydrologic time series of the different stations with respect to their sustainability. The concept of SI was first defined by Loucks [35] using reliability (R_y), resilience (R_e) and vulnerability (V_y) as the performance criteria with an aim to evaluate and compare water management policies. Thereafter, the index has been utilized by researchers for the scientific use [45, 51, 55]. It is revealed from the extensive literature search that the SI has never been applied to evaluate the performance of the hydrologic stations based on their time series records.

This chapter aims at highlighting role of time series modeling in identifying vital characteristics of the hydrologic time series. Firstly, fundamental characteristics of both time series analysis and sustainability criteria are defined and/or described. Then, the chapter summarizes theoretical procedures for applying sustainability concept by explaining its historical development and recent applications in hydrology and water resources engineering. Thereafter, a case study is presented demonstrating a comprehensive methodology for analyzing the rainfall time series in an arid region of western India. This study introduces the sustainability approach, for the first time, to analyze a hydrologic time series, and demonstrates its novel applicability to rainfall time series of arid region.

2. TIME SERIES MODELING

Time series modeling is performed by investigating a temporally sequence of dataset and is explained by the synthesis of a model for making predictions wherein time is an independent variable. Sometimes, time is not actually used as the independent variable to predict the magnitude of a random variable such as peak runoff rate, but the data are ordered by time in a series. The goal of time series modeling is to detect and describe quantitatively each of the generating processes underlying a given sequence of observations [56].

Hydrologic time series model accomplishes multiple tasks. In literature, time series modeling is employed mainly to detect a trend in several hydrologic variables especially in precipitation and temperature datasets. The time series analysis also help developing and calibrating a model that describes the time-dependent characteristics of a hydrologic variable. Additionally, the time series models may be used to predict future values of a time-dependent hydrologic variable. Besides the modeling of time-dependent hydrologic data series, the concept of time series modeling may also be used for space-dependent data series of hydrologic systems, which are known as 'spatial data series'. In spatial data series, the independent variable is site and the dependent variable is a hydrologic parameter that may have different values over the space at any time. Many of the time series modeling methods can be adequately used for spatial data series [56].

According to Rogers et al. [52], time series modeling is a four-step process involving detection, analysis, synthesis, and verification. The first step detects the systematic components, e.g. trend, periodicity, etc. of the time series. In detection step, physical and statistical significance of the systematic components is also decided. In the third step, the systematic components are analyzed to identify their characteristics including magnitudes, form and their duration over which the effects exist. In the synthesis step, information from the analysis step is accumulated to develop a time series model and to evaluate goodness-of-fit of the developed model. In the final step, the developed time series model is evaluated to verify using independent sets of data. Elaborated text on time series modeling can be found in the specialized books on time series analysis such as [6, 10, 11, 38, 54].

2.1. Time Series Characteristics

There are a set of key assumptions, which needs to be satisfied prior to use of any hydrologic time series for many statistical analyses involved in water resources studies. These assumptions include the time series is homogenous, stationary, free from trends and shifts, non-periodic with no persistence [1]. However, either none of them or only few criteria are checked to confirm that the time series follow the conditions.

2.1.1. Normality

Normality of a hydrologic time series indicates whether the distribution of the hydrologic data in the series follows or not the normal distribution. Many statistical tests used for time series modeling are based on the assumptions that the data in the series were sampled from a normal distribution. This assumption is very critical to test reliability of the test especially of parametric tests which depend upon the parameters of the data distribution, i.e. mean and standard deviation, among others. For a normally-distributed hydrologic time series, value of skewness coefficient should be zero and value of kurtosis should be three. Otherwise, the curve of the probability density function on the normal probability plot will be either left-skewed/right-skewed or platykurtic/leptokurtic.

2.1.2. Homogeneity

Homogeneity is the term, which checks whether any subset(s) of the entire time series belong to the one population. If a time series has time invariant mean then homogeneity is supposed to be present in the time series. The factors/causes responsible for arising the non-homogeneity in a time series can be anthropogenic, e.g. due to changes in the method of data collection, and/or natural such as change occurring in environment in which data collection is done [17].

