

Methods

1.1 Trend Analysis

The details on the trend analysis method along with corresponding mathematical equations are presented here.

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & \text{for } S > 0 \\ 0 & \text{for } S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & \text{for } S < 0 \end{cases} \quad (1)$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (2)$$

$$\text{sgn}(x_j - x_i) = \begin{cases} 1 & \text{for } (x_j - x_i) > 0 \\ 0 & \text{for } (x_j - x_i) = 0 \\ -1 & \text{for } (x_j - x_i) < 0 \end{cases} \quad (3)$$

$$V(S) = \frac{1}{18} \left[n(n-1)(2n+5) - \sum_{p=1}^q t_p(t_p-1)(2t_p+5) \right] \quad (4)$$

Where q represents total number of tied groups. A set of same values in a dataset is referred as a tied group. Each tied group is denoted by t_p . The positive values of Z indicate upward (increasing) trends in time series, and the negative values show downward (decreasing) trends. Trends are then tested against some critical values ($Z_{1-\alpha}$) to show that either they are statistically significant or not. For example, if $|Z| > Z_{1-\alpha}$, (e.g., $Z_{1-\alpha}$ at $\alpha = 0.05$); the null hypothesis of no-trend is rejected, and alternative hypothesis of significant trend is accepted.

Sen's slope (SS) is calculated as below:

$$SS = \text{median} \left[\frac{x_j - x_i}{j - i} \right] \quad \text{for all } i < j \quad (5)$$

Where x_i is the value of data at time step i and x_j at time step j .

1.2 Change point detection for flood time series

Pettitt's test

Pettitt's test (Pettitt 1979) is a nonparametric way to identify the occurrence of a change point in time series data. It has been commonly used to detect changes in hydrological and meteorological time series data. It is rank-based and distribution-free test for detecting an abrupt change when the exact time of the change is unknown for a data series. The Pettitt test can be mathematically described as follows,

$$U_{t,n} = \sum_{j=1}^t \sum_{i=1}^n \text{sgn}(x_j - x_i), \quad (t = 1, \dots, n), \quad (1)$$

Where the $U_{t,n}$ represents the change point year. It was used to detect the change point year in the time series of different flood indicators to study the flood regime in the KRB, Pakistan.

Buishand's Range Test (Buishand 1982)

The adjusted partial sum (S_k), that is the cumulative deviation from mean for k^{th} observation of a series $x_1, x_2, x_3 \dots x_k \dots x_n$ with mean (\bar{x}) can be computed using following equation:

$$S_k = \sum_{i=1}^k (x_i - \bar{x}) \quad (2)$$

A series may be homogeneous without any change point if $S_k \approx 0$, because in random series, the deviation from mean will be distributed on both sides of the mean of the series. The significance of shift can be evaluated by computing rescaled adjusted range (R) using the following equation:

$$R = \frac{\text{Max}(S_k) - \text{Min}(S_k)}{\bar{x}} \quad (3)$$

The computed value of R/\sqrt{n} is compared with critical values given by (Buishand 1982, Wijngaard, Klein Tank et al. 2003) has been used for detection of possible change .

Standard Normal Homogeneity (SNH) Test

The test statistic (T_k) is used to compare the mean of first n observations with the mean of the remaining $(n-k)$ observations with n data points (Štěpánek, Zahradníček et al. 2009, Vezzoli, Pecora et al. 2012).

$$T_k = KZ_1^2 + (n - k)Z_2^2 \quad (4)$$

Z_1 and Z_2 can be computed as:

$$Z_1 = \frac{1}{K} \sum_{i=1}^K \frac{(x_i - \bar{x})}{\sigma_x} \quad (5)$$

$$Z_2 = \frac{1}{n-K} \sum_{i=K+1}^n \frac{(x_i - \bar{x})}{\sigma_x} \quad (6)$$

where, \bar{x} and σ_x are the mean and standard deviation of the series. The year k can be considered as change point and consist a break where the value of T_k attains the maximum value. To reject the null hypothesis, the test statistic should be greater than the critical value, which depends on the sample size (n) given in Table S3

Tables

Table S1. Basic characteristics of soil data in the KRB, Pakistan.

Symbol	HWSD-Soil Group	Texture	Top Soil Texture Class			
			%sand	%Silt	%clay	%Gravel
I	Lithosols	Medium	43	34	23	26
Be	Cambisols	Medium	42	36	22	9
Xh	Haplic Xerosols	Medium	39	40	21	4
GG	Gleysols	Medium	0	0	0	0

Table S2. Description of land use re-classes and original classes.

Re-Classes	Original Classes
Forest	Tree cover, broadleaved, evergreen, closed to open (>15%)
	Tree cover, broadleaved, deciduous, closed to open (>15%), Tree or shrub cover, Tree cover, broadleaved, deciduous, closed (>40%)
	Tree cover, broadleaved, deciduous, open (15-40%)
	Tree cover, needle leaved, evergreen, closed to open (>15%)
	Tree cover, needle leaved, evergreen, closed (>40%)
	Tree cover, needle leaved, evergreen, open (15-40%)
	Tree cover, needle leaved, deciduous, closed to open (>15%)
	Tree cover, needle leaved, deciduous, closed (>40%)
	Tree cover, needle leaved, deciduous, open (15-40%)
	Tree cover, mixed leaf type (broadleaved and needle leaved)
Urban Areas	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)
	Sparse tree (<15%), 160 Tree cover, flooded, fresh or brackish water
Grassland	Tree cover, flooded, saline water
	Urban areas
	Herbaceous cover, Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%), Mosaic herbaceous cover (>50%) / tree and shrub (<50%), Shrub land, Evergreen shrub land, Deciduous shrub land, Grassland,
	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)
Agriculture	Sparse shrub (<15%), Sparse herbaceous cover (<15%)
	Shrub or herbaceous cover, flooded, fresh/saline/brackish water
	Cropland, rain fed, Cropland, irrigated or post-flooding
Water Body	Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)
Snow Cover	Water bodies
Bare Areas	Permanent snow and ice
	Bare areas, Consolidated bare areas, Unconsolidated bare areas

Table S3. Critical values of test statistics for different change point detection tests.

Number of observation	Critical values for test statistic at different significance level					
	Pettit Test		SNHT		Buishand Range test (R/\sqrt{n})	
	1%	5%	1%	5%	1%	5%
20	71	57	9.56	6.95	1.6	1.43
30	133	107	10.45	7.65	1.7	1.5
40	208	167	11.01	8.1	1.74	1.53
50	293	235	11.38	8.45	1.78	1.55
70	488	393	11.89	8.8	1.81	1.59
100	841	677	12.32	9.15	1.86	1.62

Results

Table S4. Optimized parameters for HEC-HMS model (6-hourly scale).

Parameters	Sub-basin/Reach	Lower Bound	Upper Bound
Initial abstraction(mm)	19 sub-basins	9.27	13.95
Lag time(minutes)	19 sub-basins	35.64	3341.6
Initial discharge ($m^3 sec^{-1}$)	19 sub-basins	80	80
Recession constant	19 sub-basins	0.65	0.8
Ratio to peak	19 sub-basins	0.38	0.43
Muskingum K	9 Reaches	0.11	13.7
Muskingum X	9 Reaches	0.25	0.46

