TRENDS AND PATTERNS OF VARIATIONS IN THE HYDROLOGICAL CHARACTERISTICS OF MOUNTAIN RIVERS: CENTRAL JAPAN

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Abstract

Due to highly mountainous topography and typhoon-associated floods, the short and high-gradient rivers of Japan exhibit distinctive behavioral characteristics. A crucial issue that confronts the people of such mountain-dominated and typhoon-affected countries is the extent to which the hydrological characteristics of the rivers will be affected by global climate changes associated with greenhouse warming. The questions that are important in this regard are: 1) Are there significant inter-regional differences in the mean and highest discharges on record? 2) How flashy are the flood discharges? and 3) What is the nature of long-term trends in the mean and annual peak discharges?

This paper attempts to answer these questions on the basis of statistical analysis of daily discharge data available for over 20 years (1974-1998) for 103 river gauging sites located in the Kanto, Hokuriku and Chubu Regions of central Japan. Four major conclusions emerge from the analyses – (a) there are statistically significant inter-regional differences in the mean discharges, but the inter-regional differences in the maximum discharges are not significant, (b) flood variability is highest in the Kanto Region and least in the Hokuriku Region, (c) none of the gauging sites reveals statistically significant long-term trends either in the mean or annual peak discharges; however, there is a tendency for an increase in the mean and annual peak discharges in the Kanto Region and a decline in the other two regions, and (d) cluster analysis demonstrates that most sites in the three regions (74 to 93%) have comparable hydrological characteristics. Since the recent global warming projections and future climatic simulations have indicated wilder weather patterns and enhanced possibility of extreme events in Japan, the main findings of this study have important implications for millions of people living in central Japan especially the Kanto Region.

Keywords: Japanese rivers, spatial patterns, discharge variability, flood flash magnitude index, long-term trends

1.0 Introduction

The Japanese Archipelago is generally described as the land of volcanoes, mountains and fast-flowing rivers. Mountains constitute about ¼ of the land area. Due to highly mountainous topography and typhoon-associated floods, the short and high-gradient rivers of Japan exhibit distinctive behavioural characteristics. The average peak discharge per unit area is 1 to 2 orders of magnitude higher than that of the large world rivers. A crucial issue that confronts the people of such mountain-dominated and typhoon-affected countries is the extent to which the hydrological characteristics of the rivers will be affected by global climate changes associated with greenhouse warming. The questions that are important in this regard are:

a) Are there significant inter-regional differences in the mean and highest discharges on record?

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b) How flashy are the flood discharges? and  
c) What is the nature of long-term trends in the mean and annual peak discharges?

This paper attempts to answer these questions on the basis of the analysis of daily discharge data available for over 20 years for 103 river gauging sites located in central Japan.

Figure 1. Regression plot of stream length versus drainage basin area for the Japanese rivers (this study) and the regression line for world rivers (after Mulder and Syvitsky, 1992).

Figure 2. Map of central Japan showing the location of all the river gauging sites (stars) included in the present study. The map also shows the location of major cities (circles) and some major rivers. The inset map shows the location of the study area. The basin boundaries are shown in the background.
2.0 The Japanese Rivers: An Introduction

High-relief mountains, heavy storms, active mass movements and strong tectonic activity characterize the Japanese landscape. Elevation is linked to tectonic movements (Ohmori, 2000) and associated volcanic activities. Therefore, the tectonically-active Japanese Archipelago is dominated by high relief. Mt. Fuji (3776 m ASL) is the highest peak in Japan. Analysis of the digital elevation data reveals that the mean elevation is 377 m ASL and over one-third of the geographical area is above 400 m ASL.

The hydrology of Mountain rivers is predominately controlled by climate on the regional scale and by orographic and elevation effects at the local scale (Wohl, 2000). Japan has a warm, humid climate with high precipitation. Typhoons and the Polar front are primarily responsible for heavy rainfall on the islands and high-magnitude floods on the Japanese rivers. The 1-day rainfall exceeding 200 mm has a recurrence interval of about 10 years (Iwai and Ishiguro, 1970). Due to highly mountainous topography and typhoon-associated floods, the short and high-gradient rivers of Japan exhibit distinctive hydrological characteristics (Oguchi et al., 2001).

