

Hydrologic response characteristics of a tropical catchment to land use changes: a case study of The Nerus catchment

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Abstract Hydrologic response of a catchment with the most common expression through runoff coefficient reflects a complex response of interaction between the rainfall and catchment physical properties. In this study, an attempt has been made through the mean rainfall–runoff polygon method to explore the impact of land use change on the mean monthly runoff coefficient estimated from 27 years of the hydrology and land use records of a tropical catchment located in the east coast of Peninsular Malaysia. Specifically, the land use and flow records are divided into three intervals: (1982–1990), (1992–2000) and (2002–2010). The mean monthly rainfall–runoff polygon plotted is rendered to the three time intervals. The results have shown that contrasting shapes were computed which demonstrate the significant variability in the rainfall–runoff response characteristics under the linkage of land use changes. Ample information describing the hydrological responses of the study area has been attained through the quantitative approaches. The study has concluded that the rainfall–runoff polygon method can be used as a simple alternative method for assessing the impact of land use changes on the hydrological response.

Keywords Rainfall–runoff polygon · Mean monthly runoff coefficient · Hydrological response · Land use changes · Tropical catchment

Introduction

Since 1980, there has been an extensive alteration of land use in the Nerus catchment area predominantly for agricultural activities affecting the natural hydrological components, such as surface runoff. In a hydrological study, surface runoff is a part of hydrological components generated from a complex relationship between the rainfall, runoff, climatic disparity and land use pattern. In fact, land use changes act as a key in controlling the hydrological response (Li et al. 2007; Fohrer et al. 2001) in many ways, at all watersheds under different climates (Siriwardena et al. 2006; Costa et al. 2003; Niehoff et al. 2002). The characteristic of the surface runoff over the entire catchment is a popular hydrological component to measure the impact of land use changes (Tran and O’Neill 2013; Couto and Vega 2007; Shi et al. 2002). In hydrological studies, the rainfall that appears as runoff on the surface of the catchment is known as the runoff coefficient (Linsley et al. 1975). Over the decade, the runoff coefficient is one of the most significant and fundamental hydrological terms of the rainfall–runoff non-linear relationship and acts as an important role in the designing of engineering such as reservoirs (dams), culverts, groundwater recharge estimation and flood control assessment used runoff coefficient as the significant input variables (MASMA, DID, Malaysia 2000). The runoff coefficient value, C , is the expression derived from the response of the factors affecting the relationship of the peak flow to the average rainfall intensity together with the area and response time (Ven te Chow et al. 1988). There are many studies on the determination of the runoff coefficient especially to improve the peak discharge estimation or particularly in the Rational Method and Soil Conservation Services-Curve Number (SCS-CN 1986). The runoff coefficient in water resources design

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study simply uses the C 's taken from tables based on a set of drainage features which contain the list of possible values depending on the characteristics of the area of study (Maidment 1993). Among the factors are the moisture condition of soils, rainfall intensity and duration, degree of soil compaction, vegetation, etc. Blume et al. (2007) have studied the event runoff coefficient to investigate the rainfall–runoff response with a relatively short observation period and compared it with different climates and catchments using different base flow separation methods. Norbiato et al. (2009) investigate the variability of runoff coefficients depending on the climate, geology, land use, flood types and initial soil moisture for 14 mountainous catchments in the eastern Italian Alps using hourly rainfall, runoff and snowmelt data. Merz and Blöschl (2009) have analysed the event runoff coefficients with respect to the spatial temporal variability in 459 Austrian catchments and found that, antecedent soil moisture conditions strongly control the runoff coefficient than does the event rainfall. Sen (2008) develops a simple rainfall–runoff model using an infinitesimal runoff coefficient (IRC) which considers the instantaneous change of runoff with respect to the rainfall during a storm. Recently, Al-Hasan and Mattar (2013) study the relationships between measured and estimated runoff coefficients and some geomorphological characteristics of studied catchments in Saudi Arabia using the linear regression relation. The hydrological effects of land use change can potentially occur at all spatial scales, and studies on this effect will provide valuable information with regard to socio-economic and environmental protection. Several studies have explored the relationship of the land use impact to hydrological characteristics in their own methodology. In fact, many researchers have used different methods to assess the impact of land use on hydrological properties. Carlson and Arthur (2000) illustrate the impact of land use changes due to urbanization at Chester County, Philadelphia under the satellite imagery perspective. They analysed satellite imageries within the 1986–1996 period to extract all the parameters affected by land use changes. Sullivan et al. (2004) reveal that the land use changes influence the river flow regime and its flood response study conducted at an agricultural catchment in Southwest England.

The use of GIS-linkage software gives a better understanding in providing risk assessment on different scenarios of land use. Fohrer et al. (2005) have used IOSWAT and SWAT-G which consist of various pre- and post-processing tools to provide a risk map with regard to hydrological impact that is able to predict the annual trends of the water balance component at all different scenarios of land use. Bi et al. (2009) have also studied the effects of precipitation associated with land use on the runoff pattern using lengthy 50-year records in the Loess Plateau watershed, China showing that the forestation reduced the runoff each year. Another study using the Soil and Water Assessment Tools

(SWAT) model at the same catchment also reveals that land use changes and climate variability do influence the hydrological cycle in Loess Plateau (Li et al. 2009). Nejadhashemi et al. (2011) use SWAT to evaluate the impact of land use changes on the hydrological fluxes in the agricultural regions in Michigan and Wisconsin based on three spatial scales: sub-basin-level, watershed level and basin level. Indeed, the forest cover plays as an important factor controlling water yield quantity in the Western Ghats of peninsular India (Singh and Mishra 2012). Recently, Zokaib and Naser (2012) elucidate the rainfall, runoff and soil loss relationship under different land use characteristics in the Hilkot watershed, Pakistan. Studies conducted by Wijesekara et al. (2012) have successfully assessed the future land use impact on hydrological processes using a combination of land use-cellular automata (CA) model, and the distributed physically based MIKE-SHE/MIKE-11 hydrological model has been done in the Elbow river watershed of southern Alberta, Canada.

Kadioglu and Sen (2001) were the first who studied the rainfall–runoff polygon to determine the mean runoff coefficient of monthly data available at selected catchments around the city of Istanbul, Turkey. Sen and Altunkaynak (2006) specifically evaluate and narrow down the qualitative and quantitative aspects of the method through a comparative analysis. The rainfall–runoff polygon method is capable of dealing with different seasonalities and this is interpreted in a single matrix diagram (Ali et al. 2013). However, no study has described the enlightening assessment related to the use of the rainfall–runoff polygon method in evaluating the land use changes impact on hydrologic response characteristics. Thus, the main objective of this study is to evaluate the impacts of land use change on the characteristics of the hydrologic response by extending the application of the rainfall–runoff polygon method for a tropical catchment environment.

