Elucidating the Hydrological Functions in Forested Watershed by Long Term Analysis of Water Balance

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Abstract

Study water balance is central to the investigation of hydrological cycle. One of the major challenges often encountered to develop a reliable model for water balance study is the lack of distributed data that affect determining water balance in the river basin. Such hurdles are even more complicated in a highly inaccessible area comprised of steeped mountains and dense forest as prevalent in Japan. In the other hand, forest cover plays a role in regulating hydrology. Since variables such as density of foliage, temperature, the humus (or decomposed vegetation) layer on the forest floor, permeability of soils, slope and geology all affect the flow of water, it is not possible to state categorically that forests increase or decrease water flow. It would be accurate to say, however, that forest cover does mitigate the effects of events reducing the downstream flooding and extending the time during which water flows can recharge underground reserves. In the other word, hydrological functions of the forestland strongly regulate by ground cover. Hydrological functions are often cited as being among the most important benefits of forest preservation, for preventing soil erosion, maintaining water supply, preventing floods and maintaining rainfall patterns. Current study was conducted at Gamansawa catchment in Futatsumori, a typical Japanese forested mountainous catchment located in Nakatsugawa city, Gifu Prefecture, with broad objective to elucidate the hydrological functions by long-term analysis of water balance. This broad objective was divided into three parts. The first part to show the hydrological impact of forest growth by estimates the discharge ratio as parameter in reduction of water yield. Here, the rougher the relief and vegetation covered surface and the lower the compaction of the topsoil, the lower is the amount of surface runoff. The second part applied a process model to show the flow characteristic changed and predict hydrological response as a water balance components. It explained that surface runoff was delayed and rainwater temporarily stored in the topsoil layer was increased. It is confirmed that the flood mitigation features is improved. The third part attempted to develop a simple linear model to predict hydrological function index value by correlation between water balance components with NDVI values. Positive correlation between evapotranspiration factors, discharge ratio and NDVI was found. In addition, by using Geographic Information System (GIS) identified hydrological function index values of water conservation forest over study area. It might be provide an effective predictive tool for determining water balance components in forest area that lacking data or inadequate observation data. In spite of the fact that limited data availability, thus the precision of this model could be further improved by add more hydrological and NDVI data. However due to time and resource constrains, present study shows only in single location. In addition, the result recommended for the use only in the small-scale river basins of similar size to current study. This model might be utilized as a reliable water balance monitoring, flood mitigation and drought mitigation function. Results of this study are encouraging and suggestion to further utilization of winter data in reliable modeling of long-term monitoring of water balance.

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Chapter 1

General Introduction

1.1 Background

Forests are globally important in regulating climate and locally important in sustaining communities and supporting biodiversity. In Japan, forest management and conservation are promoted according to the “Forest and Forestry Basic Plan” based on the “Forest and Forestry Basic Law” as well as the “National Forest Plan”, “Prefectural Forest Plans,” and “Municipality Forest Plans” to improving multiple functional roles (*Ministry of Agriculture* 2013).

Forest ecosystem influence on the environment, including hydrological regimes, varies depending on environmental conditions and forest stand distribution. However, the mechanisms of forest water protection functions are not clearly understood and quantification of effects of natural forest disturbances and needs further improvement as new information is developed and new contradictions occur.

The watershed protection function of forests is also referred to as the green dam, has been widely recognized as one of the most important forest function. Watershed function is classified into a flooding mitigation function for reducing the peak discharge during floods, water resources reservoir function for maintaining the river flow when no rain or drought mitigation functions. These features are overall results of the various hydrological processes, soil layer thickness, permeability, the various elements of the crown sparse, etc. As a matter of fact, to evaluate the watershed function of each forest is a difficult problem. Consequently, a better understanding of hydrological processes for forest management area is also needed for evaluation of watershed function that will certainly help improve quantification of hydrological function.

Furthermore, the water balance equation is a fundamental hydrology equation that is valid for all temporal and spatial scales. It is generally used on large areas such as watersheds (*Ward et al.*, 2004) and also water balance at global scale is a traditional research subject of geographical hydrology, there many estimations of it. *Korzun* (1978) summarized such results, which were obtained by observations of precipitation and runoff at the surface, and calculated evaporation rate using climatological temperature. Study water balance is central to the investigation of hydrological cycle. One of the major challenges often encountered to develop a reliable model for water balance study is the lack of distributed data that affect determining water balance in the river basin. Such hurdles are even more complicated in a highly inaccessible area comprised of steeped mountains and dense forest as prevalent in Japan.

Moreover, remote sensing data play a rapidly increasing role in the field of hydrology. Although only very few remotely sensed data can be directly applied, such information is of great value since many hydrological relevant data can be derived from remote sensing information. It was noticed that remote sensing data would be particularly valuable for regions with complex terrain, may vary significantly over small areas and such data need to be compared with observation data (*Stancalie, G.et al.,* 2004)

The relationship between forests and water is a critical issue that must be accorded high priority. *Li et al.* (2004) analyzed the influence of water conservation forest on water quality, the function of water conservation of the forests (*Zhang et al.,* 1994) also has been studied. However, these studies could not provide the index value of water conservation. Therefore, the shortage of knowledge in the characteristics of water conservation of forest ecosystem inevitably reduces the effects of forest resources protection and management in study area.

1.2 Review of Literature

The term watershed hydrology was defined by *Singh and Woolhiser* (2002) as the branch of hydrology that deals with the integration of hydrological processes at the watershed scale to determine the watershed response. Hydrologic processes and their spatial non uniformity are defined by climate, topography, geology, soils, vegetation, and land use and are related to the basin size. Recent reviews (*Vertessy et al.* 2001; *Brown et al*. 2005; *Farley et al*. 2005; *Jackson et al*. 2005; *Benyon et al*. 2007; *Dijk and Keenan*,

2007) have postulated that water yield from afforested catchments declines with increasing plantation, specifically through the relationship with leaf area index (*Watson et al*., 1999). In addition, most plantation establishment involves actively modifying the soil to reduce runoff and improve infiltration (*Evans et al.*, 2004). It is logical that these changes to the soil may affect hydrology and affect both base and peak flows (*Guillemette et al*., 2005). This effect would appear to operate at a time-scale commensurate with the alleged age-dependent water use trend, but relatively few publications have examined the potential interaction of land use history on the runoff (*Ferreira et al*. 2005). With regard to the effects of land use change on water quantity variables, the review of the hydrological literature reveals that the conventional wisdom that forests conserve water and act like a sponge persists in face of a good deal of empirical evidence of cases where this does not apply (*Bonell et al*, 2005)

The Environmental Protection Agency (EPA) defined the term model as a physical representation of natural systems, with or without a series of mathematical equations (mathematical models). The processes included in a watershed model can be complex and may require knowledge of several ongoing systems. Including all processes which influence the response of the system to the various climatic conditions is not possible since generation and transmission of surface runoff require complex mathematical description and data available to define the parameters are limited in both space and time (*Choi and Ball,* 2002). As a result of these limitations, simplifying assumptions are made and the real situation is idealized. Tank is the simplest of the models, it consists of four “tanks” that represent surface stores. The amount of water in each tank is affects the amount of evaporation, infiltration and runoff. The tank storage is calculated in order so that conceptually it is moving down a soil/bedrock profile (*Davie, T.* 2003). Among all the other rainfall–runoff models, the tank model is most popular in Japan. It was firstly proposed by Sugawara in the 1950s but its application spread later in other regions (*Jaywerdena et al.* 1988), when the associated literature was disseminated in English (*Sugawara et al*. 1984). The Tank model is a continuous, lumped, deterministic, non-linear and time-invariant model, that transforms the measured precipitation or rainfall into a corresponding runoff without having to estimate losses and base flows separately. The method used to explain the water flow phenomena of a watershed (*Sugawara et al*. 1984).

Current methods for the prediction of Eco hydrological systems response based on historical observations and assumptions of system stationarity, which does not provide a reliable guide for the future acclimation of vegetation or changes in watershed structure (*Milly et al*. 2008). It is essential for hydrologists to improve the understanding of the controls on the growth and water use of terrestrial ecosystems in order to predict the effects of climate change and improve management of watersheds for flood control, water supply, biodiversity, and environmental watershed services. Remotely sensed measurements of the watershed's vegetation greenness (i.e., Normalized Difference Vegetation Index, NDVI) provide a logical choice, because satellite products are available for all watersheds, they are able to resolve spatial variability in vegetation, and greenness products are frequently used to model ecosystem productivity, evapotranspiration, and surface radiation balances (*Choudhury*, 1994; *Fisher et al.* 2008). NDVI is sensitive to the hydrology of terrestrial ecosystems (Brooks *et al.*, 2011), and is therefore a useful independent measure on which to compare the accuracy of hydrological water balance models.

1.3 Objectives of the thesis

This wide-ranging review of the literature offers sufficient evidence to challenge the accepted paradigm that the reduction in runoff is due to plantation growth, to support the possibility of alternative explanations. A tank model has the ability to analyze flow characteristic change, including runoff process details at small scales within a watershed, the impact forest growth have on the overall hydrologic response of a watershed. At the same time, the tank models have been proven to be more efficient in many situations. Finally, we develop a simple linear model to predict hydrological function index value by correlation the water balance components with NDVI values that could help for predictions of hydrologic components in ungauged catchments. In addition, to produce more empirical knowledge for proper modelling of the effects of various land-use scenarios on water resources.

Chapter 2

Study Site and Data

2.1 Study Area

The study site was made in Futatsumori experimental watershed, Fukuoka district of Nakatsugawa, southeast of Gifu Prefecture, which belongs to the Kiso River system Japan at 35º33'N, 137º24'E with elevation range from 440 to 1223 m (fig. 2.1**)**. The main catchment is the Gaman Stream lower catchment (GS, 3.2km^2) and sub-catchments are the Gaman Stream upper catchment (GU, 0.6km^2), the Morigahora intermediate catchment (MR, 0.5km^2), respectively, where the gauging weir is installed. Tree species composition over the area dominated by cypress 67.0%, red pine 4.5%, cedar 4.3%, needle leaf forest 19.9% hardwood and broadleaf forest 4.3%. The mean annual precipitation is 2284.7 mm and the main temperature is 11.8ºC. The temperature analysis of study site has shown weak trend (+0.00540ºC/year) of changing rates of temperature over the last 24 years.

This watershed as target region is included water and soil conservation enhancements comprehensive model project in the simultaneously 5 years period from 1983 fiscal year that carried by Gifu Prefecture Forestry Agency to achieve the effective use of water and soil conservation features and forest resources, such as construction of multi-layer forest, installation of infiltration facilities, infrastructure maintenance, installation of hydrological observation facilities, etc (*Report of integrated model work of reinforcing water and soil conserving function*, 2004*)*. Moreover, forest management such as silvicultural thinning has been implemented from 1986 to 1988 in the study site. The historical activities of forest management at study site was showed on fig. 2.2. Because of the multi-layer forests formation has been carried out, it was expected to have increased as the green vegetation.

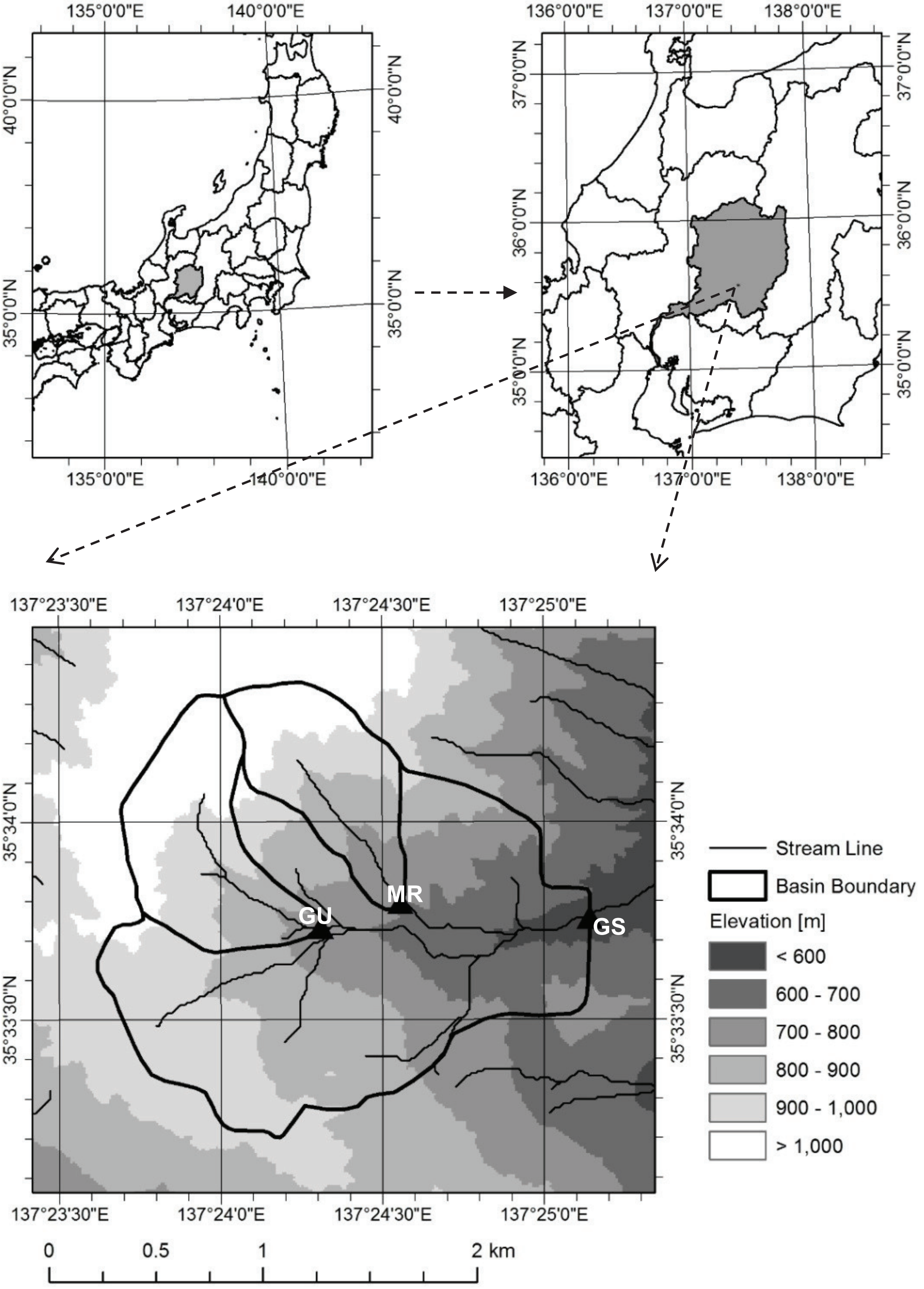


Fig. 2. 1 Location study area at Futatsumori, Nakatsugawa City of Gifu Prefecture

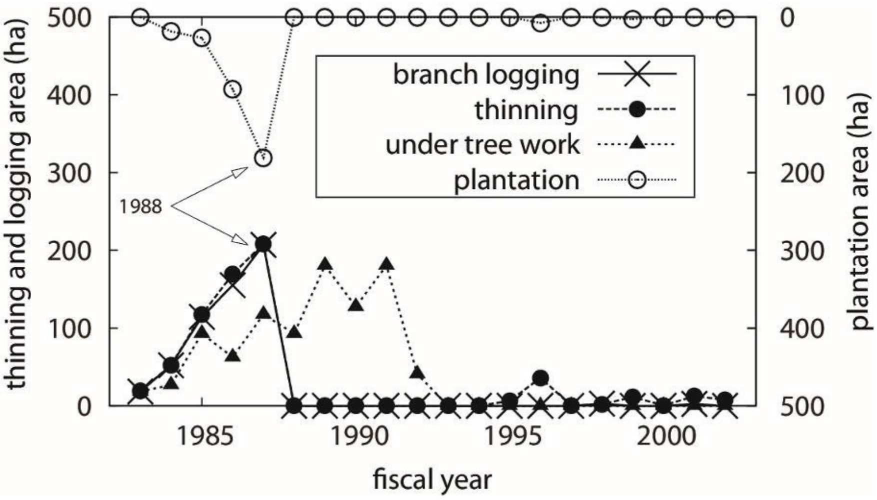


Figure 2. 2 History of forest activities at study site

2.2 Data used

2.2.1 Hydro-meteorological data

The necessary hydro-meteorological data have been collected for data analysis. The long-term hydrological data (rainfall and streamflow) have been measured for a period of 1984 to 2007 by Forest Division of Gifu Prefecture. Historical data observed at different time interval and fewer data have not been recorded due to instrument trouble. Satisfactory solutions to water resources problems, require reliable data on hydrological variables. Therefore before using any hydrological data, it is very important to make sure that the data are consistent, correct, sufficient and complete.

