STREAM WATER TEMPERATURE STUDIES AT FORESTED WATERSHEDS: A REVIEW

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ABSTRAK

Temperatur air sungai yang berpengaruh terhadap proses biologi, kimia, dan fisika yang terjadi di dalam ekosistem sungai telah menjadi perhatian utama dari sejumlah kegiatan para peneliti. Dianalisis secara statistik menggunakan root mean square (Rms), harmonik metode (A: Amplitude, φ: waktu tunda) dan perubahan dari spesifik debit (ΔQs), temperatur udara (ΔTa) dan temperatur air (ΔTw) selama periode hujan telah dilakukan dalam penelitian ini. Berdasarkan nilai-nilai fluktuasi, kita bisa mengklasifikasikan daerah aliran sungai menjadi tiga kelompok luasan DAS: kecil, menengah, dan besar. Di daerah aliran sungai besar, nilai fluktuasi Tw dijelaskan sebagai pengaruh radiasi matahari dan proses perpindahan panas, sedangkan daerah aliran sungai kecil, menunjukkan waktu yang lebih pendek bagi pola aliran yang mempengaruhi Tw. Selanjutnya, hasil analisis menunjukkan pola aliran yang berbeda, digambarkan oleh karakteristik loop histeresis antara Qs dan Tw di DAS menengah selama periode hujan. Perbedaan-perbedaan dalam loop histeresis dapat dijelaskan sebagai perbedaan Tw dan kecepatan respons terhadap curah hujan antara aliran permukaan/aliran bawah permukaan dan aliran air tanah.

Kata kunci: *Suhu air; Aliran sungai; Daeah aliran sungai; DAS*

INTRODUCTION

Research background

Because most physical properties of water and the rates of many chemical and biological processes in water are expressed as functions of temperatures,[1,2,3] stream water temperature has a vital role in various processes that determine whether an aquatic environment is suitable for fish, organisms and human being. For example, most aquatic species have specific ranges of stream water temperature that they can tolerate.[4,5]

Human use of stream water may also be affected by stream water temperature. The efficiency of water purification and treatment methods, the palatability of domestic supplies, the effectiveness of irrigation, the economics of commercial aquaculture and industrial processes requiring cooling water, and the suitability of water courses for recreation, are related to stream water temperatures.[6] Concern on natural water quality has increased markedly because of the greatly increased potential for human influence on water quality that has accompanied economic and technological development. Forested watersheds as one type of natural water sources are an important subject of water quality research. Studies on forested ecosystems are important and beneficial in improving water quality and storing water quantity for human using.

The climate changes of mountain and forest regions are especially complex because of their temporal and spatial variability, and are poorly recorded by existing systematic records. The climate changes will inevitably impact forested rivers. As vegetation and soil-forming processes respond to changes in stream water temperature and precipitation, infiltration capacity, water yield, stream chemistry, and slope stability will change. Changes in the magnitude, frequency, duration, temperature, and predictability of flow play an important role in regulating river ecological processes and patterns.[7]

The lack of consideration on the aspects of watershed area and rainfall events, which could play important roles in changes and fluctuations in stream water temperature, has suggested the necessity of its investigation as aim of this study.

THE PARAMETERS CONTROLLING STREAM WATER TEMPERATURE

Stream water temperatures are primarily controlled by the exchange of heat across the water surface (atmospheric heat exchange). In addition, heat inputs into the stream water associated with inflows from reservoir release, groundwater, melt water and overland runoff, or heat content of wastewater and cooling water discharges may have strong secondary effects on stream water temperature.[2] The early studies by Edinger *et al.* (1968) stated that the atmospheric conditions have influence on heat transfer at the water/air surface. All the heat exchange processes across the air-water interface are the most important.[9] The heat transfer between the stream and its surrounding environment is composed of the net heat exchange between the stream water and atmosphere and the net heat exchange between the stream water and the streambed.

The meteorological parameters, watershed conditions and flow path processes were involved in stream water temperature changes. The parameters which emerge from Figure 1, there are at least six main modes of energy transfer in stream water temperature: short wave solar radiation, long wave radiation exchange between the stream-the adjacent vegetation and the stream-the adjacent the sky, evaporative exchange between the stream and the air, convective exchange between the stream and the air, conduction transfer between stream and streambed, and groundwater exchange with the stream. The importance of each mode varies according to the condition. In every condition, there are always several energy transfer modes involved and this makes it difficult to establish precise predictive equations for each mode for streams in natural settings. It could be explained that the various stream geometry, meteorological and hydrological components determined stream water temperature.

Generally, stream water temperature has a strong relationship with air temperature. Some studies show that meteorological (air, solar radiation, humidity, rainfall) and hydrological (water discharge, groundwater percentage) parameters influenced stream water temperature changes.[10,11,12,13,14] In addition, riparian vegetation can also directly affect stream water temperature by intercepting solar radiation and reducing stream heating. The natural process of heating and cooling of streams is highly dependent on meteorological conditions and physical characteristics of streams.