Methodology

Study area

As shown in Fig. 1 above, the site selected for this study was the Nerus catchment, which is located in the tributaries of Terengganu river basin. It is the largest catchment in Terengganu river basin with an area of 350.49 km². In general, Nerus catchment is characterized by a low-lying slope over the area (mostly at the Eastern part) with a high degree of slope located at the West of the catchment. General watershed characteristics are represented in Table 1. The long formation of the stream length (92.85 km) and large area produces the large amount of surface runoff. Both the Gravelius index and Shape index

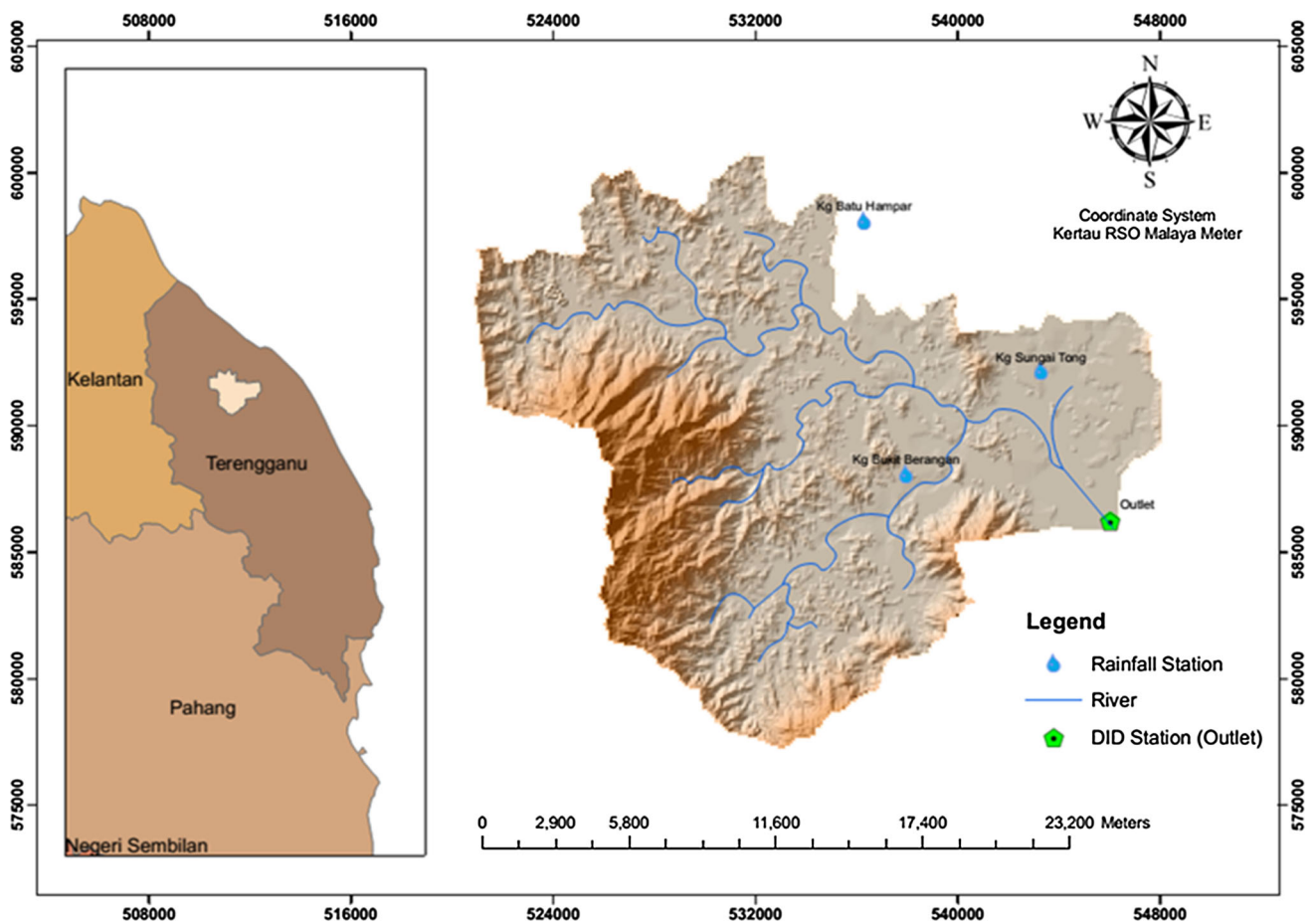


Fig. 1 Study area

Table 1 General watershed characteristics of the Nerus catchment

| Description | |
|-----------------------------------|---------|
| Catchment area (km ²) | 350.49 |
| Perimeter (km) | 102.38 |
| Stream length (km) | 92.85 |
| Minimum catchment altitude (m) | 20 |
| Maximum catchment altitude (m) | 1209.83 |
| Gravelius index | 1.54 |
| Shape factor | 0.32 |
| Strahler's catchment order | 4 |

of this catchment show that it tends to be circular and consists of many branches of river on the entire area, whereby the higher the time of concentration, the more water will infiltrate and evaporate or be utilized by the vegetation. The Nerus catchment has Strahler's catchment order of four, with most of its river branches originally created from the hilly area (West part of the catchment).

Data availability

Recorded daily runoff time series data of Nerus River at the Drainage and Irrigation Department (DID) Station (5224369) are used in the study. At the same time, recorded daily time series of rainfall data representing three DID stations were also obtained, namely from the DID Station 5428001 (Kg Batu Hampar), DID Station 5328044 (Kg Sungai Tong) and DID Station 5328043 (Kg Bukit Berangan). All the runoff and rainfall stations are operated by the Department of Irrigation and Drainage (DID) Malaysia. The data consist of the daily time series observations from the year 1982 to 2010. A land use map provided in this study is obtained from the Department of Agriculture, which covers the different patterns of land use for the period of 1982–1990, 1992–2000 and 2002–2010.