Hydrological data was available with 11 years (1984-1994) daily data and 10 years (1998-2007) 10 minute data in each station of GS, GU and MR. Furthermore, the 10 minute data on period 1998 to 2007 were amended to daily data to produce similar response. For the purpose of rainfall-runoff modelling and runoff characteristic at catchment area, only GS station data was selected for the estimation. Data consistency checking for both rainfall and runoff at GS was carried out using double-mas curve analysis technique. The first part in this study, the rainfall data produced from observation data of GS station only. The second and third part, the rainfall data produced from AMeDAS (Automated Meteorological Data Acquisition System) data in order to cover the error and missing data.

The meteorological data inputs such as temperature, sunshine hours used for computations were recorded from AMeDAS. The 10 years (1998-2007) temperature data for one station of study site were available during this study and it was checked by comparing temperature data between nearby meteorological stations. Average monthly and annual temperature variations in study site and nearby area was showed in fig. 2.3 and 2.4, respectively.

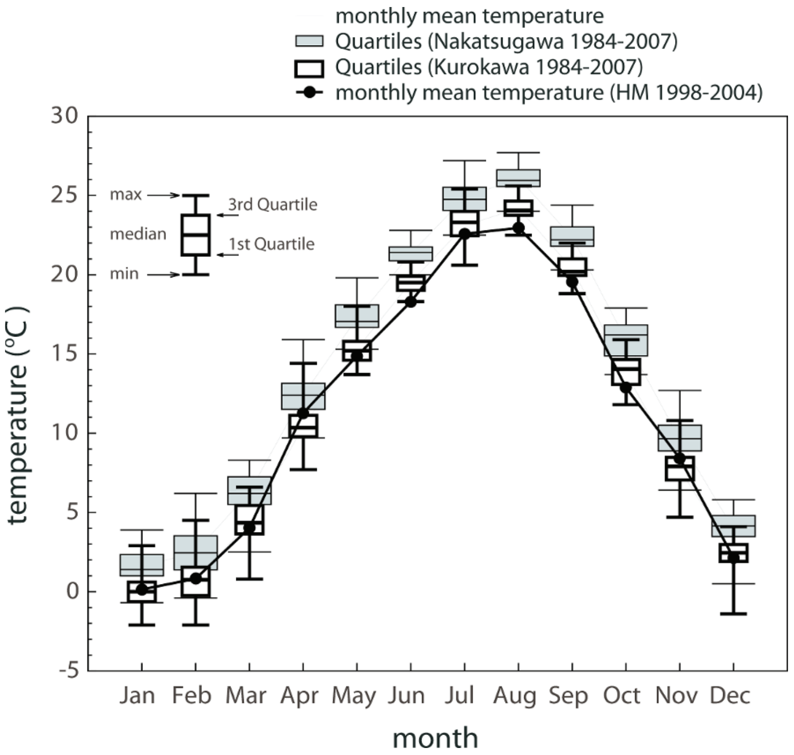


Fig. 2. 3 Average monthly temperature variations

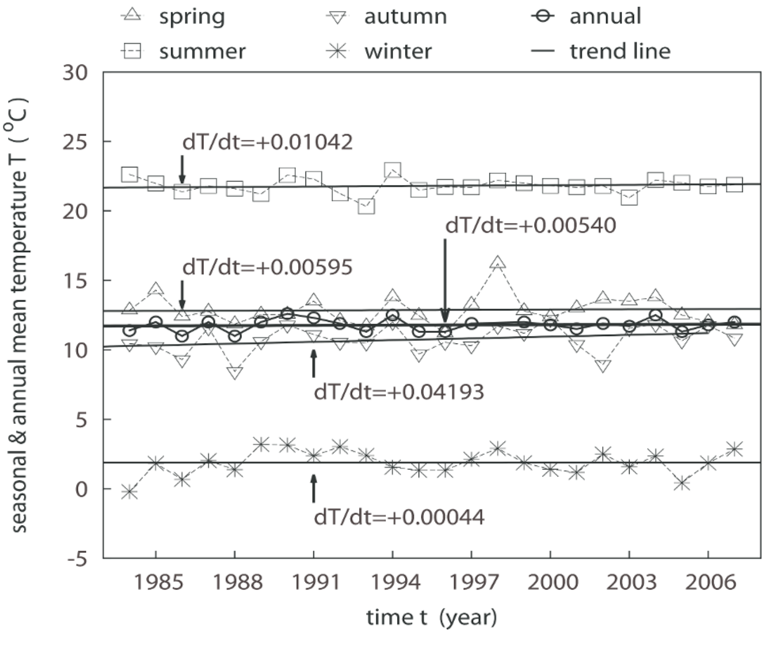


Fig. 2. 4 Long-term temperature trends of study site (1984-2007)

2.2.2 Satellite Data

Satellite remote sensing has long been used for land cover mapping with its ability to collect information on large regional scale and to monitor vegetation cover since the early 1980's. Table 2.1 provide available data, Landsat Multispectral Scanner (MSS), Thematic Mapper (TM) and ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer). This satellite data that required for this study has been ordered through RESTEC.

Landsat Multispectral Scanner (MSS) sensor was onboard Landsats 1 through 5 and acquired images of the Earth nearly continuously from July 1972 to October 1992. MSS on the first 3 Landsat satellites each had 4 spectral bands labeled 4, 5, 6, and 7. The bands were relabeled to 1, 2, 3, and 4 on Landsat 4 and 5 satellites. Two of the bands are in the visible range while 2 of them are in the reflective near-infrared. These bands have a spatial resolution of 79m x 79m. Hereafter, Landsat Thematic Mapper (TM) sensor was carried onboard Landsats 4 and 5from July 1982 to May 2012 with a 16-day repeat cycle, referenced to the Worldwide Reference System-2. Landsat 4-5 TM image data files consist of seven spectral bands. The resolution is 30 meters for bands 1 to 7. (*https://lta.cr.usgs.gov/MSS)*

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is an imaging instrument onboard Terra, the flagship satellite of NASA's Earth Observing System (EOS) launched in December 1999. Its features are high spatial and radiometric resolution, broad spectral coverage (visible-through thermal infrared) and stereo capability for the same path. To allow such broad coverage as from visible through thermal infrared regions of spectrum, ASTER consists of three separate subsystems: VNIR, SWIR and TIR. The VNIR subsystem has a spatial resolution of 15m. Consisting of two telescopes - one that looks backward and the other looks nadir, it enables to produce pairs of stereo images with a base-to-height ratio of 0.6. The SWIR subsystem has a spatial resolution of 30m and operates in six bands in the shortwave infrared (SWIR) portions of spectrum, while its forerunner, JERS-1/OPS, operated in four. Given this ability, it is expected to obtain finer data for rocks, minerals, plants, etc. The TIR subsystem has a spatial resolution of 90m and five bands in the thermal infrared (TIR) spectral range; multiband operation from space is unprecedented. It is expected to derive land surface temperature and land surface emissivity with a precision that no previous scanners have reached. *(http://www.science.aster.ersdac.jspacesystems.or.jp*)

Table 2.1 Satellite Imagery data

Satellite, Sensor	**Spatial Resolution (m)**	**Available date**
Landsat4, MSS	80	1984/11/10
Landsat5, MSS	80	1987/11/11
Landsat5, TM	30	1985/11/21 1987/11/11 1992/11/24
ASTER	15	2001/05/17 2004/03/15 2005/11/04 2006/10/31 2007/11/19 2010/11/11

2.3 Data Processing

In this section, the NDVI technique is used for extracting the various features in the 3-band Satellite image of study site. The NDVI is one the most useful and used index to quickly identify vegetated area with the use of multispectral remote sensing data. Vegetation indices allow us to delineate the distribution of vegetation based on the characteristic reflectance patterns of green vegetation. The NDVI is a simple numerical indicator that can be used to analyze the remote sensing measurements, from a remote platform and assess whether the target or object being observed contains live green vegetation or not. The performance of NDVI relies on the absorption of energy from red light by chlorophyll and scattering of near infrared energy by green plants. The decrease of red reflectance and increase of near-infrared made NDVI sensitive to canopy fluctuations (Chai 2011). NDVI is calculated as

$$\text{NDVI} = (\text{NIR-RED}) / (\text{NIR+RED}) \tag{2.1}$$

Where RED is visible red reflectance, and NIR is near infrared reflectance. These indices describe condition of plants and estimate quantity the concentrations of green leaf vegetation. Calculation of NDVI for a given pixel always result in a number that ranges from minus one (-1) to plus (+1); however, no green leaves gives a value close to zero that means no vegetation and close to +1 indicates the highest possible density of green leaves. *(http://earthobservatory.nasa.gov/)*

Chapter 3

Investigation of long-term trends of runoff coefficient

3.1 Introduction

The aspects of climate variability and forest management are likely to have major effects on forest hydrology. *Wei et al.* (2010) have indicated that climate variability and forest disturbance are commonly recognized as two major drivers influencing runoff change. Forests are unique among land uses because they are long-lived, relatively stable and respond to climate through the process of evapotranspiration; yet, management and/or natural disturbances can substantially alter their structure and function. These structural and functional changes can be either positive or negative, and either transient or long-term, depending on the magnitude and intensity of the management action or disturbance.

Japan Meteorological Agency (JMA, 2011*)* has indicated, the seasonal mean temperatures in northern and eastern Japan were the highest for the summer since 1946, and that in western Japan was the fourth-highest on record. Monthly mean temperatures for August in northern, eastern and western Japan were also the highest on record since 1946. *JMA* issued a statement on the atmospheric circulation characteristics causing the extremely hot conditions and primary factors contributing to them in accordance with the advice of the Advisory Panel on Extreme Climatic Events. Understanding how climate change effects the supply of water from forested watersheds, and developing management strategies to mitigate or offset those impacts, is critical to maintaining water supplies for human use and aquatic species (*Vose et al.*, 2011).

Japan is one of the most broadly forested countries in the world, where the forest cover runs up to 68% (*Ogawa*, 2002). The Forest Division of Gifu Prefecture is implementing forest management project by experimental forest at the Futatsumori research area in the Nakatsugawa City, Japan. According to the historical forest management data, forest can be regarded as streamflow regulator that influences it timing and distribution. Streamflow response to disturbances and forest recovery may be almost immediate or considerably delayed, depending on climate, topography, soils and other factor. However, opposition to the concept has been appealed since the commencement of discharge measurement, and the dispute has been still spotlighted. Thus, a number of long-term forest hydrological researches over a wide area are required to settle the dispute and precisely understand the mechanism of hydrological cycle in forests (*Ogawa*, 2002). Long-term catchment research can offer valuable insights into the interactions among forest management and climate on water availability.

The objective of this study is to quantify runoff ratio (discharge ratio) as a function of the catchment state condition. Then, to demonstrate trends of the discharge ratio associated with climate variability and forest management by looking in hydrological and climate data. Based on this argument, need to assessment climate change properties, estimation of evapotranspiration that is one of indicator, and estimate of forest growth. In addition, this study is using for understanding the consequences of forestry activities on water resources. Experimental watershed studies to provide basic data that will lead to better understanding of the ways in which forests function in the control of water and the conservation of water resources.

3.2 Climate Trend in Study Site

We used the monthly temperature data from three nearby sites because no long term temperature data in Futatsumori site. The sites were Higashimori (one of sub-catchment area in Futatsumori area), Kurokawa and Nakatsugawa, respectively. Kurokawa and Nakatsugawa data were collected during 24 years data from AMeDAS (Automated Meteorological Data Acquisition System) of Japan Meteorological Agency. Fig 2.3 presents comparison mean and quartiles monthly temperature data during 24 years. Nakatsugawa city temperature is higher than Kurokawa and Higashimori temperature. It shows the urban area was around 2°C higher than the rural land and mountain area. In order to determine the temperature as climate trend surrounding catchment area, Kurokawa long term temperature data is appropriate. According to fig 2.4, the temperature analysis of study site has shown weak trend (+0.00540ºC/year) over the last 24 years. The summary statistical in table 3.1 shows the coefficient correlation is small and have weak trend.

Table 3.1 Statistic and linear regression of Kurokawa Temperature

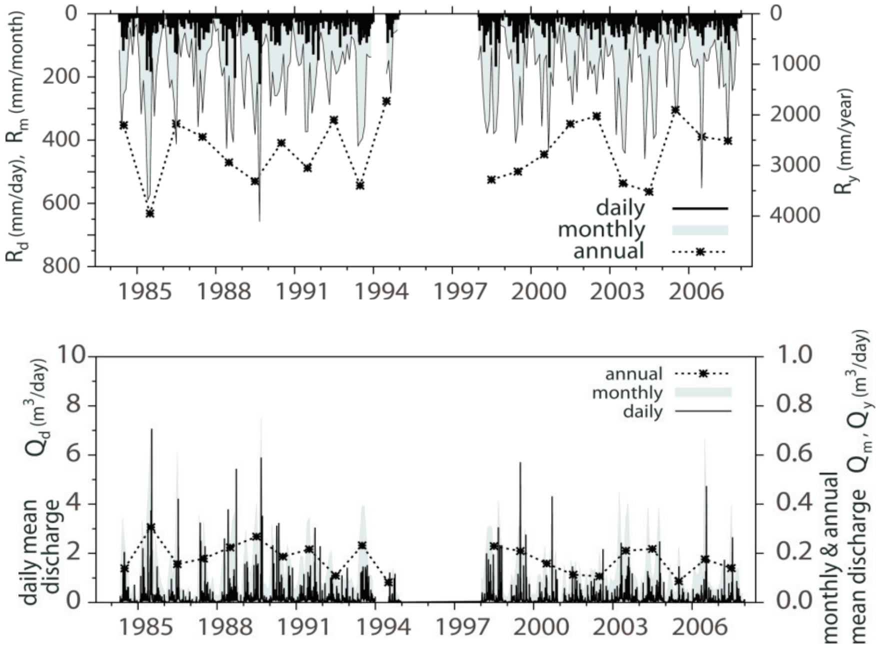
Summary statistics (°C)	
Mean	11.8
Standard deviation	0.5
Minimum	11.0
1st quartile	11.4
Median	11.9
3rd quartile	12.0
maximum	12.6
Linear regression	
Slope	0.00540
Intercept	0.00427
Determination R^2	0.00410

3.3 Long term variation of rainfall, discharge and discharge ratio

This study was conducted in downstream study area, GS catchment. Here, the long term variation of rainfall and discharge in study site has been recorded during 24 years (see fig 3.1(a) and (b)). Fig. 3.1(c) shows monthly discharge ratios with some variability higher than 1 at dashed line compared to solid line. Here, only discharge ratios with range value 0 to 1 were considered and used. In the winter season, if there is no heating mechanism, then the precipitation can't be measured. The snow fall on the funnel of tipping bucket rain gauge and block subsequent rain with resulting in inaccurate data. At study area, absolute errors are occurred during winter months where frozen precipitation is common. Therefore, the winter data that show in dashed line was negligible. The fig 3.1 (a), (b), (c) shows differ in peak flow before and after 1994. It may an effect a smoothing of the variation of the daily data which high frequency and low amplitude fluctuations. In these case, amplitude distortion ten minute data become aliases. Periods of rainfall and discharge data available for analysis have been taken from 1984 to 2007, but fewer data have not been recorded on 1995, 1996 and 1997 caused by instrument trouble.

