Marsland Press
Journal of American Science 2009:5(2) 97-104

Vegetation coverage influence on rainfall-runoff relation based on wavelet analysis

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Abstract:

This investigation proposes a new approach for establishing rainfall-runoff-forest coverage relationship by wavelet-based analysis. First, the Db4 discrete wavelet transform is used to decompose the rainfall and runoff time series to obtain wavelet coefficients at multi-resolution level. The results show that trends of rainfall and runoff were similar. However, runoff did not always follow rainfall, as it was also influenced by other factors. Second, these wavelet coefficients are applied to model. The results show that potential impacts of forest coverage on hydrological response are of significant importance in Lao Shi-Kan watershed. Runoff decreases along with the increase of vegetation coverage. [Journal of American Science 2009:5(2) 97-104] (ISSN: 1545-1003)

Key word: Wavelet transform; Rainfall; Runoff; Vegetation Coverage; Trends

1. Introduction

Vegetation, especially in the case of forests, plays an important role in regulating runoff, as it reduces dramatically surface water volume, runoff velocity and peak discharge (Karvonen et al., 1999; Pizarro et al., 2005). Many studies showed that the variation in runoff is attributed to the vegetation cover and land use management changes (Bryan and Campbell, 1986; Kosmas, et al., 1997; Newson, 1985).Removal of forest coverage causes important changes in the hydrological balance of a watershed, although the magnitude of the response is highly variable and unpredictable (Anderson, 1990). Increased forest coverage, replacing pasture areas, can trigger a reduction of annual flow of up to 40% (Bosch and Hewlett, 1982). It is therefore essential to study the relationship of rainfall, runoff and forest coverage.

The establishment of a clear rainfall–runoff–forest coverage relationship is difficult due to the large number of variables which affect the process. It’s more challenging to quantify the impact of vegetation change on rainfall-runoff relations for large basins where the interactions between land use, climatic characteristics and underlying hydrological process are more complex and dynamic [Bultot et al, 1990]. Pizarro et al. (2005) studied runoff coefficients, and their relation to vegetation coverage and water yield in the Purapel River basin, as influenced by land use and the replacement of native forest by plantations. Since hydrology is controlled and influenced by complex factors, distributed or semi-distributed rainfall-runoff models are developed, which consider spatial heterogeneity [Beven, 1992; Jain 2004]. A kind of model include only rainfall, runoff and vegetation coverage will be more useful for those who could not get detail data, and simply want to predict how vegetation coverage affect rainfall-runoff relationship. Most methods and models available for analyzing and simulating the rainfall-runoff process involve hydrological time series with the original data [Croke and Nethery, 2006; Kothyari, et al, 2004; Labat, et al, 2002]. For time series data, periodical change caused by noise or some mechanism should be determined. We need find a method to eliminate noise and reflect real trend of hydrological data.

Wavelet analysis has been applied in the investigation of the rainfall–runoff relationship (Partal and Murat, 2006; Zhang, et al, 2006). The distinct feature of a wavelet is its multi-resolution characteristic, which is becoming an increasingly important tool to process images and signals. Since a wavelet is a localized function both in time and frequency domain, it can be used to represent an abrupt variation or a local function vanishing outside a short time interval adaptively [Morlet et al, 1982; Kumar and Georgiou, 1993]. So, in the field of hydrology, use of wavelets could be essential in the analysis of rainfall and runoff.

Using this framework, the present paper analyzes the influence of changes in forest coverage on the runoff over a period of 43 years from 1962 to 2004, in the watershed of Lao Shi-Kan in the Anji of China. This article is organized as follows. First, the original hydrological time series, including rainfall and runoff, is decomposed into detail and approximation by discrete wavelet transform. Then, the relationship of rainfall-runoff is developed which include vegetation coverage. Finally, the results are discussed and conclusions drawn.

2. Method

2.1Wavelet transform

In recent years, there has been an increasing interest in the use of wavelet analysis in a wide range of fields in science and engineering. Wavelet transform analysis, developed during the last two decades, appears to be a more effective tool than the Fourier transform (FT) in studying non-stationary time series (Torrence and Compo, 1998 ; Wang, et al, 2004). Of course, this provides an ideal opportunity to examine the process of energy variation in terms of where and when hydrological events occur.