Areal precipitation method and baseflow separation

Daily rainfall data obtained from all stations were computed as the averages of daily rainfall values using the

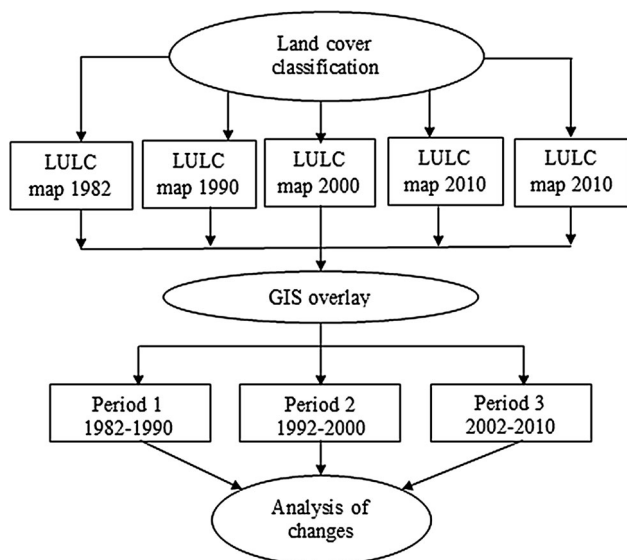


Fig. 2 Steps in land use changes analysis

Thiessen polygon method. In this study, the recursive digital filter method Eckhardt (2005) using the Web-based Hydrograph Analysis Tool (WHAT) system developed by Lim et al. (2005) is applied to separate the baseflow from the daily streamflow. The recursive digital filter method baseflow separation technique proposed by Eckhardt is expressed as follows:

$$b_t = \frac{(1 - BFI_{\max}) \times \alpha + b_{t-1} + (1 - \alpha) \times BFI_{\max} \times Q_t}{1 - \alpha \times BFI_{\max}}$$

where b_t is the filtered base flow at the t time step; b_{t-1} is the filtered base flow at the $t - 1$ time step; BFI_{\max} is the maximum value of long-term ratio of base flow to total streamflow; α is the filter parameter; and Q_t is the total streamflow at the t time step.

Land use changes analysis

The Geographic Information System (GIS) is used as a computational platform to analyse the land use map for the years of 1984–2010. Based on the review of literature (Chen et al. 2009; Wu and Zhang 2012) and general survey based on Department of Agriculture (DOA) databases, classification of land use is determined into six categories of land covers within the study area. These land covers are agriculture, bare land, forest, shrub, residential and mining. Figure 2 show the steps used in land use changes analysis. Land use changes are identified based on the transition matrix method (Xiao et al. 2006; Bernetti and Marrinelli 2010).

Mean rainfall–runoff polygon

- (a) Polygonal diagrams are built by plotting the mean monthly rainfall and the surface runoff as a

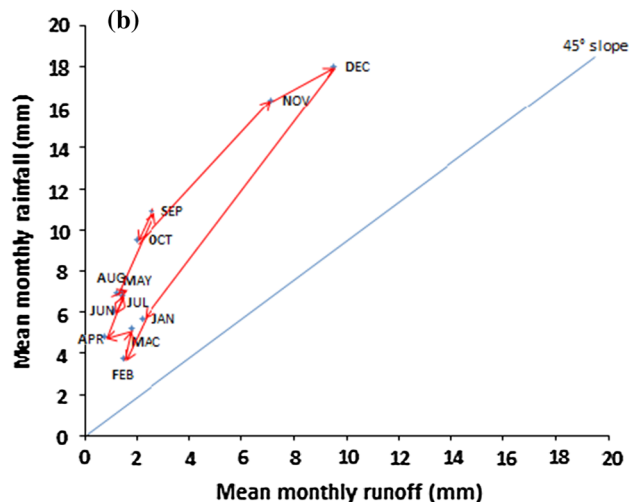
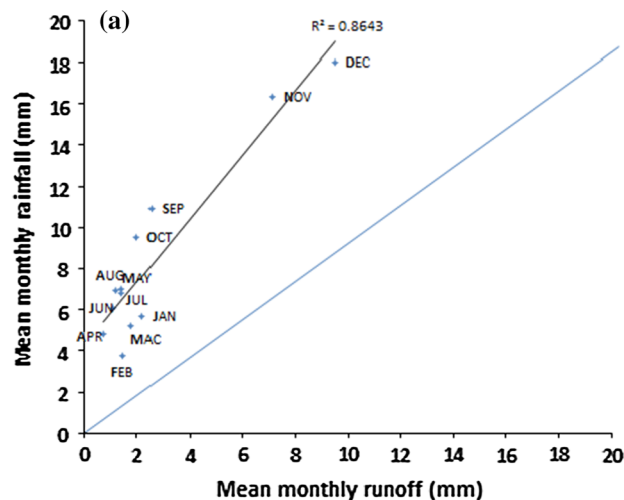


Fig. 3 Linear regression scatter-plot and mean rainfall–runoff polygon

scattergraph with polygonal lines is formed by connecting the line on the graph (Fig. 3) on a month-to-month basis (Kadioglu and Sen 2001).

- (b) The quantitative and qualitative approaches have been used to express and interpret the hydrological response characteristics of the Nerus catchment through the mean rainfall–runoff polygon.

Quantitative interpretation

The mean monthly runoff coefficient for the monthly period is calculated as the arithmetic average of the preceding and current month's runoff ratios.

$$RC_m = \frac{\sum R_{rc} + R_{rp}}{2} \quad (1)$$

where RC_m is mean monthly runoff coefficient, R_{rc} is runoff to rainfall ratio of current month, R_{rp} is runoff to rainfall ratio of preceding month. Meanwhile, the average annual runoff coefficient is calculated as the arithmetic average of 12 months.

$$RC_a = \frac{\sum RC_m}{12} \tag{2}$$

where RC_a is the average annual runoff coefficient RC_m is the average monthly runoff coefficient

Qualitative interpretation

The qualitative interpretation of the mean runoff coefficient is derived based on the characteristics of the polygonal geometry. All in all, it can be divided into several aspects as established below:

- (a) Annual hydrological cycle characteristics
 Polygon indicator: polygonal sides (PS)
 First, the polygon sides represent the change in the average values of precipitation or runoff for the preceding months. All sides considered together are defined as a closed polygon expressing the natural balance of the precipitation–runoff flow in a year. The endpoint of polygon sides is the average value of rainfall and runoff for a particular month (Kadioglu and Sen 2001).
- (b) Seasonality behaviour of the mean runoff coefficient
 Polygon indicator: polygonal sequence (PSQ)
 The closed polygon consists of upward and downward sequences representing a wetter and drier condition of the catchment prior to the contribution of the rainfall and ground water. The rising sequences mean that the catchment becomes wetter with time and the decreasing sequence indicates that the catchment becomes drier with time.
- (c) Temporal trend indication
 Polygon indicator: size and shape of polygon (SSP)
 Besides, significant variations of monthly precipitation in an annual hydrological cycle create a steep and narrow polygon. The closeness of the slope of each side vertically or horizontally indicates the relative proportions of the rainfall and runoff in making up the numerical value of the monthly runoff coefficient. A narrow polygon (smaller area) indicates the consistency of the monthly rainfall and runoff coefficients. The smaller area means that the rainfall and runoff coefficient are consistent. Moreover, it also indicates the trend of the rainfall and runoff over the given period.
- (d) Rainfall–runoff conversion behavioural
 Polygon indicator: length of polygon peripheral

(LPP)

The sum of the length of the polygon peripheral shows the total amount of the surface runoff and rainfall in that particular area. It also shows whether or not there is a seasonal effect on the hydrological cycle of the catchment.

