

Engineering Seminar for Disaster Resilience
in ASEAN countries 2

Water Resources Engineering

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Yasuto TACHIKAWA

Department of Civil and Earth Resources Engineering,
Graduate School of Engineering, Kyoto University

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1. Hydrology and Water Resources Engineering

Hydrology is the science which deals with the waters of the Earth, their occurrence, circulation and distribution on the planet, their physical and chemical properties and their interactions with the physical and biological environment, including their responses to human activity. Hydrology is a field which covers the entire history of the cycle of water on the Earth (UNESCO International Hydrological Decade, 1964). Water is the source of all lives on the Earth and is a resource that is indispensable for our social and economic activities. The water cycle and its time and space distribution depend on the solar radiation, topography and various conditions of the Earth surface. Hydrology is a discipline that provides the understanding of the physical processes of the water movement and the foundations for proper use and protection of water resources.

Keywords : hydrology, hydrologic cycle, waters budget, water resources

1.1 The Science of Water Cycle: Hydrology

Water constantly circulates on the Earth due to solar energy and gravitational energy, and changes its phases (ice, liquid, and vapor). **Hydrology** is the science that clarifies the movement of water and the distribution of water in time and space on and beneath the surface of the Earth, involving transports of sediment, dissolved nutrients, and contaminants. Hydrology provides the basics for applied fields such as engineering and agricultural sciences, which aim for proper development, protection and management of water resources, mitigation of water-related disasters such as floods and droughts, and agricultural production by drainage and irrigation.

Fig. 1.1 illustrates the major components of the **water cycle**. **Precipitation** falls on the Earth surface. Part of the precipitation is intercepted by trees and vegetation, which does not reach the ground surface and is evaporated into the atmosphere. Pre-

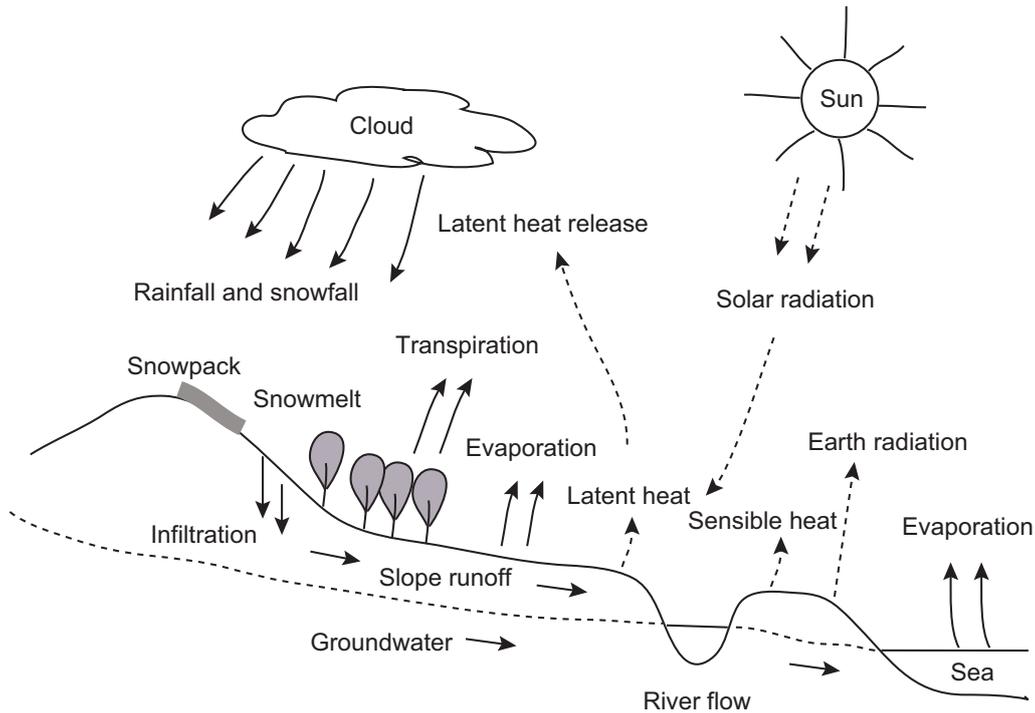


Fig. 1.1: Hydrologic processes and water and energy movement with change of water phase.

precipitation which reaches on the land surface infiltrates into the soil layers and forms **subsurface flow** and **groundwater flow**. Rainfall which exceeds the **infiltration capacity** forms **surface runoff**. Precipitation falling on the ground as snow is accumulated as snow cover, which melts and flows through similar routes to rainfall-runoff. The water in the surface layer evaporates and returns to the atmosphere. Trees and vegetation roots absorb the soil moisture from the roots and release the vapor through the stomata. This process is called **transpiration**. Combining **evaporation** with **transpiration**, it is collectively called **evapotranspiration**.

The water cycle causes the **energy cycle**. When the soil moisture on the ground surface evaporates and changes the phase from water to vapor, the **latent heat** moves from the Earth surface to the atmosphere. When the vapor changes to raindrops, the latent heat is released to the atmosphere as **condensation heat**. In other words, the solar energy provided to the Earth surface is transferred to the atmosphere through evaporation and precipitation. The solar energy given to the Earth surface is different depending on time and location. Therefore, the water cycle and the energy cycle are closely related to the climate of the Earth and the spatiotemporal distribution of water.

To understand the water cycle and energy cycle, it is necessary to understand the

physical mechanism of water and energy movements by solar radiation as well as the mechanism of water movement governed by the conservation of water mass (continuity equation) and the moment (momentum conservation). Water movement cause the movement of soils and chemical substances dissolved in water. These movements are closely associated with our lives and the environment. Therefore, the scope of hydrology includes the cycles of water, energy and physical, chemical, and biological processes associated with the cycles of water and energy.

1.2 Hydrologic Cycle and Water Resources

Hydrological science has both pure and applied aspects. The first aspect relates to questions about how the Earth works, and specifically about the role of water in natural processes. The second relates to using scientific knowledge to provide a sound basis for proper use and protection of water resources (Hornberger *et al.*, 1998). The second aspects is the main themes of water resources engineering. Research topics includes:

- flood and drought
- flood risk management
- water resources management
- climate change and water resources

【Example 1.1】 Topics of hydrologic cycle and water resources

Describe any topics related to the hydrologic cycle and water resources in your countries. For example, flood, drought, water quality, water resources development, climate change and so on.

1.3 Water on the Earth

The radius of the Earth is 6,371km and the surface area is 5.1×10^8 km². 71% of the surface is ocean, and 29% is land. The total volume of water existing on the Earth surface is estimated about 14.6×10^{20} kg (14.6×10^8 km³). Approximately 97% of such

water is seawater, and the remaining 3% is inland water, such as snow, ice, groundwater, lakes, and rivers. Vapor and cloud water in the atmosphere account for 0.001%.