Stream water temperature and hydrological processes

Stream water temperature is as a supplementary tracer used to identify and evaluate the water sources contributing to runoff processes at forested watersheds.[15,16] Tracers can be used to obtain better insight into thermal processes and possibly to separate hydrographs into different runoff components.[17,18] The types of interactions among stream water temperature, runoff and groundwater flow depend on whether the stream is losing or gaining water in a given reach.[19] It could be indicated by the changes in stream water temperature.

METHODOLOGY

Study area

In order to gain insight into the effect of forested watershed conditions on stream water temperature, I considered stream water temperature data at 28 sites in five regions in Japan (Aichi, Kochi, Mie, Nagano, and Tokyo) for more than one year. The watershed description, particularly for geological, topological and forest type conditions for each site has been described by Subehi *et al.*[20]

Next, to compare with those observed at 28 sites, the stream water temperature data from five rivers with larger watersheds[21] were also analyzed. The sites and their watershed areas were the Shinanno (11,900 km^2), the Ota (1,540 km^2), the Tama (1,054 km^2), the Okuri (42 km^2), and the Hoshioki (6 km^2) Rivers. The watersheds of the Tama and the Okuri Rivers are urbanized, and that of the Hoshioki River is mostly covered with forest. The watershed of the Shinano River

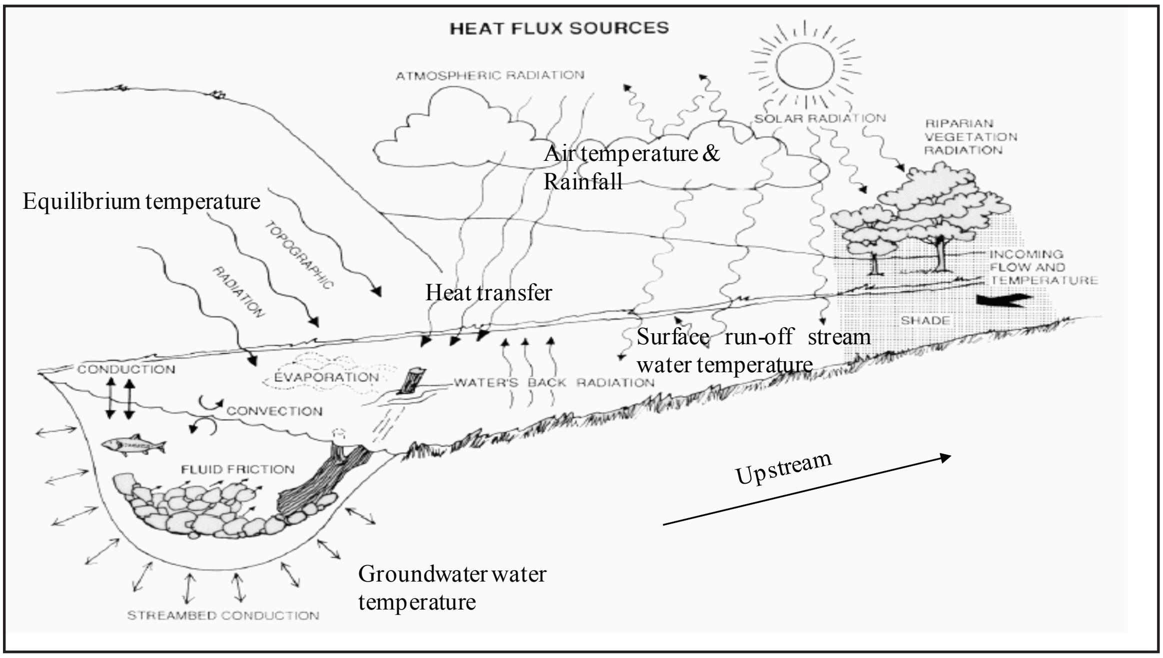


Figure 1. Representation of meteorological parameters, flow processes and stream water temperature[32]

is large in comparison with other watersheds and has diverse land uses. All site locations are shown in Figure 2.

Data collection

The data on stream water temperature and water depth were taken at intervals of 5 minutes from January 2005 to December 2005. Based on the previous published paper,[20,22] these measurements used stream water temperature sensors with a range of -30°C to 70°C, with an accuracy of 0,3°C and water depth with an accuracy of 1 mm (TruTrack WT-HR, Intech Instruments Ltd, New Zealand). Data on hourly air temperature from the nearest Automated Meteorological Data Acquisition System (AMeDAS) station to each respective stream were used for analysis. The correlation analysis between AMeDAS and field-measured air temperatures indicated fairly similar variations.[20] Water discharge was calculated from the formulas based on the given size of the Parshall flume and observed water depth.[23] In addition, precipitation was measured by a tipping bucket rain gauge (Davis Instruments Company, Rain collector Metric Standard #7852 M) located in open areas adjacent to the monitored watersheds.