- (e) Groundwater and evaporation behavioural
 Polygon indicator: slope of each polygon sides (SPS)
 The steep slope between the connected sides implicates that the amounts of runoff are negligible but there is a significance of groundwater recharge and evaporation.

Results

Land use changes analysis

Table 2 and Fig. 5 show the general land use characteristics of the Nerus catchment for each period of years of 1982–1990 (1st period), 1992–2000 (2nd period) and 2002–2010 (3th period). The development of the agricultural area during the first period was 70.32 km², increased rapidly during the second period to 121.19 km² and later developed slightly more to 124.76 km² in 2010. The conversion of the forest area to agricultural area was evident in the reduction of the forest area from 234.81 km² in the 1st period to 191.91 km² in the 2nd period and 160.55 km² in 3rd period with the total reduction of 21.18 % in 27 years.

Relationship between hydrologic response and the changes on land use

The general characteristics of the mean monthly surface runoff and rainfall in the Nerus catchment during the periods of 1982–1990, 1992–2000 and 2002–2010 show a similar pattern with the increase in both the surface runoff and rainfall amount by the end of the year (Fig. 4). In fact,

Table 2 General land use characteristics of the Nerus catchment

| Land use types | Period | | | | | |
|----------------|--------------------|-------|--------------------|-------|--------------------|-------|
| | 1982–1990 (1st) | | 1992–2000 (2nd) | | 2002–2010 (3rd) | |
| | km ² | % | km ² | % | km ² | % |
| Agriculture | 70.32 | 20.06 | 121.19 | 35.57 | 124.76 | 35.60 |
| Bareland | 3.11 | 0.89 | 0.94 | 0.27 | 1.9 | 0.54 |
| Forest | 234.81 | 66.99 | 191.91 | 54.75 | 160.55 | 45.81 |
| Residential | 3.72 | 1.07 | 4.3 | 1.23 | 7.86 | 2.24 |
| Shrub | 38.53 | 10.99 | 32.15 | 9.17 | 54.92 | 15.67 |
| Mining | – | – | – | – | 0.5 | 0.14 |

the monthly variations of the surface runoff and rainfall show a clear seasonal pattern, which is highly influenced by the North East Monsoon that usually starts from November to March every year (Meteorological Department of Malaysia). The month of December has the maximum rainfall and surface runoff at different patterns of land use characteristics. It shows that the hydrological response in the Nerus catchment is highly influenced by the seasonal impact. April is the month where the minimum surface runoff for the catchment can be recorded. The minimum rainfall for all the periods of land use changes is

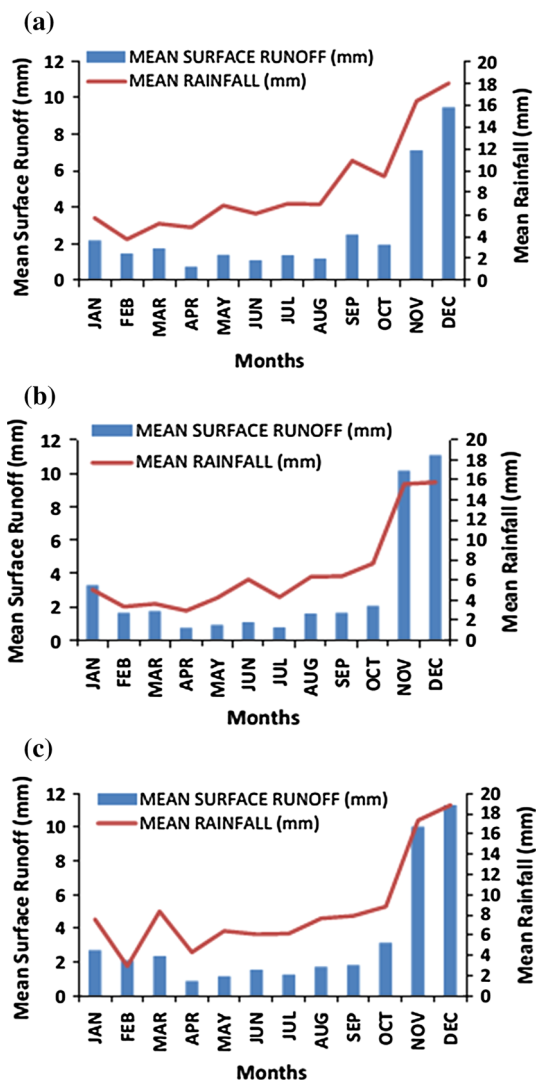


Fig. 4 Mean monthly surface runoff and rainfall in the Nerus catchment for each land use changes period. **a** Period of 1982–1990, **b** period of 1992–2000 and **c** period of 2002–2010

not consistent with the minimum rainfall for the period of 1982–1990 which was on February, the period of 1992–2000 on April and during 2002–2010 on February.

Figure 5 below illustrates the mean monthly rainfall–runoff polygon method for the Nerus catchment with much variability of characteristics. In addition, such a polygonal diagram reveals many useful qualitative elucidations about the rainfall–runoff transformation phenomenon. Practically, if all of the sides fall along a single direction within 5 or 10 % of the deviations, the corners in the polygon diagram might be considered as scattered along a straight line, which represents the monthly precipitation–runoff relationship. This polygon is the key-point in describing the hydrological response of the rainfall–runoff relationship in a scientific manner. Besides, the runoff coefficient determined in this study and results indicate that this C value can be changed temporally with the variation of rainfall in that particular area. The C value also changes with the changes in the surface runoff amount. However, the generation of surface runoff from the rainfall depends on the characteristics of land use in the catchment area. Detailed explanations about the mean monthly rainfall–runoff polygon with considerations on the land use changes in three periods of land use patterns used in this study are as follows.

