

Addressing the Issues of Uncertainties in Change Point Detection of Hydrological Time Series in Runoff Alteration Studies

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ABSTRACT

Relying solely on step change techniques can lead to the wrong selection of the change point which makes uncertainty. In this study, an attempt has been made to assess the influence of change point selection on annual runoff and also suggested how to select a real change point in consideration of step change techniques and field proofs. This case study was conducted on the South Koel River Basin, Eastern India and subsequently, runoff data were obtained from the Ministry of Jal Shakti, Government of India during 1981-2018. The results of the Shapiro-Wilk test suggested that the annual runoff has a normal distribution. Here, three robust step-change techniques were applied namely, Buishand U Test, Buishand Range Test, and Standard Normal Homogeneity Test. The first two tests detected a change point in the year 2001 while the latter one detected in the year 2008. After the change points of 2001 and 2008 runoff decreased by 35.31 and 46.82%, respectively, from their reference periods. However, the dissimilarity in the results of step change techniques leads to the careful consideration of field proofs, even if the results of these tests were consistent. Field proofs indicated that a substantial portion of water has transferred from the South Koel River to the Subarnrekha River after the year 2008. This information proved that the step change occurred in the runoff after the year 2008. The findings of the study could aid the researchers in enhancing the reliability and acceptability of their runoff alteration studies.

Key words: Runoff change; Impact assessment; Ground proofs; Real change point

INTRODUCTION

Runoff is a significant indicator to assess our valuable water resource which is immensely vital to life and livelihood. This valuable water resource is under threat due to the simultaneous effect of climate change and human activities (Bao et al. 2022). Two types of alteration can be taken place in the runoff. One is a gradual change and the other is a step change. To assess the impact of climate change and human activities, researchers first detected a change point in the time series data of annual runoff then the whole study period was divided into two parts, before the change point which is called the reference period, and after the change point it is referred to as human interference period. Pettitt test (Zhang et al. 2021); moving t-test (Zheng et al. 2007); Mann-Kendall-Sneyers rank test (Li et al. 2007); Mann-Kendall rank statistic (Bao et al. 2012); Yamamoto method based on t-test (Zhang et al. 2011), ordered clustering analysis (Wang et al. 2009); Pettitt-Mann-Whitney test (Liu et al. 2010); precipitation-runoff double cumulative curve method (Jiang et al. 2011), sliding t test (Tan et al. 2022)

and sequential Mann-Kendall test (Dey and Mishra 2017) were used to detect step change in runoff alteration studies.

Researchers applied seven types of approaches to find out the exact role of climate change and human activities on the alteration of runoff. These were the hydrological modeling approach (Liang et al. 2013, Kang et al. 2022), scenario combination coupled with hydrological models (Li et al. 2009), conceptual approaches (Budyko framework and Tomer Schilling approaches) (Tomer and Schilling 2009, Wang and Hejazi 2011), analytical approaches (climate elasticity and hydrological sensitivity models) (Fu et al. 2007, Zuo et al. 2014), experimental approaches (paired catchment and time trend approaches) (Lee 1980, Zhao et al. 2009), empirical statistics (Saifullah et al. 2016) and machine learning (Kratzert et al. 2018).

The issue of runoff alteration in the context of climate change and human activities has been explored in different parts of the world. Li et al. (2007) studied Wuding River Basin in China and reported that the contribution rate of climate change was lesser (13%) than human activities

(87%) to reduce the annual runoff. Similar kind of findings was also reported in Central Rift Valley Basin, Ethiopia (70%), and Tapi River Basin, India (85%) by Seyoum et al. (2015) and Sharma et al. (2019), respectively. On the other hand, climate change played a dominant role in Central Spanish Pyrenees, Spain (70%) (Beguería et al. 2003), Heihe River Basin, China (95.8%) (Li et al. 2009) and Zhenjiangguan Watershed, China (83%) (Zhang et al. 2020) to decrease the annual runoff. Lyu et al. (2019) and Nkhoma et al. (2021) reported that both climate change and human activities enhanced the annual runoff in Xihe River Basin, China, and Wamkurumadzi Basin, Southern Africa, respectively. The bi-directional responses were also reported by Peng et al. (2013) and Zhang et al. (2018) where climate change increased the annual runoff and human activities decreased the annual runoff. However, these studies mainly focused on the evaluation of the extent to which climate change and human activities have impacted the runoff and the partitioning of the contribution rate to changes in the runoff based on the step change. The functional responses of runoff greatly vary from one basin to another basin depending on geophysical conditions like topography, climate, soil, human activities, and many other factors. Even basins having similar geophysical conditions produced different results. This unique response insisted to the basin-specific study.