Analysis of stream water temperature fluctuations at different watershed areas

In order to analyze the temperature fluctuations, I used the root mean square variation over 7 days (*Rms 7-days*). The equation can be described in the following manner:

$$Rms\ 7\text{-}days = \sqrt{(1/n)\sum_{i=1}^{n}(x_i - x_i^m)^2} \qquad (1)$$

where n represents the number of days analyzed (monthly: 28–31, yearly: 365), $_i$ is the daily average temperature (°C), and $_i^m$ is the m-day moving average of daily temperature with 7 days for m. The weekly average temperature is commonly used to quantify stream water temperature changes[2] because the weekly (7-days) timescale gives a good correlation between air and stream water temperatures.[24,25]

I also applied harmonic analysis. I used a sine function with a period of one year because other sine waves with shorter periods displayed negligible amplitudes ($R^2 = 0.935 \pm 0.020$ for the average determination coefficient value between the sine curve with a period of one year and the original data at all sites). The equation is defined as follows:

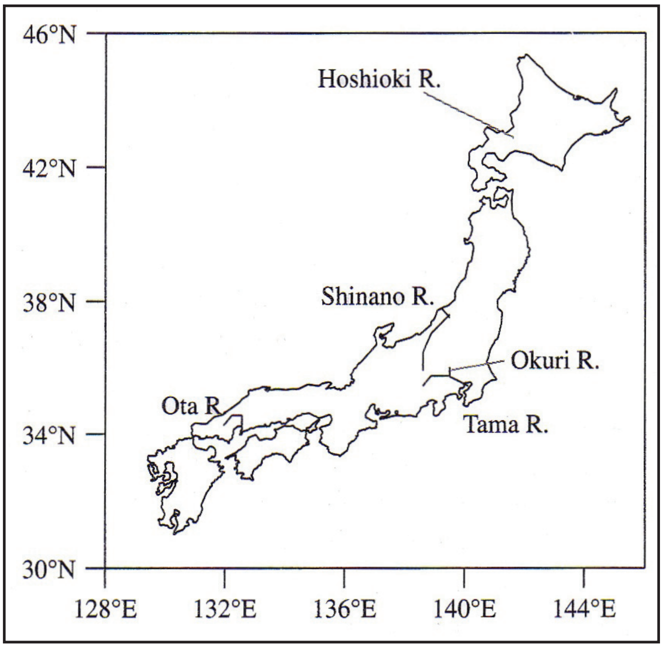
$$y_T = A \sin(c(t + \varphi)) \quad (2)$$

where y_T represents the sine curve of temperature T; t is the time (day); A is the amplitude of temperature fluctuations; c equals $2\pi/L$ (L = time period = 365 days) and φ represents the phase shift or delay time (day).

To consider the influence of watershed area on stream water temperature fluctuations in various slope gradients, I divided the watershed areas into three groups. They are small (< 0.5 ha), medium-sized (0.5–100 ha), and large (> 100 ha) watershed areas. The average and standard deviation of slope gradient (relative height/ maximum length of watershed) were shown in Table 1.

Analysis of stream water temperature changes during rainfall events

I selected 16 streams with various forested watersheds in four regions (Aichi, Kochi, Mie, and Tokyo) during rainfall for analysis. The watershed areas ranged from 0.6 ha to 56.0 ha (medium-sized watersheds) with various slope gradients from 0.08 to 0.56. In order to obtain the significant changes of stream water temperatures response, I selected the rainfall events in which the intensities were more than 5.0 mm/hour with no rainfall at least 12 hours before and after those events. Based on those criteria, I obtained 61 sets of data on stream water temperature for 21 rainfall events at 16 forested watersheds. Data were collected over all seasons except winter, due to its smaller rainfall intensity. Seasonal analysis of air and stream water temperatures should be done by separating one year into two periods.[22] Period I, warm weather, is defined by the average of air temperature being higher than that of stream water temperature during April to September. Period II, cold weather, is defined as when the reverse holds during October to March.



Solid circles: this study; *open squares*: Ozaki *et al.*,[21]
Figure 2. Study area[20]

Table 1. Average and Standard Deviation of Slope Gradients (Relative Height/Maximum Length of Watershed)

Watershed area (ha)	Slope gradient	n-data
Small (< 0.5 ha)	0.63 ± 0.05	n = 3
Medium-sized (0.5 – 100 ha)	0.35 ± 0.19	n = 24
Large (> 100 ha)	0.08 ± 0.07	n = 6

For more detailed analysis, I selected the changes in stream water temperature (*ΔTw*) and specific discharge (*ΔQs*) during rainfall events with similar intensities in different topological areas (slope gradients) and seasons (Period I and Period II). Next, the magnitude changes in stream water temperature (|*ΔTw*|) were also calculated.