2.1.3. Stationarity

Stationarity in a time series is considered to be present if values of the statistical parameters such as mean and standard deviation do not significantly change for different samples of the series. Some changes in the statistical parameters of the time series may be due to sampling variations, which are not accounted while testing stationarity of the time series. The stationarity in a time series may be of two types; strict stationarity if statistical properties of the time series do not vary with changes of time origin, and weak stationarity or second-order stationarity when the first- and second-order moments depend only on time differences [9]. In nature, it is rare to find strict stationarity in a time series, and a time series with weakly stationarity is practically considered as stationary time series.

2.1.4. Presence of Trends

Trends in a time series indicate some kind of change occurring over time. A change in the hydrologic time series can place in many ways. For example, a change can occur gradually over the time where it is difficult to locate a clear-cut point of change. Such kind of change is known as trend. On the contrary, a change in the hydrologic time series may be abrupt over an instant time, which is known as step change or jump. The trend may also take more complex form completely different from gradual and abrupt changes [56]. A trend is determined by a unidirectional and gradual change in the mean value of a hydrologic variable that may be either falling or rising [56].

Trend present in the time series may or may not be statistically significant, which may be confirmed by testing strength of relationship (positive or negative) between the observed values and time. Usually, trends and shifts in a hydrologic time series are incurred due to gradual natural or human-induced changes in the hydrologic environment [19, 53]. Factors causing gradual or natural changes in hydrologic variables can be global or regional climate change, gradual urbanization in an area surrounding the monitoring site, changes in the method of measurement at the monitoring site, or by moving the monitoring site even a short distance away. On the other hand, step changes or jumps in a time series usually result from catastrophic natural events such as earthquakes, tsunami, cyclones, or large forest fires which quickly and considerably alter the hydrologic regime of an area. In addition, the anthropogenic changes such as the closure of a new dam, the start or end of groundwater pumping, or other such developmental activities may also cause jumps in some hydrologic time series [19]. Similar to trends, the jumps can also be either positive or negative.

2.1.5. Periodicity

Periodicity of hydrologic time series explains a steady or oscillatory form of movement that recurrently occurs over a fixed time interval [56]. The periodicity in the hydrologic time series is generally introduced by astronomic cycles, e.g. earth's cyclic rotations made around the sun [19, 30]. Impact of the astronomic cycles is clearly observed in most of the hydrologic time series such as rainfall, temperature, evapotranspiration, streamflow, groundwater levels, seawater levels, soil moisture, etc. [19]. In addition to annual-scale periodicity, there may be periodicity at lesser scales of time such seasonal, monthly and weekly periodicity. The seasonality in the hydrologic time series may be caused due to seasons. For example, rainfall in the northwest part of the India falls during four-month period (June to September) when southwest monsoon sets in the region. Hence, the rainfall will concentrate in rainy season and there will be negligible rainfall during the dry period. Accordingly, streamflow in seasonal rivers will exist during monsoon and post-monsoon seasons but the stream may be completely dry during pre-monsoon or summer season.

The seasons may also affect the groundwater level time series. In monsoon season, there will be adequate availability of the surface water, and negligible quantities of the groundwater will be extracted for agricultural purposes. However, in response to negligible rainfall received during the post-monsoon or rabi season, large groundwater withdrawals will be made and that may lower down the groundwater levels in the aquifer system. Even weekly cycles may also be observed in the water-use data of domestic, industrial, or agricultural sectors; many times the water-use time series contain both annual and weekly periodicities [19]. In order to identify the periodicity in the hydrologic time series, it is suggested in the literature that the time scale should be less than a year, e.g. monthly or seasonal [38].