However, the detection of step change is the main task of the researchers before going to the runoff alteration assessment. It is found that, in most cases, they heavily rely on only the results of step change techniques. Furthermore, several researchers incorporated only one step change technique in their studies. However, these available techniques are not the panacea to detect real change points. It only provides the expressions of probability, not certainty. It is the geographical knowledge with field proofs which until or unless substantiated by the outcome of the statistical analysis, the results of change detection cannot be justified. Moreover, different methods identified different change points for the same data series, so it is very much needed to apply more than one change point detection technique so that one test result is used to substantiate the other (Kundzewicz and Robson 2004). The main objective of the study is to assess the influence of change point selection on the study of runoff alteration under changing climate conditions and human activities. Also, an attempt has been made how to find out the real change point so

that the ultimate decision-making becomes subjective depending upon the geographical conditions of the basin.

STUDY AREA

The South Koel River basin has been taken as a case study area to solve the present objectives because the past couple of decades the climatic conditions and the basin's surficial features through human activities have changed. Tirkey et al. (2018) found that the basin is gradually experiencing by warming effect and rainfall is likely to be decreasing which is thought to have an adverse impact on stream flow and water resources. They also reported that the destruction of the forest to create new agricultural fields is the old tradition of this basin while on the other hand, lack of water resources, some agricultural fields are turning into fallow and barren lands. However, the South Koel River basin was demarcated based on the most downstream gauged station i.e., Jarikela (approx. 22°19'N and 85°5'E). It has an aerial coverage of 10356.3 Km² and maximum portion of the basin lies in the state of Jharkhand. The elevation ranges from 198-1089 m with a mean elevation of 643.5 m. The mean annual rainfall is 1442.53 mm, about 82% of which occurs in the monsoon season (CWC 2014). As of 2005-06, agriculture and forest are the two dominant land use land cover classes occupying 52.04% and 34.37% of the total basin area, respectively (CWC 2014).

MATERIALS AND METHODS

Daily runoff (also called discharge) data was collected from the Department of water resources, RD & GR, Ministry of Jal Shakti, Govt. of India (<https://indiawris.gov.in/wris/#/>) from 1981 to 2018 for the Jarikela station which was the most downstream station of the South Koel River basin (Fig. 1). The methods were discussed in the following section.

Normality check

It is necessary to check the normality of the runoff datasets to make a decision about which techniques are suitable for step change analysis. If the datasets are found to be normal then the Buishand U test, Buishand range test, and standard normal homogeneity test can be used other than the Pettitt test and the sequential Mann-Kendall test can be incorporated into the study.

