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Hydrological regions in monsoon Asia

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Abstract:

Monsoon Asia is characterized by its diversity of natural and social environments. These environments range from humid tropics to arid regions and there exist associated various hydrological phenomena. This paper attempts to characterize the hydrological regions of monsoon Asia based on the water budget calculated using grid-based global datasets. A map of hydrological regions is created by ranking the value of water surplus and deficit. A humid zone with large water surplus extending from Southeast Asia to the Japanese archipelago, rapid transition from humid to arid environments in eastern China, and an arid region surrounded by a humid region in continental Southeast Asia are the most remarkable features in monsoon Asia. The map reveals that an essential characteristic of monsoon Asia is the proximity of the arid and humid environments. Many water problems and water management practices in a region can be easily understood by plotting them on a map. The boundaries of several large river basins are superimposed on the map, and examined for the water budget and flow regimes. The results are found to explain the regional characteristics of the seasonal runoff regimes satisfactorily. The importance of using a spatial framework for the comparative hydrological study in Monsoon Asia is highlighted. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS Monsoon Asia; water budget; hydrological region; regional characteristics; large river basins

INTRODUCTION

Hydrological processes related to land surface and water resources management are strongly influenced by the characteristics of a region. Many reports on field surveys or experiences of water resources management in the region are traced from a huge repository of lower level investigations. The development of an appropriate framework could aid the collection and accumulation of experiences in the regions and the extraction of knowledge to the benefit of water resources management. Of these, the first necessity is the classification of the land surface into regions with the same hydrological conditions.

A region is defined as the geographic extent with similarity concerning the multiplicity and interrelationships of the components that form the regional environment with their spatial and historical attributes. The definition of a region thus enables the accumulation of local knowledge or experiences within spatial databases over large-scale extents, such as the continental or global scale.

The hydrological division of monsoon Asia based on the water budget is attempted in order to understand the region as part of the hierarchy of global hydrological environments. Such a hydrological division was first attempted by Kayane (1972). Although many climatological divisions exist, it was the first attempt taken from a hydrological point of view. He stated that specific water usage practices and water resources development are necessary for a region, and the knowledge related to the hydrological cycle and water budget should be fully utilized to avoid environmental degradation.

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According to Kayane (1972), hydrological regions are described as regions with similar hydrological conditions. The indices of the regional division used for concrete and objective classification were water surplus and water deficit, and their seasonal fluctuation. Because water surplus and deficit have a close relationship to plant growth and human activities, they have important and practical meanings. The concept of hydrological regions helps in understanding the nature of water problems in the region, and provides the strategic remedial measures to tackle water problems. The purpose of this paper is to refine and update these ideas expressed by Kayane (1972) using new datasets and advanced computer technology.

Kayane (1972) emphasized the characteristics of climatological water budget as a means of hydrological regionalization. Monthly water budget was calculated by the book-keeping technique, which was used for the first time by Thornthwaite (1948), for thousands of meteorological stations in monsoon Asia, and a map of hydrological regions was subsequently generated. This paper follows Kayane's method; however, the current data and computing power available for the calculation has been greatly improved. This paper uses the global datasets available through the Internet or on CD-ROMs, and makes a grid-based water budget map to draw new hydrological regions in monsoon Asia. As a result, new understandings of monsoon Asia are sought using geographic information system (GIS) techniques by combining various natural conditions.

DATA AND METHODS

Global datasets

Table I shows the list of global datasets used for water budget calculation. These data are collected from Worldwide Web (WWW) sites and purchased from various institutions. Datasets (1)–(5) in Table I are included in the Global Ecosystem Database (GEDB) CD-ROM V.1 (NOAA-EPA, 1992). Dataset (6) is provided by UNEP/GRID through WWW site http://www.grid.unep.ch/. Dataset (7) is a global river channel dataset available from http://hydro.iis.u-tokyo.ac.jp/∼taikan/TRIPDATA/TRIPDATA.html (Oki and Sud, 1998).

The details of each dataset are available in the document files on the WWW or on the CD-ROM. As for precipitation and air temperature, two datasets exist. Accordingly, calculations were undertaken for two combinations of datasets. Parameter set 1 uses Leemans and Cramer's and parameter set 2 adopts Legate and Willmott's. Although the accuracy of these datasets is not necessarily guaranteed, they are used because these data are currently the most advanced available. Climatic data represent the average of a certain period. Consequently, the results of the water budget denote the long-term average, namely climatological values.