The discharge ratio relates to direct runoff or quickflow only, so it was necessary to separate quickflow and baseflow. In this study, fig. 3.2 represented method of direct runoff separation was used, that assumed the baseflow was constant. Here, three conditions are required to separate baseflow on a discharge flow by identify the start (*Qs*) and the end of an event (*Qe*) also the ratio between *Qe* and *Qs* in each event. For each event, the start of an event was searched within *dQ/dt* >+ 0.001; the end of an event was found by -0.01<*dQ/dt*<0 after rainfall stop (Re=0) and the ratio was found with expression *Qe/Qs*<5, these conditions as parameter to filter the runoff data time series. The discharge ratios were calculated for each rainfall event. Discharge ratio *f* estimated as the ratio between streamflow *Q*, (m^3/day) and rainfall *R* (mm) over a certain area *A* (m^2) and time *t (*day), as a function of the catchment area.

$$f = \frac{\int Q dt}{10^{-3} RA} \tag{3.1}$$



(a)

(b)

[redacted]

(c)

Fig. 3.1 (a) Rainfall, (b) Discharge and (c) Discharge ratio over periods study

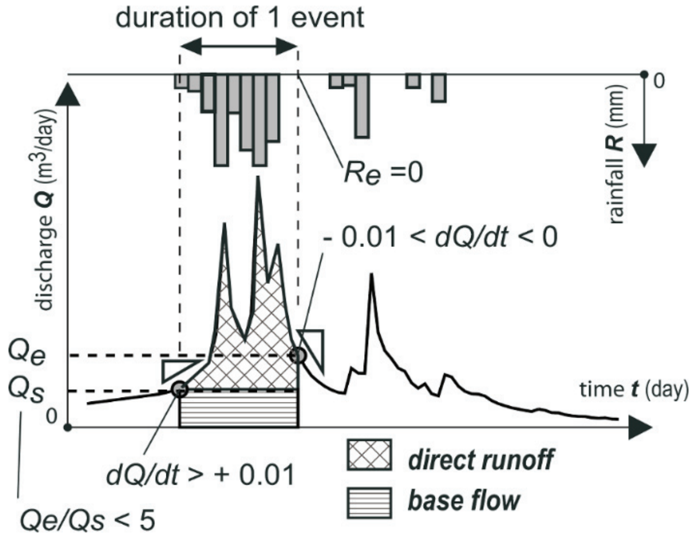


Fig. 3.2 Representation of extract rainfall event

3.4 Long term trends in annual and seasonal of direct discharge ratio

Seasonal term is important variable to show streamflow response to thinning. The trends analyzed in different season with rainfall as the predictor variable. The seasonal trend analyses in fig. 3.3 indicate that trends exist in spring, autumn and summer allow us to infer that forest cover change were affecting rainfall-discharge ratio relationship and the winter trend had some variability of errors and interpreted as an evidence of fig. 3.1(c). The comparison of discharge ratio trend between the period of thinning and no thinning in fig. 3.4 were analyzed without winter data. The average reduced of discharge ratio about 11% and 14% for 100 mm and 200 mm of rainfall, respectively. Therefore the results imply that the dealing with discharge ratio as constant value is not appropriate. It can be attributed by effect of forest growth. Land use change can direct the runoff response of a catchment depending on the rainfall partitioning. The total rainfall of unit event has a large variation through the catchment area. The short rain occurs mainly bigger than 400 mm and the long rain occur smaller than 50 mm.

The long term trends of relationship rainfall variability with discharge ratio in every season described by fig. 3.5 (a), (b), (c) where decreasing of discharge ratio trends during the growing season. This is likely due to relatively a new vegetation slightly growth at the early stage and become more mature, their take up more water through transpiration. In addition, more mature forest typically have greater leave area index with consequently higher canopy interception and leading to more water loss. In winter (fig 3.5 (d)), the trend of discharge ratio is increasing in total rainfall per event smaller than 50 mm with 111 events. It may some error data have been recorded and may snow dominated at area as same as seasonal analysis in fig. 3.1(c). The responses of discharge ratio in fig. 3.5(b) were very rapid and significant with proportionately larger rainfall in summer.

The analysis of fig. 3.6 during periods showed that break in the trend or change point that indicates the effect of thinning and no thinning activity. The total rainfall 400mm was decline as 0.00508 [y^{-1}] and total rainfall less than 50mm was decline as -0.00424 [y^{-1}]. Discharge ratio increases shown in proportion of high rainfall due to thinning, but they are short lived due to rapid growth of vegetation. During period without thinning showed reduction of discharge ratio where plantation took place cumulatively. In other word, it can reduce high flow by storing them in the soil, which means less chance for floods and enhance low flow which means less chance for droughts.

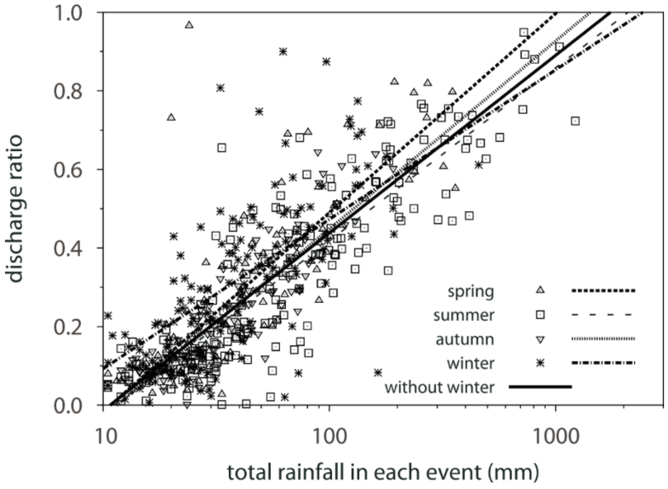


Fig. 3.3 Seasonal trend of direct discharge ratio

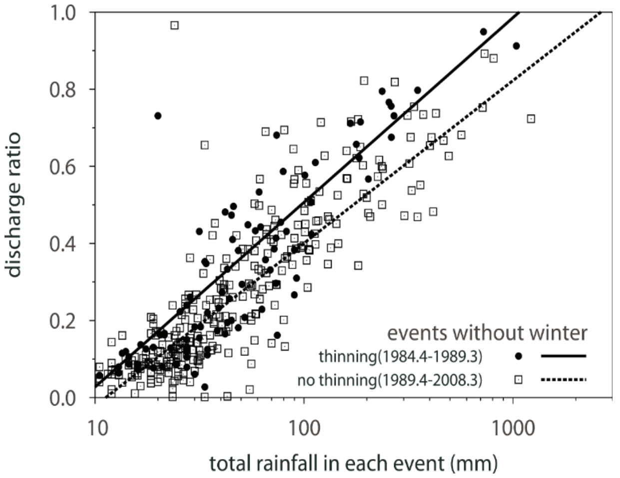
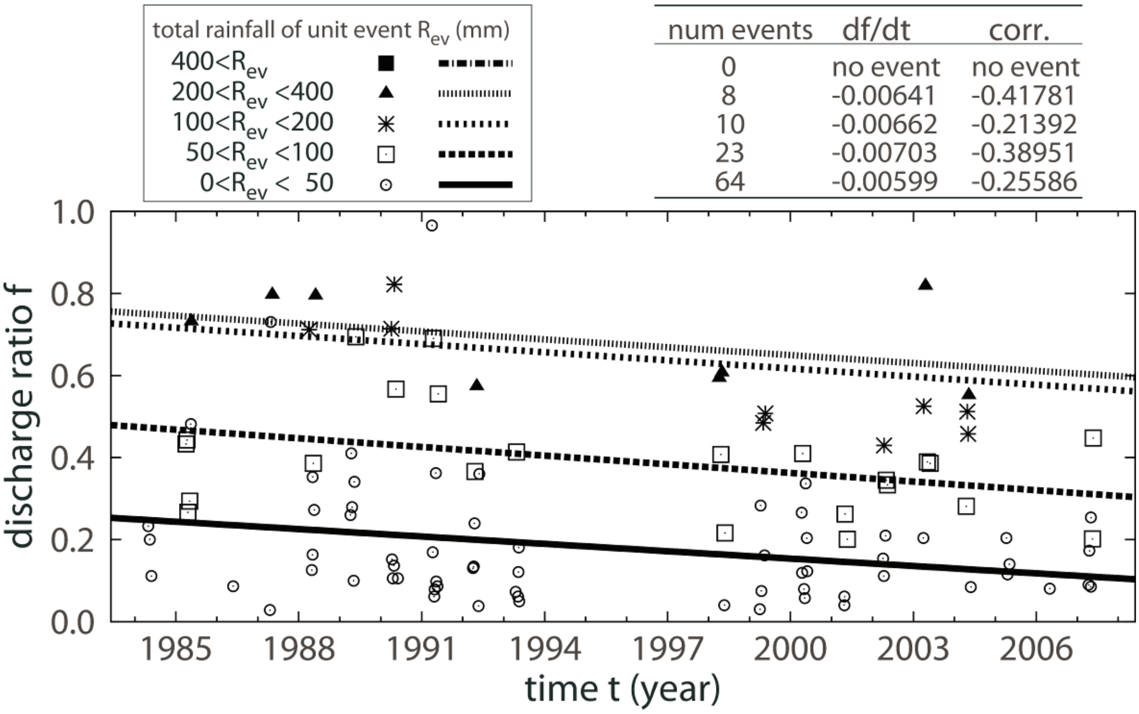
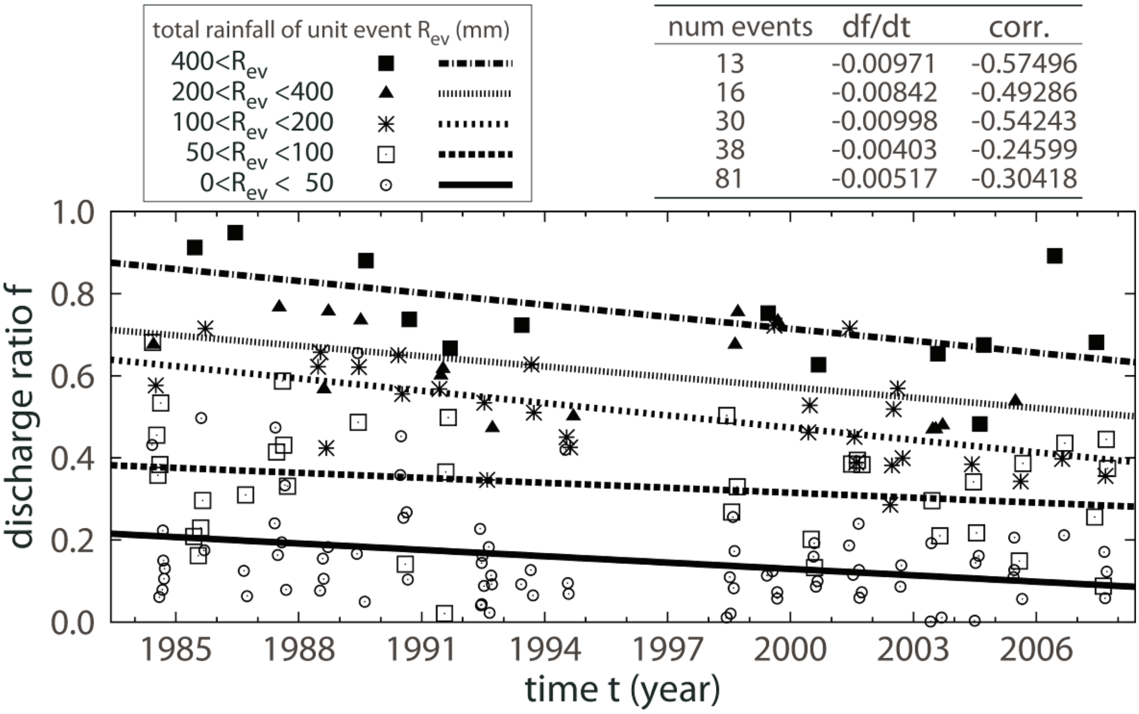


Fig. 3.4 Trend of direct discharge ratio during forest management



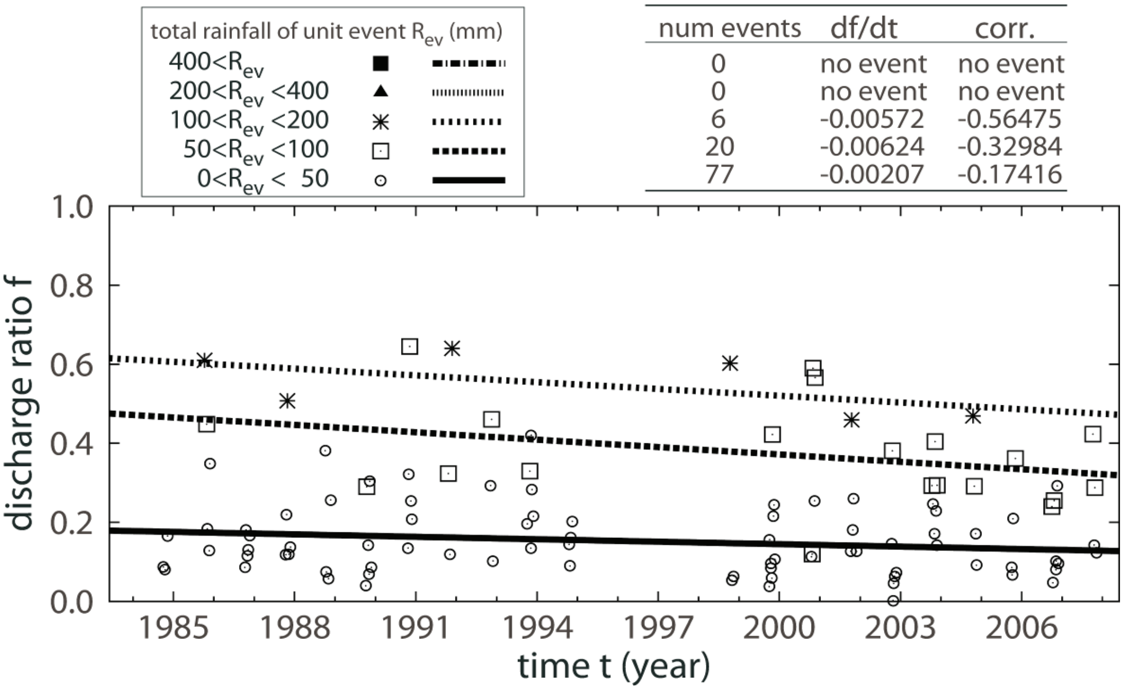
num events	df/dt	corr.
0	no event	no event
8	-0.00641	-0.41781
10	-0.00662	-0.21392
23	-0.00703	-0.38951
64	-0.00599	-0.25586