Table 3 shows the results of the polygonal shape and geometric characteristics of each period representing the difference of interpretations of the runoff coefficient and hydrological properties based on the land use pattern. However, the significant differences are indicated by the temporal trend and rainfall–runoff conversion behaviour.

Discussion

Prolonging the qualitative and quantitative interpretations of the mean rainfall–runoff polygon method

General characteristics of monthly and annual runoff coefficients

At first glance, the dotted points in the polygon represent the ratio of the runoff to the rainfall as shown in Table 4 below and Fig. 5 above. It is simply calculated by dividing the mean of the monthly runoff amount to the mean monthly rainfall depth. However, the average monthly runoff coefficients for the monthly period are calculated as the arithmetic average of the preceding and current month's runoff coefficients as shown in Eq. (2).

Meanwhile, the mean annual runoff coefficient is calculated as the arithmetic average of 12 months. All the calculated values are presented in Table 5. In general, the annual runoff coefficient on three different periods of the land use characteristics shows that the different values with the smallest runoff coefficient are during the 1982–1990

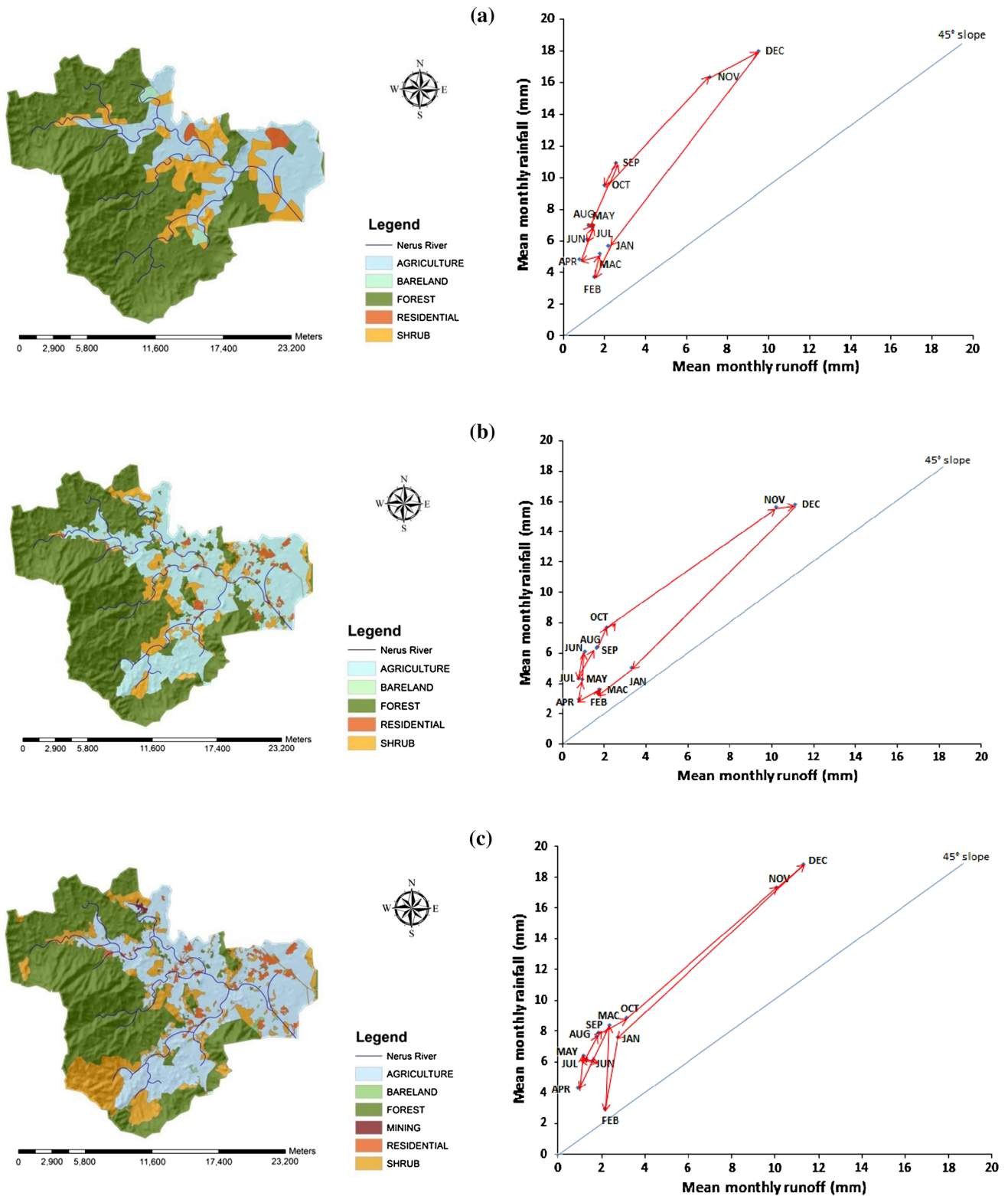


Fig. 5 Land use characteristics in each period and the mean monthly rainfall–runoff polygon method

period (0.28). The largest runoff coefficient value is during the 1992–2000 period with 0.42 followed by 0.39 in the period of 2002–2010. The different values of the runoff

coefficient are largely affected by the different characteristics of land use in the catchment. The study by Watts and Hawke (2003) indicates that the runoff coefficient is related