Mountain rivers in South Asia and Oceania, including Japan, are known for their remarkably high sediment load and yields (Milliman and Syvitski, 1992). Heavy rainfall and steep slopes are responsible for frequent and widespread slope failures and landslides. Consequently, a very high proportion of the river sediments is contributed by such mass movement processes (Oguchi et al., 2001). The mean annual sediment delivery rates range from $10^1$ to $10^3$ m$^3$ km$^{-2}$ yr$^{-1}$ (Ohmori, 2000). The highest rates are observed in central Japan.

On account of high relief and limited geographical area, majority of the Japanese rivers are short and have small catchments. The river length seldom exceeds 300 km and the basin area is usually less than $10^4$ km$^2$. Only four rivers (the Ishikari, Kitakami, Tone and Shinano) have basin area more than $10^4$ km$^2$, and only two rivers (the Tone and Shinano) have river length exceeding 300 km. Using the data given in the Atlas of Japan (Teikoku-Shoin, 2004), the following relationship between river length ($L$) and basin area ($A$) was derived for the major Japanese rivers (Fig. 1):

$$L = 18.77 A^{0.27} \quad (r^2=0.31; \; n = 23; \; \text{significant at 0.001 level})$$

Mulder and Syvitsky (1996) have shown that a strong relationship ($L = 2.73 A^{0.501}$) exists between river length and basin area for the world rivers. For the Japanese rivers, the regression exponent (0.27) is significantly lower than the regression slope estimated for the world rivers (0.501), but the intercept is much higher. This implies that the rate of change in river length with drainage basin area is lower. In other words, the Japanese rivers have more area for a given stream length. This has significant implications for runoff accumulation and flood generation in high-gradient rivers of Japan.

3.0 The Study Area, Data Collection and Methodology:

The hydrological characteristics of the Japanese rivers have been the subject of very few studies in international journals and books (Oguchi et al., 2001; Grossman, 2001; Siakeu et al., 2004). Therefore, an attempt is made in this paper to analyze the hydrological characteristics of over 30 major and minor rivers in the Kanto, Hokuriku and Chubu Regions of central Japan. The rivers under review include the two largest rivers in Japan, namely the Tone and the Shinano. Other important rivers included in this study are Ara, Tama, Tsurumi, Fuji and Agano.

Daily discharge data available for about 25 years (1974-1998) for 103 river gauging sites located in the three regions of central Japan (Table 1) were obtained from the River Discharges Year Book of Japan, published by the Japan River Association. The discharge data were collected by the Ministry of Land, Infrastructure and Transport, Government of Japan. Of the 103 gauging sites, 82 sites have, more or less, complete record of daily
discharge for 25 years. For the remaining 21 sites, discharge data are available for 15 to 24 years. The location of all the 103 gauging sites is shown in Fig. 2.

The daily discharge data were analyzed to derive a number of hydrological parameters for each gauging station, such as the mean discharge \( (Q_m) \), the annual peak discharge \( (Q_p) \), the highest or maximum discharge on record \( (Q_{max}) \), the maximum discharge per unit area \( (UQ) \) and the flash flood magnitude index \( (FFMI) \); Baker, 1977). In addition, the long-term trends in \( Q_m \) and \( Q_{max} \) were evaluated for each gauging site by deriving the regression coefficients \( (b) \) of the relationship between years (time) on one hand and \( Q_m \) or \( Q_{max} \) on the other. Further, in order to evaluate the rate of change in discharge with basin area, bivariate relationships between upstream basin area \( (A) \) vis-à-vis \( Q_m \) or \( Q_{max} \) were also derived. Cluster analysis in Matlab software was carried out to identify groups by using some of the critical hydrologic parameters for all the 103 gauging sites, such as \( A, Q_m, Q_{max}, \) the \( Q_{max}/Q_m \) ratio \( (= Q_r) \), \( UQ \) and \( FFMI \). Finally, to understand the nature of spatial variations in these hydrologic parameters, shaded isoline maps were prepared in ArcGIS.

4.0 Results and Discussion

The crucial questions that motivated the present study were raised in section 1.0. In this section, an attempt is made to present and discuss the results of the analyses with reference to these questions.