2.1.6. Persistence

Persistence in the hydrologic time series remains present when successive members of a time series are linked in some dependent manner [56]. Persistence can also be defined as a memory effect or the tendency by which magnitude of a hydrologic event remains dependent on the magnitude of its previous event(s); for example, the tendency for low rainfall to follow low rainfall and that for high rainfall to follow high rainfall. Consequently, persistence is considered identical to autocorrelation [49]. Persistence, for the first time, was described in a comprehensive manner in the studies on a reservoir design across the Nile River [25, 26]. At that time, the persistence was defined by a parameter known as 'Hurst's coefficient', having average value of approximately 0.73 for a time series with very large samples/dataset. Capodaglio and Moisello [8] suggested that its theoretical value is 0.5 for an independent Gaussian process to which hydrologic series are assimilated. When the theoretical and the observed values of Hurst's coefficient do not match each other, then it is known as 'Hurst's phenomenon'. Almost all the stochastic models proposed to represent hydrologic processes attempt to include the persistence. However, it is virtually impossible to identify any long-term persistence in the hydrologic time series with the time series records commonly available in hydrology [8].

2.1.7. Stochastic component

A time series model consists of a systematic pattern explained in terms of two components, i.e. trend and seasonality, and a stochastic component. The stochastic component is usually makes the pattern difficult to be identified. The systematic pattern is deterministic in nature, whereas the stochastic component accounts for the random error. In general, the stochastic component contains a dependent part that can be described by a p-order autoregressive (AR) and q-order moving average (MA) model abbreviated as ARMA(p,q), and an independent part that can only be described by some sort of probability distribution function. When $p = 0$, the ARMA(p,q) represents an MA(q) model, and when $q = 0$, it represents an AR(p) model.

3. CONCEPT OF SUSTAINABILITY

It is revealed from the literature that the concept of sustainable development was introduced, for the first time, by the *World Conservation Strategy*. Several researchers have attempted to define and develop methodologies for assessing the sustainability of water resources systems [3, 15, 27, 34, 35, 40, 47, 57, 58, 59, 61, 62].

Later on, the sustainability index (SI) was proposed to initially evaluate the performance of alternative policies from the perspective of water users and the environment[35].The SI can also be defined as a measure of a system's adaptive capacity to reduce its vulnerability. For example, if implementing a policy makes a system more sustainable then the SI will suggest that the system has larger adaptive capacity. Thus, the concept of SI described by [35] considered three performance criteria, i.e. reliability (R_y), resilience (R_e) and vulnerability (V_y) in order to evaluate and compare different water management policies. Afterwards, the SI has been utilized in many scientific studies by researchers [45, 51, 55]. In literature, the R-R-V based sustainability concept is mainly used to evaluate performance of the water resources systems [2, 29, 35, 55]. It is also revealed from the literature that the sustainability concept has not applied for any other purpose except to evaluate performance of water resources systems, e.g. to assess sustainability of the storage reservoirs.

3.1. Sustainability of Water Resources Systems

Before defining sustainability of the water resources systems, few important issues need to be considered. Loucks[36] identified the most important issues as change, scale, technology, risk and training. The first four issues are said to be of direct importance to methodologies for assessing sustainability and, the same are discussed in this section.

3.1.1. Change

In nature, stationarity seldom occurs in most of the hydrologic processes and environmental systems due to changing conditions over the course of time. It is well-known fact that the natural, economic, environmental and social subsystems are interrelated, and therefore, change in any of the system(s) will have an effect on the other system(s) and, this will have an effect on the entire system. In addition, the management objectives might change over time and simply guessing about the future may result in wrong predictions. In order to handle with such situations and to cope up with dynamic natural systems, adaptive management was introduced as a tool in natural resources management [36]. It is suggested that a method used for assessing sustainability should also be able to work within an adaptive management framework.