Table 3 Polygonal shape and geometric characteristics

| Period | Interpretations division | Polygon indicators | Characteristics |
|---|---|---|--|
| Period 1 (1982–1990) | Annual hydrological cycle characteristics | PS | Closed polygon Over-extended length of PS between October and December and between December and January Short length of PS between the months of January and October |
| | Seasonality behavioural mean runoff coefficient | PSQ | Upward trend from April to December Downward trend from December to March |
| | Temporal trend indication of runoff coefficient | SS | Wide polygon shape |
| | Annual hydrological cycle | LPP | Short length peripheral from February to October Long length of periphery from October to November–December–January |
| | Rainfall–runoff conversion behaviour | PSlope | Degree of slope approximately $\sim 60^\circ$ No negative slope |
| | Groundwater and evaporation behavioural | SPS | Polygon sides from the month of February to March and April to July are almost vertical |
| | Period 2 (1992–2000) | Annual hydrological cycle characteristics | PS |
| Seasonal behaviour of mean runoff coefficient | | PSQ | Upward trend from April to December Downward trend from December to March |
| Temporal trend indication of runoff coefficient | | SS | Wide polygon shape |
| Annual hydrological cycle | | LPP | Short length peripheral from February to October Long length peripheral from October to November–December to January |
| Rainfall–runoff conversion behaviour | | PSlope | Degree of slope approximately $\sim 50^\circ$ No negative slope |
| Behaviour of the groundwater and evaporation | | SPS | Polygon sides from the months of February–March and April–July are almost vertical |
| Period 3 (2002–2010) | Annual hydrological cycle characteristics | PS | Closed polygon Over-extended length of PS between October and December and between December and January Short length of PS between the months of January and October |
| | Seasonal behaviour of the mean runoff coefficient | PSQ | Upward trend from April to December Downward trend from December to March |
| | Temporal trend indication of runoff coefficient | SS | Narrow polygon shape |
| | Annual Hydrological Cycle | LPP | Short length peripheral from February to October Long length peripheral from October to November–December–January |
| | Rainfall - Runoff conversion behaviour | PSlope | Degree of slope approximately $\sim 55^\circ$ No negative slope |
| | Behaviour of Groundwater and Evaporation | SPS | Polygon sides for the months of February to March and April to July are almost vertical |

with the percentage of impervious cover of the basin. As the percentage of the imperviousness increases, the C values may increase. As the percentage of the imperviousness increases, the amount of infiltration and storages decreases, resulting in more surface runoff. The well-vegetated area

may produce similar flow patterns to the disturbed areas due to the saturated watershed storage conditions. In the Nerus catchment, a large area of forest during the period of 1982–1990 is one of the controlling factors on the generation of a small amount of the surface runoff. Here, most of

Table 4 Monthly runoff to rainfall ratio

| Period/ Month | Jan | Feb | Mar | Apr | May | Jun | July | Aug | Sept | Oct | Nov | Dec |
|---------------|------|------|------|------|------|------|------|------|------|------|------|------|
| 1982–1990 | 0.39 | 0.40 | 0.34 | 0.16 | 0.21 | 0.18 | 0.20 | 0.17 | 0.23 | 0.21 | 0.44 | 0.53 |
| 1992–2000 | 0.66 | 0.49 | 0.49 | 0.26 | 0.22 | 0.18 | 0.18 | 0.26 | 0.26 | 0.27 | 0.65 | 0.70 |
| 2002–2010 | 0.36 | 0.73 | 0.28 | 0.21 | 0.18 | 0.26 | 0.21 | 0.23 | 0.24 | 0.36 | 0.58 | 0.60 |

Table 5 Monthly and Annual runoff coefficients

| Period/ month | Jan | Feb | Mar | Apr | May | Jun | July | Aug | Sept | Oct | Nov | Dec | Annual |
|---------------|------|------|------|------|------|------|------|------|------|------|------|------|--------|
| 1982–1990 | 0.38 | 0.35 | 0.25 | 0.16 | 0.20 | 0.19 | 0.19 | 0.20 | 0.22 | 0.33 | 0.49 | 0.46 | 0.28 |
| 1992–2000 | 0.58 | 0.49 | 0.38 | 0.24 | 0.20 | 0.18 | 0.22 | 0.26 | 0.27 | 0.46 | 0.68 | 0.64 | 0.42 |
| 2002–2010 | 0.55 | 0.51 | 0.25 | 0.20 | 0.22 | 0.24 | 0.22 | 0.24 | 0.30 | 0.47 | 0.59 | 0.58 | 0.39 |

the areas do not produce any storm flow. The source area that produces storm flow is very limited. The large distributions of forest areas in the catchment reduce the conversion process of rainfall to the surface runoff due to the interception by the plants, making the rainfall infiltrate dynamically and increase the water storage capability.

However, during the 2nd period (1992–2000), the annual *C* value has increased by about 14 % (0.42). This increment is controlled by the reduction of the well-vegetated area, the increase of the impervious area for residential and large areas converted into agricultural land for palm oil and rubber plantation. During the 3rd period (2002–2010), the annual runoff coefficient had small changes with a decrease up to 0.39. Obviously, the expansion of the shrub area reduces the surface runoff flow on the entire catchment. As shown in Fig. 2c, the shrub area increases dominantly at the surrounding forest area. In addition, the agricultural practices in the Nerus watershed influence the reduction of the annual runoff coefficient. Basically, the terracing and contouring of the low hilly slope after the year of 1990 onwards change the water flow in that particular area. After 5–10 years, the grown-up palm oil and rubber trees produce a large amount of dead branches and litter of palm oil and rubber trees that are trapped on the terracing hill. These conditions will influence the time of the water retention and increase the infiltration rate of rainfall. Hence, there is a decrease in the runoff coefficient for the 3rd period.

Similarly, the seasonal rainfall patterns may also produce different *C* values. During the North East monsoon season, the rainfall comes in characteristically high amount and occurs in long durations, thus generating a large value of runoff coefficient (November–March has high value of *C*).

Annual hydrological cycle characteristics

Polygon indicator sum length of the peripheral The sum length of the peripheral indicates the magnitude of the

rainfall–runoff for the annual hydrological cycle. Nerus catchment does have significant maximum and minimum of rainfall and runoff amount. Obviously, as shown by the rainfall–runoff polygonal diagram of all periods, the extent of length of the peripheral of the polygon is controlled by the rainfall amount, which contributes a large generation of the surface runoff. As such, the length of peripheral is short from the month of April to September due to the consistency of the rainfall pattern as the rainfall amount on each event is low (Fig. 5). However, at the end of October to the end of January, there is a long peripheral length due to the Monsoon season, which carries heavy rainfall, thus there is an increased frequency and rainfall amount. Hence, the average monthly rainfall increases and responds to the larger surface runoff. The catchment area located in Malaysia, especially the eastern part of Peninsular Malaysia, is represented by an immensely colossal value of the sum length of peripheral compared because of the Monsoon season that carries heftily ponderous rainfall at the cessation of the year. In fact, the length of the peripheral is highly influenced by the climate variability rather than the land use characteristics.