Assuming a continuous time series $f(t)$, $t \in [\infty, -\infty]$, a wavelet function $\psi(t)$ that depends on a non-dimensional time parameter t can be written as

$$\psi(t) = \psi(a, b) = |a|^{1/2} \psi\left(\frac{t-b}{a}\right),$$

where t stands for time, a for the time step in which the window function is iterated, and b for the wavelet scale. $\psi(t)$ must have zero mean and be localized in both time and Fourier space. The continuous wavelet transform (CWT) is given by the convolution of $f(t)$ with a scaled and translated $\psi(t)$,

$$W_f(a, b) = |a|^{-1/2} \int_{t=-\infty}^{\infty} f(t) \overline{\psi}\left(\frac{t-b}{a}\right) dt$$

The lower scales refer to a compressed wavelet, and these allow us to trace the abrupt changes or high frequency component of a signal. On the other hand, the higher scales composed by the stretched version of a wavelet and the corresponding coefficients represent slowly progressing occurrences or low-frequency components of the signal.

Calculating the wavelet coefficients at every possible scale is a fair amount of work, and it generates a lot of data. If one chooses scales and positions based on powers of two (dyadic scales and positions), then the analysis will be much more efficient as well as accurate. This transform is called discrete wavelet transform (DWT). Assuming $a = a_0^{\,j}$, $b = kb_0 a_0^{\,j}$ $a_0 > 0$ and $a_0 \neq 1, b_0 \in R$, then DWT has the form as

$$W_f(j,k) = a_0^{-j/2} \int_{-\infty}^{\infty} f(t)\overline{\psi}\left(a_0^{-j} t - kb_0\right)dt$$

The discrete wavelet transform decomposes the input hydrological time series into detailed signal, and an approximation, so the original hydrological time series is expressed as a combination of wavelet coefficients, at various resolution levels.

2.2 Rainfall-runoff relationship

After rainfall begins, precipitation can be intercepted by forest ecosystem, until the interception capacity is exceeded. Once their storage capacity is exceeded, runoff can begin. Many predictive models have been developed to predict canopy interception. Horton (1919) found that interception loss is proportional to the amount of precipitation (*P*). Due to canopy storage capacity is not filled during small rainfall events, Merriam (1960) suggested a relationship which included an exponential term to consider amount of precipitation. Rutter (1971, 1975) and Gash (1979) move away from empirical regression approach to physical and analytical model.

We did not try to analyze these models any further, because the models are focus on canopy or litter interception. However, precipitation intercept by whole ecosystem contain canopy interception, litter water-holding capacity and soil water storage. We develop the relationship according to Merriam's idea, which is exponential regression.

Precipitation that captured by vegetation eventually either evaporates or used in plant transpiration and returned to the atmosphere. So we denote *IT* here, as rainfall interception by whole forest ecosystem, which contain canopy interception, litter interception, soil water storage and evaporation. Regardless variation of vegetation characteristics, *IT* varies with the amount of precipitation (*P*).

$$\frac{dIT}{dP} = \exp(-K \cdot P)$$

When rainfall amount P approach zero, initial interception rate may attain 1. Interception rate decreased exponentially with increasing gross rainfall amounts. When the rainfall amount surpasses the maximum interception capacity of the forest system, then the excess amount of rainfall drains and is no longer intercepted by the forest.

Where K stands for the speed at which the rainfall interception rate decreases progressively with the rainfall amount, has a close correlation with vegetation coverage. We carry out the integration of the above equation and yields:

$$IT(P) = \frac{1}{K}\left(1 - e^{-KP}\right)$$

When $P \to \infty$, we obtain the possible maximum rainfall interception loss (*ITM*):

$$ITM = \frac{1}{K}$$

According to the water volume balance, runoff (Q) can be defined as

$$\begin{aligned} Q &= P - IT \\ &= P - \frac{1}{K}\left(1 - e^{-KP}\right) \end{aligned}$$

ITM is determined by land cover and the roughness and soil in watershed (Toba, 2005;

Wang, 2005). Vegetation cover represents one of the most powerful factors influencing *ITM*, since it modifies and moderates many others. Dense vegetation coverage has a higher interception storage capacity than rock or pavement.