Table I. Global datasets used for water budget calculation

Dataset[a]	Product name	Resolution (deg)
(1) Precipitation	1. Leemans and Cramer IIASA mean monthly precipitation	0·5
	2. Legates and Willmott monthly average precipitation	0·5
(2) Air Temperature	1. Leemans and Cramer IIASA monthly surface air temperature	0·5
	2. Legates and Willmott monthly average air temperature	0·5
(3) Sunshine Duration	Leemans and Cramer IIASA average month cloudiness	1·0
(4) Albedo	Matthews seasonal albedo	1·0
(5) Elevation	ETOPO5 (Edwards global gridded elevation and bathymetry)	0·083
(6) Soil Moisture	Bouwman soil water-holding capacity	1·0
(7) TRIP	Total runoff integrating pathways	0·5

[a] Sources: (1)–(5) Global Ecosystem Database version 1·0; (6) http://www.grid.unep.ch/; (7) http://hydro.iis.u-tokyo.ac.jp/∼taikan/TRIPDATA/TRIPDATA.html.

There are many grid data available for a 0·5° latitude and longitude lattice resolution. The water budget calculation has been performed based on a 0·5° grid. Datasets with coarse resolution are simply divided to a 0·5° grid and fine data are aggregated to a 0·5° grid.

Dataset (6) provides the water content of the upper 30 cm soil layer in field capacity. The soil storage capacities of selected soil classes are given in Table II. The maximum value is found to be 120 mm. Thornthwaite (1948) initially used 100 mm as the soil water storage capacity, which was later revised as 300 mm. The values in Table II seem to be underestimated in comparison with those values.

The root-zone depth of the wheat field in the North China Plain is about 1 m (original data by the author). The zero-flux plane in the Kanto loam formation, consisting of volcanic ash soil typical in central Japan, is about 1 m (Higuchi, 1978). Numerical simulation shows that the effect of evaporation reached 0·8 to 1·0 m depth after 10 days of dry weather (Hillel, 1971). These observational and simulated results indicate that the soil depth that should be considered in the short period water budget calculation is about 1 m. In addition, the maximum of the soil storage capacity value Wc from Table II is 120 mm, which is close to three times that of Thornthwaite's value. A soil depth of 1 m is also about three times that of 30 cm. Based on these observations, it is appropriate to consider that the soil depth which is important to the water budget calculation is 1 meter, and the maximum soil water capacity is set to be three times that of the value in Table II.

Method of evapotranspiration calculation

Evapotranspiration is calculated based on the grid-based global datasets. However, it is desirable to use the method based on the heat budget rather than an empirical method. The Thornthwaite (1948) method is widely practised in the world because it requires only monthly air temperature data as input. The assumption that the air temperature is the index of net radiation is suppressed in the method. Since the air temperature has less correlation with the net radiation in humid tropical regions and during the Japanese rainy season, Baiu, the accuracy of calculations tends to be poor in monsoon Asia (Kayane, 1972; Kondoh, 1994). The Penman method, however, is based on the heat budget and requires not only air temperature, but also wind speed, humidity, and sunshine duration, making it difficult to apply to the grid-based global data.

Ahn and Tateishi (1994a) developed a procedure to calculate the potential evaporation using global datasets. The basic equation is the one used by Preistley and Taylor (1972), based on the heat budget. By using the three raster datasets, namely air temperature, albedo, and sunshine duration, the global evapotranspiration can be calculated.

Potential evaporation Ep can be expressed as follows:

$$\mathrm{Ep} = \alpha \frac{\Delta}{\Delta + \gamma} (\mathrm{Rn} - G) \tag{1}$$

where Rn is net radiation, G subsurface heat flow, Δ is the slope of saturated water vapour curve γ, and α is a constant. Preistley and Taylor (1972) obtained 1·26 for α for large wet surfaces, and this value is used in this study. G is assumed to be negligible.

Table II. Soil storage capacities of some selected soil classes

(Rendzinas, Lithosols, Rankers)	15	(FAO Soil codes 22, 40, 85)
1-Coarse (e.g. Sand)	40	–
2-Coarse/Medium (Vertisols)	60	(FAO Soil codes 86, 87)
3-Coarse/Fine (vertic Cambisols)	80	(FAO Soil code 13)
3-Coarse/Medium/Fine (Ferralsols)	80	(FAO Soil code 55)
3-Medium (vertic Luvisols)	80	(FAO Soil codes 23–28)
4-Medium/Fine	100	–
5-Fine (Andosols)	120	(FAO Soil codes 81–84)
6-Organic	60	–