【Example 1.2】 The volume of water on the Earth

Using the numerical values provided above, calculate the average thickness of seawater, inland water, and atmospheric moisture supposing each of them is spread out evenly on the ocean, the land, and the surface of the Earth, respectively.

(Solution)

The average thickness of water in the ocean is given by dividing the volume of seawater by the area of the ocean:

$$\frac{14.6 \times 10^8 \text{ km}^3 \times 0.97}{5.1 \times 10^8 \text{ km}^2 \times 0.71} = 3,911 \text{ m}$$

The average thickness of water on the land is given by dividing the volume of inland water by the area of the land:

$$\frac{14.6 \times 10^8 \text{ km}^3 \times 0.03}{5.1 \times 10^8 \text{ km}^2 \times 0.29} = 296 \text{ m}$$

The average thickness of atmospheric water is given by dividing the volume of moisture in the atmosphere by the surface area of the Earth:

$$\frac{14.6 \times 10^8 \text{ km}^3 \times 0.00001}{5.1 \times 10^8 \text{ km}^2} = 28.6 \text{ mm}$$

1.4 The Water Budget and Water Resources

1.4.1 Water balance equation

To discuss the spatiotemporal distribution of water, suppose a closed compartment (referred to as a control volume) shown in **Fig. 1.2**. M_{in} is the rate of mass flowing into the control volume [M T^{-1}]; M_{out} is the one flowing out of the control volume [M T^{-1}]; and M is the mass stored in the control volume [M]. The equation of **conservation of mass** is given by

$$\Delta M = (M_{\text{in}} - M_{\text{out}})\Delta t \quad (1.1)$$

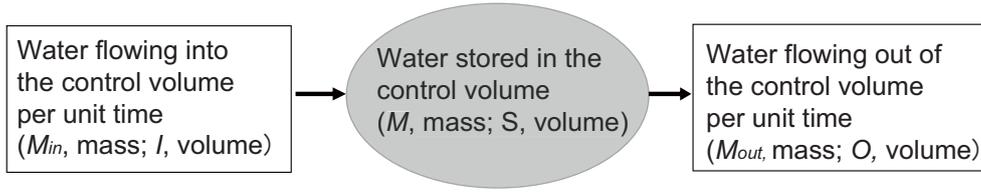


Fig. 1.2: Water budget and continuity relation.

where ΔM is the change of the water mass in the control volume over time Δt . Using the **density** of water ρ , $M = \rho S$, $M_{\text{in}} = \rho I$, and $M_{\text{out}} = \rho O$, where S is the volume of the water stored in the control volume [L^3]; I is the volume inflow rate [L^3T^{-1}]; and O is the volume outflow rate [L^3T^{-1}]. Canceling the the density from both sides of Eq.(1.1)

$$\Delta S = (I - O)\Delta t \quad (1.2)$$

By dividing both sides by Δt and taking the limit of Δt , the equation of volume conservation (continuity equation) is given as:

$$\frac{dS}{dt} = I - O \quad (1.3)$$

Generally the density of water is regarded as constant and that the continuity equation is expressed with volume, not with mass. The continuity equation is often referred as a **water balance equation** or a **water budget equation**.

1.4.2 Global water budget

We can develop a global water budget equation using Eq.(1.3). For the land, S is the volume of water stored on and in the land, I is precipitation P [L^3T^{-1}], and O consists of evapotranspiration E [L^3T^{-1}] and runoff Q [L^3T^{-1}]. Integrating Eq.(1.3) over a time period τ , the continuity equation becomes

$$\int_{\tau} dS = \int_{\tau} I dt - \int_{\tau} O dt = \int_{\tau} P dt - \int_{\tau} (E + Q) dt \quad (1.4)$$

The integration of dS/dt over a year could be negligibly small. In the case, the continuity equation becomes

$$\int_{\tau} P dt = \int_{\tau} (E + Q) dt \quad (1.5)$$

and evapotranspiration is estimated from observed precipitation and discharge.

【Example 1.3】 Annual precipitation

The motion of water is described in terms of reservoirs that store water and the movements between them. **Fig. 1.3** indicates the volume of water stored in the atmosphere, oceans and lands on the Earth and its annual movement volume. Using the values shown in **Fig. 1.3**, calculate the annual precipitation per unit area on the ocean, the land, and the surface of the Earth.

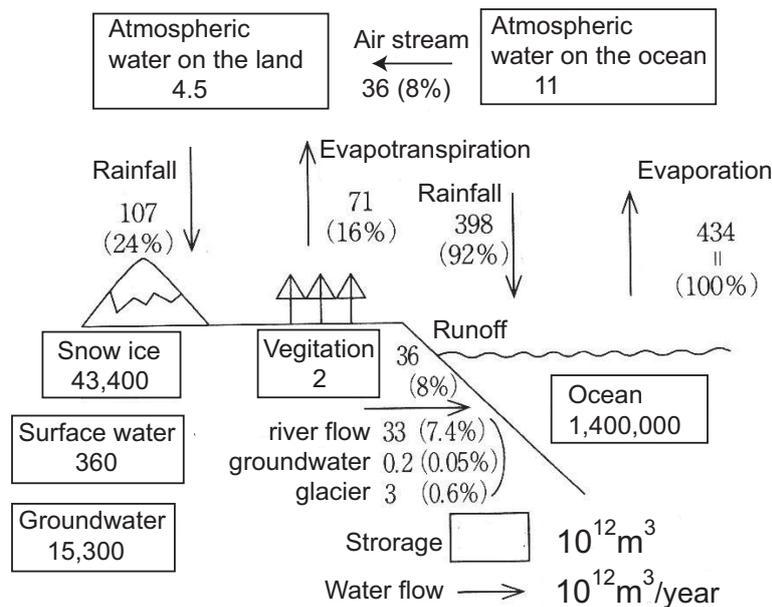


Fig. 1.3: The water stored on the Earth and the annual movement. The percentage represents the ratio when the annual evaporation from the ocean is 100%. (Takeda, T. *et al.*, Meteorology in water environment, University of Tokyo Press, 1992)

(Solution)

The annual precipitation per unit area on the ocean is given by dividing the total volume of the annual precipitation on the ocean by the sea surface area:

$$\frac{398 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}}{5.1 \times 10^8 \times 0.71 \text{ km}^2} = 1,099 \text{ mm} \cdot \text{yr}^{-1}$$

The annual precipitation per unit area on the land is given by dividing the total volume of the annual precipitation on the land by the land surface area:

$$\frac{107 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}}{5.1 \times 10^8 \times 0.29 \text{ km}^2} = 723 \text{ mm} \cdot \text{yr}^{-1}$$

The annual precipitation per unit area on the Earth surface is given by dividing the total volume of the annual precipitation on the Earth surface by its area:

$$\frac{(398 + 107) \times 10^{12} \text{ m}^3\text{yr}^{-1}}{5.1 \times 10^8 \text{ km}^2} = 990 \text{ mm}\cdot\text{yr}^{-1}$$

The annual precipitation amount in Japan is approximately $1,700 \text{ mm}\cdot\text{yr}^{-1}$ on average, which is substantially greater than the average annual precipitation on the land.