1. Are there significant inter-regional differences in the mean and highest discharges on record?

The distribution of runoff varies considerably owing to differences in the basin physiography as well as the path of flood-generating storms. Statistical analyses of the discharge data reveal that there are subtle to significant differences in the magnitude of mean \( (Q_m) \) and the highest or maximum discharge on record \( (Q_{max}) \). The mean discharges vary between 2 \( m^3/s \) (Chubu Region) and 508 \( m^3/s \) (Hokuriku Region), and the maximum discharges range from 150 \( m^3/s \) (Chubu Region) to 7921 \( m^3/s \) (Kanto Region) (Table 2). The highest discharge during the gauge period was recorded on the Tone River in the Kanto Region. In the Hokuriku Region, the highest discharge was recorded on the Shinano River and its major tributary, the Ägano River. In the Chubu Region, the Kiso and Tenryu Rivers have the highest discharge on record.

In order to establish whether there are significant inter-regional differences in the mean \( (Q_m) \) and maximum discharges on record \( (Q_{max}) \), the Analysis of Variance (ANOVA) test was applied. The ANOVA test demonstrates that while there are statistically significant inter-regional differences in the mean discharges \( (F = 3.77; p = 0.02) \), the inter-regional differences in the maximum discharges are not statistically significant \( (F = 1.34) \). The variance ratios indicate that while the inter-regional (between) differences in the mean discharges are more than the intra-regional (within) differences, in case of the highest discharges on record the intra-regional (within) differences are significantly greater than the inter-regional differences (between). This in other words implies that the magnitudes of large floods in different basins are comparable, in spite of significant differences in the basin size, shape and relief. Perhaps because all the basins are affected by the same factor: heavy rainfall associated with typhoons and the Polar front.

Drainage basin area has a significant control on the discharge (Mulder and Syvitsky, 1996; Wohl, 2000). To establish the relation between these two parameters, regression analysis was carried out. The power-law regressions between \( Q_m \) or \( Q_{max} \) on one hand and \( A \) on the other are given below (Fig. 3A and B)

\[
Q_m = 0.19 A^{0.78} \quad (r^2 = 0.75; \ n = 103; \ \text{significant at 0.001 level})
\]
\[
Q_{max} = 15.29 A^{0.66} \quad (r^2 = 0.74; \ n = 103; \ \text{significant at 0.001 level})
\]
The b-coefficients indicate that the mean discharge increases more rapidly with the catchment area than the highest discharge on record in central Japan. The intercept and the exponent of mean discharge are comparable to the exponent of world rivers ($Q_m = 0.16 A^{0.75}$) derived by Mulder and Syvitsky (1996).

Regionwise regression analyses indicate that the rate of change in $Q_{\text{max}}$ with $A$ is highest in the Hokuriku Region (0.79), followed by the Chubu (0.71) and Kanto (0.63) Regions. The corresponding exponents for the mean discharge are 0.65, 0.93 and 0.84. The rate of change in $Q_m$ is highest for the Chubu Region and least for the Hokuriku Region. The present study, thus, demonstrates that there are subtle to noteworthy inter-regional differences in the hydrological characteristics of the area under review.
Figure 4. Pattern of spatial variation in the ratio between maximum discharge on record ($Q_{\text{max}}$) and mean discharge ($Q_{\text{m}}$) in central Japan. Classes based on natural breaks.

Figure 5. Spatial pattern of variation in the flash flood magnitude index (FFMI) in central Japan. Classes based on natural breaks.
Table 1: Details of the river gauging sites included in the present study.

<table>
<thead>
<tr>
<th>Region</th>
<th>Name of the Rivers</th>
<th>Number of Gauging sites</th>
<th>Basin Area in km²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kanto</td>
<td>Kuji, Naka, Tone, Ara, Tama, Tsurumi, Fuji</td>
<td>46</td>
<td>121 to 12458</td>
</tr>
<tr>
<td>Hokuriku</td>
<td>Agano, Shinano, Seki, Hime, Kurobe, Jyoganji, Jintsu, Sho, Oyabe, Tedori, Ara, Kakehashi</td>
<td>28</td>
<td>121 to 9719</td>
</tr>
<tr>
<td>Chubu</td>
<td>Kano, Abe, Oi, Kiku, Tenryu, Toyo, Yahagi, Shonai, Kiso, Suzuki, Kumozu, Kushida, Miya</td>
<td>29</td>
<td>34 to 4880</td>
</tr>
</tbody>
</table>