Ahn and Tateishi (1994a) obtained the combination of equations for the use of available global datasets. Net radiation is calculated as follows, based on Linacre (1968):

$$\mathrm{Rn} = (1 - r)\mathrm{Rs} - 1{\cdot}11(0{\cdot}2 + 0{\cdot}8n/N)(100 - T) \tag{2}$$

where r is albedo, Rs is solar radiation, n/N is sunshine fraction, and T is air temperature. As for Rs, the following equations are used:

$$\mathrm{Rs} = (a + b \times n/N)\mathrm{Re} \tag{3}$$

$$a = 0{\cdot}29\cos(\phi) \tag{4}$$

$$b = 0{\cdot}71 - 0{\cdot}29\cos(\phi) \tag{5}$$

where Re is extraterrestrial solar radiation and ϕ is latitude. Re can be calculated by assigning the latitude and time.

The required data for the computation are air temperature, albedo, and sunshine duration. All these data are available as raster global datasets as listed in Table I, and thereby the grid-based global potential evaporation can be calculated.

Method to calculate monthly water budget

The potential evaporation given by Priestley and Taylor (1972) is an imaginary potential rate from a large saturated plane without advection. Actual evaporation is controlled by water availability, or simply by the soil moisture. Thornthwaite and Mather (1955) calculated the actual evapotranspiration by assuming the soil moisture storage capacity and obtaining the climatologically derived monthly water budget. Ahn and Tateishi (1994b) adopted the same book-keeping procedure, but with a different evapotranspiration algorithm, and produced a grid-based global water budget map. This paper follows the method of Ahn and Tateishi, but the primary difference is the soil water storage capacity as described before. The procedures are as follows.

Actual evapotranspiration is first calculated using the following algorithm:

$$\begin{array}{ll} \text{if} & P_i < \mathrm{Ep}_i \\ & \mathrm{Ea}_i = P_i - (\mathrm{Sm}_i - \mathrm{Sm}_{i-1}) \\ \text{else} & \\ & \mathrm{Ea}_i = \mathrm{Ep}_i \end{array} \tag{6}$$

where P (mm month^{-1}) is precipitation, Ep (mm month^{-1}) is potential evapotranspiration, Ea (mm month^{-1}) is actual evapotranspiration, Sm (mm month^{-1}) is soil moisture storage, and i denotes the month.

Monthly soil moisture can be calculated using the method of Donker (1987):

$$\begin{array}{ll} \text{if} & P_i < \mathrm{Ep}_i \\ & \mathrm{AWL}_i = \mathrm{AWL}_{i-1} + \mathrm{Ep}_i - P_i \\ & \mathrm{Sm}_i = \mathrm{Wc}\ \exp(-\mathrm{AWL}_i/\mathrm{Wc}) \\ \text{else} & \\ & \mathrm{Sm}_i = \mathrm{Sm}_{i-1} + (P_i - \mathrm{Ep}_i) \end{array} \tag{7}$$

where AWL (mm) is accumulated potential water loss and Wc (mm) is soil water storage. Soil moisture approaches zero but does not fall below zero when AWL increases, so the parameterization simulates actual conditions well.

Water surplus S and deficit D are calculated based on Legates and Mather (1992):

$$\begin{aligned}
&\text{if} \quad \mathrm{Sm}_i > \mathrm{Wc} \\
&\quad S_i = P_i - \mathrm{Ea}_i - (\mathrm{Sm}_i - \mathrm{Sm}_{i-1}) \\
&\quad D_i = 0 \\
&\text{else} \\
&\quad S_i = 0 \\
&\quad D_i = \mathrm{Ep}_i - \mathrm{Ea}_i
\end{aligned} \tag{8}$$

Accuracy of the results

The accuracy of the methods, especially for actual evapotranspiration Ea, is hard to validate because of the variety of datasets with different uncertainties; however, the spatial distribution of Ea does provide assurance through comparison with existing evidence.

Actual evapotranspiration Ea is about 800 mm year^{-1} in the middle of Japan, and it exceeds 1000 mm year^{-1} at the southern edge of Kyushu Island. The accuracy seems reasonable around the Japanese archipelago. The value increases to the south and it reaches a maximum of about 1800 mm year^{-1} in the humid tropics. Kondoh *et al.* (1999) constructed a basin water budget database by collecting the results of water budgets in experimental watersheds, and showed a map of annual actual evapotranspiration. The distribution of measured Ea corresponds well with the calculated one, and the accuracy of calculation can be considered acceptable. As for the maximum evapotranspiration in the tropics, the value can be read as around 1800 mm year^{-1} from the diagrams provided by Solomon (1967), Kayane (1989), and Kondoh *et al.* (1999), who plotted annual water loss (equal to annual actual evapotranspiration) against annual precipitation. This also confirms the accuracy of the calculation.