We assuming $ITM = b\alpha + c$, where α is vegetation coverage, refers to the ratio of area of afforested land to total land area (According to State Forestry Administration (SFA) of China). *c* represents water storage by surface and soil, when vegetation coverage is 0%. *b* is *ITM* increase rate in the direction of vegetation coverage. So runoff can be described as function of rainfall and vegetation coverage,

$$Q(P,\alpha) = P - (b\alpha + c)\left(1 - e^{-\frac{P}{b\alpha + c}}\right)$$

3. Results and discussion

3.1 Study basin

This work demonstrates the feasibility of applying the wavelet-based method to model the relationship of rainfall, runoff and vegetation coverage by selecting the Lao Shi-Kan watershed located in 119°53′-119°14′E, and 30°52′-30°23′N, northern Zhenjiang as the study area. The area of the watershed of Lao Shi-Kan is 258 km^2, as displayed in Fig.1. The mean annual precipitation in these watersheds is 1714.2 mm; the mean annual runoff is 226 million m^3. As for temperatures, the annual mean corresponds to 15℃, with maximum and minimum of 40.8℃ and -17.4℃, respectively. There are four rainfall stations and one hydrologic station in the basin (Fig.1).

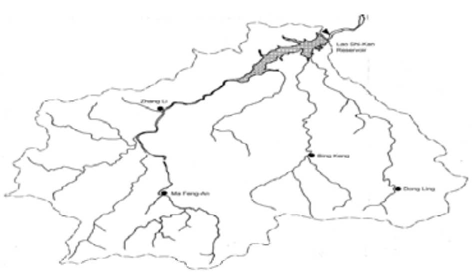


Fig.1 The map of Lao Shi-Kan watershed showing the study area, Anji Zhejiang

The time series of yearly mean rainfall and runoff were obtained from the hydrology stations of Anji, Zhejiang. The length of record is 43 years, from 1962 to 2004. But one of the rainfall stations, Bing-Keng, missed data from 1996 to 2001. The problem of missing data was solved by interpolation of neighboring points.

3.2 Trend analysis results of wavelet transform

In this section, we used DW transform coefficients at three decomposition levels. By using discrete wavelet components of time series, we aimed to find which periodicities are mainly responsible for trend of the series.

The original signal f (t) is decomposed into series of approximations and details by db4 wavelet. Db4 wavelet is simple and compact. It is suitable to detecting a sudden change of the error signal due to amplitude mutation. The process consists of a number of successive filtering steps. The original signal is first decomposed into an approximation (a1) and accompanying detail (d1), then the first level approximation (a1) is decomposed into an approximation (a2) and accompanying detail (d2). The decomposition process is then iterated, with each successive approximation being decomposed in turn, so that the original signal is broken down into many lower-resolution components.

The time series of the DW transform coefficients represent rainfall and runoff variations. The time series of multi-resolution levels are generated and are presented in Fig. 2. The top panels in Fig.2 represent the original time series of annual total rainfall (mm) and runoff (mm). The time series of DW coefficient give the contributions to total annual rainfall and runoff in each year. Time series of first level mode (a1, d1), second level mode (a2, d2), and third level mode (a3, d3) are presented in other lower panels of Fig.2.