(a) Spring



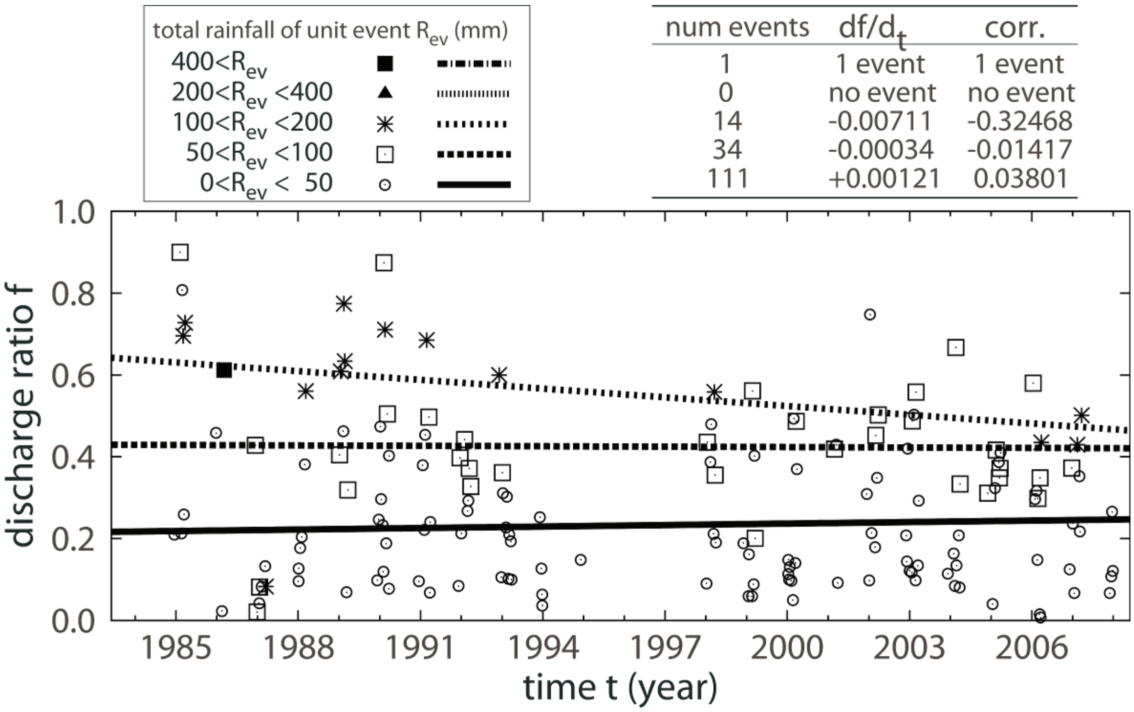
num events	df/dt	corr.
13	-0.00971	-0.57496
16	-0.00842	-0.49286
30	-0.00998	-0.54243
38	-0.00403	-0.24599
81	-0.00517	-0.30418

(b) Summer



num events	df/dt	corr.
0	no event	no event
0	no event	no event
6	-0.00572	-0.56475
20	-0.00624	-0.32984
77	-0.00207	-0.17416

(c) Autumn



num events	df/d$_t$	corr.
1	1 event	1 event
0	no event	no event
14	-0.00711	-0.32468
34	-0.00034	-0.01417
111	+0.00121	0.03801

(d) Winter

Fig. 3.5 Long term trends of direct discharge ratio in every season

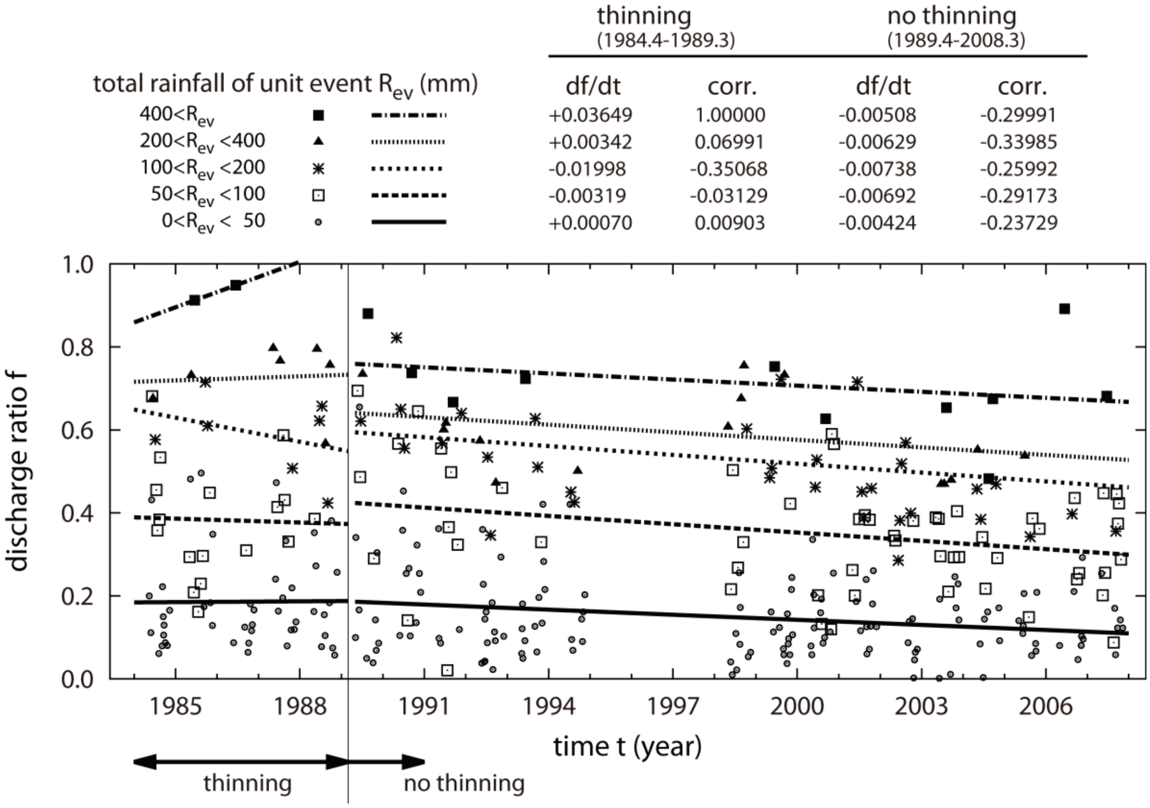


Fig. 3.6 Long term trends of direct discharge ratio during forest management

3.5 Conclusion

Discharge ratio for the period 1984-2007 was analyzed and observed that given a result with decreasing trend by variations in distribution of rainfall event over study site. Long term annual changes, adjustment time scales and trends in both annual and seasonal figure were indicating reduce in discharge ratio, although the influence factor could not identify yet, suggest that forest growth is contributing as indicated increase in NDVI trend. Furthermore, temperature could not recognized as drivers influencing factor. The relationship between long term discharge ratio against climate change and forest growth in Gamansawa has not been well noticed. In addition, reducing direct runoff which means less chance for floods.

Chapter 4

Investigation of long-term variability of rainfall-runoff characteristic using tank model

4.1 Introduction

Forests have multiple functional roles, including landslide prevention, watershed conservation, carbon sequestration, biodiversity conservation and wood production. Under the Forest Law, forests providing particularly important public benefits, including securing water resources and preventing disasters, are designated as conservation forest, but it is difficult to assess its value quantitatively (*Annual Report on Forest and Forestry in Japan*, 2013). Among the multiple functions of forests, green dam is the name used to refer to the fact that forest plays the role of an artificial forest or dam by holding onto the rainwater and that it flows out the water slowly. Green dam functions of the forest can be divided into three major functions; flood control function that reduces the flood risk during heavy rain; drought mitigation function that does not allow water in the valley to dry off even when there is no rain for a long time; water quality purification function that reduces sediment runoff and keeps the water clean and the ability to reduce about 20% of precipitation become runoff by blocking in the crown part (*Tsukamoto*, 1992). The main purpose of flood control function is to reduce the peak flow in downstream areas to be protected. This is accomplished by temporary storage of a portion of the flood flow, which reduces the peak *(Gardiner, J.*, 1994).

Forest conversion may affect the quality and quantity of water flows in a number of ways, based on the combined effects on crown interception, effects on rainfall patterns as such, rainfall interception by plant canopies, infiltration of the soil surface, subsequent water use for evapotranspiration and partitioning over surface and surface flow pathways (*Masakazu,* 1998). Of these effects, the interaction between land use mosaics and rainfall is the least understood and most speculative one. Changes from natural forests to landscapes used for agriculture or production forestry normally involve many terms of the water balance, with a mixture of positive and negative effects. Although watershed functions in forests are generated based on the combination of hydrological processes, that quantification is extremely difficult. However, green dam is not only in flood mitigation function, the report of the Science Council of Japan also is summarized green dam for disaster prevention.

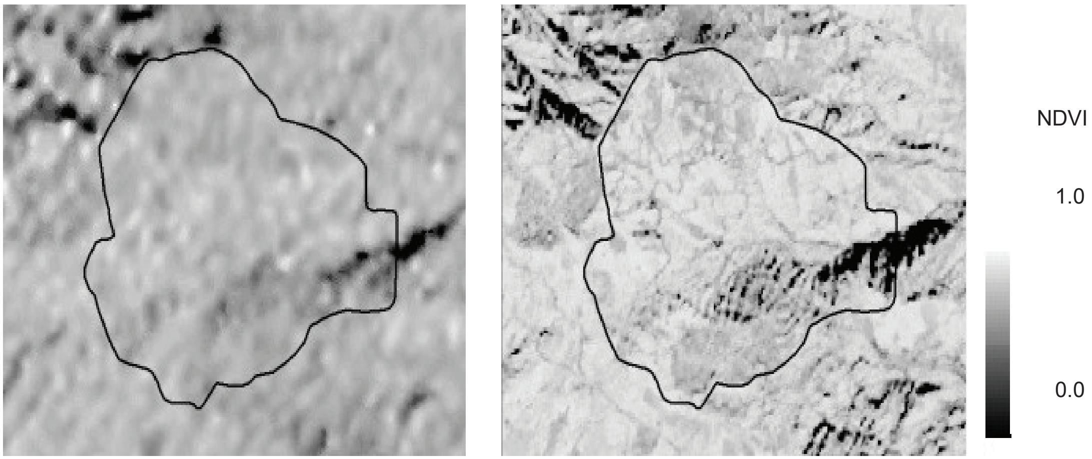
On the other hand, (*Nakane et al.,* 2003) using a long-term hydrological observation data series with the three-stage tank model in forest watershed was confirmed that the coefficient of the lower penetration hole of the first-stage tank along with the growth of the forest is increased. Penetration into the groundwater zone, it can be considered to have a high impact on the forest of watershed function. However, changes in forest soils due to the growth of the forest is mainly increase in the surface layer, soil layer thickness and the organic matter content in the layer, the formation of the litter layer of fallen leaves, etc., which is considered that the increase. The lower layer does not change significantly which is formed by the weathering of rocks. Loss of stored water by evapotranspiration at no rainfall also is an important element that becomes the topic as a negative feature of green dam.

The goal of this research is to characterize the watershed`s hydrologic response on reducing flood peak discharges that using a hydrologic model. As described above, the green dam function is a combination of very complex hydrological process, forest growth, changes in the runoff characteristics associated, whole aspect has not yet been elucidated. In this study, we analyzed the mountainous forest watershed of 300ha, by the analysis of long-term change in the long-term hydrological observation data and the tank model coefficients, to perform a study on changes in the flow characteristics of the mountainous forest watershed due to the growth of the forest.

4.2 Forest Growth analysis by satellite image

Vegetation analysis using satellite image that shown in table 2.1 to confirm forest situation in study site were carried out. Landsat 1 was launched on 1972 as first Earth-observing satellite with the express intent to study and monitor our planet`s landmasses. Multispectral Scanner System (MSS) with spatial resolution 80m, Thematic Mapper (TM) 30 m is slightly inferior accuracy when compared to the latest Earth observation satellites, therefore it is possible to use a relatively long period of high-resolution data.

Here, Landsat MSS and TM data from 1984, 1987, 1992 and continue with Terra/ASTER data were used. By given the characteristic of ASTER sensor system which provide imagery data at higher spatial resolution (15m on VNIR) than ETM+ (30m), *Viana H.*, (2010) has been compared both imagery performance in the mapping of a specific class of forest land cover and both images provide quite similar results.



(a) 1984/11/10

(b) 2007/11/19

Fig 4. 1 NDVI image in study area

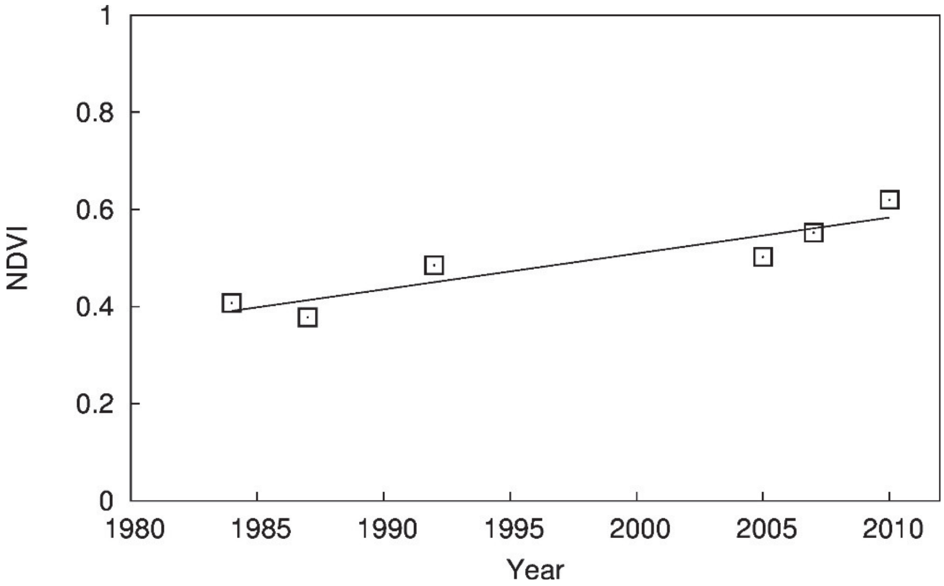


Fig 4. 2 Vegetation change in study area (average NDVI)

As a matter of fact, we need to remove cloud effects to avoid possible errors due to seasonal variation among the images captured in November 1984. DN (Digital Number) values recorded by sensor then convers to spectral radiance and to apparent radiance with the true units are Wsr-1m-2μm-. In order to make less error in measure of radiance at Earth's surface, the atmospheric correction by using software 6S was carryout with removal of atmospheric effects due to absorption and scattering. Then calculates the Normalized Differential Vegetation Index (NDVI) to analyzed vegetation amount. NDVI is an index to investigate vegetation amount by utilizing the physiological activity of plants that it can be determined by the following equation.

$$\mathrm{NDVI} = \frac{NIR - R}{NIR + R} \qquad (4.1)$$

Here, *NIR*: the reflectance of near infrared, *R*: the reflectance of visible red.