Although further discussion on the accuracy is left for future study, the procedure is currently the best one available using the latest datasets, and the absolute values and the spatial distribution of water budget terms look reasonable compared with previous studies.

HYDROLOGICAL REGIONS

Classification of hydrological regions in monsoon Asia is attempted using the water budget map calculated in the former section. The criteria are based on the water surplus and deficit. The values of 400 mm year^{-1} for water surplus and 200 mm of water deficit are regarded as boundaries between the regions. The underlying reason is related to the baseflow of the rivers in humid regions (Kayane, 1972). The average baseflow in humid regions such as Japan is about 1 mm day^{-1}, and the annual amount is approximately 400 mm. Therefore, regions with more than 400 mm of water surplus are referred to as very humid regions. According to Shimada (1982), the annual amount of groundwater recharge was 913 mm in the upland composed of Kanto loam formation (volcanic ash soil) in Kanto District, Japan. So, regions with an annual water surplus over 400 mm do exist in monsoon Asia.

Monsoon regions witness both rainy and dry seasons in a year. If it is accepted that the annual groundwater recharge (equal to baseflow) is 400 mm in humid regions, then 200 mm of recharge is expected during the wet season. The upper limit of sustainable water usage is 200 mm year^{-1}, and a region with more than 200 mm of water deficit is considered to be an acutely water scarce area in the monsoon region.

Based on the above standards, eight regions are defined as follows:

- Region A1, year-round water surplus (ATS > 400 mm)
- Region A2, year-round water surplus (ATS < 400 mm)
- Region B1, water surplus with some months of deficit (ATD < 200 mm)
- Region B2, water surplus with some months of deficit (ATD > 200 mm)
- Region C1, water deficit with some months of surplus (ATD < 200 mm)

- Region C2, water deficit with some months of surplus (ATD > 200 mm)
- Region D1, year-round water deficit (ATD < 200 mm)
- Region D2, year-round water deficit (ATD > 200 mm)

where ATS (mm) is annual total surplus and ATD (mm) is annual total deficit.

Figure 1 shows the map of hydrological regions in monsoon Asia with parameter set 1. Because the extent of Monsoon Asia is not, as yet, well defined (Yoshino, 1999), Figure 1 shows the broad area including monsoon Asia. Though the details are different in some parts between the results of parameter sets 1 and 2, the overall characteristics are the same. The discussion hereafter is based on the result from parameter set 1.

Most wet regions A1 are occupied by Japan, the coastal area in east China, and parts of islands in Southeast Asia. The wet regions extending from equatorial regions to the middle latitudes around Japan are remarkable features in monsoon Asia. Though an A1 region is found to exist to the east of the Tibetan Plateau, parameter set 2 did not generate an A1 region (not shown). This part is important, because it is located at the upper