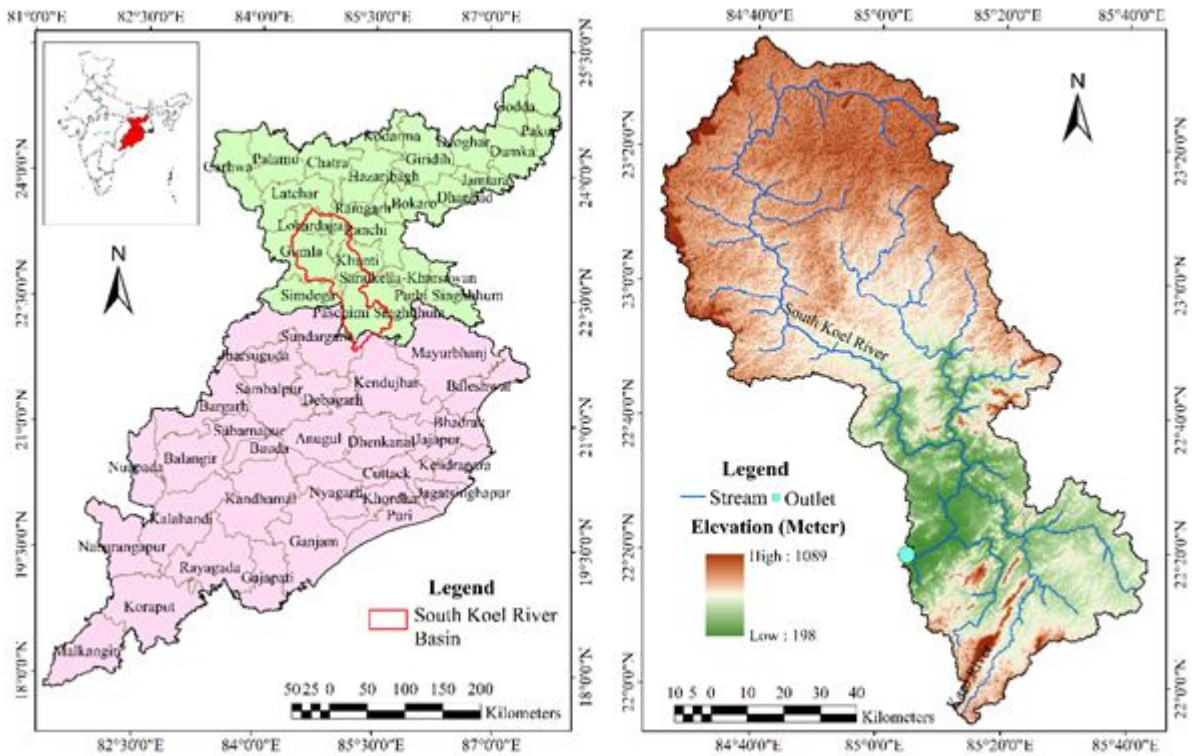


Figure 1. Location of the study area

However, in this study, Shapiro-Wilk Test was used for checking the normality of the annual runoff using SPSS v.17.0.

Shapiro-Wilk test

The Shapiro-Wilk (SW) test is a statistical method used to assess whether sample data follows a normal distribution or not. It was generally used when the sample size is less than 50, although it is also being used for large sample datasets with equal importance (Mishra et al. 2019). In the study, if the p-value is less than or equal to 0.05, the null hypothesis is rejected, indicating that the data does not fit a normal distribution. The test statistic, W, reflects the difference between the observed frequency distribution and the expected normal distribution. To calculate W, the data is first sorted in ascending order, and the coefficients a_i are taken from a table. The p-value is then calculated using a linear ratio based on the W statistic, following the original method proposed by Shapiro & Wilk (1965).

$$W = \frac{(\sum_{i=1}^n a_i x_{(i)})^2}{\sum_{i=1}^n (x_i - \bar{x})^2} \dots \dots \dots (1)$$

Step change techniques

In this study, the Buishand U test, the Buishand range test, and the standard normal homogeneity test were used

because runoff data sets were found to have a normal distribution. These tests were performed using R statistical software v 1.2.5042.

Buishand U test

The Buishand test is a parametric statistical method given by Buishand (1981, 1982, 1984) to detect the specific year in which the mean of an annual time series shifts. The adjusted partial sum was used to detect breaks in the middle of a time series and it was calculated based on the mean value of \bar{Y} of the series Y_1, \dots, Y_n (Buishand 1982, Hänsel et al. 2016).

$$S_0^* = 0, \text{ and } S_k^* = \sum_{i=1}^k (Y_i - \bar{Y}), k = 1, \dots, n \dots (2)$$

The term “summation” (for $i = 1, 2, \dots, k$) refers to the process of calculating the cumulative sum of a variable S_k^* . When $k = n, S_n^* = 0$, then variable S_k^* is applied to a homogeneous series with no consistent pattern in the deviations of the series components from their mean, the variable will tend to fluctuate around zero. However, if there is a break in the series at a particular year (K), the variable will reach either a maximum (if there is a negative shift) or a minimum (if there is a positive shift) near that year (Yozgatligil and Yazici 2016). To test for statistical significance, Buishand (1982) developed three test statistics.

$$Q = \max_{0 \leq k \leq n} \left| \frac{S_k^*}{D_Y} \right|; \dots\dots\dots (3)$$

$$R = \left[\max_{0 \leq k \leq n} S_k^* - \min_{0 \leq k \leq n} S_k^* \right] / D_Y \dots\dots\dots (4)$$

$$U = \frac{1}{n(n+1)} \sum_{k=1}^{n-1} \left(\frac{S_k^*}{D_Y} \right)^2 \dots\dots\dots (5)$$

The variable has been standardized by dividing it by its standard deviation of the series. Three test statistics have been calculated using this standardization: Q-statistic, which is the maximum value of “rescaled adjusted partial sum”; R-statistic, which is the “rescaled adjusted range”; and U-statistic, which is based on Gardner’s original formulation assuming that the variance is known (Pérez et al. 2011). If the variance is unknown, the sample variance can be used to calculate the U-statistic (Buishand 1982). The series has a break at time k where the Q-statistic is observed. The null hypothesis (H0) assumes that the series is homogeneous, while the alternative hypothesis (H1) suggests that there is a break in the series.