Seasonal behaviour of the mean runoff coefficient

Polygon indicator the polygonal sequences (PSQ)

(a) Wetter and drier sequences

In all periods, the tropical catchment of Nerus experiences a wetter condition, which started from the month of April until the end of December due to the rising sequences of the runoff coefficient as represented in the rainfall–runoff polygon (Fig. 5). The rising sequence indicates the increase in the rainfall amount that makes the catchment infiltrate much water into the ground, thus becoming wetter and continuing with the same trends until the end of December, thus known as wetter condition (Fig. 6a). Then, after the end of December to April, there was

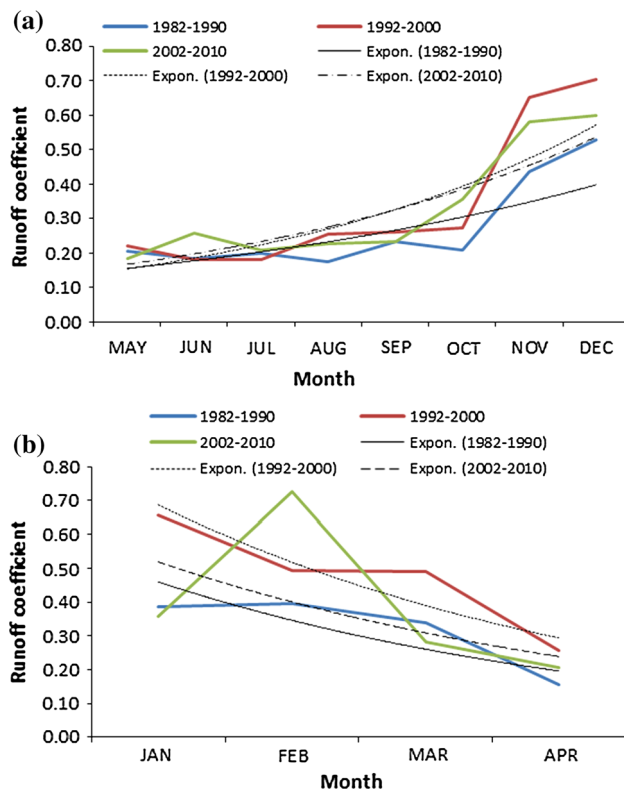


Fig. 6 Wetter and drier catchment conditions as in monthly sequences. **a** Wetter sequences of the Nerus catchment and **b** drier sequences of the Nerus catchment

the falling sequence, which represents the drier catchment condition that causes the runoff coefficient values to become smaller. A drier sequence indicates the decreasing runoff coefficients (Fig. 6b). In Malaysia, the North East monsoon is from November to March, but the period of January to March is not considered as having wetter sequences because the exact month in which the increasing rainfall amount starts is from September to the end of December as shown by Fig. 6a, b. In fact, December is the peak month or peak point for the monsoon and after that month, the amount of rainfall will become smaller (January–April) as January to March are a period considered as the end of the monsoon season. From this observation, different interpretations of the term ‘wetter/drier sequences’ and ‘wet/dry seasons’ have been concluded. For the ‘wetter/drier sequences’, it starts with the month which has the increasing/decreasing trend of the runoff coefficient until the month with the maximum runoff coefficient (peak point). Meanwhile, ‘wet/dry seasons’ are the months which consist of high/low runoff coefficient value with most of the wet month influenced by the monsoon (North East monsoon).

Wetter and drier sequences are not associated with the land use changes of the Nerus catchment. This is because, at all interval years, there is no change in the wetter/drier sequences.

(b) Wet and dry seasons

The runoff coefficient value during the wet season is greater than that during the dry season (Fig. 7). The wet season consists of the months of November and December. As shown by Fig. 7, the calculated runoff coefficients throughout the wet season have the high runoff coefficient for all three land use change periods. One of the factors contributing to the high runoff coefficient during the wet seasons is the continuous increase of water infiltration during the month of October which influences the groundwater storage capacity which increases the antecedent soil moisture. In addition, soil characteristics in the Nerus catchment consist of the composition of clay-loam and sandy clay loam which are easily infiltrated, stored and saturated instantaneously. It transmits larger runoff amounts in the preceding month. This is associated with the size of the catchment area (350.49 km^2) and the length of the river for the Nerus catchment (92.80 km) signifying the response of the surface runoff conversion to rainfall that might occur at distant parts takes more time for water to be retained in the catchment area. Thus, the increased infiltration rate of water as such increases the recharge of the groundwater. Furthermore, the large capacity of groundwater storage in October is associated with high rainfall intensity due to the monsoon season starting from November to December that generates a larger amount of surface runoff. Hence, the runoff coefficient becomes larger. Apparently, the conversion of forest area to agriculture gives a significant impact on the surface runoff generation as the amount of surface runoff increased in the period of 1992–2000 and 2002–2010. In fact, the amount of the surface runoff increased by 10 % after 1992.

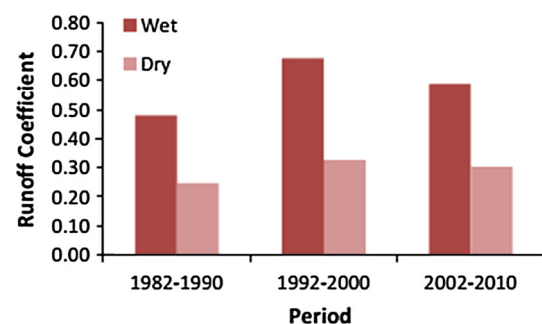


Fig. 7 Average runoff coefficient of wet and dry seasons

Rainfall–runoff conversion behaviour

Polygon indicator shifting of polygon’s slope

Land use changes provide a significant impact to the runoff coefficient polygon with the shifting of its slope position, which tends to be horizontal or shifting downwards. The smaller the overall slope of the polygon from the horizontal axis, the more precipitation is converted to the runoff by the catchment system. In this study, a slope line is built 45° and acts as the indicator line for the shift of the polygon as in Fig. 5. The reduction of the well-vegetated area and increase of agricultural and impermeable area during 1992–2000 triggered a large generation of surface runoff; even the maximum rainfall of the period was less than that in the period of 1982–1990 (Fig. 4). Hence, the reduction of the vegetated area shifted the polygonal diagram to be horizontal.

Polygon indicator downward slope

Since Nerus catchment is located at the equatorial, the climate of which is hot, temperate and humid throughout the year, there is no frost event attributed. Hence, there is no downward slope (negatively slope) on the rainfall–runoff polygon. The negative slope means the increase in the runoff amount although the rainfall continues to decrease. In other words, the catchment is located and categorized as hot, humid and temperate, with no snow or frost event having the upward slope (positive slope) on the rainfall–runoff polygon. This is because of the fact that the large amount of rainfall is easily infiltrated into the soil during the rain event, and that it can evaporate in a short time due to the hot temperature, and consequently not much appearing in the form of runoff.