In addition, two statistical test methods were employed in this paper. The *t-test* was used with the value of $p < 0.05$ for statistically significant differences and the *F-test* for the precision of the spread of data from two samples (similar or dissimilar), with the value of $p < 0.05$ for statistically significant.

Results and Discussion

Stream water temperature fluctuations over a one-year period

Figure 3 shows monthly *Rms 7-days* at all sites (28 sampling points). This indicates that monthly *Rms 7-days* of daily air and stream water temperatures changed nearly simultaneously (R^2 values 0.778 ± 0.120). This high value can be explained by noting that the seasonal variability of atmospheric conditions influenced air and stream water temperature fluctuations nearly proportionally. Stream water temperature changes both seasonally and daily, but to a lesser degree than air temperature.

The three correlation curves of *Rms Tw/Rms Ta*, *A-Tw*/*A-Ta* and delay time (φ) with watershed area are described for all sites, including the five rivers with larger watersheds (Figure 4). The correlations between the logarithm of the watershed area and stream water temperature fluctuations expressed by *Rms* and harmonic methods have similar curve patterns that show minimum values at medium-sized watersheds. Meanwhile, the delay time analysis shows a curve with the opposite tendency. In addition, the *F*-test indicated that the curve models were statistically significant ($p < 0.05$).

The high variability at points with large watersheds indicated the dominance of solar radiation and surface heat transfer on determining stream water temperature. In addition, those values at the Hoshioki River with an almost forested watershed were smaller than those at the Tama, the Ota, and the Okuri Rivers with urbanized watershed areas. Generally, at large watersheds that include urbanized areas, surface heat transfer processes and exposure to solar radiation are involved.[8,9,2] At large watersheds that are rather flat and sparsely vegetated, the water moves more slowly, with more time to absorb heat from the ground surface and from the sunlight that influenced stream water temperature fluctuations. Next, at small watersheds with steep slope gradients, runoff water (surface water) will move quickly, and the flow time of groundwater is rather short if water infiltrates the groundwater layer; then, stream water temperature could not be far from rainwater temperature which follows air temperature. Probably, this is the reason for considerably high variability of stream water temperature at small watersheds.

In contrast, the delay time values are scattered at medium-size watersheds, depending on the watershed topological characteristics that influenced infiltration rate and the groundwater flow path length. Brown[26] showed that groundwater advection was often ignored when large rivers were being modeled but that it might be significant for small streams under low flow conditions. The moderate values of slope gradient with high variations could control various flow paths as infiltrated or surface flow and bring about scattered values of stream water temperature fluctuations. The different topological characteristics determined the flow paths of groundwater. In addition, Figure 5 shows schematically that proportions of surface flow and groundwater flow, meteorological parameters, and topological characteristics in various watershed areas determined the fluctuations in stream water temperature.

Stream water temperature changes during rainfall events

The values of *ΔQs* more significantly influenced |*ΔTw*| ($p < 0.05$) than those of *ΔTa* during rainfall events at 16 sampling points (Figure 6). Rainfall amount influenced the change in stream water temperature (*ΔTw*) through the change in specific discharge (*ΔQs*).[22] The rainfall amount in each period affected *Tw* at various topological watersheds by changing the proportions of the different flow paths. Most likely, stream water