Buishand range test

The Buishand range test is a parametric statistical method also given by Buishand (1981, 1982, 1984) to identify a change point of a normally distributed variable. The test involves calculating rescaled adjusted partial sums using Eq. 2, and defining the test statistic as using Eq. 4. To determine the p-value of , a Monte Carlo simulation method is used with m replicates. The critical values are determined based on m=19999 Monte Carlo simulations, as provided in the table by Buishand (1982).

Standard normal homogeneity test

This is a parametric statistical test developed by Alexandersson (1986) to identify a single change point in the time series data. The test relies on two assumptions: first, that the data follows a normal distribution, and second, that there is only one change point that results in a shift in the mean level. The null hypothesis (H0) assumes that a series has a homogenous distribution with a mean of zero and unit standard deviation. On the other hand, the alternative hypothesis (H1) suggests that there is only one break at some point in time (year) between the first and last observation (k must be between 1 and n i.e., 1d”k<n). According to Alexandersson (1986), if there is indeed a single break in the series, the mean of the

series before the break (i_1) is not the same as the mean of the series after the break (i_2), i.e., i_1 ““ i_2.

If you have a set of annual observations (for) with a mean of and a standard deviation of , then the test statistic for evaluating the null hypothesis can be calculated using.

$$T_0 = \max_{1 \leq k \leq n} \{T_k\} \dots\dots\dots (6)$$

$$T_k = k\bar{z}_1^2 + (n - k)\bar{z}_2^2, \text{ for } k = 1, 2 \dots n \dots\dots\dots (7)$$

$$\bar{z}_1 = \frac{1}{k} \sum_{i=1}^k \left(\frac{X_i - \bar{X}}{s_X} \right) \text{ and } \bar{z}_2 = \frac{1}{n-k} \sum_{i=k+1}^n \left(\frac{X_i - \bar{X}}{s_X} \right) \dots\dots (8)$$

The symbol used in the formula to create the variables and represents the sum of all values in a sequence, where k ranges from 1 to n (for). If the value of (the test statistic) is greater than the critical value, then the null hypothesis is rejected. The critical values for different sample sizes ranging from 10 to 5000 were given by Khaliq and Ouarda (2007).

RESULTS AND DISCUSSION

Normality check

The results of the Shapiro-Wilk test suggested that the annual runoff of the basin follows a normal distribution at a 95% confidence level () because it is influenced by several factors that are known to follow a normal distribution (Table 1). The amount of rainfall, which is the primary driver of runoff in the basin, is known to follow a normal distribution. Other factors such as soil properties, topography, and land use also affect runoff to follow a normal distribution.

Step change detection

In the present study, three robust step change techniques were applied, and found that all the tests detected significant change points at a 95% confidence level () but the change point was not consistent with each other. Buishand U test and Buishand Range Test both detected a significant change point in the year 2001 while Standard

Table 1. Results of the normality test

Variable	Shapiro-Wilk		
	Statistics	p-Value	Remarks
Annual runoff	0.984	0.851	Normal
Annual rainfall	0.975	0.532	Normal

* Lower bound of the true significance

^a Lilliefors significance correction

Table 2. Results of step change analysis for normal distribution of runoff data

Variable	Buishand U test			Buishand range test			Standard normal homogeneity test			Remarks
	U	p-value	Change point	R/sqrt (n)	p-value	Change point	T	p-value	Change point	
Annual runoff	0.855	0.003	2001	1.747	0.009	2001	12.58	0.004	2008	Significant

Normal Homogeneity Test suggested that the significant step change point occurred in the time series data in the year 2008 (Table 2). The variation in the change point was due to the variation in the calculation algorithms of the tests. It can be mentioned that it is generally recommended to use more than one test in change detection in order to avoid the possibility of detecting any disguised breakpoint into the series (Kundzewicz and Robson 2004). However, the ultimate change point depends on the actual situation of the concerned area.