Fig. 1.3 indicates that approximately $66\%(=71/107)$ of precipitation on the land originates from evapotranspiration from the land. Most of precipitation in Japan is brought in the rainy season and typhoons and the rainwater originates from the evaporation on the ocean.

【Example 1.4】 Annual evapotranspiration

Using the values shown in **Fig. 1.3**, calculate the annual evapotranspiration per unit area on the ocean, the land, and the surface of the Earth.

(Solution)

The annual evaporation per unit area from the ocean is given by dividing the annual total volume of evaporation from the ocean by the sea surface area:

$$\frac{434 \times 10^{12} \text{ m}^3\text{yr}^{-1}}{5.1 \times 10^8 \times 0.71 \text{ km}^2} = 1,199 \text{ mm}\cdot\text{yr}^{-1}$$

The annual evapotranspiration per unit area from the land is given by dividing the annual total volume of evapotranspiration from the land by the land surface area:

$$\frac{71 \times 10^{12} \text{ m}^3\text{yr}^{-1}}{5.1 \times 10^8 \times 0.29 \text{ km}^2} = 480 \text{ mm}\cdot\text{yr}^{-1}$$

The annual evapotranspiration per unit area from the Earth surface is given by dividing the total volume of the annual evapotranspiration from the Earth surface by its area:

$$\frac{(434 + 71) \times 10^{12} \text{ m}^3\text{yr}^{-1}}{5.1 \times 10^8 \text{ km}^2} = 990 \text{ mm}\cdot\text{yr}^{-1}$$

【Example 1.5】 Annual runoff and runoff ratio

Calculate the annual runoff per unit area and runoff ratio on the land using the values in **Fig. 1.3**.

(Solution)

The annual runoff per unit area from the land is given by dividing the total volume of the annual runoff by the land surface area:

$$\frac{36 \times 10^{12} \text{ m}^3 \text{ yr}^{-1}}{5.1 \times 10^8 \times 0.29 \text{ km}^2} \times 10^3 = 243 \text{ mm} \cdot \text{yr}^{-1}$$

or annual precipitation minus annual evapotranspiration ($723 - 480 = 243 \text{ mm} \cdot \text{yr}^{-1}$).

The runoff ratio is given by dividing the annual runoff by the annual precipitation:

$$\frac{243 \text{ mm} \cdot \text{yr}^{-1}}{723 \text{ mm} \cdot \text{yr}^{-1}} = 0.34$$

1.4.3 Catchment water budget and water resources

A **catchment**, as shown in **Fig. 1.4**, is an area in which rain water drains into a **channel network** (river network) and finally flows into the river mouth. A catchment is separated by a topographically defined watershed boundary. Consider A is the area of a catchment basin [L^2]; r is the precipitation rate [LT^{-1}] (volume of precipitation falling on the catchment basin per unit time per unit area); e is the evapotranspiration rate [LT^{-1}] (the volume of water evaporating per unit time per unit area); and Q is the runoff rate flowing out of the catchment [$\text{L}^3 \text{T}^{-1}$]. The inflow rate into the catchment I in Eq.(1.3) is

$$I = Ar$$

and the outflow rate is

$$O = Ae + Q$$

Substituting these into Eq.(1.3), the continuity equation in the catchment is defined as

$$\frac{dS}{dt} = A(r - e) - Q \quad (1.6)$$

Integrating Eq.(1.6) from time t_s to t_e , the continuity equation becomes

$$\int_{t_s}^{t_e} dS = S(t_e) - S(t_s) = A \left(\int_{t_s}^{t_e} r dt - \int_{t_s}^{t_e} e dt \right) - \int_{t_s}^{t_e} Q dt$$

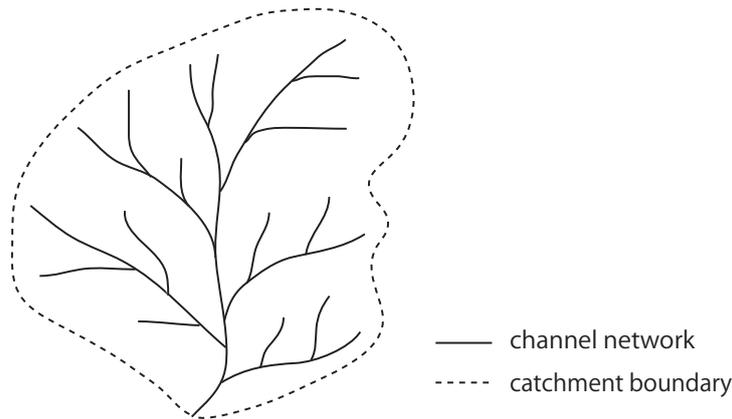


Fig. 1.4: Watershed divide and catchment basin.

If we take the start time t_s and the end time t_e as $S(t_s) = S(t_e)$, the continuity equation becomes

$$A \left(\int_{t_s}^{t_e} r dt - \int_{t_s}^{t_e} e dt \right) - \int_{t_s}^{t_e} Q dt \quad (1.7)$$

For the time period, the total volume of water flowing into the catchment basin is equal to that flowing out of the basin. If we take t_s in the dry season and t_e after one year, the time-integrated value of dS/dt is negligible, and the evapotranspiration value for the time period can be estimated using the observed precipitation and discharge data.

【Example 1.6】 Hydrologic characteristics in Asian regions

Table 1.1 shows the annual precipitation, evapotranspiration, and runoff at the Chao Phraya River basin (CPRB) in Thailand (157,925 km²) and the Katsura River basin in Kyoto, Japan (887 km²). Calculate the values in (1) and (2) in **Table 1.1** and discuss the difference of the catchment hydrologic variables from the view point of water resources.

Table 1.1: Annual catchment hydrologic variables.

Region	Precipitation	Evapotranspiration	Runoff
CPRB (Thailand)	1,144	962	(1)
Bandung (Indonesia)			
Hanoi (Vietnam)			
Kyoto (Japan)	1,796	708	(2)
World (mean)	723	480	243

*unit is mm/year.

(Solution)

(1) $1,144-962=182$ mm/yr. (2) $1,796-708=1,088$ mm/yr.

