Research paper

Estimation of the Ability of a Forest Watershed to Conserve and Regulate Water by a Baseflow Approach

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【Summary】

The ability of forest watersheds to conserve and regulate water has received much attention recently. Much research has tried using different approaches such as the infiltration capacity, porosity of soil layers, recession-curve-displacement analysis, and water budgets to estimate the water conservation ability of a watershed. However, many factors are involved in the ability to conserve water, and therefore it is difficult to use some physical quantities to give accurate estimations. Baseflow is the discharge of water that drains from deeper subsurface runoff or originates from the groundwater system, and it is the best and more direct index to describe the ability of a watershd to conserve water. This study used the variable-slope baseflow separation method to analyze rainfall events of the Lienhuachih no 5 experimental watershed to estimate the quantiles of conserved water of the target watershed. From results of 46 rainfall event analyses, the average daily baseflow discharge was about 1.164 (range, 0.474~3.265 mmd^{-1}), which is equivalent to 11.64 $m^3d^{-1}ha^{-1}$ or 4284 $tonsha^{-1}yr^{-1}$ and accounts for 21% of annual rainfall. Combining the estimated baseflow amount and temporal rainfall distribution can give a more-reliable estimate of the ability of a forested watershed to conserve water.

Key words: water conservation, baseflow, baseflow separation, Lienhuachih.

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研究報告

以基流量推估森林集水區之水資源涵養功能

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摘　要

森林集水區的水資源涵養功能日益受到重視，但此一功能定量性的分析卻始終為一爭論的課題。已有許多研究者以集水區地表滲透率、土壤孔隙率、退水曲線及水平衡方法進行推估；然而影響集水區涵養水資源功能的因素眾多，難以簡單的物理量就可得到精確的數值。基流為源自較深層的次地表逕流或源自地下水系統的流量，最能反應集水區涵養水資源的能力。本研究分析蓮華池五號集水區的降雨事件，以變動斜率法進行基流分離，進而求得各場降雨的基流量，藉以評估森林集水區涵養水資源的能力。經分析46場暴雨事件，獲知該集水區平均基流量約為1.164 mmd^{-1} (0.474至3.265 mmd^{-1})，相當於公頃每天可排出11.64 m^3的水量，每年每公頃由基流供應的水量約為4284公噸，約佔全年降雨量的21%。由所推估的基流量，再配合降雨的強度及時間分佈，當可有效推估森林涵養水資源的水量。

關鍵詞：水資源涵養、基流、基流分離、蓮華池試驗集水區。

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INTRODUCTION

The roles of forests in soil and water conservation were the major research topics for hydrologists in the last century. Much of this knowledge was proven in previous studies, such as erosion control, mitigating flood disasters, regulating microclimates, and water conservation and regulation (Bosch and Hewlett 1982, Wheathead and Robinson 1993, Lu 1996). However, most of these functions were qualitatively described, not only because there are no general rules that can be followed but also because many regional variables are involved. Of all these functions, the ability of a watershed to conserve and regulate water is controversial. Water conservation and regulation are defined as the ability of a watershed to minutely adjust the magnitude and time distribution of discharge from the watershed, and those discharges generally originate from water which is stored in soil pores or in groundwater systems. In other words, this portion of discharge is the water that has infiltrated into soil layers, and stored short-term in soil pores, which is known as detention storage and depleted by drainage away from storage locations.

Due to impacts of global warming, temporal and spatial distributions of rainfall have become more uneven in Taiwan. Consecutive days of no rainfall have increased throughout the entire island, and this phenomenon has made water supply on days without rainfall more severe in Taiwan (Hsu and Chen 2002, Wang 2004). Water conservation and regulation of watersheds have become increasingly important for water management, especially in the dry season and in the southwestern part of Taiwan. Therefore, much research has tried to evaluate water conservation by forest watersheds which are believed to have the maximum potential for water conservation (Wei 1983, Chen 1993, Wu et al 2004, Lin 2015). Most previous research used infiltration capacity or water budget approaches to evaluate this ability of a watershed. However, the infiltration capacity of soils is only one of the complex factors that govern water conservation. It ignores the rainfall input which is the decisive factor that determines how much water can be conserved, because if there is no rainfall input how can water be conserved and regulated by watersheds. In this study, the baseflow approach was used to evaluate the ability for water conservation. Baseflow, also called drought flow, groundwater recession flow, low-water discharge, and sustained or fair-weather runoff, is the portion of streamflow that comes from the deeper subsurface flow, groundwater system flow, and delayed shallow subsurface flow. Baseflow water must infiltrate into soil layers and be stored there for a period of time and eventually being discharged into streams. Therefore, baseflow can directly reflect how much water has infiltrated into soil layers and stored as detention storage and how much rainfall can be conserved.