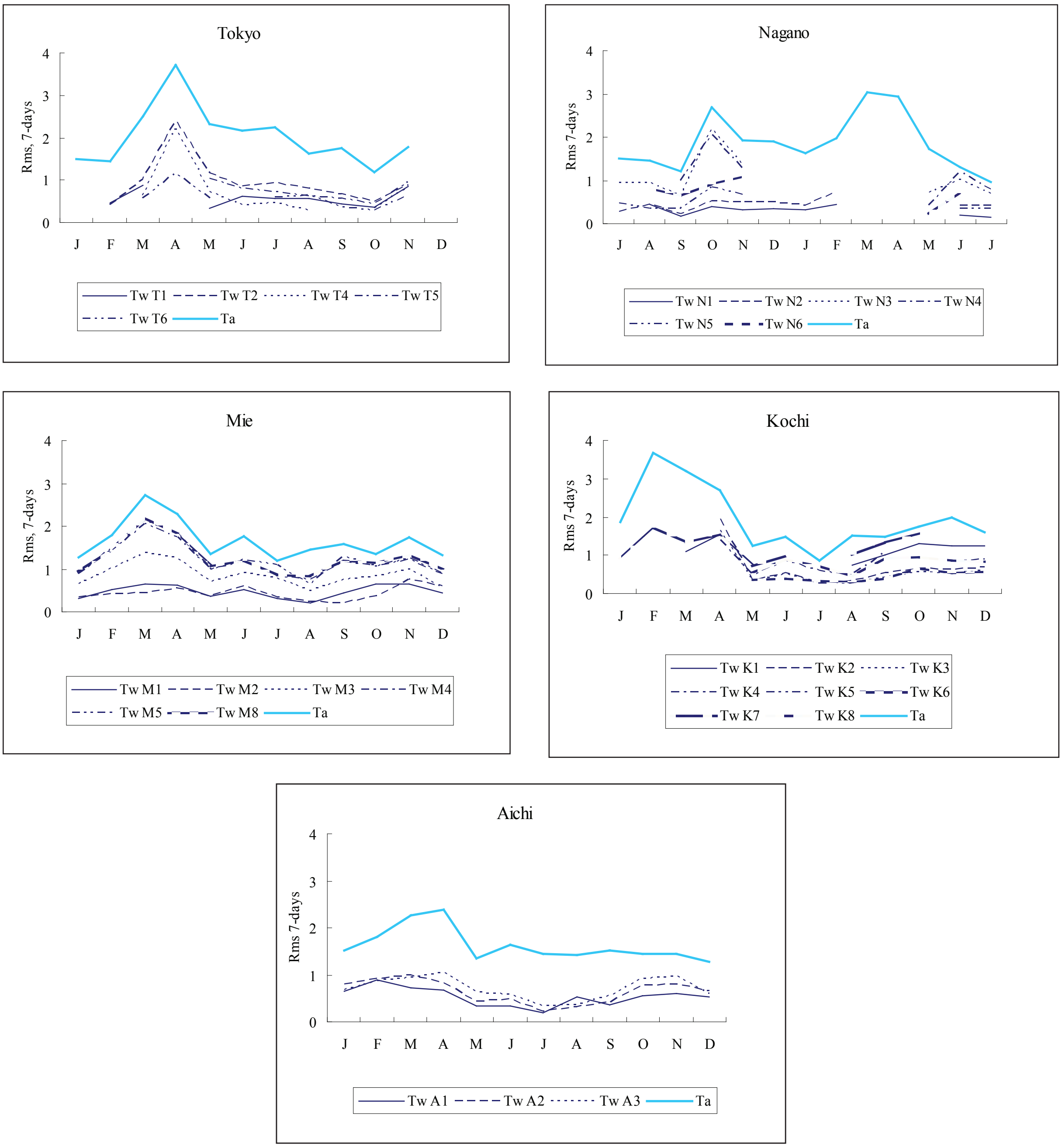


Figure 3. Monthly changes in *Rms 7-days* of daily air and stream water temperatures at five regions[20]

temperature response to rainfall/storm events resulted from advective energy inputs, primarily from surface and subsurface hill slope pathways and by groundwater, rather than from a direct heat flux by falling precipitation.[27] This is because the perennial channel system occupies only a small proportion (1%–2%) of the area of the most catchments without lakes or swamps.[28] Thus, the advective thermal energy flux from the upstream of the channel depends on the sources of runoff waters: surface/subsurface runoff and groundwater flow.

Figure 7 shows schematically the hydrological processes of rainfall, surface/subsurface runoff, percolation and groundwater flow in various slope gradients of the watersheds. Two types of surface runoff should be considered. They are overland flow due to infiltration excess precipitation, and saturation excess near the soil surface, resulting from the return outflow from