【Example 1.7】 Annual water resources in Thailand and Japan

Table 1.2 shows the estimated mean annual runoff in Thailand, Japan and the world. Calculate the per capita maximum water resources for one year for each area and discuss the difference of the water resources.

Table 1.2: Annual water resources in Thailand and Japan.

Region	Runoff (mm/yr)	Area (km ²)	Population (person)
Thailand	182	513×10^3	69.5×10^6
Japan	1,088	378×10^3	126.5×10^6
World	243	147.9×10^6	$6,968 \times 10^6$

(Solution)

The maximum water resources per capita in Thailand is obtained by dividing the total annual runoff volume by the population, which is

$$\frac{182\text{mm/yr} \times 513 \times 10^3\text{km}^2}{69.5 \times 10^6\text{person}} = \frac{93,366 \times 10^6\text{m}^3/\text{yr}}{69.5 \times 10^6\text{person}} = 1,343\text{m}^3/\text{person/yr}$$

The maximum water resources per capita in Japan and the world are

$$\frac{1,088\text{mm/yr} \times 378 \times 10^3\text{km}^2}{126.5 \times 10^6\text{person}} = \frac{411,264 \times 10^6\text{m}^3/\text{yr}}{126.5 \times 10^6\text{person}} = 3,251\text{m}^3/\text{person/yr}$$

$$\frac{243\text{mm/yr} \times 147.9 \times 10^6\text{km}^2}{6,968 \times 10^6\text{person}} = \frac{35,940 \times 10^9\text{m}^3/\text{yr}}{6,968 \times 10^6\text{person}} = 5,158\text{m}^3/\text{person/yr}$$

1.5 Mean Residence Time

The mean residence time refers to the times that are required for the water in the drainage basin to be completely replaced with new water flowing into the drainage basin. The mean residence time provides a time scale of the movement of water and substances that travel with water in the basin. Assuming the **steady state** condition ($dS/dt = 0$), the mean residence time is easily calculated by dividing the volume of water stored in a control volume by the volume of water that flows into the region per unit time, or by the volume of water that flows out of the region per unit time.

【Example 1.8】 Mean residence time in global water budget

Calculate the mean residence time of water that exists on the land and in the atmosphere, using the values provided in **Fig. 1.3**.

(Solution)

The annual mean precipitation on the lands (sum of annual evapotranspiration and runoff from the land) is $107 \times 10^{12} \text{ m}^3\text{yr}^{-1}$. The total volume of water stored on and beneath the land is $(43,400 + 360 + 15,300 + 2) \times 10^{12}\text{m}^3$. Therefore, the mean residence time of water on the land is:

$$\frac{(43,400 + 15,300 + 360 + 2) \times 10^{12} \text{ m}^3}{107 \times 10^{12} \text{ m}^3\text{yr}^{-1}} = 552 \text{ year}$$

The annual precipitation on the lands and oceans is $(107 + 398) \times 10^{12}\text{m}^3\text{yr}^{-1}$. The total volume of water stored in the atmosphere is $(4.5 + 11) \times 10^{12}\text{m}^3$. Therefore, the mean residence time of water in the atmosphere is:

$$\frac{(4.5 + 11) \times 10^{12} \text{ m}^3}{(107 + 398) \times 10^{12} \text{ m}^3\text{yr}^{-1}} = 11.2 \text{ day}$$

The mean residence time of water in the atmosphere is very short, indicating that water is frequently exchanged with heat energy.

The volume of water in snow ice and groundwater accounts for more than 99% of the water on and beneath the land, and runoff from snow ice and groundwater accounts for less than 10%. Assuming only surface water and water in vegetation move, the mean residence time of the water on the land is

$$\frac{(360 + 2) \times 10^{12} \text{ m}^3}{107 \times 10^{12} \text{ m}^3\cdot\text{yr}^{-1}} = 3.4 \text{ year}$$

Most of surface water is stored in lakes and soil layers. Movement such water is slower than that of water in rivers. Therefore, the mean residence time of water in rivers is estimated as several ten days.

【Example 1.9】 Mean residence time in dam reservoirs

Table 1.3 shows the characteristics of the largest dams in Thailand and Japan. How many years it take to completely replace the water in the full storage capacity

at the Bhumibol Dam, the Tokuyama Dam, and the Hiyoshi Dam? Use the annual hydrologic variables in **Table 1.1**.

Table 1.3: Characteristics of the dams in Thailand and Japan.

Dam	Storage capacity($\times 10^6 \text{m}^3$)	Catchment area (km^2)
Bhumibol Dam	13,420	26,400
Tokuyama Dam	660	254.5
Hiyoshi Dam	66	290

(Solution)

The annual inflow to the Bhumibol Dam is $182 \text{ mm/yr} \times 26,400 \text{ km}^2$. The mean residence time of the dam reservoir is given by dividing the storage capacity by the annual inflow:

$$\frac{13,420 \times 10^6 \text{ m}^3}{26,400 \text{ km}^2 \times 182 \text{ mm/yr}} = 2.8 \text{ year}$$

Similarly for the Tokuyama Dam

$$\frac{660 \times 10^6 \text{ m}^3}{254.5 \text{ km}^2 \times 1088 \text{ mm/yr}} = 2.4 \text{ year}$$

and for the Hiyoshi Dam

$$\frac{66 \times 10^6 \text{ m}^3}{290 \text{ km}^2 \times 1088 \text{ mm/yr}} = 0.21 \text{ year}$$

References

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- [2] Maidment, D. R.: Hydrology, in Hydrology Handbook of Hydrology, edited by D. R. Maidment, McGraw-Hill, Chapter 1, pp. 1.1–1.15, 1993.

2. Water Resources under a Changing Climate

2.1 Climate Change Scenario and GCMs

General circulation models (GCMs) provide future atmospheric and hydrologic variables under various climate change scenarios. One of the latest GCMs is MRIAGCM3.1S, which is with about 20 km spatial resolution developed by the Meteorological Research Institute in Japan. The products of MRI-AGCM3.1S consist of various atmospheric and hydrologic variables for the present climate experiment (1979-2003), the near future climate experiment (2015-2039), and the future climate experiment (2075-2099), which were simulated under the SRES A1B scenario.

2.2 Water Resources Simulation in Thailand

Fig. 2.1 shows the change ratio of the mean of the annual maximum hourly discharge for the near future climate experiment (a) and the future climate experiment (b), with respect to the present climate experiment. Generally, the mean annual maximum hourly discharge of the main stream of the Chao Phraya River did not change significantly in both near future and in future experiments; however, that of the tributaries changed from location to location. Notably, the mean of the annual maximum hourly discharge of some tributaries in the north-central and the southwestern part of the basin showed an increasing trend in near future experiments, and this trend was clearly visible in the future climate experiments.