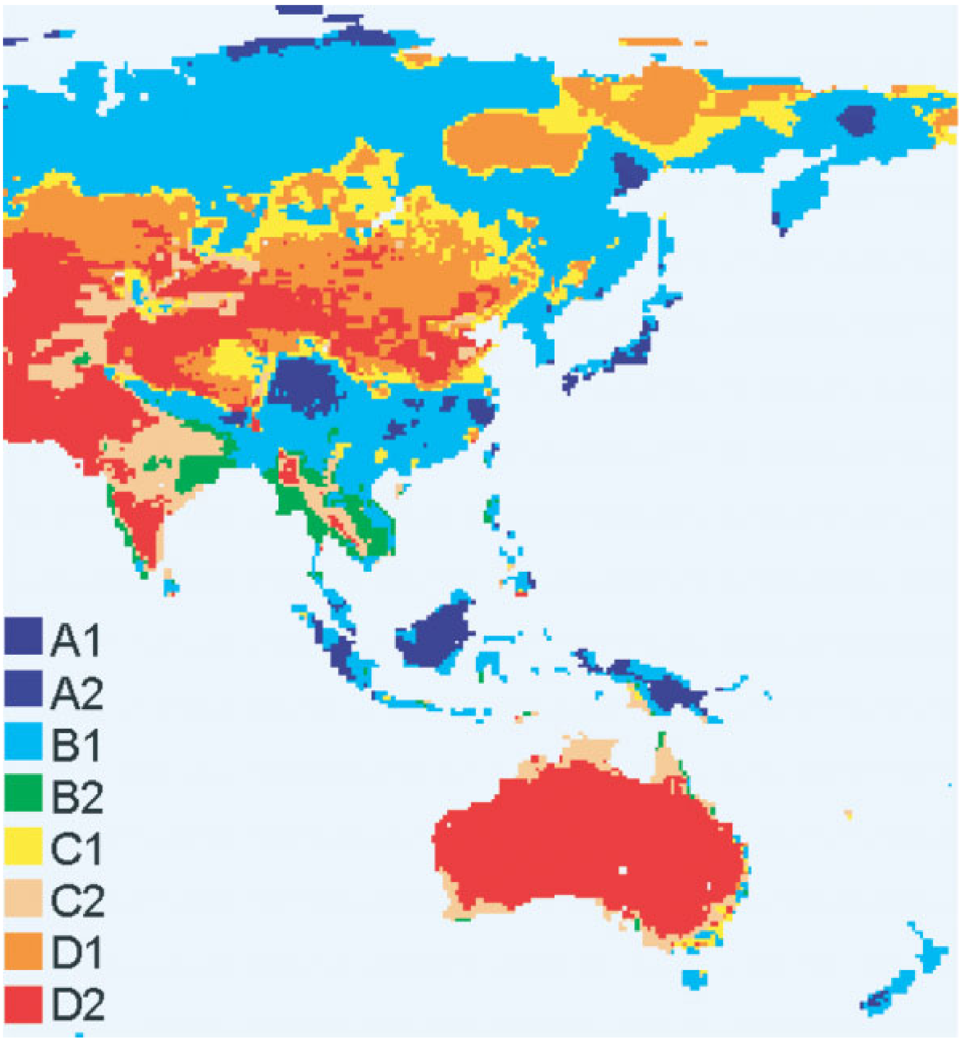

Figure 1. Hydrological regions in monsoon Asia

reach of the Changjiang (Yangtze) and Mekong Rivers. Whatever the cause, the discussion about the accuracy of the datasets is left for future study.

Amongst the A regions, the distribution of A1 regions dominates that of A2 regions. This means that the water surplus is quite large in regions with year-round water surplus. There are few transition zones, and that the wet and dry regions lie in close proximity is one of the characteristics of monsoon Asia.

Region B1, where a small water deficit exists, has a large spatial extent. The western part of the Western Ghats Mountains and Assam in India belong to the B1 category. These regions record a large amount of precipitation; however, the rainfall is concentrated in the wet season. This results in a considerable water deficit during the dry season.

Region B2 has a large water deficit with some water surplus. The extent is the eastern side of India, the area from Myanmar to Thailand along the Bay of Bengal, Rao PDR, and Cambodia. These areas are markedly noticed by the occurrence of distinct wet and dry seasons, and the amount of precipitation during the wet season is relatively large. Region B is considered to be the region where efficient operation of reservoirs could produce augmentation from available water resources.

Region C1 is noted for greater water deficit than surplus, even though the water deficit is relatively small. The extent includes Mongolia and parts of the Tibetan Plateau, and cannot be found in low latitudes. In contrast, C2 regions with relatively large water deficit are spread over the Deccan Plateau in India and the leeward area of the southwest monsoon in Myanmar and Thailand.

Water deficit persists throughout the year in region D. D1 regions are spread across the north of Qinling Mountains and Huaihe River in China. D2 regions are found surrounding D1 regions. In southern Asia, D2 regions are located adjacent to C2 regions lacking D1 regions. It is important to note that D2 regions appear in Myanmar and Thailand surrounded by B regions. The proximity of wet and dry regions is one of the typical characteristics of monsoon Asia.

The North China Plain, the major granary in China, is classified into D1 and D2 regions adjacent to an A region in the south. The proximity of wet and dry again forms the characteristics of the region. There are some concerns pertaining to the water problems that pose serious threats to food production in these areas (Kondoh *et al*., 2001). The route of the south-to-north water transfer project in China crosses the boundary between A and D regions.

WATER BUDGET IN LARGE RIVER BASINS

Monthly water budgets are calculated for the large river basins in East and Southeast Asia. Eight river basins are selected from the TRIP database. Haihe drains river water from the North China Plain near Tianjin to Bohai Bay. Huanghe (Yellow River), Changjiang and Zhujiang (Pearl River) are the three large river basins in China. The Mekong, Chao Phraya and Irrawaddy are the main river basins in continental Southeast Asia. Barito River basin is located in Kalimantan Island, Indonesia. Table III shows the fraction of each hydrological region in the watershed with annual water budget for the whole basin.