NDVI as equation (1) is an index that is normalized by the sum of NIR and R, has the characteristic that the effect of the incident light varies with the slope direction and the sun altitude relatively less susceptible. It shows an example of the NDVI image in the subject watershed in fig. 4.1, where (a) NDVI image on 1984 taken by Landsat-4/MSS and (b) are NDVI image on 2007 captured by Terra / ASTER. Black border indicates the catchment boundaries. Spatial resolution is significantly different, but NDVI values in the catchment area shows good result. Here, in fig. 4.1 (b) it appears slightly higher. Fig. 4.2 shown the change of NDVI average in the catchment area. In spite of the fact that there is a slight variation of NDVI value tends to increase, forest through the analysis over period are believed to be growing.

4.3 Analysis runoff characteristic due to forest growth by tank model

As mentioned in the previous section, the growth of forests in the study area and decline in the runoff rate is confirmed, but not well understood the causes. In this chapter, to perform a study on the factors of the change the runoff characteristics associated with the forest growth by the analysis of the tank model coefficients.

4.3.1 Analysis Method

A tank model is a simple concept that uses one or more tanks that illustrated as reservoirs in a watershed. It is considering rainfall as the input and generate the output as the surface runoff, subsurface flow, intermediate flow, subbase flow and base flow, as well as the phenomenon of infiltration, percolation, deep percolation and water storages in the tank that can be explained by the model.

In this study, first-stage tank has two lateral outlet holes as shown in fig. 4.3 where first hole simulates the surface flow on the soil layer and second hole simulates the intermediate flow. The second-stage tank to four-stage tank as using a general model with one lateral outflow hole that simulates the baseflow. The outflow rate of the first-stage tank side hole is q_1, q_2 [mm/d] and the penetration rate of underlying tank is i_1 [mm/d], respectively, are calculated by the following equation.

$$q_1 = a_1(h_1 - c_1) \qquad (4.2)$$

$$q_2 = a_2(h_1 - c_2) \qquad (4.3)$$

$$i_1 = b_1 h_1 \qquad (4.4)$$

Here, a_1, a_2 : discharge coefficient of the first stage tank [d^{-1}], b_1 : penetration coefficient of the first stage tank [d^{-1}] c_1, c_2 : the height of the side outlet hole of the first-stage tank [mm], h_1 : water depth of the first stage tank [mm]. In addition, continuous first stage tank water level is as follows.

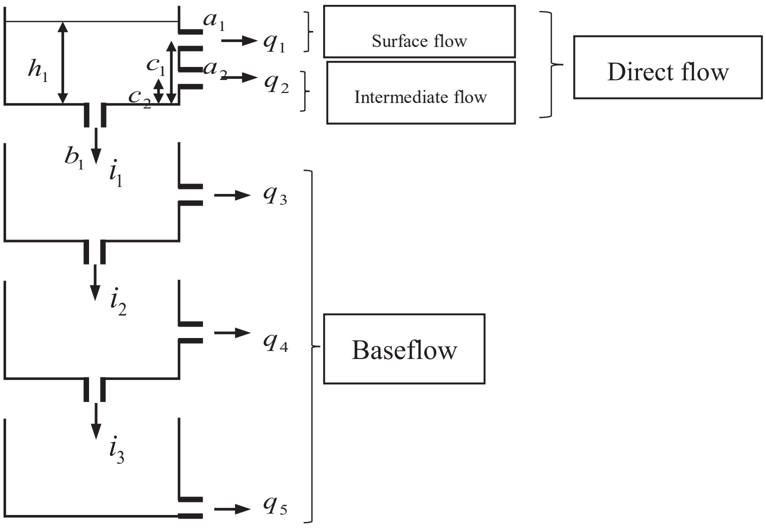


Fig 4. 3 Concept of Tank model

$$\frac{dh_1}{dt} = r_e - q_1 - q_2 - i_1 - Et \qquad (4.5)$$

Here, t :time[d], r_e : Effective rainfall [mm/d], Et : Evapotranspiration [mm/d].

The procedure of the analysis shows below:

1. Using the observed hydrological data of 1984 to 2007, to identify the best model coefficients through the whole period. However, 1995-1997 years are excluded from the analysis because data loss is large.
2. Divided the hydrological data into four periods: 1984-1987, 1988-1994, 1998-2002, 2003-2007
3. The side infiltrate hole of first stage tank is fixed to identify the optimal value of a1 and a2 coefficient in the each periods.
4. Set the evapotranspiration 0 and also use potential evapotranspiration which calculate by Hamon formula using the daily mean temperature and sunshine time due to rising temperatures.

Nakane et al. (2010) applies the serial three-stage tanks that performed adjustment for all the coefficients in each tank. As a result, the coefficient of the lower penetration hole of the first-stage tank related to the vertical penetration speed and vertical permeability coefficient of topsoil layer is increased. It is concluded that the recharge rate of the groundwater zone is increased due to the growth of the forest. However, changes in forest soil by growth of the forest by increase in surface soil layer thickness and increase in coarse pores due to mix of organic matter was considered.

Otherwise, the recharge of the groundwater zone and vertical penetration speed will effect weathering of bedrock layer. It was consider that greatly affected but not change significantly in most about 100 years. Therefore, the vertical permeability coefficient of topsoil layer in this study assumed that no big changes due to the growth of the forest. In this study, the coefficient b_1 of the lower penetration hole of the first stage tank and underlying tank are fixed. We only focus in change of coefficient a_1 and a_2 to perform increase of direct runoff in surface soil layer without changes in recharge rate of the groundwater zone in order to explain whether the green dam function as reduction flood peaks can be worked.

4.3.2 Result and Discussion

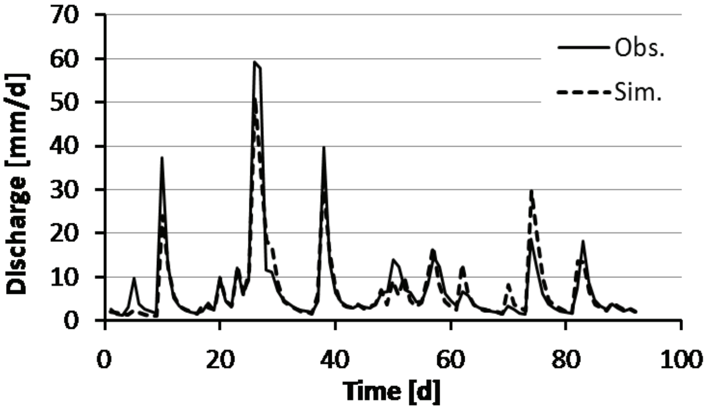


Fig 4. 4 The observed and estimated hydrograph on summer 1984

Table 4.1 Tank model coefficients in each period

Coefficients	1984-1987	1988-1994	1998-2002	2003-2007
a_1	0.900	0.718	0.660	0.653
a_2	0.425	0.320	0.295	0.284
a_3	0.510	0.510	0.510	0.510
a_4	0.001	0.001	0.001	0.001
a_5	0.001	0.001	0.001	0.001
b_1	0.30	0.30	0.30	0.30
b_2	0.30	0.30	0.30	0.30
b_3	0.01	0.01	0.01	0.01
c_1	20.0	20.0	20.0	20.0
c_2	10.0	10.0	10.0	10.0
c_3	10.0	10.0	10.0	10.0
c_4	3.0	3.0	3.0	3.0

Figure 4.4 shows the estimated and the observed hydrograph of 1984 of summer (June-August) with computation time interval is day. Tank model has characteristics that difficult to reappearance the peak flow rate and generally the result has good accuracy, even though a slight error was found in precipitation events during period.

Table 4.1 shows the tank model coefficients that are identified in this study. Here, the mean square error and skewness of flow rate was calculated by trial error for the observed and estimated flow rate. In table 4.1 shows the value of the lateral outlet hole coefficients a_4, a_5 of the third and fourth stage tanks are given a smaller value as compared to the side outlet coefficients of upper tank. Here, the third and fourth stage tanks almost no flow rate contributes, in light the fact that study area is a relatively small catchment and the target basin almost in upstream area. Therefore there is a very small contribution caused by flow rate of the deep groundwater zones in the observation flow. The deep groundwater zone of the third and four-stage tank contribute to the outflow of further downstream point in the target basin. Although in this study the method is four-stage tank model, in fact it is mainly considered as the behavior of the upper tanks that affect the outflow hydrograph.

In general, the series four-stage tank model described as: the first-stage tank surface runoff, the second stage tank intermediate outlet and the third stage tank to represent the base flow. In the model present study, the outflow from the second-stage tanks are large contribution if no rainfall. The outflow total in the first tank is direct flow and intermediate flow as shown in figure 4.3. The outflow of second stage tank and others is equivalent to slow intermediate flow and base flow.

Next, we will discuss the model coefficients of the first-stage tank. As shown in fig. 4.5, the coefficient a_1, a_2 are both gradually decreases. The peak flow rate is reduced and it is confirmed that the flood mitigation features was improved. On the other hand, Hamon formula is a formula for determining the evapotranspiration from the daily mean temperature that affected by the temperature rise due to recent climate change. The difference on the case where the evapotranspiration 0 is the coefficient a_2 about 0.3, the trend is not changed much over period. The reason for the value of a_2 is slightly smaller on the case of evapotranspiration 0, in accordance to decrease of water level in the first stage tank by exist of evapotranspiration and tried to suppress the outflow from the lower outlet hole. Therefore, it considered the effects of climate change to changes the runoff characteristics are very small in study area, but relative to the improvement of green dam function by the growth of forest. However, coefficient value in the results of considering the evapotranspiration is increasing slightly in the last 10 years.

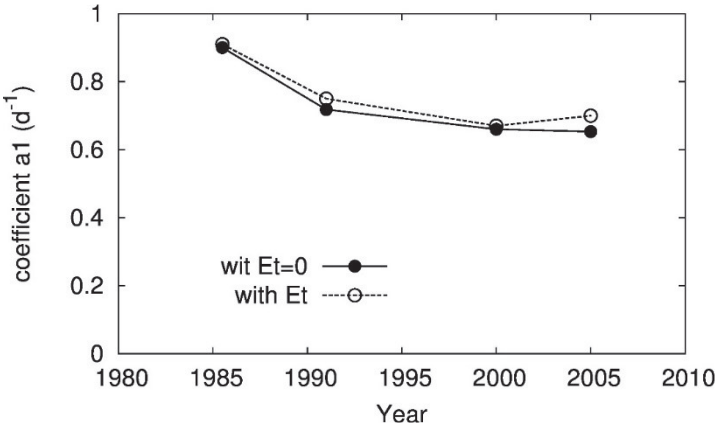


Fig 4. 5 (a) Coefficient change in upper hole, a1

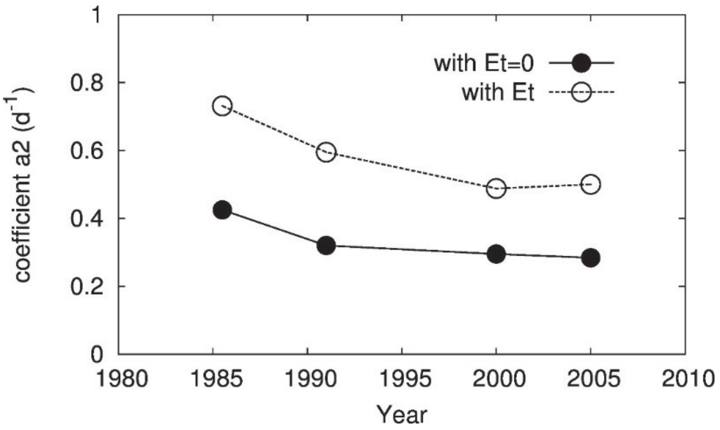


Fig 4. 5 (b) Coefficient change in lower hole, a2

The rainfall parameter values 50 mm/day, 100 mm/2days, 200 mm/2days, 150 mm/3 days, 300 mm/3days were identified for tank model simulation over period. The outflow rate of first stage tank was calculated with rainfall event variation (see fig. 4.6). The outflow rate in lees and heavy rainfall model can be seen the decline trend. The whole, the direct runoff rate has decreased trend in regards to -0.0029 [y^{-1}]. It shows almost the same trend of outflow rate by analysis of long term hydrological data in this watershed. (*Zainal, E. et.al*, 2012). It understood that the function of reducing the flood flow is improved.

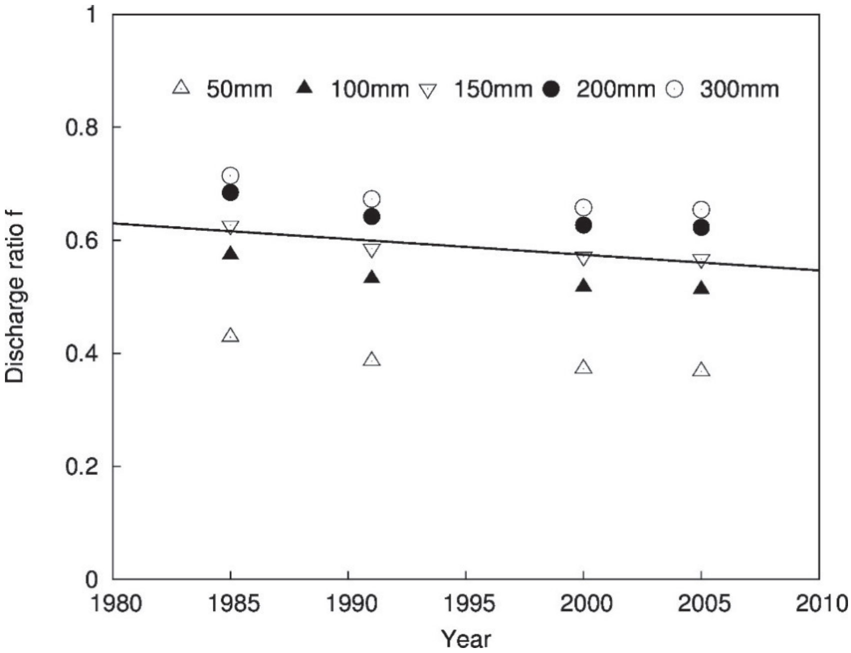


Fig 4. 6 Change of the direct runoff rate over period with rainfall event variation

4.4 Evaluation of Green Dam function

In this study was explained properties of the base rock layer by growth of the forest does not change according to analysis. The coefficients of the hole from bottom tank that related to the vertical permeability coefficient doesn't change. The flow characteristics changes due to the growth of the forest and groundwater recharge amount also found to increase. This phenomenon can be explained by the schematic diagram as shown in figure 4.7. The soil layer thickness associated with the growth of the topsoil layer with increase of coarse pores and due to increase in amount of the crown that causes the occurrence of surface flow suppressed, reduction in peak runoff.