To estimate dry basins, the mean annual potential evapotranspiration was calculated using the Hargreaves temperature based equation. **Fig. 2.2** shows the changes in the mean annual precipitation and the mean annual potential evapotranspiration estimated by the Hargreaves method. As shown in **Fig. 2.2**, we clearly observe that the mean annual

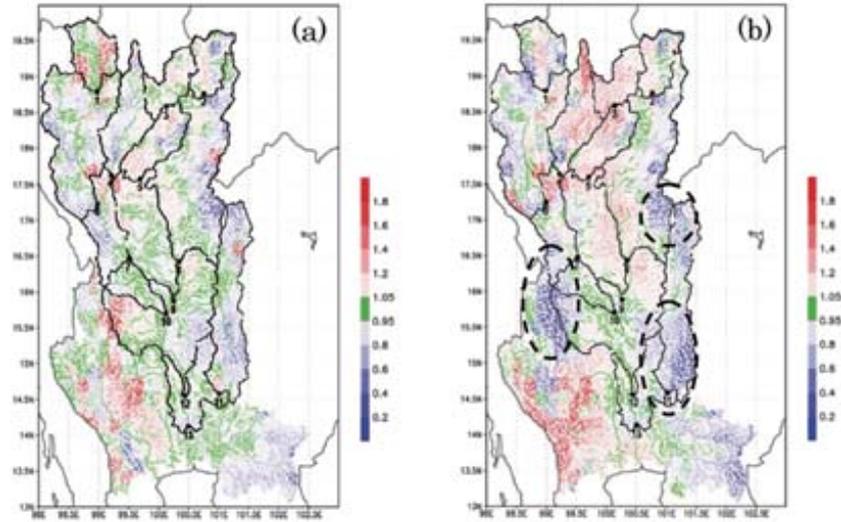


Fig. 2.1: The change ratio of the mean of the annual maximum hourly discharge for the near future climate experiment to the present climate experiment (a), and the future climate experiment to the present climate experiment (b).

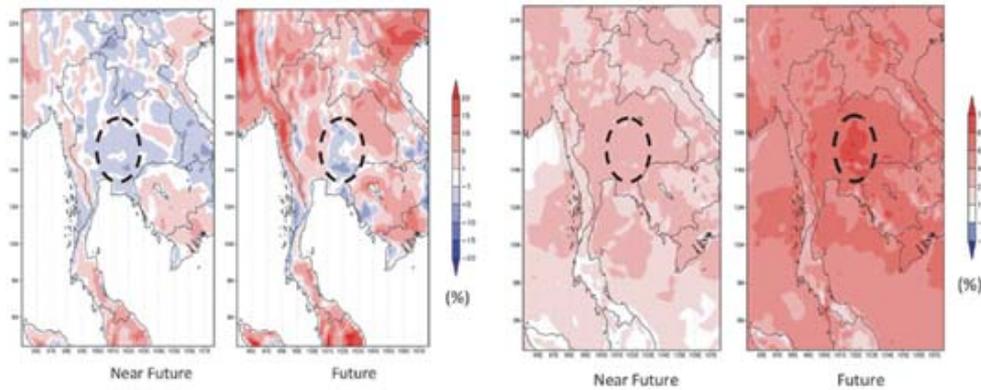


Fig. 2.2: Percentage difference of the mean annual precipitation (left) and potential evapotranspiration (right) in the near future and the future climate experiment with respect to the present climate experiment. The area designated by the circle corresponds to the Pasak River basin area.

precipitation tends to decrease significantly, while the potential evapotranspiration tends to increase in the circled areas of the figure. The rate of increase of the potential evapotranspiration may not be the same as the rate of increase of actual evapotranspiration in dry basins, as the soil moisture controls the latter.

Fig. 2.3 shows the change ratio of the mean rainy season (May to October) discharge in the near future climate experiment (a) and the change ratio in the future climate experiment (b) with respect to the present climate experiment. The mean rainy season

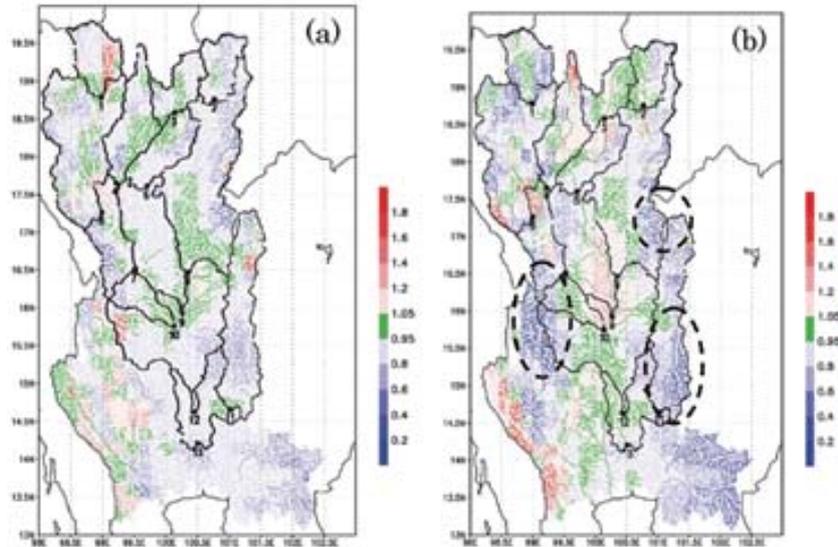


Fig. 2.3: The change ratio of the mean rainy season (May to October) discharge for the near future climate to the present climate experiment (a), the future climate to the present climate experiment (b).

river discharge of many tributaries and the main streams showed a decreasing trend in the near future climate. In the future climate experiment, the mean rainy season discharge of the main streams showed less change compared with the present climate. However, a decrease trend of the mean rainy season flow in small tributaries became clearer in the future climate experiment.

2.3 Water Resources Simulation at the Pasak Dam

A change of water resources in the late 21st century at the Pasak River basin in Thailand (**Fig. 2.4**) is analyzed using a distributed rainfall-runoff model and a rainfall and evapotranspiration output projected by MRI-GCM3.1S. **Fig. 2.5** shows observed mean monthly precipitation (APHRODITE) and GCM precipitation. The GCM output overestimates in the beginning of the rainy season, however for other months both match well. **Fig. 2.6** shows the change of the GCM precipitation and evapotranspiration. The annual mean precipitation for the present and future climate experiment are 1178mm and 1199mm, which shows 1.8% increase. The annual mean evapotranspiration for the present and future climate experiment are 981mm and 1027mm, which shows 4.7% increase.