Almost all the rivers drain over multiple hydrological regions. Annual water budgets in Haihe and Huanghe are in deficit where D regions occupy more than 70% of the basin. In the case of Changjiang, a B1 region occupies about 60% of the basin, and it flows through various hydrological regions. Similarly, the Zhujiang basin is also dominated by a B1 region, which covers more than 80% of the basin and is considered to have identical characteristics to the Changjiang River. B1 and B2 regions dominate the Mekong River basin, with a few patches of C2 and D2 regions. This indicates that there is a seasonal water deficit, and the situations are almost the same as that of the Irrawaddy River.

Even though the Chao Phraya and Irrawaddy basins are close to each other, their hydrological characteristics are different. Domination of the Chao Phraya basin by a C2 region reveals a seasonal water deficit in the region. On the other hand, nearly 60% of the basin is occupied by a B region in the Irrawaddy basin.

Table III. Areal fractions of hydrological regions within the watershed and annual water budget

	A1	A2	B1	B2	C1	C2	D1	D2	*P*	*E*	*P* − *E*
Haihe	—	—	—	—	10·6	7·6	28·8	53·0	450·0	491·2	−41·2
Huanghe	5·7	0·6	9·7	—	10·3	1·1	28·8	43·9	492·3	502·7	−10·3
Changjiang	19·8	1·6	61·3	0·7	10·9	0·7	4·0	0·9	1253·1	801·2	451·9
Zhujiang	5·1	—	84·7	—	10·2	—	—	—	1425·8	1052·0	373·8
Mekong	12·2	—	32·3	34·4	—	18·3	—	2·9	1741·5	1075·0	666·5
Chao Phraya	—	—	5·0	28·3	—	58·3	—	8·3	1429·5	1180·5	249·0
Irrawaddy	6·0	0·4	35·3	23·7	5·3	14·7	6·4	8·3	1547·7	877·5	670·2
Barito	80·0	—	20·0	—	—	—	—	—	2805·9	1645·2	1160·7

Barito River is located in the wet tropics, where the annual water surplus is quite large. Approximately 80% of the basin is covered by the most humid A1 region.

Figure 2 shows the seasonal water budget in each river basin. It has been noticed that the water deficit occurs in spring to early summer in Haihe and Huanghe. The water surplus becomes low during the winter season in Changjiang and Zhujiang, although the summer water surplus is large. The annual water budget is in surplus in the Mekong, Chao Phraya and Irrawaddy, in spite of a water deficit appearing in the winter season. Chao Phraya basin is located in a leeward area during the southwest monsoon, and precipitation is relatively low during early summer; however, 30% of the basin is a B region.

Although strict verification of the calculated water budget for the whole basin is cumbersome, we can compare the results with the measured runoff data. Figure 3 shows the long-term average of monthly runoff of selected stations provided in the *Databases* page of the UNESCO/IHP homepage (http://webworld.unesco.org/water/ihp/). Though the exact runoff values are different, some runoff characteristics, such as duration of low-flow period, annual amplitude, and peak position, are found to be firmly in correspondence with the calculated basin water budget as shown in Figure 2. From the viewpoint of long-term runoff, the calculated characteristics of water budget satisfactorily reflect the regionality of the runoff from the basins.

DISCUSSION

Distribution of hydrological regions

Monsoon Asia is characterized by its wet environment in general; however, there are wet and dry regions in close proximity. For example, regions B and D are bordered by a narrow and linear C region in eastern China. This zone is marked by a border of crop and paddy fields, showing a transition from dry to wet regions. Since the Huaihe lies between the Huanghe and Changjiang, and runs eastward, much of the rain water in the southern wet region does not reach the North China Plain, resulting in the reinforcement of semi-arid conditions in the North China Plain. The geographical setting of the river course is an important aspect in understanding the hydrological region.

In the area around Myanmar and Thailand, region D is surrounded by B regions. These dry areas are created by mountain shadow effects of the southwestern monsoon, which is one of the peculiarities of monsoon Asia. The existence of river channels, such as Chao Phraya and the Irrawaddy, which bring water from upper basins, is very important in these regions. In the lower Chao Phraya, paddy cultivation is observed during the dry season, though dry-season irrigation does not have a long history, having commenced soon after the construction of dams in the upper reaches of the river during the 1960s. The decline in water level in the reservoirs during the dry season, however, does constitute a serious problem (Shintani *et al.*, 1994). The proximity of wet and dry regions is one of the important characteristics of monsoon Asia.