3.1.2. Scale

The sustainability should be assessed by considering the appropriate scale, over both time and space. When finalizing the temporal scale, both the planning horizon and the duration of the time steps used in the analysis need to be considered. One of the key elements of the sustainability is need of future or predicted events (water supply), however there is no guideline as to how many future events should be considered for the analysis. The appropriate duration of time steps may be decided by taking into account the variability of the water supply systems. The extreme events, such as occurrence of droughts and floods, are naturally occurring in the water cycle, but they can temporarily put at risk the efforts to achieve sustainable development [32]. Therefore, the assessment of sustainability for the water resources system should adopt a time scale making the inclusion of possible extreme events. Loucks [35] suggested that the duration of the time steps used for the sustainability analysis should be such that natural variation in a resource, like water, is averaged out over the period. Thereafter, many researchers recommended various time lengths for the planning horizon and time steps [3, 24, 33, 35, 36, 40, 41, 43, 44, 52, 59].

3.1.3. Risk

There are external causes such as extreme events (floods and droughts) and degraded water quality, etc., which may result in failure of water resources systems completely. These influencing factors should be given careful due considerations while planning and designing of the water resource systems. In most developing countries, water resources systems are not dependable due to political and economic constraints, however a sustainable water resources system should definitely experience diminishing frequency and less severity of failures over time [36]. Conventionally, the water resources systems, e.g. reservoirs, were designed to have a high degree of reliability or low probability of failure. However, following the suggestions and recommendations of [18, 22], generous efforts have been devoted to the two additional risk criteria, i.e. resilience defined as likelihood of return to normal operation after a failure, and vulnerability explaining likely magnitude of failure. A sustainable system should have a high degree of resilience and low vulnerability [15].

3.1.4. Technology

Advent of sophisticated technologies along with advancement of computer-based modeling work resulted in rapid development of tools for sustainability assessment [23, 62]. One of the advanced developed modeling system tools for sustainability assessment is Decision Support Systems (DSS), which are supposed to assist the decision-makers in making informed decisions. It is well-understood fact that participation of the stakeholders is a key component in achieving success in the water resources management [63], and hence, the developed DSS should have relatively simple models with an easy to understand graphical user interface enhancing the user-friendly possibilities for achieving a useful shared-vision model set-up [36].

3.2. Sustainability Index for Hydrologic Time Series

The sustainability concept to evaluate performance of the hydrologic time series based on R-R-V approach is applied for the first time for rainfall time series [39]. The performance criteria, initially defined and applied to water resources systems, are slightly modified in order to apply them to assess the sustainability of hydrologic time series. The estimators of reliability, resilience, vulnerability and sustainability index along with their explanations are described ahead.

3.2.1. Reliability

Reliability of water demand in the water resources systems is defined as the probability at which the available water supply meets the water demand during the period of simulation [22, 31].For a hydrologic time series, the 'reliability' is expressed as ratio of the number of data in a satisfactory (successful) state to the total number of data in the time series. It is considered that the satisfactory state for a particular hydrologic variable will be such that its value in the entire time series x_n with n sample size remains equal to or greater than the mean threshold x^T, and then the reliability of the hydrologic time series can be expressed as [39]:

$$R_y = f_{SE}/n \quad (1)$$

Where, R_y = reliability; f_{SE} = number of successful events or satisfactory values in hydrologic time series (x_n), when $x_t \geq x^T$ (t=1, 2, … n); and n = sample size of time series.

3.2.2. Resilience

Resilience of a water resources system is defined as its capacity to adapt to changing conditions [64]. The 'resilience' of a hydrologic time series is described as the probability or the changes of occurrence that if value of a hydrologic variable in a time series is in an unsatisfactory (failure) state at any time, the next state will be satisfactory (successful). It may also be explained as the probability of having a satisfactory value or successful event in time period t-1, given an unsatisfactory value or failure event in any time period t. The resilience of the hydrologic time series can be expressed as shown below [39]:

$$R_e = f_{FE-SE}/f_{FE} \quad (2)$$

Where, R_e = resilience of time series; f_{FE-SE} = number of times a satisfactory value (successful event) follows an unsatisfactory value (failure event); and f_{FE} = number of times an unsatisfactory value occurs in the time series.