Table 2: Mean, minimum and maximum values of mean discharge and highest discharge of record for the three regions of central Japan.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Kanto Region</th>
<th>Hokuriku Region</th>
<th>Chubu Region</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q&lt;sub&gt;m&lt;/sub&gt;</td>
<td>Q&lt;sub&gt;max&lt;/sub&gt;</td>
<td>Q&lt;sub&gt;m&lt;/sub&gt;</td>
</tr>
<tr>
<td>Mean</td>
<td>67.1</td>
<td>2600.5</td>
<td>112.3</td>
</tr>
<tr>
<td>Minimum</td>
<td>4.4</td>
<td>280.3</td>
<td>15.7</td>
</tr>
<tr>
<td>Maximum</td>
<td>228.6</td>
<td>7921.6</td>
<td>508.3</td>
</tr>
</tbody>
</table>

Q<sub>m</sub> mean discharge, Q<sub>max</sub> highest discharge on record; both in m³ s<sup>-1</sup>

2. How flashy are the flood discharges?

Highest discharge on record indexed by drainage area (U<sub>d</sub>) and the ratio between highest discharge on record and mean discharge (Q<sub>r</sub>) have been used as measures of discharge variability (Kale, 2003). Another widely used measure of the flood variability is the
flash flood magnitude index \((FFMI)\), which is the standard deviation of the logarithms of the annual peak discharge (Baker, 1977). Analysis of the discharge data reveals that \(Q\) ranges between 4 and 171 (Table 3), indicating that the discharges are highly variable and that the maximum discharges sometimes could be higher by 1 or 2 orders of magnitude. The Kanto region, particularly its western part, is dominated by high \(Q\) (Fig. 4).

The average maximum discharges per unit area \((0.23–7.5 \text{ m}^3 \text{s}^{-1} \text{km}^{-2})\) in the Chubu Region are generally higher than those in the Kanto and Hokuriku Regions. However, the maximum discharge generated per square km \((U_Q)\) is highest in the Kanto region (Table 3). The flash flood magnitude index \((FFMI)\) values also indicate that the floods are flashier in the Kanto Region (Table 3, Fig. 5). The mean \(FFMI\) value for the Kanto Region is higher than the world average \((0.28;\text{Erskine and Livingstone, 1999})\), implying that the year-to-year differences in peak flood magnitudes are larger in this region. The analysis, thus, demonstrates that the rivers in the Kanto region are characterized by higher interannual variability in flood discharges than the Hokuriku and Chubu Regions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Kanto Region</th>
<th>Hokuriku Region</th>
<th>Chubu Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Q_r)</td>
<td>Mean</td>
<td>53.08</td>
<td>40.86</td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>17.75</td>
<td>14.61</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>171.61</td>
<td>82.69</td>
</tr>
<tr>
<td>(U_Q) in \text{m}^3 \text{s}^{-1} \text{km}^{-2})</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Mean, minimum and maximum values of maximum-to-mean discharge ratio \((Q_r)\), unit peak discharge \((U_Q)\) and \(FFMI\) for the three regions of central Japan.

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of gauging sites</th>
<th>% of sites showing a tendency for an increase in mean discharges</th>
<th>% of sites showing a tendency for an increase in annual peak discharges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kanto</td>
<td>46</td>
<td>85</td>
<td>74</td>
</tr>
<tr>
<td>Hokuriku</td>
<td>28</td>
<td>39</td>
<td>36</td>
</tr>
<tr>
<td>Chubu</td>
<td>29</td>
<td>24</td>
<td>21</td>
</tr>
</tbody>
</table>

High \(FFMI\) values are associated with the Ara, the Tone and the Tama \((0.56)\) Rivers and the \(Q_r\) is greater than 100 for the Ara and the Tama Rivers. All these highly flashy rivers drain the Kanto region. The major finding that emerges is that the flood variability is highest in the Kanto Region and least in the Hokuriku Region. The watersheds of the three rivers mentioned above are under strong human impacts because they are located in and around the Tokyo Metropolis. Highly urbanized conditions in downstream areas and enhanced agricultural activities and deforestation in upstream areas seem to account for more flashy regimes of these rivers. In addition, moisture supply from the Pacific in summer and autumn is more abundant in the Kanto region than the other regions, leading to stronger storms and floods. In contrast, rivers in the Hokuriku region are more affected by snow due to winter moisture supply from the Japan Sea and subsequent gentler floods during the time of snowmelt.
3. What is the nature of long-term trends in the mean and annual peak discharges?