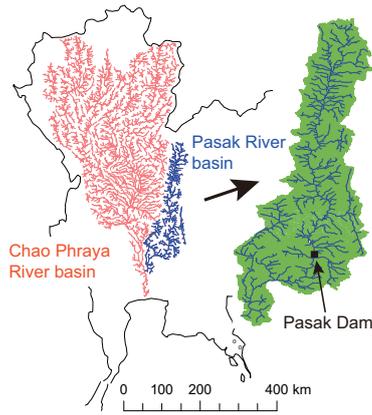


Fig. 2.4: Pasak River basin.

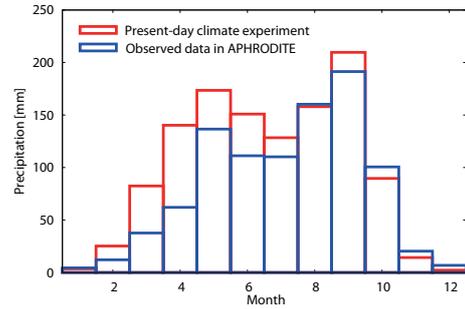


Fig. 2.5: Comparison of observed monthly precipitation (APHRODITE) and GCM precipitation.

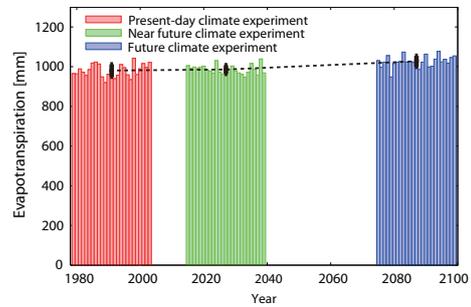
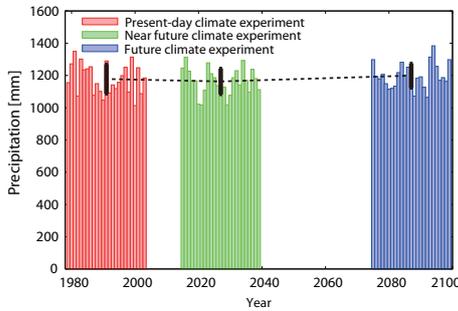


Fig. 2.6: Precipitation(left) and evapotranspiration (right) projected by MRI-GCM3.1S.

Fig. 2.7(left) shows a projected mean annual inflow to the Pasak Dam reservoir for the near future and the late 21st century experiments, which decrease by 3.8% and 3.5% compared with the present climate experiment. A projected mean monthly inflow using the output of the late 21st century experiment decreases except from July to September. Fig. 2.7(right) shows a change of water storage in the Pasak Dam assuming the dam outflow (water demand) does not change. The result shows to maintain a present dam outflow is difficult in the future under a scenario of the same water demand.

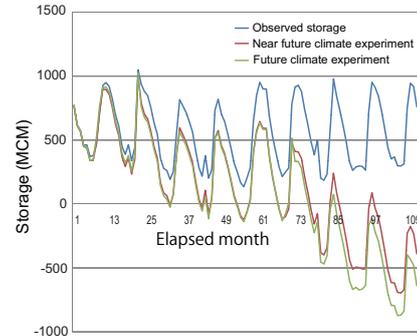
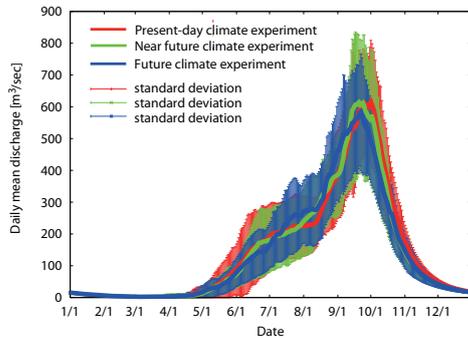


Fig. 2.7: Projected inflow to the Pasak dam and reservoir storage.

2.4 Water Resources Simulation in Japan

River discharges in the Japanese archipelago of a total of 75 years of the present day climate experiment, the near future climate experiment, and the end of the 21st century climate experiment were calculated with a 1-km spatial resolution, using information on future climate estimations by a 20-km-mesh global atmospheric model (MRI-GCM3.1S). Then, the annual maximum discharge with a return period of 100 years and the drought discharge with a return period of 10 years were calculated based on the river discharge data of each experiment period. **Fig. 2.8** spatially indicates the change ratio of the 100-year annual maximum discharge and the 10-year drought discharge of the end of the 21st century climate experiment to the present day climate experiment.

The results of an analysis show an increasing tendency in the 100-year annual maximum discharge in Hokkaido, the northern part of the Tohoku area, the Chugoku and Shikoku areas, and the northern part of the Kyushu area in the end of the 21st century climate experiment. However, the annual maximum discharge tends to decrease in areas where freshets are caused by accumulated snow or melting of snow such as the southern part of the Tohoku area and the Hokushinetsu area, due to a decrease in the snow accumulation or snowmelt. This tendency appears in the near future climate experiment and becomes more evident in the end of the 21st century climate experiment.

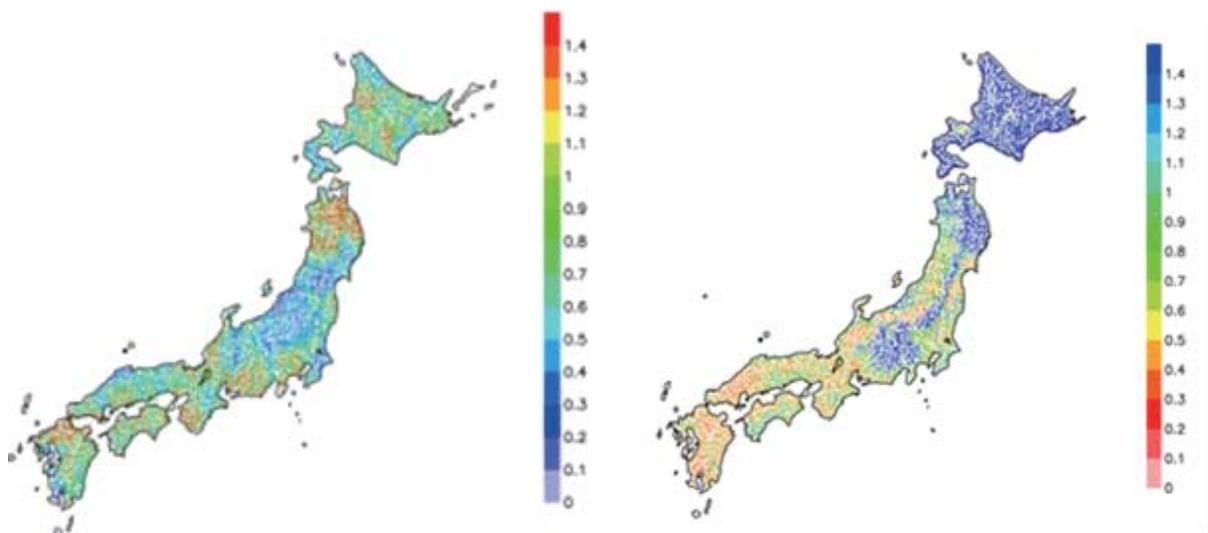


Fig. 2.8: Change ratio of the 100-year annual maximum discharge (left) and the 10-year drought discharge (right) from the present day climate to the end of the 21st century.