Change point and runoff alteration

Based on the detected change point, the whole study period (1981-2018) was divided into a reference period and an interference period. Before the change point, it is called the reference period and after the change point, it is called the interference period. If we consider the change point 2001 then the reference period would be 1981-2001 and the interference period would be 2002-2018. Similarly, if we take 2008 then the reference period would be 1981-2008, and the interference period would be 2009-2018. The results suggested that the mean annual runoff in the reference period (1981-2001) of the change point 2001 was 466.58 mm and it was reduced to 301.85 mm in the interference period (2002-2018). The mean annual runoff was decreased by 35.31% from the reference period. On the other hand, the mean annual runoff was also reduced to 238.30 mm in the interference period (1981-2008) from 448.09 mm in the reference period (2009-2018) based on the change point in 2008. The mean annual runoff was reduced by 46.82% from the reference period (Table 3). Therefore, two change points produced different influences on the mean annual

runoff due to the different reference and interference periods. This will lead to uncertainty in the results if we did not fix the problem of the real change point before the impact assessment.

Selection of real change point

Now the question is which change point will be selected for assessing the impact of climate change and human activities on runoff alteration. These tests provided merely the evidence, not the proof. That's why to overcome this problem field proofs are very much needed, even though the change points for all three cases were found to be consistent with each other. Not only that, we have to check the discrepancies in the dataset before collecting field proofs. In the present study, field proofs were collected, and found that two Inter-Linking rivers (ILR) projects were successfully completed after 2008. The South-Koel-Sunarnarekha ILR project transferred a huge amount of water (1684 MCM) to the Subarrekha River which was 68.24% of the mean annual runoff of the interference period during 2009-2018. Sinha (2017) also mentioned these ILR projects which were constructed for irrigation, domestic and electricity purposes. Therefore, the field proofs suggested that the change point occurred in the year 2008, not in 2001 (Fig. 2).

CONCLUSIONS

Scientists and researchers are accustomed to using statistical tools and techniques to detect change points in hydrological time series (such as runoff) but the application of these techniques is not giving the certainty

Table 3. Influence of step change on runoff alteration

Reference period	Interference period	Runoff in reference period	Runoff in interference period	Change (Reduced)	Change (%)
1981-2001	2002-2018	466.58 mm	301.85 mm	164.73 mm	35.31
1981-2008	2009-2018	448.09 mm	238.30 mm	209.79 mm	46.82

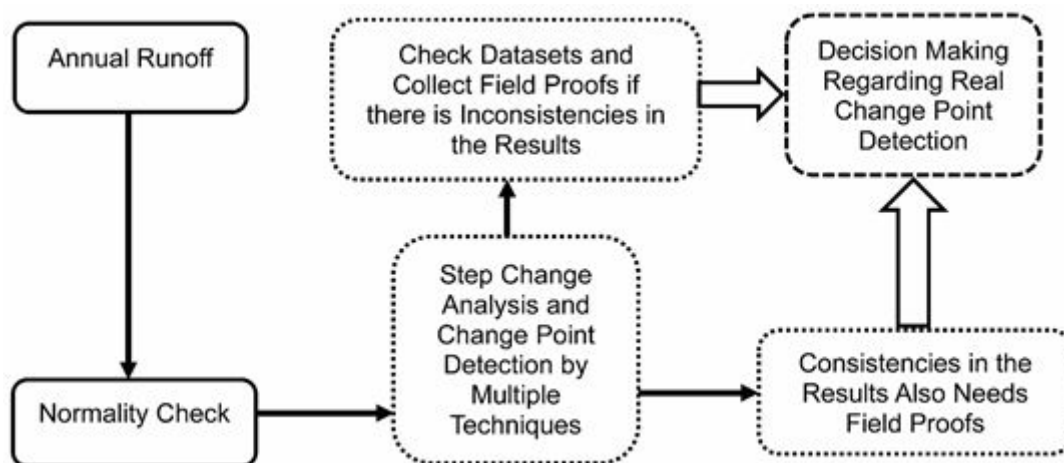


Figure 2. Methodology of selecting real change point

of the results. That's why field proofs are very much needed to accurately detect the change points, otherwise, there is a chance of uncertainty in the impact assessment results. It is always preferred to use more than one-step change techniques. But several researchers were confined to using only one change detection technique. However, the ultimate success of the investigation depends on intuition, logical thinking, and the experience of the researchers. The findings of the results will be helpful to enhance the acceptability and reliability of the runoff alteration studies which will assist the policymakers to take more rational decisions in a sustainable way.

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Authors' contributions: Senior author (RKP) conceptualized the work, finalized the methodology, supervised the drafting, reviewing and finalizing the manuscript. The second author (SM) reviewed the state of knowledge, conducted the analysis and wrote, edited the original manuscript.

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