Surface runoff was delayed and rainwater that temporarily stored in the topsoil layer was increased. This phenomenon was expressed by tank model as a temporary increase in water level when the rainfall events in the first stage tank. In the event that the top soil layer, the first stage tank is assumed to be in correspondence and rainwater temporarily stored in the topsoil layer is increased. Then, according to equation (4) the penetration into the ground water zone is increased. As a result, even if there is no change in the characteristics of vertical infiltration due to the growth of forests, but reduction of direct runoff and improvement of green dam function of increased groundwater recharge amount can be seen. It is described using a single-stage tank with simplified equation (2) to (5) as follows. The outflow rate of side holes q [mm/d] in equation (2) with water level 0 to equation (6). The similar permeation high i [mm/d] of the bottom tank in the equation (3) indicated to equation (7). Here, a, b are coefficient [d^{-1}] of side hole and coefficient of the penetration hole, respectively. Eq. (8) was described change of water level in any point time h [mm] that assume amount of rainfall and evaporation can be defined as 0.

$$q = ah \tag{4.6}$$

$$i = bh \tag{4.7}$$

$$\frac{dh}{dt} = -q - i \tag{4.8}$$

Therefore, equation (6), (7) and (8) can be modified as the following equation,

$$\frac{dh}{dt} = -(a+b)h \tag{4.9}$$

Solving differential equation of the equation (9) in the variable separation method, the equation (10) is obtained.

$$h = Ce^{-(a+b)t} \qquad (4.10)$$

Where C is the integration constant. Therefore, from equation (7) and (10), penetrating height i is expressed as equation (11).

$$i = bCe^{-(a+b)t} \qquad (4.11)$$

Here, the total amount of penetration from the surface soil layer [mm] can be expressed as equation (12) as the integral of penetration height i of the integral from $t = 0$ to infinite.

$$I = \int_0^{\infty} bCe^{-(a+b)t} \qquad (4.12)$$

Thus, the total penetration of the surface soil layer from equation (12) that a, b, C can be expressed as equation (13). Similarly the total outflow amount Q [mm] from the surface soil layer can also be expressed as equation (14).

$$I = \frac{bC}{a+b} \qquad (4.13)$$

$$Q = \frac{aC}{a+b} \qquad (4.14)$$

Here, discharge coefficient a can be considered as a model coefficient representing the delay of the outflow rate due to increase in surface soil layer and growth of the forest. The equation (13) and (14) was explained the runoff coefficient was decreased by growth of forest, slow in flow rate, penetration increased even penetration coefficient b is fixed. Meanwhile, equation (14) can be deformed further as follows.

$$Q = C - \frac{bC}{a+b} \qquad (4.15)$$

Thus, it is clear that the total outflow amount Q is decreased with the decrease of the discharge coefficient a. Figure 5 explain the simply phenomenon increase in vertical infiltration capacity by growth of forest and simple factor of delay the runoff coefficient in the top soil layer.

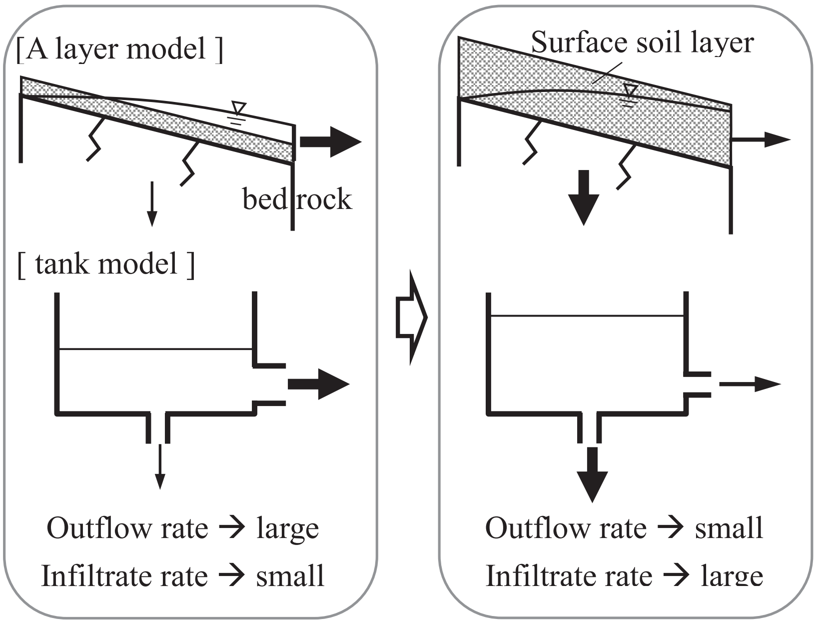


Fig 4.7 Concept of flow characteric change due to forest growth

4.5 Conclusion

In this study that study area in the small watersheds of mountain forest in Nakatsugawa City, Gifu Prefecture has been analyze the change of runoff characteristic caused by growth of the forest by using the hydrological observation data and tank model over 24 years and evaluate the green dam function. The result are finding as follow;

- The growth of the forest has been confirmed by the analysis of satellite data.
- The change of tank model coefficients shown downward trend from the side outlet hole and found that the peak outflow of flood can be suppressed due to forest growth.
- There is difference in the trend of tank model coefficients when the E_t presence and absence, but it is relatively small impact on the characteristics flow.
- The rainfall-runoff analysis by tank model indicates that reduced in the tendency of -0.0029 [y^{-1}]. This tendency is almost the same as the analysis result of the long-term hydrological data.
- Changes in the forest catchment due to the forest growth. The base rock layer does not change according to analysis. The coefficients of the bottom tank that related to the vertical permeability coefficient doesn't change. The flow characteristics changes due to the forest growth and groundwater recharge amount also found to increase. Flood mitigation features in change of the lateral outlet coefficients and the improvement of water resource storage function was indicated.

Chapter 5

Development of hydrological function index values of water conservation forest by relationship long term water balance and NDVI

5.1 Introduction

Forest management and conservation are promoted according to the “Forest and Forestry Basic Plan” based on the “Forest and Forestry Basic Law” as well as the “National Forest Plan”, “Prefectural Forest Plans,” and “Municipality Forest Plans” to improving multiple functional roles (*Annual Report on Forest and Forestry in Japan Fiscal Year*, 2013). The watershed protection function of forests is also referred to as the green dam, has been widely recognized as one of the most important forest function. Watershed function is classified into a flooding mitigation function for reducing the peak discharge during floods, water resources reservoir function for maintaining the river flow when no rain or drought mitigation functions. These features are overall results of the various hydrological processes, soil layer thickness, permeability, the various elements of the crown sparse, etc. As a matter of fact, to evaluate the watershed function of each forest is a difficult problem. Consequently, a better understanding of hydrological processes for forest management area is also needed for evaluation of watershed function.

Evapotranspiration from forest is one of the major hydrological components influencing the water cycle. It is can define as the total amount of water that is returned to the atmosphere from the surface of the soil, water bodies and vegetation by the influence of climatic factors and physiological vegetation. *Zhang et al.,* (2001) discovered the long term impact of vegetation changes on mean annual evapotranspiration at catchment scales by reviewing and collating over 250 catchments from around the world. They suggest that long term average annual evapotranspiration under the same climatic conditions is mainly determined by vegetation characteristic, and the difference may be attributed to the way different kinds of vegetation use soil water. Moreover, *Komatsu et al.*(2008) examined the change of water yield because of forest management such as thinning of coniferous plantation and obtained the evapotranspiration from the catchment water balance measurement.

In spite of the fact that evapotranspiration processes are complex and difficult to measure, the estimation may be represented by indirect procedures through correlation with meteorological factors and is called potential evapotranspiration (PET) that has been proposed. *Alkaeed et al*. (2006) compared the Thornthwaite, Hargreaves, Hamon, and the R_s- and R_n- methods with FAO56-PM on their daily performances under the given climatic condition in the western region of Fukuoka City. When considering the availability and reliability of the input data, the use of these methods are suggested as practical methods for estimating evapotranspiration, if the standard FAO56-PM equation can't be used due to the complexity of its input parameters. In recent studies, Priestley-Taylor PET method gave the most reasonable estimates of forest PET compared with FAO56 grass reference and Hamon PET (*Rao et al*., 2011). For the reason that the net radiation data are generally unavailable in Japan, Priestley-Taylor PET method is not helpful for the evapotranspiration estimate. However, the conclusion mentioned that Hamon method was easy to use in the event that accompanied by correction factor, especially for regions lacking detailed meteorological data. *Xystrakis et al*. (2011) also suggested that the Hamon equation perform considerably well.

Some procedures use to predict evapotranspiration involve some type of PET and the combination method to derive the actual evapotranspiration. For the reason that the Hamon PET can't be used for directly estimating forest PET, then a correction factor proposed by *Tsukamoto* (1992) involving Japan's forest area was introduced. It is a simple enough to provide the correction factor and is called as an evapotranspiration factor.

$$e_t = f \, . \, e_p \tag{5.1}$$

where: e_t is actual evapotranspiration, f is evapotranspiration factor and e_p is PET.

In this study, the Hamon PET is considering for estimation e_p and the water balance method is considering as e_t. On the occasion of determination of actual evapotranspiration from catchment water balance must following some criteria, which assume negligible change in catchment water storage by using long term data (*Brutsaert*, 2005). It can often be assumed that the storage returns to the same value at the end or the beginning of the same season in the previous year; therefore, an annual period is usually considered long enough to make water storage negligible.

The concept requires closer specification if it is to serve as an unequivocal parameter and need validation of PET method for over longer period. *Shimizu et al*. (2003) and *Kosugi et al.* (2007) validated forest water use using the eddy covariance method agreed well with the water balance losses in some Japan forest area. In addition, the heat fluxes of eddy-covariance measurements over a forest on steep slopes in region with cool temperate evergreen coniferous forest that experiences snowfall have a similar accuracy as those over other topography (*Saitoh et al.*, 2011). In order to assess the validity of the method, we compared eddy covariance evapotranspiration adjusted using the energy budget for 3 years over a nearby study site and used the "reference of evapotranspiration factor" by *Tsukamoto* (1992) as the standard way to represent the correction factor of forest PET, thus make factor of evapotranspiration PET estimates comparable.

The direct methods such as satellite-based vegetation index, NDVI methods, to estimate evapotranspiration that has been convert potential evapotranspiration into actual evapotranspiration (*Senay et al.,* 2011). *Kondoh et al.* (2001) demonstrated that the evapotranspiration was well correlated with NDVI. A simple linear regression model is developed to establish a general relationship between a normalized difference vegetation index (NDVI) from satellite data and the crop coefficient that calculated based on estimation of crop evapotranspiration (*Kamble et.al*, 2012). By using the same logic, the similarities between forest evapotranspiration factor and NDVI have potential for modeling a factor evapotranspiration as a function of the vegetation index, also for modelling runoff index.

The objectives of the study were to: (1) analysis water balance in study site (2) develop ways for estimate forest evapotranspiration factor by ratio of actual ET derived from catchment water balances over the Hamon PET across a range of the long term availability data, (3) develop ways for estimate runoff index, (4) evaluate the watershed function easily by using the hydro meteorological data, satellite data and GIS in the area that inadequate observation data. In this study, we also attempt to develop a method to assess the watershed function easily by using the hydrological observation data and satellite data in small forest watersheds that have long-term observation of the runoff data.

5.2 Methods

5.2.1 Hamon PET

Among various PET, *Hamon* (1960) expression is a method to calculate a simple monthly average potential evapotranspiration by using the mean monthly temperature and daylight hours which depends on latitude. It does not require fine weather observation, so it is possible to easily calculate the potential evapotranspiration in all parts of the country. In Japan, the temperature and daylight sunshine as the input parameter available from Automated Meteorological Data Acquisition System (AMeDAS). Hamon developed a simplified expression for potential evapotranspiration, represented by

$$e_p = 0.14 D_0^2 P_t \tag{5.2}$$

where, e_{p} is the potential evapotranspiration in mm/day; D_0, the possible hours of daily sunshine in units of 12 hours; P_t, the saturated water vapor concentration at the mean temperature in g/m^3. The P_t variable is expressed as

$$P_t = 216.7 \left(\frac{e_s}{T+273.3}\right) \tag{5.3}$$

where, e_s is the saturated vapor pressure in hPa over water at temperature (T) in ºC was given by Tetens [21] as

$$e_s = 6.1078 \times 10^{17.27T/(T+273.3)} \tag{5.4}$$

5.2.2 E_t Estimation

Over a land surface area, the actual evapotranspiration rate over a period of years can be expressed in terms of the water balance equation, which for the study purpose can be written as follows (*Ward et al.*, 2004):

$$e_t = P - Q \tag{5.5}$$

where, P is the precipitation in mm; Q, the streamflow in mm; e_t, actual ET. Here, it must be applied over sufficiently long period data, so that water storage become less important. The water storage in the basin is not easily determined, an annual period is usually considered long enough to make water storage negligible.

The long-term hydrological data (precipitation and runoff observation data) for the period of 1985 to 2007 has been measured in each catchment, but fewer data have not been recorded on 1995, 1996 and 1997 caused by instrument trouble. Monthly and annual e_t was calculated for the years 1985 to 2007 as well as PET.

5.2.3 Validation

5.2.3.1 Monthly evapotranspiration factor

The evapotranspiration factor in the PET models are an empirical that has been derived for many land surfaces for estimating either PET or AET. *Zhou et al*. (2008) and *Lu et al.* (2005) indicated difference evapotranspiration factor for forest Hamon PET in differ site. However, it was unclear if this parameter appropriate for forest. Thus, the comparison of monthly evapotranspiration factor on each catchment forest site has been shown on table 5.1, fig. 5.1 to assess the validity of both methods and to evaluate the amplitude of seasonal fluctuations of evapotranspiration factor over the long term and to provide a more accurate PET estimate.

Table 5.1 Monthly evapotranspiration factor for Hamon forest PET

Month	Aichi	Kiryu	TKC	GS
1	1.60	1.80	0.96	2.53
2	1.40	1.48	1.42	1.90
3	1.30	1.63	1.31	2.18
4	1.10	1.12	1.31	0.85
5	0.95	0.93	1.15	0.86
6	0.80	0.75	0.95	1.01
7	0.85	0.68	0.86	0.36
8	1.05	0.80	0.93	0.78
9	1.20	0.92	0.93	1.14
10	1.50	1.48	1.03	1.23
11	1.50	1.62	0.91	1.58
12	1.55	1.23	0.91	1.70

The analysis results from short-term water balance method at Kiryu site in Shiga Prefecture and Higashiyama site in Aichi Prefecture have been reported for the seasonal fluctuations of the evapotranspiration factor (*Tsukamoto et al*., 1992). *Saitoh et.al* (2011) evaluated energy balance closure by eddy covariance method was carried out at Takayama site (TKC site, 36º08'N, 137º22'E; 800 m a.s.l.). The e_t in TKC site was obtained using three years of continuous data (2006 to 2008). The average monthly evapotranspiration factor over 3 years on TKC site and over 23 years on GS study site for Hamon PET was calculated according to the equation (1) base on evapotranspiration eddy covariance and water balance measurement, respectively. The f_{ep} estimated value of January and December on the TKC site were lower than other site. It may contain a slight error in the winter season; therefore the value has been underestimated. In the other hand, the f_{ep} of GS site seems over estimated, thus f_{ep} for winter appears to be a poor correction factor for Hamon PET. In general, winter PET show no systematic underestimation but fail to reproduce the spatial variability of PET (*Prudhomme et.al*. 2013). In spite of that, the variations of monthly evapotranspiration factor both site are well corresponded for other season. It suggest that possible to obtain the evapotranspiration factor for each method in growing season. Thus, the f_{ep} of GS was confirmed and validated to provide a good alternative for estimate the evapotranspiration rate when only daylight sunshine and temperature data are available.