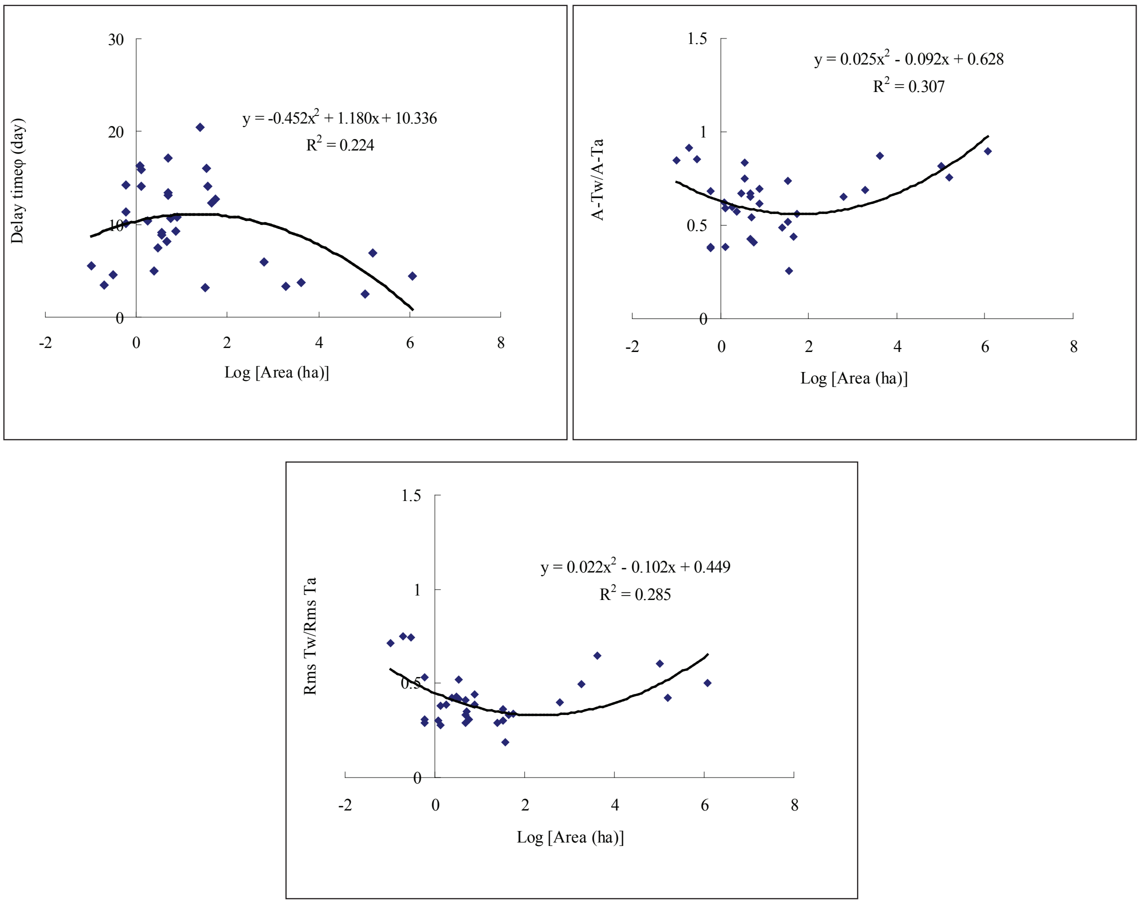


Figure 4. Logarithm of the watershed area vs. *Rms Tw/Rms Ta* (1), *A-Tw/A-Ta* (2) and delay time (3) at all sites[20]

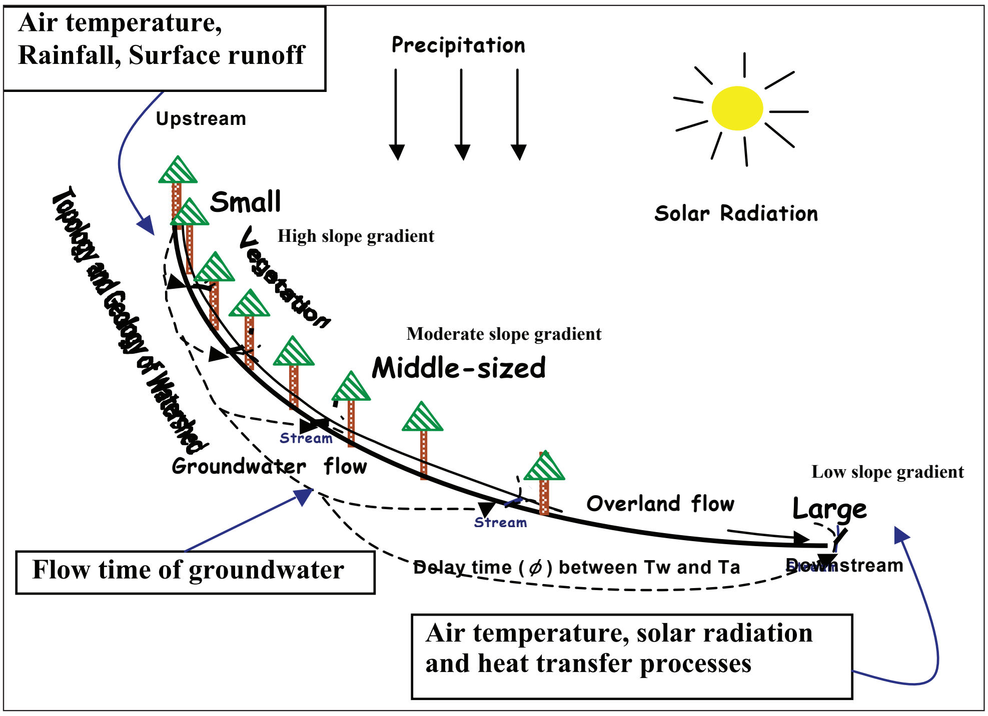


Figure 5. Representation of water and groundwater flow processes under different watershed conditions[20]