MATERIALS AND METHODS

Site description

The Lienhuachih no. 5 experimental watershed was the study area for the storm analysis in this report. Its physiographic factors are tabulated in Table 1 (Koh et al 1978, Lu et al 2009). The watershed is a first-order upstream catchment and is well covered by vegetation. The vegetation cover of this watershed is characterized by almost entire canopy closure, and the composition of its species mainly belongs to Lauraceae and Fagaceae families. The average annual temperature, rainfall, relative humidity and evaporation for the Lienhuachigh area are 20.8℃, 2181.3 mm, 85.6%, and 1032.9 mm, respectively (Lu et al. 2000), and the annual average discharge for this watershed is about 0.0033 m^3s^{-1} (average of records from 1975 to 1999). The geology of this watershed belongs to Tertiary sandstone and shale. The topsoil is grayish-brown sandy clay loam, and deeper soil is yellowish-brown silty clay loam due to the chemotactic effects of reddening. Soil depths of this watershed generally range 20~50 cm (Chen and Her 1996).

Table 1. Physiological factors of the Lienhuachih no. 5 watershed

Area (ha)	8.40
Average slope (%)	33.5
Maximum elevation (m)	789
Minimum elevation (m)	741
Main stream length (m)	289.0
Mean width (m)	291
Form factor	1.00
Compactness	0.57
Aspect	southeast

Materials

Historical discharge and rainfall records from 1975 to 1999 were used as the raw materials for the storm analysis in this report. These records have daily resolution and have been inspected through outliers test (Chow et al 1988). Units of rainfall and discharges are mm and m^3s^{-1}, respectively. Records of discharge and its corresponding rainfall records for each storm were conducted by a baseflow separation analysis.

Baseflow separation

Division of a hydrograph into direct and groundwater runoff or baseflow is known as hydrograph or baseflow separation. Since there is no definite basis for distinguishing between direct and groundwater flows in a stream at any instant, and since definitions of these 2 components are relatively arbitrary, the method of baseflow separation is equally arbitrary. Therefore, many techniques of baseflow separation are generally developed by rule of thumb and involve subjective judgements. Commonly used baseflow separation methods are the straight-line method, the fixed-base-length method, and the variable-slope method. The volume of flow below the separation line is considered as the baseflow for all of these methods. The straight-line method draws a line from the point when direct runoff begins to the inflection point on a hydrograph. The fixed-base-length method assumes the surface runoff ends at a fixed time, N, after the hydrograph peak. The baseflow before the surface runoff began is projected ahead to the time of the peak. A straight line is used to connect this projection at the peak to the point on the recession limb at time N after the peak. The variable-slope method extrapolates the baseflow curve before the surface runoff began forward to the time of peak discharge, and the baseflow curve after surface runoff ceases is extrapolated backward to the inflection point on the recession line. A straight line is used to connect the endpoints of the extrapolated curves (Bethalhmy 1972, Chow et al 1988). The variable-slope method is applied in this study because it considers the value of baseflow to be related to that of discharge and can give more-accurate estimations. Detailed techniques can also be found in Lu et al. (1995).

Storm event selection

Because the starting point of basflow separation is crucial for the volume of baseflow, the storm event used for analysis must be carefully selected. The storm events used in this study were selected based on the criteria that they were independent storm events, and the discharge of the starting point was closed to the average discharge of all starting points of the rising limb of that year's independent storm events and close to that of the inflection point of the falling limb. In doing the selection, the entire hydrograph and hyetograph of a year's records were shown on the screen for storm event selection. The independent storm was subjectively selected by the criteria that the time interval between 2 storms must greater than 2 weeks, and then the average discharge of starting points of the rising limb were calculated for all selected storms. The inflection point of storms that passed the preliminary screening was checked, and second-stage selection was conducted. All these procedures were performed withthe HYGRAPH program (Lu et al. 1995).