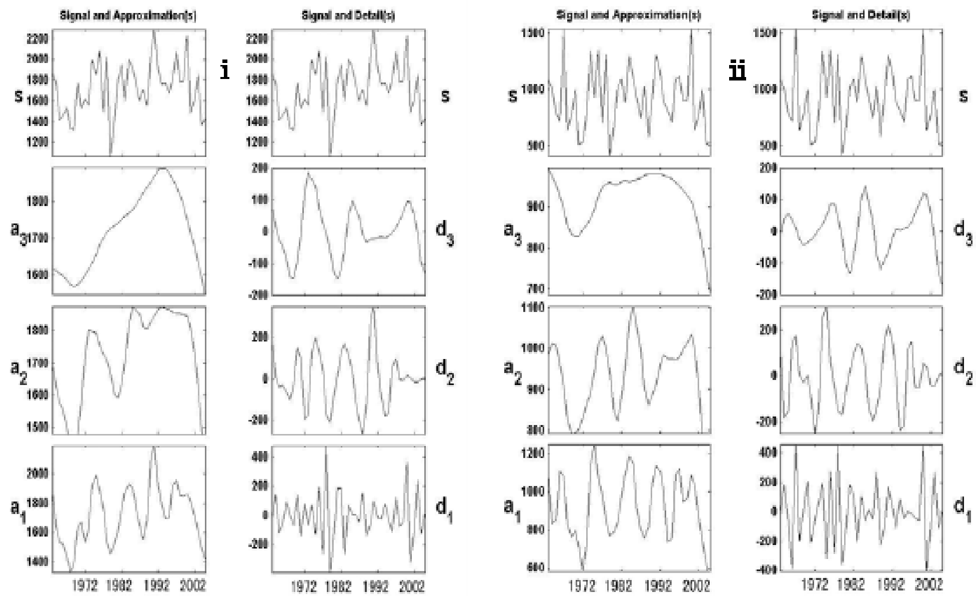
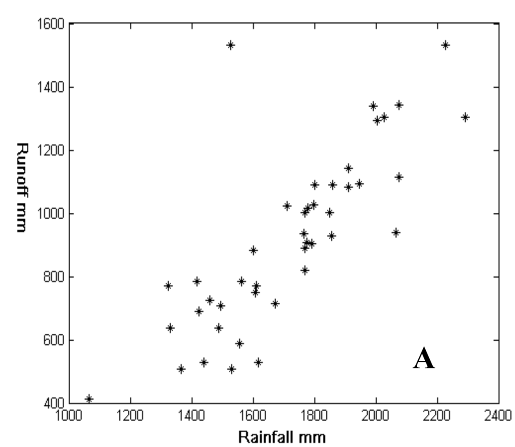


Fig.2 Top panel, rainfall (i) and runoff (ii) series for the period 1962–2004 for Lao Shi-Kan station. Other lower panels: time series of first level (a1, d1), second level (a2, d2), third level (a3, d3)

From the first level of approximation (a1), we can see that the rainfall and the runoff trends are similar on the whole. The second level (a2) shows a decreasing trend during 1973-1980, however the runoff increased continuously until 1977. From the third level (a3), we find that rainfall had a slowly decreasing trend during 1962-1967. Runoff also decreased during this period of time. Rainfall started to increase during the years 1968~1993; the rainfall dropped rapidly after year 1993, the turning point being in 1993. But runoff started to increase after year 1968, increased gently until year 1977, and then had a declining trend. The third level approximation (a3) show clear relationship between rainfall and runoff, which is not linear and change along time. Detail explanation will be presented next section.

3.3 Rainfall-runoff affect by vegetation

First, we compared the graphs of the original data used in the rainfall-runoff relationship (Fig.3A) and the wavelet coefficients (Fig.3B).



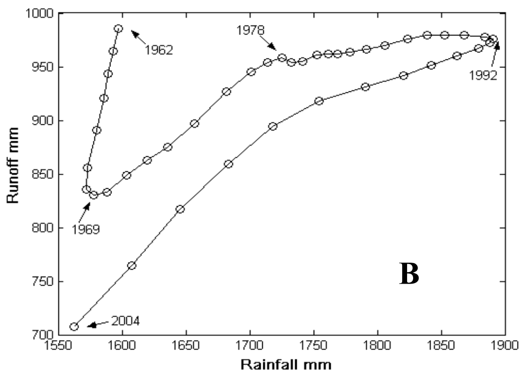


Fig.3 Runoff and the rainfall relational graphs; the original data (A) and wavelet coefficients (B) were

It is very difficult to find the real relations of rainfall-runoff in the original data; so some scholars use a simple linear model to fit it. Applying wavelet coefficients of third level approximation, we can see that rainfall and runoff do not have a unique relationship, and thus cannot fit directly into a simple linear model. This is because the forest coverage differed during different periods. 1970s runoff was much higher than that of the 1990s under the same rainfall, because the 1990s forest coverage was higher than the 1970s.