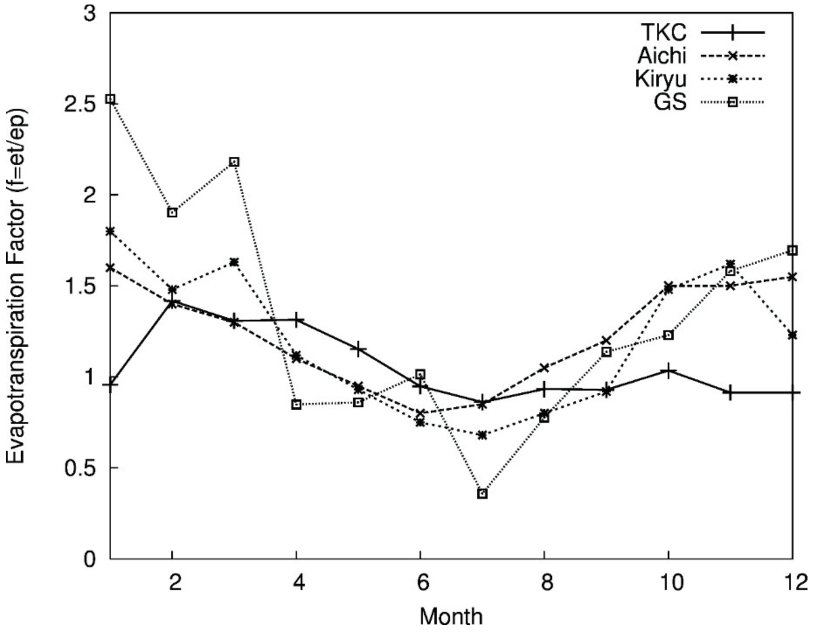


Fig 5.1 Monthly evapotranspiration factor

5.2.3.2 Fluctuations of GS Monthly evapotranspiration factor

The monthly average and range of evapotranspiration factor for Hamon forest PET at GS site are shown in fig. 5.2. The range of fluctuation in the monthly evapotranspiration factor was large in the winter season (December to March), average over 23 years indicate that the standard error of the mean (SEM) were 0.84; 1.7; 0.9; and 2.6, respectively. It probably due to e_p estimation value are lowest so might implicated to water balance estimation. During the winter there is little available sunshine time, less temperature, less leaf and little plant growth. Moreover, the winter precipitations occur as snow or rain that contributed to fluctuations of monthly water balance. Snowfall has a large impact on hydrologic fluxes because snowfall is normally stored for a significant period of time in the snowpack and is later released as melt water. Changes to land the use, change in elevation and vegetation through the basin result have profound changes on the snow cover and on magnitude of seasonal sublimation (*Pomeroy et al.* 1998).

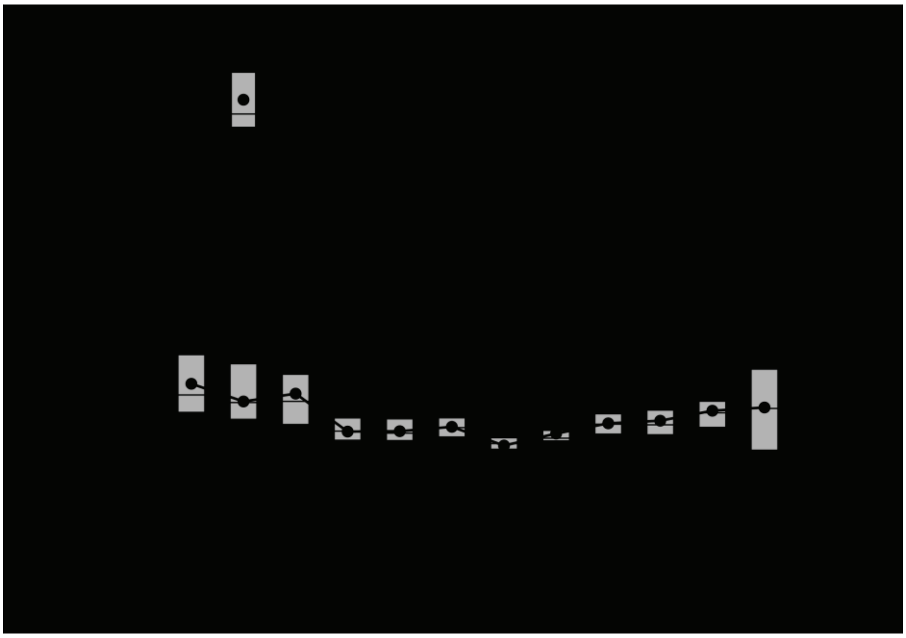


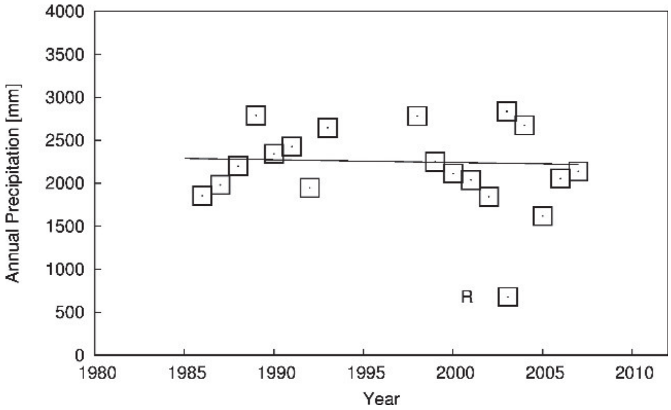
Fig 5. 2 The monthly average and range of evapotranspiration factor over study periods

5.3 Analysis of Long Term Variability

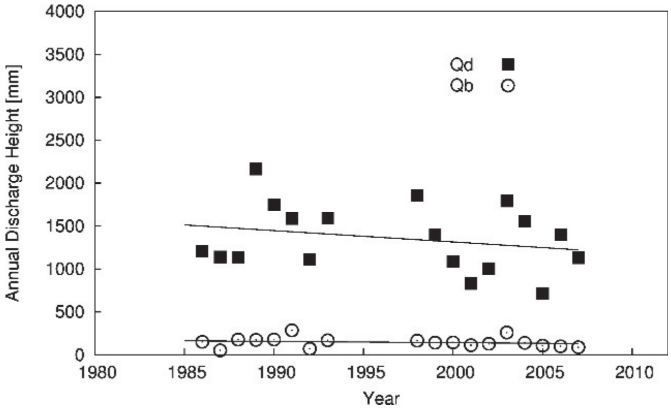
5.3.1 Water Balance

The linear trend analysis was used to analyze long term variations of the annual water balance in GS that shown in fig. 5.3. Annual precipitation and runoff are summarized from observation daily rainfall and discharge data. By subtracting observed annual runoff from annual precipitation (Eq.5), annual loss that assumed as actual evapotranspiration is obtained which values of all variables fluctuate over 23 years. Direct runoff is separated from the base flow by hydrograph separation (*Hewlett et al.* 1966). The extraction of linear trend of the water balance components: rainfall has a slightly changed trend, R= -3.143(year) + 8528; direct flow has a significant decreasing trend, Q_d= -13.211(year) + 27735; baseflow trend has a slightly changed trend, Q_b= -1.454(year) + 3048; loss (=actual ep) has a strong increasing trend, e_t= 11.52(year) - 22225; and trend of potential evapotranspiration, e_p= 0.267(year) + 97. These means rainfall and base flow tends to small change by -72 mm and -33 mm, respectively; direct flow decrease by -304 mm;

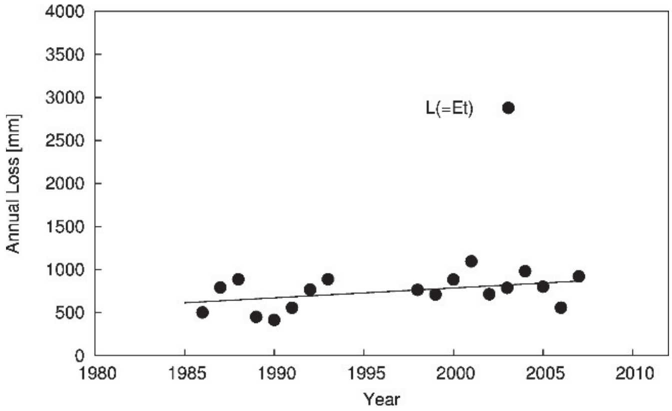
loss (actual ep) increase by 265 mm over 23 years period. Furthermore, the order of potential evapotranspiration from Hamon expression and annual loss almost same. This result founded that the Hamon PET without correction factor has been underestimate actual evapotranspiration (*Xu et al.* 2001). In the previous chapter, climate factor shown weak trend in temperature, therefore the climate variability cannot explain in the increase in actual evapotranspiration. The interpretation is forest growth expected causes the increase in evapotranspiration as well decrease in direct runoff.



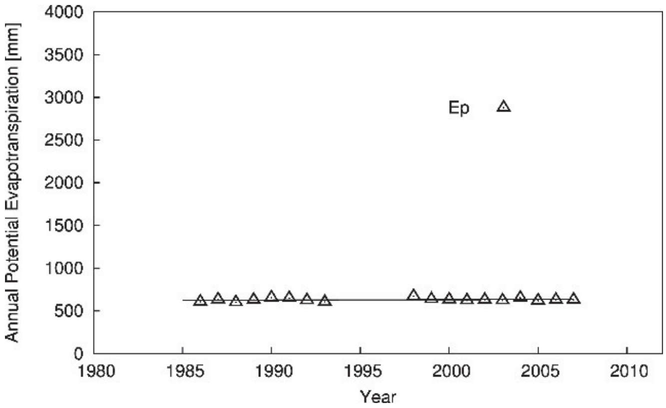
(a) Rainfall (*R*)



(b) Direct flow (Q_d) & Baseflow (Q_b)



(c) Loss (=Actual Evapotranspiration, e_t)



(d) Potential Evapotranspiration, e_p

Fig 5.3 (a), (b), (c), (d) Long-term annual water balance

5.3.2 NDVI Trend

Kojima et al. (2013) has been analyzed the long term Normalized Difference Vegetation Index (NDVI) in the study area by using the satellite image, which consisting of the Landsat/MSS, Landsat/TM and Terra/ASTER image. It was analyzed for 1984 to 2010 with atmospheric correction using 6S code (Second Simulation of the Satellite Signal in the Solar Spectrum). The observation of the vegetation has been carried out traditionally through NDVI, which is calculated using the radiometric information obtained for the red (R) and near-infrared (NIR) wavelengths of the electromagnetic spectrum (NDVI = ((NIR) - R)/ ((NIR) + R)); that respond to changes in the amount of green biomass (*Jensen et al.* 2007). The long term of NDVI trend analysis performed on the fig. 5.4 that positive and significant values indicate an increase in the vegetation biomass, which occurred during the study period in the GS, GU, and MR forest catchment. The significant correlation coefficients (r) were 0.92, 0.82 and 0.9 in each catchment, respectively. It was confirmed that forest growth due to the forest management activities.

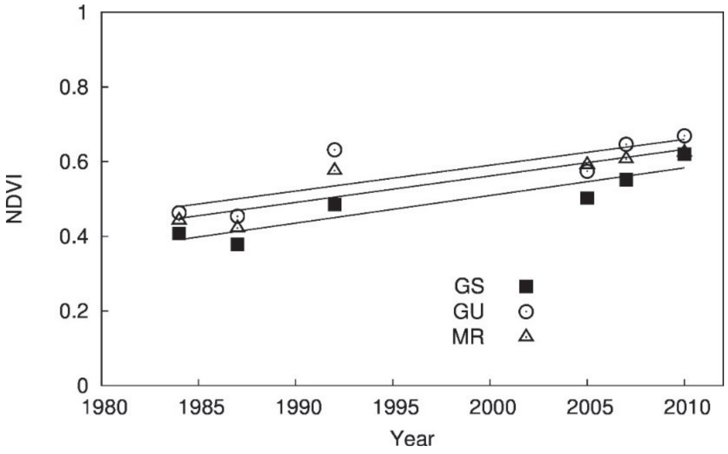


Fig 5.4 Long-term variations of NDVI

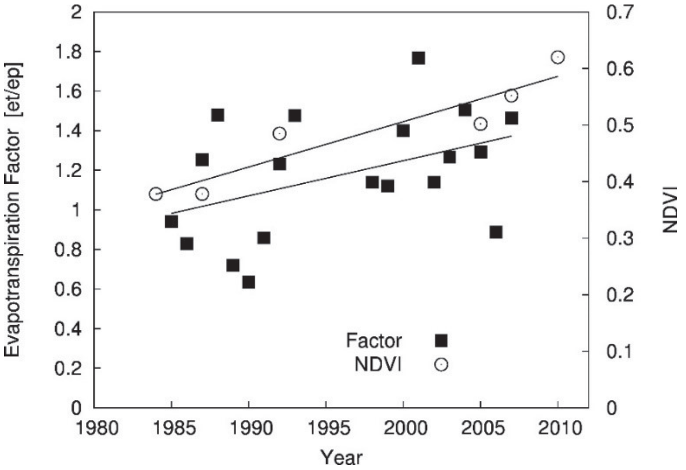


Fig 5.5 Long term variations of (e_t/e_p) and NDVI

5.4 Hydrological Function Index

5.4.1 Correlation of Potential Evapotranspiration Factor and Normalized Difference Vegetation Index (NDVI)

The evapotranspiration factor is used to adjust the Hamon PET to account for influence of the forest growth on the evapotranspiration process. Fig. 5.5 shows the trends of NDVI and evapotranspiration factor variables look similar. This means that both tree evapotranspiration and light absorption increase roughly at the same rate in long term annual estimation. The relationship between long term NDVI data and observed evapotranspiration factor for forest study area on fig.5.6 was found linear, with the correlation coefficient (r) is 0.55 and the proportion of variability (r^2) is 0.30 between them. The develop correlation equations are given below

$$f_{et} = 1.40\ NDVI + 0.488 \tag{5.6}$$

The simple equation (6) may help to monitor evapotranspiration rate in the growing season by using NDVI time series data and combining with Hamon PET estimation. Furthermore, developing relationship of evapotranspiration factor and NDVI could enhance the accuracy in estimating evapotranspiration factor values.