3.2.3. Vulnerability

The vulnerability is defined as the probable value of deficits, if they occur [22]. In other words, the vulnerability can be explained as a measure of the extent of the differences between the threshold value and the failure events among hydrologic data series. Thus, vulnerability is a probabilistic measure, which is also known as expected values, maximum observed values, and probability of exceedance to vulnerability measures. Considering an expected value measure of vulnerability is to be used, vulnerability of the hydrologic time series can be expressed as follows [39]:

$$V_y = \sum_{i=1}^{n} \text{difference}\left(x^T - x_t\right) \Big/ f_{FE} \quad \text{, for} \; t = 1, 2, \ldots n \tag{3}$$

Where, V_y = vulnerability of hydrologic time series; and $\sum_{i=1}^{n} \text{difference}\left(x^T - x_t\right)$ = sum of positive values of $(x^T - x_t)$.

3.2.4. Sustainability index

It is revealed from the literature review that sustainability index was originally developed by [35] in order to evaluate different water management policies by making quantitative measures of sustainability of water resources systems. The quantitative sustainability index facilitates comparison of the different water management policies. The sustainability index (SI) depends upon quantitative values of reliability, resilience and vulnerability, and is expressed by the following equation [35]:

$$SI = R_y \times R_e \times \left(1 - V_y\right) \tag{4}$$

Value of the SI range from 0 to 1, and it becomes zero if value of any of three performance parameters, i.e. reliability, resilience and vulnerability is zero.

4. APPLICATION OF SUSTAINABILITY CRITERIA IN HYDROLOGY

The sustainability criterion has rarely been applied to hydrologic studies as revealed from the extensive literature search. This clearly reflects that there is vast scope for applying the SI concept to several types of hydrologic time series. Definitely, the SI concept may emerge as effective tool to measure, evaluate and compare the sustainability of the hydrologic stations/sites with respect to different hydrologic variables.

In this section, a case study is presented demonstrating a comprehensive methodology for the evaluation of performance of the hydrologic stations based on rainfall time series in an arid region of India. The study was conducted in Kachchh district of Gujarat, India.

5. OVERVIEW OF STUDY AREA

Kachchh (study area), the second largest district of the country, is situated in Gujarat State and experiences hot and arid climate over the entire 100% occupied land [12, 21]. It encompasses an area of 45,612 km^2 and is situated from 22°44'08" to 24°41'30" north latitudes and 68°07'23" to 71°46'45" east longitude. The study area comes under sensitive seismic zones of the country with very high vulnerability of occurring earthquakes; one of the major earthquakes occurred in January 2001. Rainfall in the study area is highly erratic and unpredictable in nature. Scarcity of surface water resources is a common phenomenon in the study area and groundwater resources are mostly unusable due to deeper availability and considerably high salinity levels mainly due to coastal location.

6. METHODOLOGY

Annual rainfall data for a period of 34 years (1980-2013) of ten rain-gage sites (i.e. Naliya, Anjar, Bhachau, Bhuj, Gandhidham, Dayapar, Mandvi, Mundra, Nakhatrana and Rapar) were collected from Revenue Department, Gandhinagar, Gujarat, India. At Gandhidham, the rain gage was installed in the year 1998, and therefore, the data were available afterwards.

In this study, the sustainability concept was applied to annual rainfall time series of ten sites. The SI based on the reliability-resilience-vulnerability concept was computed for the rainfall time series of ten sites and then it was compared to each other in order to find the most sustainable rainfall series with respect to mean threshold rainfall value over the space. The vulnerability value of the rainfall time series was further divided by the mean threshold rainfall in order to make them range between 0 and 1. It is worth-mentioning that rainfall in a year was considered as success if the annual rainfall in that year exceeded the mean threshold rainfall value. On the other hand, a failure event indicated that the rainfall in a particular year did not exceed the mean threshold value.