The long-term trends in $Q_m$ and $Q_p$ were evaluated by deriving the regression coefficients ($b$) of the relationship between years (time) on one hand and $Q_m$ or $Q_p$ on the other. None of the gauging sites reveals statistically significant trends either in the mean or annual peak discharges. Siakeu et al. (2004) made similar observations on the basis of the investigation of time-series trend in discharge at 57 gauging sites in central Japan. Notwithstanding the insignificant long-term trends, the regression coefficients ($b$) indicate a tendency for a slight increase in the mean and annual peak discharges (Fig. 6) in the Kanto Region and a slight decline in the other two regions (Table 4). This may be related to the general trends of fast urbanization in the Kanto Region including the Tokyo Metropolis and less widespread urbanization in the other regions, but more detailed examination is needed to verify this hypothesis.

Table 5: Number of gauging sites in different cluster groups in the three regions of central Japan.

<table>
<thead>
<tr>
<th>Region</th>
<th>Number of gauging sites</th>
<th>Cluster Groups</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Group 1</td>
</tr>
<tr>
<td>Kanto</td>
<td>46</td>
<td>2</td>
</tr>
<tr>
<td>Hokuriku</td>
<td>28</td>
<td>-</td>
</tr>
<tr>
<td>Chubu</td>
<td>29</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>103</strong></td>
<td><strong>2</strong></td>
</tr>
</tbody>
</table>

4. Grouping of river gauging sites

In order to identify groups of gauging sites having similar hydrological characteristics in terms of $A$, $Q_m$, $Q_{max}$, $Q$, $U_Q$ and FFMI, cluster analysis was carried out in Matlab. Using the centroid method, five groups were identified. The regionwise number of sites is given in Table 5 and the parameterwise plots are illustrated in Fig. 8. The analysis reveals that a very
large number of sites (74 to 93%) in the three regions have comparable hydrological characteristics. Only in the Kanto Region, a dozen gauging sites display distinct hydrological characteristics. These sites are located on the Tone, Edo and Fuji Rivers and are characterized by comparatively larger basin areas (>3000 km$^2$) and higher peak discharges, but lower unit discharges and FFMI (Fig. 7).

5.0 Conclusions
This study, for the first time, has investigated the details of the hydrological characteristics of the high-gradient Japanese rivers at regional scale. The following major conclusions emerge from the analysis of about 25-year daily discharge data for 103 gauging sites in central Japan.

1. There are statistically significant inter-regional differences in the mean discharges, reflecting differences not only in rainfall but also the basin size, shape and relief, but the inter-regional differences in the maximum discharges are not significant.

2. Flood variability in terms of $Q_r$, $U_Q$ and FFMI is highest in the Kanto Region and least in the Hokuriku Region. This could be attributed to the differences in the levels of human activities in the watersheds and different rainfall characteristics between the Pacific and Japan-Sea sides of Japan.

3. None of the gauging sites reveals statistically significant long-term trends either in the mean or annual peak discharges. However, a propensity for an increase in the mean and annual peak discharges is displayed by sites in the Kanto Region and a tendency for a decline in the mean and peak discharges is revealed by the other two regions. This may reflect the different trends of urbanization among these regions.

4. Cluster analysis demonstrates that most sites (74 to 93%) in the three regions have comparable hydrological characteristics, and exceptional sites occur only in the Kanto region.

It is evident from the above discussion that the Kanto Region displays some distinct hydrological characteristics. As noted, the Kanto Region is one of the most urbanized and densely populated regions of Japan, with the Tokyo Metropolis, one of the largest cities in the world. Recent global warming projections and future climatic simulations have indicated wilder weather patterns, with increased intensity of typhoons, increased inter-regional variability in precipitation and enhanced possibility of extremes in Japan (Kusunoki et al., 2006). On this background, the major findings of this study have important implications for flood hazard management and water resource management for central Japan in general and the Kanto Region in particular.

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References