Next we want to incorporate vegetation coverage data to rainfall-runoff relationship. Due to the difficulty of forest assessment, it is impossible to get vegetation coverage each year. Six nation forest censuses have done since 1950s. The recorded data of forest resources in the basin of Lao Shi-Kan are listed in Table 1. Vegetation coverage changed significantly during last 40 years, especially when the catchment was enclosed and became a natural reserve on 1985, vegetation coverage increased drastically.

The percentages of vegetation coverage in Table 1 only represent the average levels over those periods. In contrast to approximately 40 years of detailed data on rainfall and runoff, the percentages of vegetation coverage are available for only six time periods. Lacking vegetation coverage for each year, model parameter estimation will be more difficult. In order to avoid unnecessary error, this article estimates parameters as follows:

1. Classify rainfall and runoff data into six groups, according to correspondingly years of the six forest censuses. Calculate average rainfall and runoff during these periods.
2. Estimate the initial model parameters by Nelder-Mead method.
3. Hind casting corrected value of the vegetation coverage use rainfall and runoff data as inputs. This will generate 43 years vegetation coverage.
4. Classify new corrected vegetation coverage into six groups, use these six paired data estimate parameters again.
5. Repeat processes 3 and 4, until the estimated parameters don't change.

Following the above process, a Matlab code is developed to estimate parameters, yielding the result b=1346.8, c=16.9. After the computer programming, the simulation produces the relations as shown in Fig.4.

Fig. 5 gives runoff-rainfall relations curves when forest coverage is 0, 50%, 100%, respectively. When $\alpha = 0,\ Q = P - c\left(1 - e^{-P/c}\right)$,

$$K = \frac{1}{ITM} = \frac{1}{b\alpha + c} = \frac{1}{c},\quad \frac{dIT(P)}{dP} = e^{-P/c}.$$

As parameter c is smaller than normal rainfall, the rate of impounding can trend toward 0 quickly as P increases, and then under 0 vegetation coverage the runoff (Q) is approximately equal to rainfall (P). As the vegetation coverage increase, Q increase more gradually when rainfall is low. When rainfall is exceed a threshold, like a storm, runoff approach linear relation with rainfall. But for same rainfall, high vegetation coverage has lower runoff than low vegetation coverage.

Fig.6 gives the runoff-vegetation coverage relationship curves when rainfall is 2500, 1500, and 500mm, respectively. When rainfall is 2500mm (representing periods of abundant water), the runoff is decreased by 1123.7mm, or 45.27%, when the vegetation coverage is increased from 0% to 100%. When the rainfall is 1500mm (representing multi-annual means), the runoff is decreased by 889.6mm, or 60.02%, when the vegetation coverage is increased from 0% to 100%. When the rainfall is 500mm (representing a dry season), the runoff is decreased by 81.8mm, or 83.03%, when the vegetation coverage is increased from 0% to 100%.

Runoff decreases rapidly as soon as vegetation coverage increases from 0 to 20%, when the rainfall is 500mm. As the forest coverage continues to increase, the rate of decrease decelerates. Runoff no longer decreases after vegetation coverage increases beyond about 40%. It also means that vegetation coverage of 40% is necessary to impound rainfall for a low flow period. More vegetation coverage is needed for impounding rainfall, when rainfall is at a high level. It is hard to conclude the precise optimal vegetation coverage. From the figure, we can estimate that about 80% is necessary for impounding rainfall when it is at an average level.

This model can provide the relationship of runoff, rainfall and vegetation coverage. Runoff has a downward trend as vegetation coverage increases. The influence is more prominent under conditions of less rainfall.

Acknowledgements

This work was supported by the Key Project of National Science and Technology During the 11th Five-Year Plan [No. 2006BAD03A16].

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