7. RESULTS AND DISCUSSION

Values of reliability (R_y), resilience (R_e) and vulnerability (V_y) for rainfall time series of ten sites are shown in Fig. 1. It is revealed from this figure that value of R_y for annual rainfall time series of two rain-gage sites, i.e. Mundra and Mandvi is 0.50, which is relatively high compared with to that of other sites. On the other hand, the value of R_y for annual rainfall series of Bhachau and

Dayapar sites is the lowest ($R_y \leq 0.35$) among all sites. Whereas, the R_y may be considered as moderately low for the annual rainfall of five sites, i.e. Naliya, Anjar, Bhuj, Nakhatrana and Rapar.

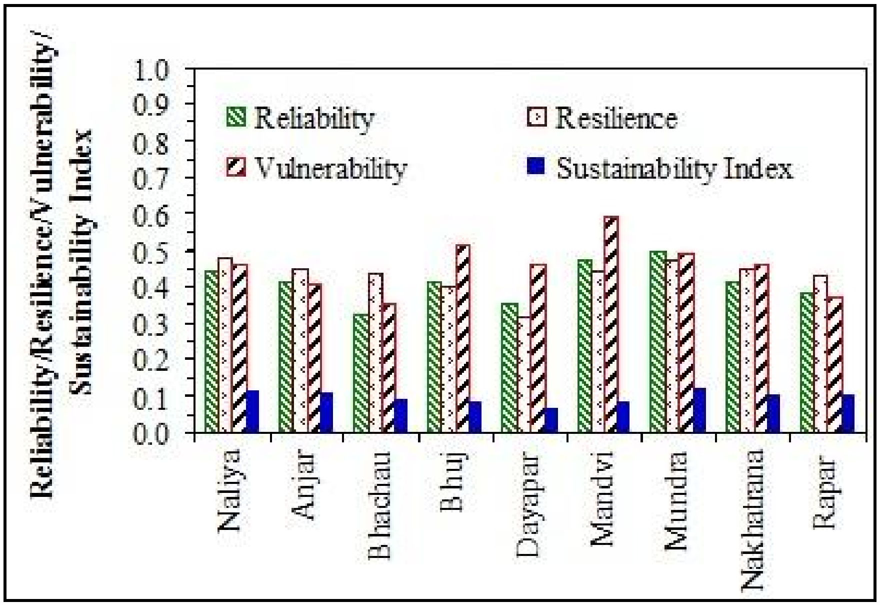

FIGURE 1 Reliability, resilience and vulnerability of annual rainfall time series for ten sites

It is seen from Fig. 1 that the value of R_e is the highest (0.47) for Naliya and Mundra sites, which indicates that the annual rainfall time series of these two sites is the most resilient for a period of 34 years. However, value of R_e=0.32 for Dayapar site renders it as the least resilient for the annual rainfall time series. The R_e values for the annual rainfall of the other sites is moderately low.

Furthermore, it is apparent from Fig. 1 that the value of V_y is the lowest for two rain-gage sites, i.e. Bhachau (V_y=0.36) and Rapar (V_y=0.37), which suggests that the annual rainfall of these two sites is less vulnerable among others. On the contrary, the annual rainfall of two stations, i.e. Mandvi (V_y=0.59) and Bhuj (V_y= 0.541) is the most vulnerable among other sites. A peculiar observation of the sustainability approach is the least vulnerability for annual rainfall series of Bhachau site (V_y=0.36), which has the least reliability (R_y=0.32) and moderate resilience (R_e=0.43). Likewise, the annual rainfall of Rapar rain-gage site is relatively less vulnerable (V_y=0.37) even with less reliability (R_y=0.38) and less resilience (R_e=0.43) of the annual rainfall time series. The site having the most dependable and sustainable rainfall time series is Mundra (R_y=0.50; R_e=0.47; V_y=0.49) followed by Naliya (R_y=0.44; R_e=0.47; V_y=0.46).