Temporal trend indication of runoff coefficient

Polygon indicator less steep and narrow polygon

Nerus catchment represented by the less steep and narrow polygon indicates the fact that the catchment response to precipitation is different in each month with a significant variation, especially at the end of October to the end of January. The shape of the polygon elongates and becomes narrower towards November and December at all periods due to the significant differences of the rainfall and runoff amounts between the two seasons. This elongated and narrow polygon shape is due to the two different seasons implied by the rainfall–runoff polygon in the Nerus catchment. Wide polygons imply heterogeneous temporal runoff coefficients for the catchment area. It also means

nonlinearity in the precipitation–runoff relationships for the catchment area considered.

However, the width of the polygon shape represents the types of rainfall and runoff time series. Wider polygon means that there is no trend in the rainfall and runoff patterns of the time series; meanwhile, narrower polygon indicates that the more uniform is the representative runoff coefficient for the catchment concerned. Besides, the time series is composed of a trending (either positive or negative) pattern. The result of the linear regression of the rainfall and runoff time series shows that there is no trend in the series of the period of 1982–1990 and there is a significant increasing trend during the period of 2002–2010 as represented in Fig. 8.

Trends in the rainfall and runoff time series are also conducted using the non-parametric Mann–Kendall test with $\alpha = 0.05$ (5 %) significance level. The Mann–Kendall non-parametric test is extensively used and well recognised in detecting trends of hydro-meteorological time series (Eris and Agiralioglu 2012; Jhajharia et al. 2012; McCuen 2003). As shown in Table 6, there is a trend in both rainfall

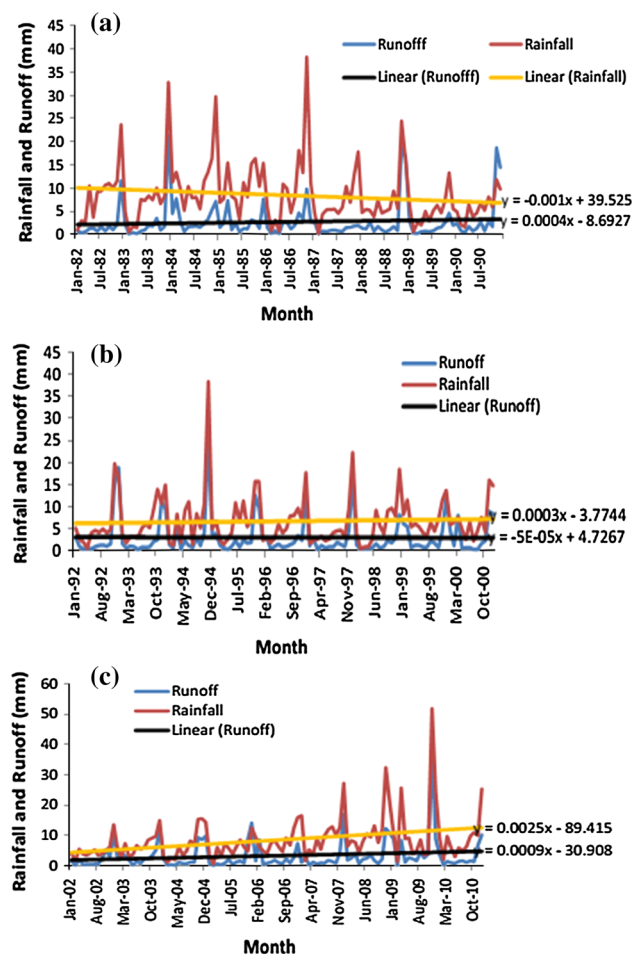


Fig. 8 Time series of the rainfall–runoff

Table 6 Mann-Kendall trend analysis

| Period | | Kendall's tau | S | p value (two-tailed) | p | Interpretation |
|----------|----------|---------------|----------|----------------------|------|----------------|
| Period 1 | Rainfall | -0.123 | -710.000 | 0.060 | 0.05 | No trend |
| | Runoff | 0.026 | 152.000 | 0.689 | 0.05 | No trend |
| Period 2 | Rainfall | 0.096 | 554.000 | 0.142 | 0.05 | No trend |
| | Runoff | 0.034 | 194.000 | 0.608 | 0.05 | No trend |
| Period 3 | Rainfall | 0.259 | 1498.000 | <0.0001 | 0.05 | Trend |
| | Runoff | 0.152 | 876.000 | 0.020 | 0.05 | Trend |

and runoff in the years of 2002–2010. Hence, one can realize that, a significant trend in both the rainfall and runoff is denoted by a very narrow polygon (Fig. 5c).

Behavioural groundwater and evaporation

Polygon indicator: slope of each polygon side (SPS)

At all periods of the land use, the polygon sides for the rainfall amounts in the months of February–March and April–July are almost vertical. This steep slope indicates that the amounts of runoff are negligible but they have a significant groundwater recharge and evaporation. In fact, Nerus catchment had a dry season from the months of April–July. After July, there are significant changes on the slopes, which mean that there is more contribution to the runoff amounts. This situation continues steadily until the end of December. As a conclusion, the steep slope of the polygon sides of each month is considered as the dry month which is influenced by the groundwater recharge and evaporation. Hence, the amounts of the surface runoff generated during these months are smaller as the amount of rainfall has a small disparity.

Comparison between mean rainfall–runoff polygon method and linear regression method

As a comparison, the mean rainfall–runoff polygon method extends the simple relationship of the linear regression method. The method used in this study gives advantages on the interpretation of valuable characteristics of hydrological responses in the study area. The mean rainfall–runoff polygon method was able to explain the non-linear characteristics which are interrelated with the land use changes factors that are not able to be interpreted by the linear regression method.

Conclusion

Current studies have revealed a great applicability of the polygon method for interpretations of hydrological

response through a closer look on the treatment of the rainfall–runoff as a non-linear relationship, in a study area located on the equatorial, which has a hot and humid climate. This study also elucidates the impact of land use changes to the hydrological regime through the mean monthly rainfall–runoff polygon method. This indicates that there is the applicability of this model to make qualitative and quantitative measures of the complex relationship of the rainfall and runoff in any part of the world with the availability of the rainfall–runoff data at different climates and with varying land use characteristics. Moreover, the runoff coefficient obtained in this study can practically be used as part of the determination of important parameters in the water resources designed for the proposed development in that particular area. It is an irrefutable fact that it serves as a practical method in hydrological modelling, which considers a number of time-scales like seasons, years and land use patterns.

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