5.4.2 Correlation of Runoff coefficient (f_{qd}) and Normalized Difference Vegetation Index (NDVI)

This work develop the correlation equation between observed f_{qd} and vegetation trough NDVI over study site (see fig. 5.7). The correlation equations are given below;

$$f_{qd} = -0.255 NDVI + 0.689 \tag{5.7}$$

The equation (7) may help to estimate runoff coefficient in area that inadequate observation data by using NDVI time series data. The relationship of observed f_{qd} and estimated f_{qd} that present in fig. 5.8 had a positive correlation with the proportion of variability (r^2) is 0.15 between them. In this study, a low R-squared due to the fact that limited data availability and assume require more variable.

Hwang et al. (2012) found strong correlation by computed the hydrologic vegetation index defined as the increase of NDVI per unit increase of the topographic wetness index; the topographic wetness index is defined by the properties of land surface slope. Here, equation (8) show f_{qd} estimation with adjustment by using slope of physical landform.

$$f_{qd} = -0.339NDVI + 0.00761i + 0.526 \qquad (5.8)$$

The relationship of observed f_{qd} and estimated f_{qd} that present in fig. 5.9 had a positive correlation with the proportion of variability (r^2) is 0.3 between them. In this study, the multiple linear regression analysis was applied where NDVI and slope of land surface was added as explanatory variable.

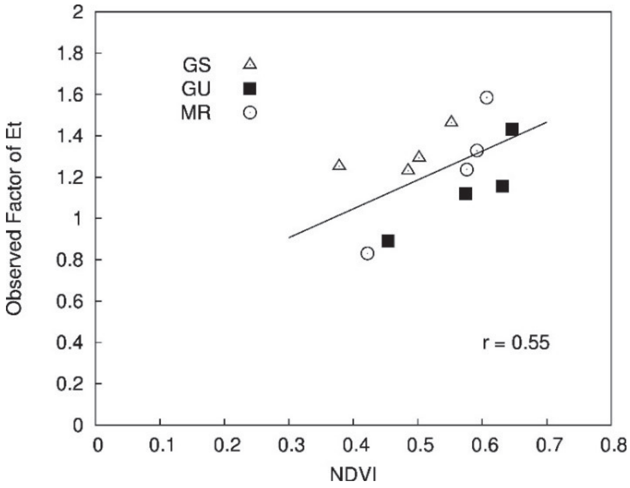


Fig 5.6 Relationship of observed f_{ep} and NDVI

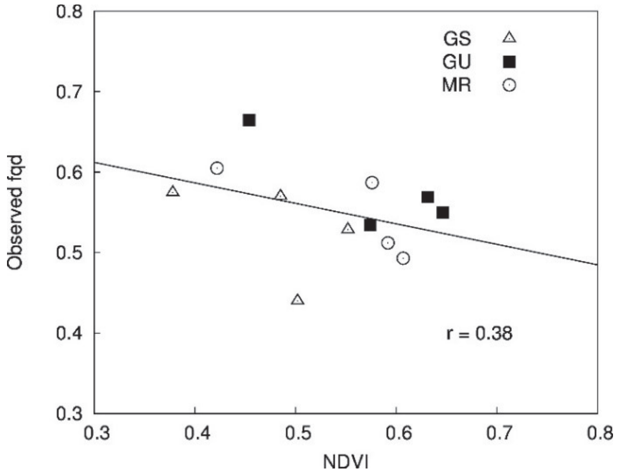


Fig 5.7 Relationship of observed f_{qd} and NDVI

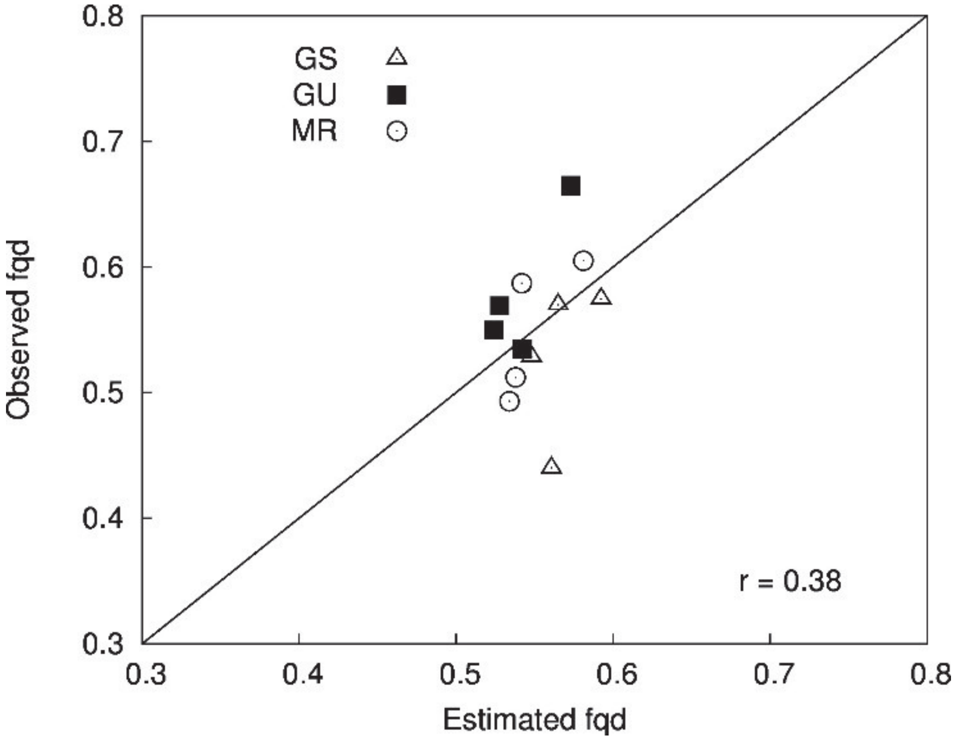


Fig 5.8 Relationship of observed f_{qd} and estimated f_{qd}

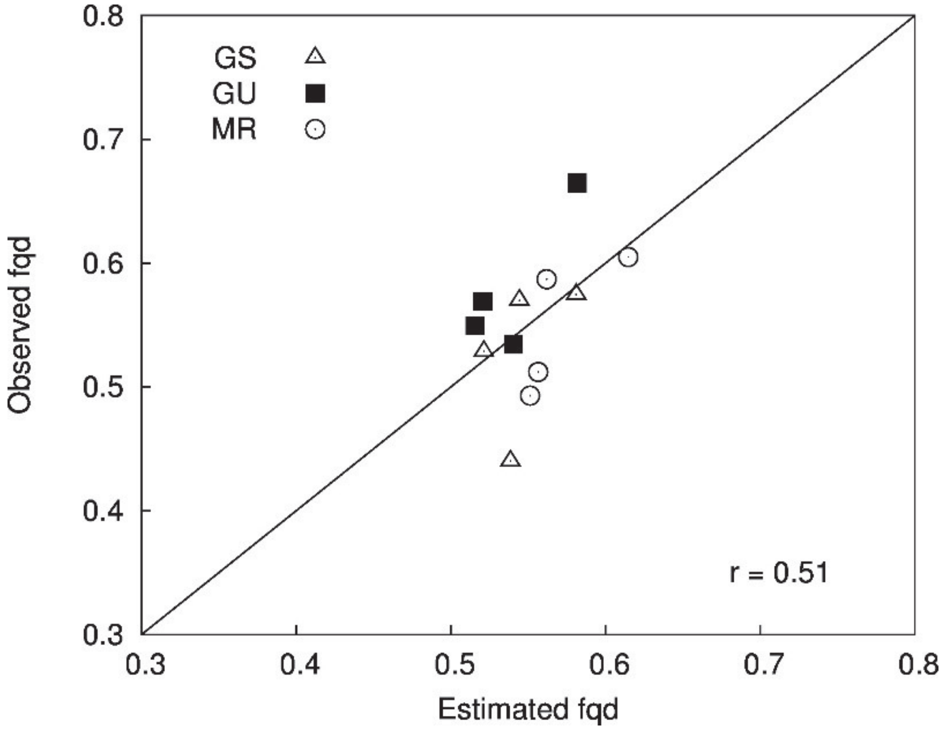


Fig 5.9 Relationship of observed f_{qd} and adjust estimated f_{qd}

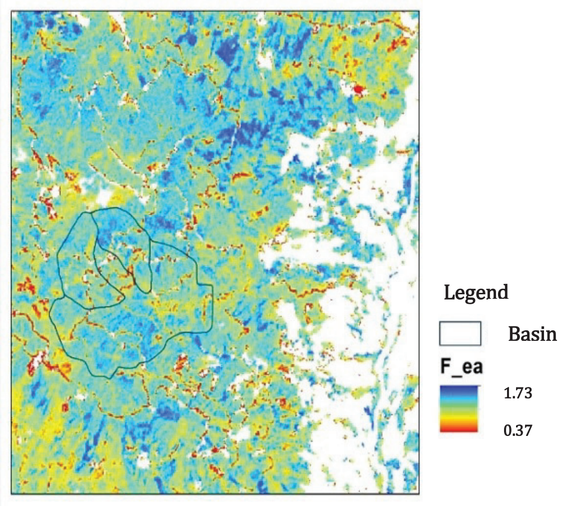


Fig 5.10 Evapotranspiration factors, f_{et} distribution image on 2001

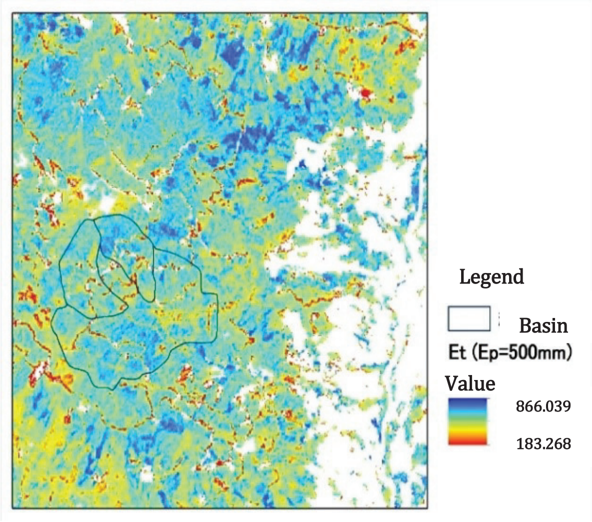


Fig 5.11 Actual evapotranspiration, E_t distribution image on 2001

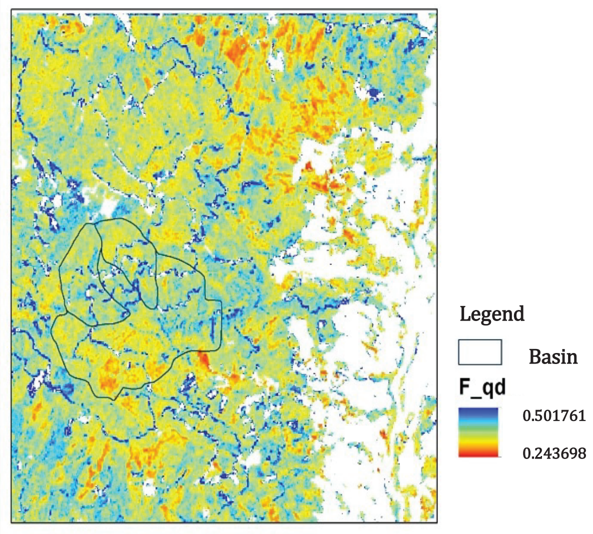


Fig 5.12 Runoff index value, f_{qd} image on 2001

5.4.3 Evaluation watershed function by using Geographic Information System (GIS)

This section presented the successful implement of linear model regression methods in ArcGIS environment demonstrated an alternative approach that can estimate hydrological function index over study area by using ASTER image on 2001/5/17. Fig. 5.10 presents an example distribution of evapotranspiration factors, f_{et} from ASTER image on 2001 that estimated using equation (6). Fig. 5.11 presents the application and testing of equation (1) to estimate the actual evapotranspiration, E_t (mm/day) by inputted potential evapotranspiration data as 500mm/day over study area. Fig. 5.12 presents testing of equation (8) to estimate runoff index value, f_{qd} as a function of NDVI and land surface slope over study area, which means high value is low flood mitigation function. In other word, it can reduce high flow by storing them in the soil, which means less chance for floods and enhance low flow which means less chance for droughts.

5.5 Conclusion

The long term annual water balance equations is formed by process of precipitation, actual evapotranspiration and runoff. Water balance analysis suggest that direct runoff decrease and actual evapotranspiration (AET) increase is mainly associated with forest growth. Due to increasing of forest cover, evapotranspiration losses in study site more able to increase than potential evapotranspiration (PET). However, no significant change was found in the long term annual precipitation.

The long term annual PET estimated from the Hamon methods were correlated with the AET values derived from the water balances. This study produce a useable the monthly evapotranspiration factor for Hamon PET during the growing season. The weak correlation shown in comparison between observation and estimation of hydrological function by NDVI in the annual period. The simple linear regression model was developed to establish a general relationship between NDVI and the evapotranspiration factor from Hamon PET. Furthermore the multiple linear regression model was developed to estimate runoff coefficient by using NDVI and land surface slope. It might be provide an effective predictive tool for determining evapotranspiration rates in forest area that lacking weather data.

In the macro perspective, less direct runoff during rainfall and no change of base flow amount over the long term in rain forest is a good forest watershed function. For the future research, it is important to accurately simulate the winter season because snowfall accumulation and subsequent melting can have such a large fluctuation and influence in hydrologic response of a watershed.

Chapter 6

Conclusion and Recommendations

Forest vegetation is among other factors, such as climate, ground cover and topography having significant influence on balance and quality of surface and ground water flows. Our long-term investigations conducted in Gamansawa catchment, Futatsumori, a typical Japanese forested mountainous catchment located in Nakatsugawa City, Gifu Prefecture, with broad objective to elucidate the hydrological functions by long-term analysis of water balance. This broad objective was divided into three parts. The first part to show the hydrological impact of forest growth by estimates the discharge ratio as parameter in reduction of water yield. Here, decreasing trend of discharge ratio was identified and suppose the rougher the relief and vegetation covered surface and the lower the compaction of the topsoil, the lower is the amount of surface runoff. The second part applied a process tank model to show the flow characteristic change and predict hydrological response as a water balance components. The result found that growth of forest over study area and indicated that decreasing trend of tank model coefficient. It explained that surface runoff was delayed and rainwater temporarily stored in the topsoil layer was increased. It is confirmed that both of the flood and drought mitigation features is improved. The third part attempted to develop a simple linear model to predict hydrological function index value by correlation between water balance components with NDVI values. Positive correlation between evapotranspiration factors, discharge ratio and NDVI was found. In addition, by using Geographic Information System (GIS) identified hydrological function index values of water conservation forest over study area. It might be provide an effective predictive tool for determining water balance components in forest area that lacking data or inadequate observation data. In spite of the fact that limited data availability, thus the precision of this model could be further improved by add more hydrological and NDVI data. However due to time and resource constrains, present study shows only in single location. In addition, the result recommended for the use only in the small-scale river basins of similar size to current study. This model might be utilized as a reliable water balance monitoring, flood mitigation and drought mitigation function. Results of this study are encouraging and suggestion to further utilization of winter data in reliable modeling of long-term monitoring of water balance.

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