Moreover, two most sustainable rainfall time series as revealed from value of the SI are Mundra (SI=0.12) and Naliya (SI=0.112) (Fig. 1). The sustainability of annual rainfall time series decreases in the order of:

Mundra>Naliya>Anjar>Rapar>Nakhatrana>Bhachau>Mandvi>Bhuj>Dayapar.

The least three sustainable rain-gage sites are Mandvi, Bhuj and Dayapar, where conservation and management of rainwater should be among the top priorities for sustainable water resources management. Overall, it is understood the annual rainfall of the area is little less reliable, less resilient and moderately vulnerable, and there is an urgent need to manage the rainwater adequately to meet the water demands on sustainable basis in case of droughts or failure of monsoon.

8. CONCLUSIONS

In this study, sustainability concept based on reliability, resilience and vulnerability approach is applied to evaluate the performance of rainfall time series in an arid region of India. Based on integrated values of three performance indicator (i.e. R_y, R_e and V_y), the results indicated that the most sustainable and dependable annual rainfall time series is for Mundra (R_y=0.50; R_e=0.47; V_y=0.49) and Naliya (R_y=0.44; R_e=0.47; V_y=0.46). These results were further supported by the findings of the sustainability index (SI) whose values for annual rainfall series of Mundra (SI=0.12) and Naliya (SI=0.112) were observed to be the highest. Finally, the less reliable, less resilient and moderately vulnerable annual rainfall of the study area suggested necessity for adopting suitable management options on sustainable basis for conserving the rainwater to meet escalating water demands during drought years.

9. SUMMARY

Climate change has emerged as the single most-pressing problems globally. Analysis of spatial and temporal patterns of rainfall is important for detecting climate change or variability especially in arid and semi-arid regions where the abrupt changes in the rainfall are more likely to occur. In general, the spatio-temporal variability of a rainfall time series is determined by employing time series modeling techniques for detecting presence/absence of trends, testing normality, examining persistence, identifying change points, computing drought indices, etc. by employing statistical analysis/techniques. Thus, time series modeling offers a comprehensive tool to investigate rainfall variability by detecting all important characteristics of a time series. It is revealed from the extensive literature search that time series modeling has been widely used to explore variability of rainfall characteristics in humid and/or semi-arid regions. However, very few attempts have been

made to analyze rainfall of arid regions of the world, which may be likely due to relatively less occurrences and low magnitudes of rainfall events in arid regions.

The concept of sustainability was originally developed for evaluating performance of the water resources systems to policy changes. Thereafter, many performance criteria and indices to measure sustainability of the systems have been reported in the literature. Among those criteria and indices, sustainability index comprised of three performance indicators of reliability, resilience and vulnerability has been widely used and discussed in the past studies. It is learnt from the literature that the sustainability index has rarely been used for evaluating performance of the hydrologic time series.

This chapter aims at highlighting role of time series modeling in identifying vital characteristics of the hydrologic time series. Firstly, fundamental characteristics of both time series analysis and sustainability criteria are defined and/or described. Then, the chapter summarizes theoretical procedures for applying sustainability concept by explaining its historical development and recent applications in hydrology and water resources engineering. Thereafter, a case study is presented demonstrating a comprehensive methodology for analyzing the rainfall time series in an arid region of western India. This study introduces the sustainability approach, for the first time, to analyze a hydrologic time series, and demonstrates its novel applicability to rainfall time series of arid region.

KEYWORDS

Abrupt change
Anthropogenic activities
Arid region
Climate change
Drought Indices
Homogeneity
Humid region
Hurst’s coefficient
Hydrologic time series
Normality
Performance indicator
Periodicity

Persistence

Probabilistic measure

Rain-gage

Reliability

Resilience

Seasonality

Spatio-temporal variability

Stationarity

Step change

Stochastic component

Sustainability

Time series modeling

Trend

Vulnerability

Water resources systems

LIST OF ABBREVIATIONS IN THIS CHAPTER

AR	autoregressive
ARMA	Autoregressive moving average
DSS	Decision support system
MA	Moving average
Re	Resilience
Ry	Reliability
Vy	Vulnerability

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