2.5 River Flow Simulation in Indochina Peninsula

River discharge projection in Indochina Peninsula region was carried out for three climate experiments: the present climate (1979-2008), the near future climate (2015-2044), and the future climate (2075-2104). Daily mean discharge, max hourly discharge in day data is stored in 5-minute spatial resolution. The simulated river discharge was analyzed to locate possible hotspot basins with significant changes of floods, droughts and water resources.

2.5.1 Change of water resources

Annual mean simulated river discharge for three climate experiments was calculated and used to analyze changes in water resources in Indochina Peninsula region. **Fig. 2.9** shows the change ratio of annual mean discharge for the near future climate and the future climate to the present climate experiment. From **Fig. 2.9(a)**, it can be seen that there are not so much changes in annual mean discharge in the near future. Slightly increases in annual mean discharge with the ratio smaller than 1.5 can be detected at the most upper parts of Salween and Mekong River basin, the lower part of Irrawaddy River basin, and western part of Vietnam. Only eastern part of Chao Phraya River basin shows a trend of

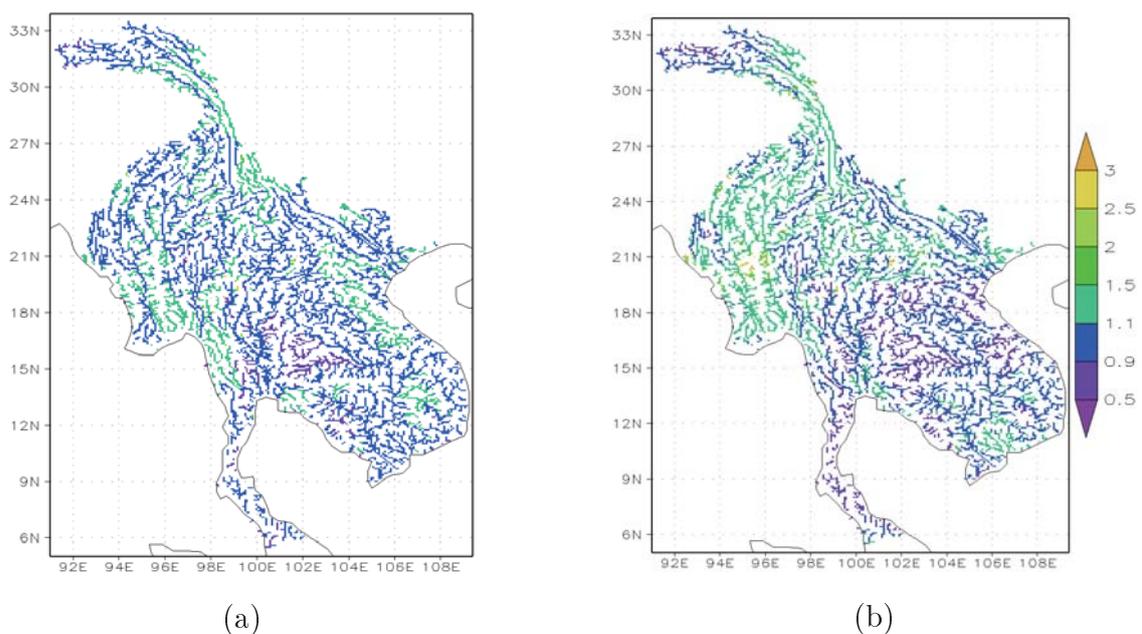


Fig. 2.9: Ratio of annual mean discharge for the near future climate to the present climate (a), and the future climate to the present climate (b).

decreasing in annual mean river flow with the ratio is between 0.5 and 0.9. **Fig. 2.9(b)** shows a similar trend with higher intensity in the future climate experiment. We can see that the area with changes in annual mean discharge and ratio range become larger, especially at the middle and lower part of Irrawaddy River basin, and eastern part of Chao Phraya River basin. However, the annual mean flow in the future climate tended to decrease in the central part of Vietnam. The change ratio is lower than 0.9.

2.5.2 Change of flood risk

Annual maximum discharge data for three climate experiments were compiled and were analyzed. The change ratio of mean of annual maximum discharge for the near future climate and the future climate with respect to the present climate experiment are shown in **Fig. 2.10**. For the near future climate experiment, the mean of annual maximum discharge has significant changes at the upper and lower part of Salween River basin, north-western part of Vietnam, and eastern part of Chao Phraya River basin. The changes, which were detected in the near future climate experiment, become more visible in the future climate experiment. Irrawaddy River basin and Red River basin showed a noticeable increasing of mean of annual maximum discharge in the future climate experiment. The ratio at some areas are larger than 2.5. It means that the risk of flooding

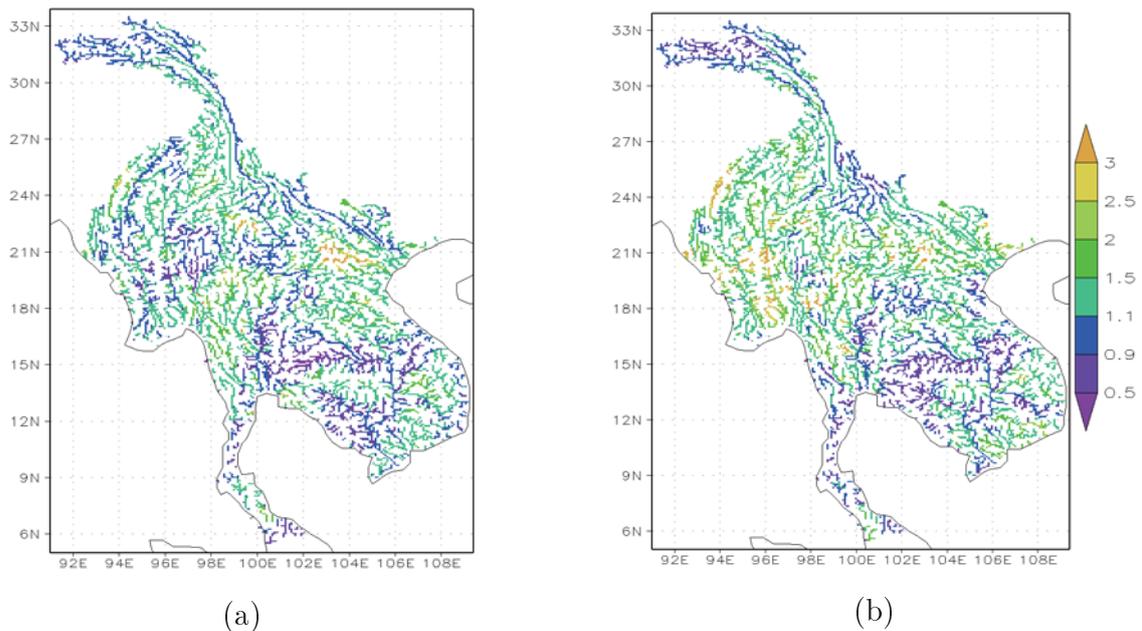


Fig. 2.10: Ratio of annual mean discharge for the near future climate to the present climate (a), and the future climate to the present climate (b).