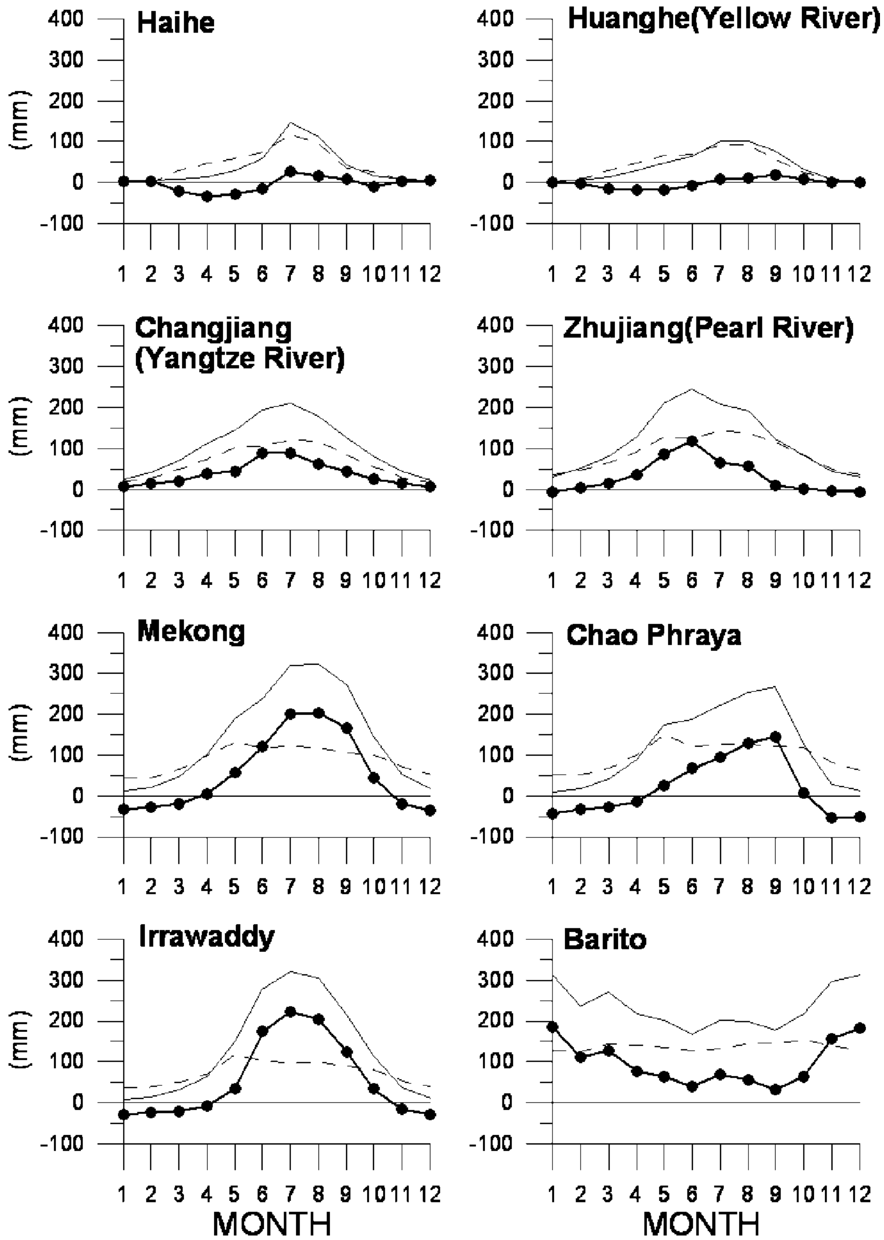

Figure 2. Seasonal water budgets of selected river basins. Solid and broken lines denote precipitation and evapotranspiration respectively. Thick solid lines with filled circles show the difference between precipitation and evapotranspiration

In the case of Japan, especially on her Pacific side, this is identified as an A1 region, indicating that Japan is very rich in water. A1 regions can sustain water usage because of their large water surplus. It is interesting that the incidence of water shortage problems has been reported sometimes even in A1 regions such as Tokyo, Japan. This is because Tokyo's domestic water supply is sourced from distant watersheds through lengthy canal and river courses. The true understanding of the problem requires an understanding of the human aspects, whereas the hydrological region indicates only the actual hydrological conditions in the