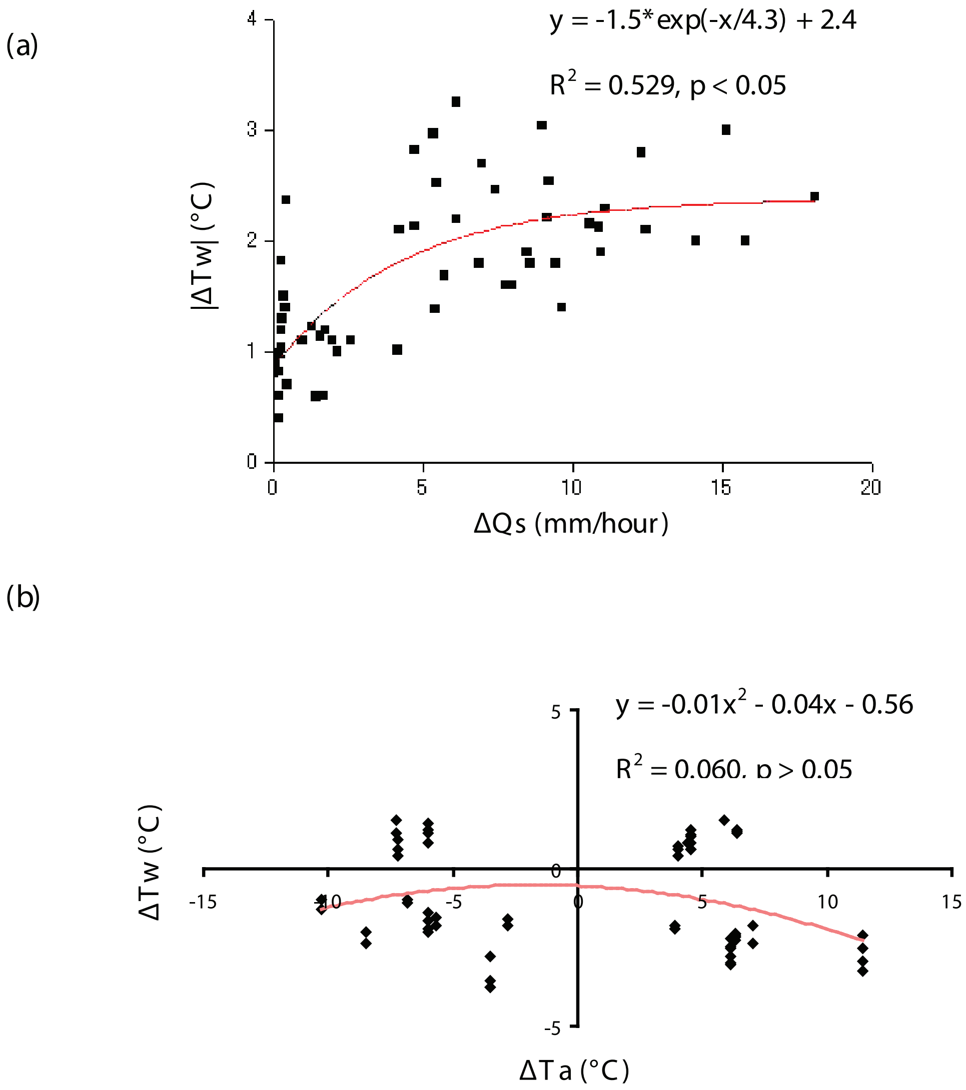
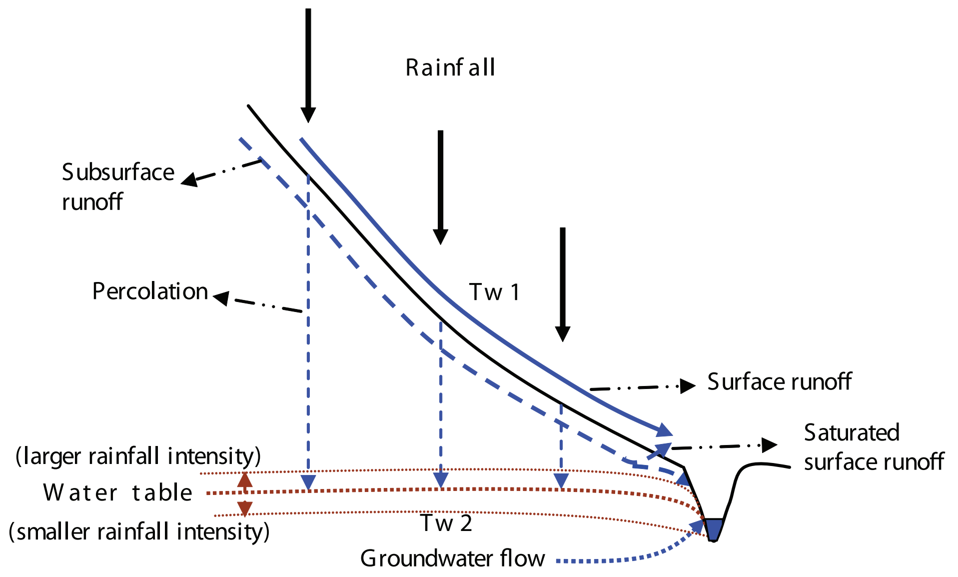