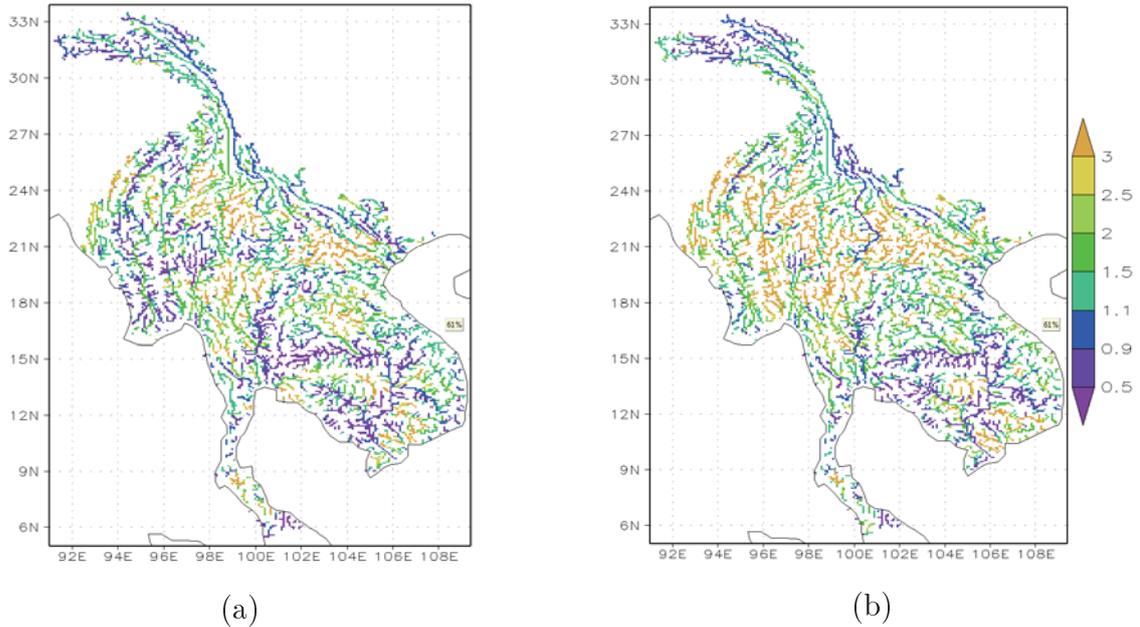


Fig. 2.11: Ratio of standard deviation of annual maximum discharge for the near future climate to the present climate (a), and the future climate to the present climate (b).

at those areas will increase.

The ratio of the standard deviation of the annual maximum discharge for the near future climate and the future climate to the present climate experiment were also calculated and analyzed. The standard deviation also showed a similar trend to the changes of mean of annual maximum discharge. The increases of standard deviation of annual maximum discharge can be found in Irrawaddy River basin, Salween River basin, and Red River basin as shown in **Fig. 2.11**.

2.5.3 Change of drought risk

The change of drought risk in Indochina Peninsula region was also analyzed by comparing the mean of annual minimum discharge in the near future climate and the future climate experiment with those values in the present climate experiment. From **Fig. 2.12**, it can be seen that there is a decrease trend at the middle part of Mekong River basin in the territory of Lao PDR, western part of Chao Phraya River basin, and the south-eastern part of Indochina Peninsula, especially the southern part of Vietnam. This trend becomes clearer in the future climate experiment.

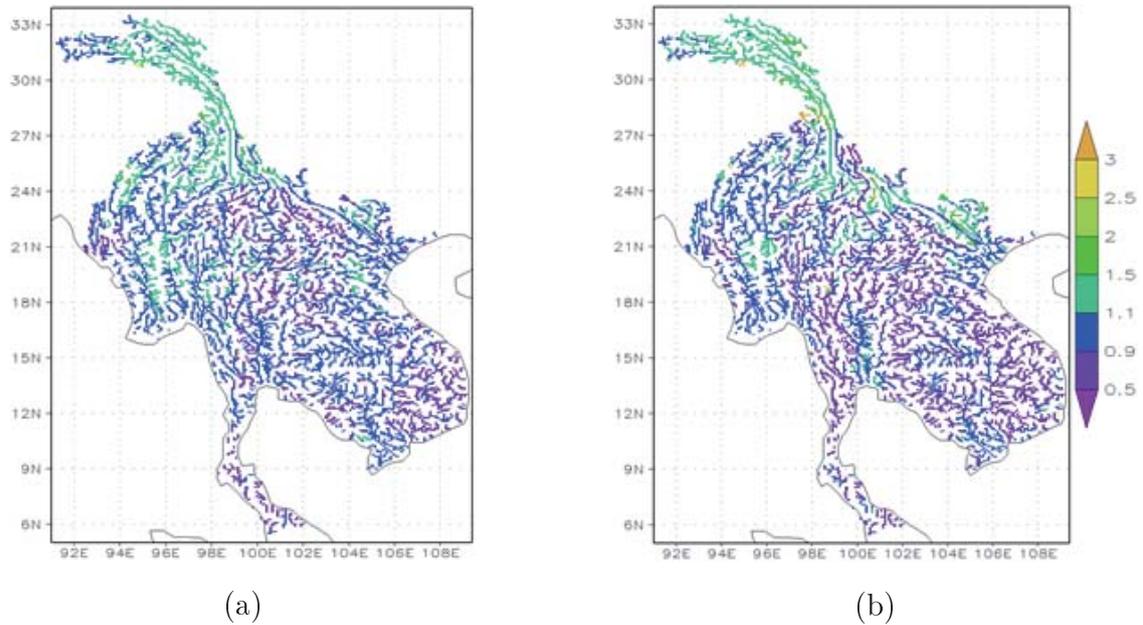


Fig. 2.12: Ratio of mean of annual minimum discharge for the near future climate to the present climate (a), and the future climate to the present climate (b).

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