RESULTS

The amount of baseflow

In total, 46 rainfall storm events were analyzed for baseflow separation. Results are tabulated in Table 2. The total rainfall is the amount of rainfall during a storm event; the effect rainfall is that rainfall which is neither retained on the land surface nor infiltrated into the soil and is also that rainfall which generates direct runoff; the ϕ index is the constant rate of abstractions that yields an excess rainfall hyetograph with a total depth equal to the depth of direct runoff; and the runoff coefficient is the ratio of the effect rainfall to the total rainfall of a storm event. Rainfall amounts of these analyzed storms ranged from 38.9~520.2 mm and durations ranged 5~90 d in this report. These storms were substantially classified as medium storms for this watershed. Rainfall amounts of these storms were greater than the total amount of interception and soil storage, and so there was sufficient time for infiltrated water to percolate into the aquifer, and gradually be discharged into streams as the main component

Table 2. Results of the baseflow separation analysis

	Average	Maximum	Minimum	Standare deviation
Event duration (d)	24.0	90.0	5.0	---
Total rainfall (mm)	225.78	520.24	38.90	129.182
Effect rainfall (mm)	95.19	373.12	4.30	81.155
ф index (mmh^{-1})	1.057	2.893	0.071	0.625
Peak discharge (m^3s^{-1})	0.0313	0.2060	0.0030	0.037
Initial discharge (m^3s^{-1})	0.0009	0.0030	0.0001	0.0007
End discharge (m^3s^{-1})	0.0013	0.0048	0.0002	0.0011
Quickflow (mmd^{-1})	4.675	18.133	0.629	4.3495
Baseflow (mmd^{-1})	1.164	3.265	0.474	0.8236
Runoff coefficient	0.3897	0.8766	0.0471	0.0367

of baseflow. Results indicated that the average baseflow of the Lienhuachih no. 5 watershed was about 1.164 mmd^{-1} (range, 0.474~3.265 mmd^{-1}), which is equivalent to 11.64 $m^3ha^{-1}d^{-1}$ (range, 4.74~32.65 $m^3ha^{-1}d^{-1}$). The amount of water per hectare per year supplied from baseflow is about 4284 tons for this watershed.

The percentage of rainfall which can be conserved

The percentage of rainfall for each storm that can be conserved seems very low. However, rainfall input occurs in a short period of time, while the baseflow drains from a watershed on the long-term and continuously occurs even in periods with no rainfall. Therefore, the percentage of rainfall that can be conserved should be calculated on a long-term basis rather than a storm basis. When estimating the monthly percentage of baseflow to rainfall amount, it is assumed that the interception loss is ignored, which has a maximum capacity of about 6 mm (Lu and Tang 1995), and if the average volume of the baseflow is higher than that of discharge for a specified month, then the baseflow volume is substituted by the volume of discharge for that month. The average monthly baseflow value of the study watershed is 34.9 mm, and this quantity was used as the numerator in calculating the percentage of baseflow to rainfall. Results in Table 3 indicate that about 21% of annual rainfall can be conserved in the Lienhuachih no. 5 watershed, and the ratio of baseflow to rainfall is relatively high in the dry season. In addition, monthly rainfall values were similar, but the percentages of baseflow to rainfall seemed quite different in these months. This phenomenon mainly concerns the amount of soil moisture. Soil water content is high at the beginning of the dry season (generally October) as it is affected by heavy rainfall in the wet season, which results in higher discharge and baseflow. While the soil water content is low due to depletion by evapotranspiration at the middle and end of the dry season, the rainfall input is used to fill soil pores and contributes smaller amounts to discharge and baseflow.

DISCUSSION

The influence of discharge at the starting point of baseflow separation

The discharge at the starting point for baseflow separation is crucial for the volume of baseflow (Cheng and Yan 2001). If the starting point of baseflow separation is at the far end of the recession line of the previous storm, the soil water storage may be exhausted due to evapotranspiration or percolation into the deep

Table 3. Monthly average rainfall, discharge, and percentage of baseflow to rainfall for the Lienhuachih no. 5 experimental watershed during the study period

Month	Rainfall (mm)	Discharge (mm)	Percentage of average baseflow to rainfall (%)
Jan	53.9	4.30	8.0
Feb	102.9	21.23	20.6
Mar	124.7	59.02	28.0
Apr	163.6	87.79	21.3
May	360.3	161.39	9.7
June	464.7	290.25	7.5
July	352.0	203.71	9.9
Aug	464.4	297.69	7.5
Sept	166.3	70.75	21.0
Oct	35.1	22.12	63.0
Nov	28.2	12.10	42.9
Dec	33.4	4.45	13.3
Average			21.1

groundwater system, and the rate of stormflow is generally low; therefore, the total amount of baseflow is generally low. In this case, the volume of baseflow will generally be low and may underestimate the ability for water conservation of a watershed. If the discharge rate of the starting point of baseflow separation is larger, the discharge of streams mainly originates from shallow subsurface runoff, and therefore the amount of baseflow will generally be larger. Thus, the ability of a watershed to conserve water will be overestimated in this case. Flow rates of the starting point of baseflow separation ranged from 0.0001~0.0030 m^3s^{-1} with an average of 0.0009 m^3s^{-1} based on the selection criteria and will be a more-reliable estimations of baseflow.