Figure 6. (a) Changes in specific discharge (*ΔQs*) vs. magnitude changes in stream water temperature (|*ΔTw*|) and (b) changes in air temperature (*ΔTa*) vs. changes in stream water temperature (*ΔTw*) at medium-sized watersheds[22]

the subsurface layer (saturated surface runoff). During Period I and Period II (relatively wet and dry seasons, respectively) at higher slope gradients, the flow time of percolation is rather longer than that at lower slope gradients; thus, a steep slope probably contributes to fast surface runoff including saturated surface runoff. Meanwhile, at a lower slope gradient during the relatively wet season, the water table is so close to the surface that deeper pathway or groundwater discharge into the stream through a rise in the water table comes more quickly than surface runoff. The fast response of groundwater flow takes place where the water table has risen to the surface. In contrast, during the relatively dry season, the water table deepens. In this case, groundwater flow hardly influences the stream because the impacts of spatial variability of topography and recharge become negligible when the water table is either very shallow/deep.[29] Surface runoff comes into the stream first; thereafter, deeper pathway or groundwater flow to the stream. Tanco and Kruse[30] stated that surface, subsurface and groundwater flows are strongly related to each other when the water table is very close to the surface. A large spatial variation in the hydrological response at the hillside scale is controlled by the contribution of water flow

a. Higher slope gradient



b. Lower slope gradient

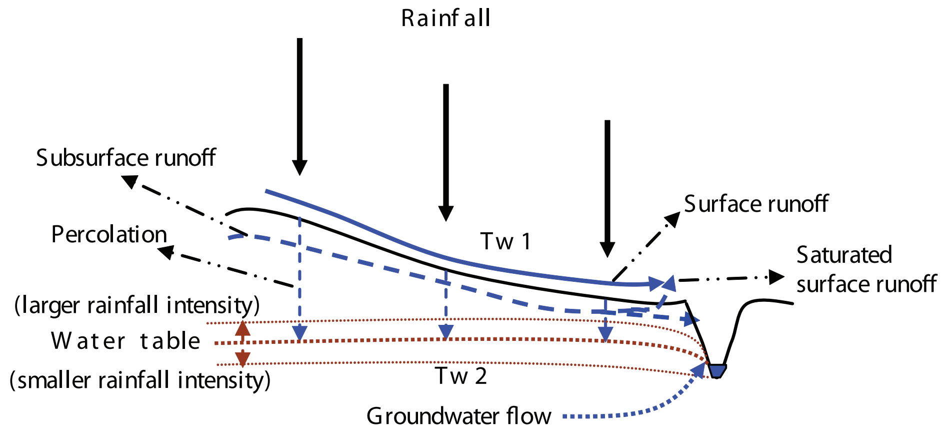


Figure 7. Rainfall, surface runoff, subsurface runoff, percolation and groundwater flow in watersheds with different slope gradients (modified from Subehi *et al.*, 2010)

from bedrock/groundwater to the stream.[31] The slope of the watershed area which will tend to affect, mainly, the amount of infiltration which is able to take place and the speed with which water moves over the surface and subsurface toward the stream channels. It was suggested that surface, subsurface and groundwater flows with different slope gradient were considered on the temperature mechanism.

Based on the explanation in Figure 7, I obtained the different loops between Qs and Tw in both periods and various slopes.[22] At higher slope gradient in Period I (warm weather), an increase in *Tw* during the rising limb of the rainfall indicates that the surface runoff has a warmer temperature than subsurface or groundwater. On the other hand, a decrease in *Tw* during the *Qs* recession suggests that the colder discharge is derived from deeper pathways. This time course brings about a clockwise loop. On the contrary, a counter-clockwise loop occurs in Period II (cold weather), indicating that the surface runoff has a colder temperature than the discharge from deeper pathways.

CONCLUSIONS

Hydro-meteorological parameters and heat transfer processes across the air-water interface were used to quantify the stream water temperature fluctuations at watersheds with different areas. Air temperature significantly influences stream water temperature. The seasonal variability of atmospheric conditions influenced fluctuations in air and stream water temperature nearly proportionally. In addition, stream water temperature had different levels of fluctuations among small, medium-sized and large watershed areas.

Next, the research findings suggest that the changes in stream water temperature during rainfall events depended on specific discharge and the slope gradient of the watershed through the flow path proportions. More specifically, the change in stream water temperature (ΔTw) was influenced more by the change in specific discharge (ΔQs) than by the change in air temperature (ΔTa). The seasonal water table changes at watersheds with lower slope gradients probably affect the response time of groundwater flow into the stream. In addition, the rainfall intensities in Period I and Period II (relatively wet and dry seasons, respectively) also influenced Qs and Tw through the different proportions of flow paths into the stream.

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Pustaka Pendukung

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