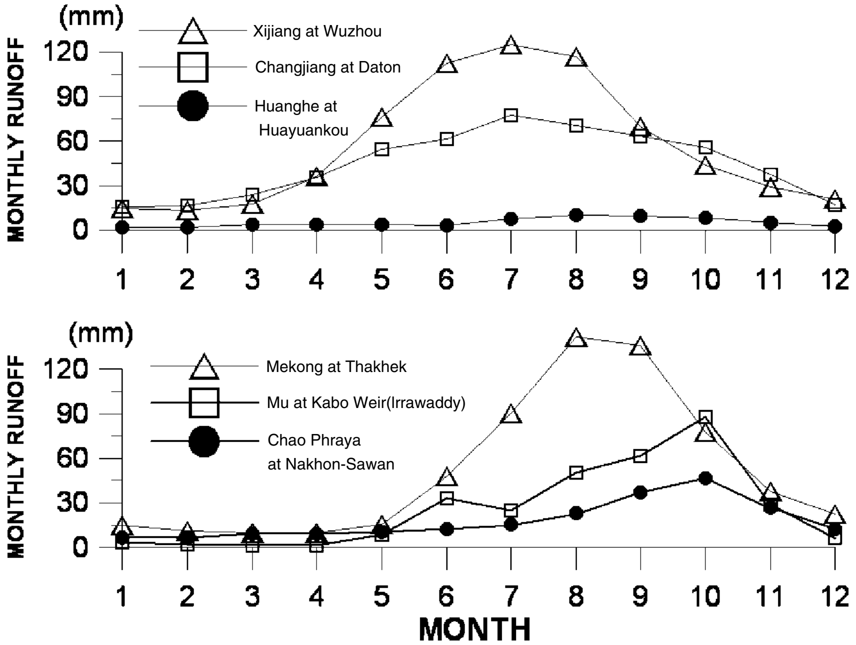

Figure 3. Long-term average of monthly runoff of selected gauge stations extracted from the *Databases* page in the homepage of UNESCO/IHP (http://webworld.unesco.org/water/ihp/). Xijiang is the largest tributary of the Zhujiang, China. Mu is one of the tributaries of the Irrawaddy

area. If water in a region is only used within the same region, then a map of the hydrological region provides fundamental information to undertake appropriate water utilization strategies on a regional scale.

Water budget of river basins

The selected basins illustrated in Table III and Figure 2 are located over wide geographic locations, ranging from the equator to 40 °N. In spite of the varied land cover observed in these basins, the agricultural practices are noteworthy among human activities. Water availability in the crop-growing season is a defining factor in the mid-latitudes in determining crop type. However, human intervention in the hydrological cycle has created new water utilization systems. For example, the water budget in the Haihe River basin, eastern China, is deficient from March to June. This period corresponds to the growing season of winter wheat, which is also dry prior to the onset of Meiyu (rainy season). This causes strong dependence on groundwater for irrigation, which leads to a decline in the water level (Kondoh *et al*., 2001).

Water budget is in deficit in most of the basins of the Indian peninsula, where groundwater resources sustain agricultural practices (Brown, 2001). The amount of groundwater is hard to estimate from the surface water budget; however, it can be stated that the main water resource responsible for maintaining life comes from groundwater in the D region.

Groundwater resources are generally considered sufficiently large enough to maintain human activities for a certain period. However, the enormous groundwater consumption exceeding its recharge causes a negative water budget and leads to a continuous water level decline. The small rate of recharge means that the restoration of groundwater level takes a very long time. Future perspectives of the groundwater in D regions are not so bright; however, there are three options for maintaining sustainable agricultural production. These are reduction of food production, water saving, and water transfer from distant regions. The project in China to transfer southern water to northern water-scarce areas is a project originating from such regional circumstances.

In low latitudes, energy is sufficient for the growth of plants and water availability determines the productivity of agricultural practices. A large water deficit situation appears during the dry season in the Mekong, Irrawaddy, and Chao Phraya basins. A facility which smoothes out seasonal distribution of water may help to increase the agricultural productivity in these regions. The dry-season paddy in Chao Phraya is one such manifestation of human control over water resources. However, as stated previously (Shintani *et al*., 1994), other water problems arise from such human intervention, such as demand for irrigation water.

CONCLUSIONS

A map of hydrological regions in monsoon Asia is created using grid-based global datasets. This classification is based on the water budget within the region. By inspecting the map, it is found that the proximity of wet and dry regions is one of the important characteristics of monsoon Asia. Using this map, the characteristics of the water budget in large river basins are described. The calculated water budget satisfactorily explains the measured long-term runoff characteristics of selected basins.

The map can be used to understand regional characteristics from the viewpoint of the water budget. Many local case studies have been completed, and similar studies will follow in the future. Such regional studies can be ranked on the continental or global scale by assigning each outcome on the hydrological region map as a base map of the spatial information database.

The local experiences, which are discrete entities of the hydrological region, can be accumulated as a knowledge base in the form of a GIS. Its operation will lead to the understanding of regional characteristics. The creation of such a database is the next target of the study, because the sound management and utilization of water resources are never realized without a proper understanding and assessment of the regional characteristics.

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