Other approaches for estimating the ability to conserve water

Many researchers have used porosity and soil depths to estimate the ability of a watershed to conserve water. This approach ignores the amount of soil water which drains out or recharges into soil layers in a specified time interval. Water in soil pores is neither lost to the atmosphere through evapotranspiration, percolates into the groundwater system, nor drains into streams. Therefore not all of the stored water in soil pores can drain into streams and become streamflow. The soil porosity approach can only estimate the potential for water storage of a given watershed, and it is difficult to accurately estimate the ability for water conservation.

The water balance approach is also used to estimate the ability for water conservation of a watershed. This method simplifies the input and output of water of a watershed into precipitation, evapotranspiration, and streamflow and treats the amount of water storage, i.e. the amount of water obtained from precipitation minus runoff and evapotranspiration, as the potential for water conservation. However, groundwater recharge may increase the amount of water storage, and it is difficult for the reckoned value to provide an accurate estimation if considering only rainfall and evapotranspiration.

Forests are the best land use type for water conservation

In discussing water conservation and regulation by a watershed, watersheds with different land use types are commonly compared. The prerequisite for water conservation and regulation in a watershed is that the water must infiltrate into soil layers. With similar soil texture conditions, a forestland has a maximum capacity of infiltration, and the forest soil has a maximum capacity of water storage with the same soil depth. The canopy and litter on the forest floor can aborb nearly all of the kinetic energy of raindrops; therefore, they have a mechanical protection function to prevent impacts from raindrops, and reduce splash erosion (the phenomenon of soil particles separating by raindrop impact), and relieve seals (the phenomenon of soil pores being blocked by inflated particulates and other impurities materials). These 2 kinds of protective abilities can maintain the best conditions for infiltration by a woodland surface. Litter on the forest floor and the complex plants staggered above greatly increase the surface roughness. They not only increase the capacity for surface depression storage but also can retard the velocity of surface runoff, thereby increasing the amount of and chance for water infiltration. Therefore, the infiltration capacity of a forestland is higher than that of non-forested lands. The upper part of the floor of forestland is mostly composed of litter and humus which is rich in organic matter and can promote the development of soil aggregates and increase soil porosity. In addition, forest soils contain abundant corrupted roots and animal cavities, so forest soils generally have good aeration and water permeability. The characteristic of highly permeability increases soil porosity and also provides a fast-track for infiltrating water, and therefore moisture can quickly access all different soil layers, and be stored in soil pores. This phenomenon is crucial for water conservation and regulation by a watershed (Hewlett and Hibbert 1967).

Because of these 2 positive effects (maximum infiltration capacity and maximum capacity of water storage), most rainfall can infiltrate into the soil layer of woodlands. If gravity is the dominant force on water that is stored in the soil pores, then water will gradually move downward and eventually flow into creeks, and streams or percolate into the groundwater layer. This portion of infiltrated water can be detained longer in soil layers and becomes the main source of baseflow. Thus the baseflow of a forested catchment is usually higher than that of a non-forested catchment and confirms the effectiveness of water conservation. There is no controversy that the function of water conservation by forested watersheds is much more effective than that of any other land use type. This ability for water conservation is crucial for water supply in drought seasons.

The amount of water resources that can be conserved in a watershed is determined by the soil depth, soil porosity, organic matter content, soil and rock fractures, impermeable layer distribution, groundwater level, slope of the watershed and so on. In addition to these factors, the amount of rainfall and its temporal distribution are crucial for water conservation of a watershed, because if there is no rainfall input, it is impossible for a watershed to conserve water resources. However, there is yet no precise and efficient way to estimate the ability of a watershed to conserve water, because factors involved in this function are very complex and vary from place to place.

CONCLUSION

The ability of a watershed to conserve and regulate water is a controversial topic for hydrologists because all methodologies of estimation involve subjective judgements. This report used the baseflow approach to estimate the ability for water conservation and regulation of the Lienhuachih no. 5 watershed. The author tried to give a more-reliable estimation by careful selection of storms that were analyzed. Results indicated that the average baseflow of the target watershed is about 1.164 mmd^{-1}, which is equivalent to 11.64 $m^3ha^{-1}d^{-1}$. The amount of water per hectare per year supplied from baseflow is about 4284 tons for this watershed and can be considered its ability to conserve water. This quantity of baseflow constitutes about 21% of the annual rainfall. Hopefully the estimation can be used as a reference for watershed management in Taiwan.

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