A Basin-scale Spatial Distribution of Probable Maximum Precipitation for the Yodo River Basin, Japan

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Synopsis

The objective of this paper is to analyze the extreme rainfall in term of the PMP estimates for the Yodo River basin. The PMP are estimated using the Hershfield statistical method. Since the method uses statistical approaches, long recorded data available in Japan were able to be fully utilized. A limitation by using the Hershfield statistical method is that only point PMP are estimated. Using the point PMP estimates, a spatial PMP of 1-day, 2-day, 3-day, 5-day, and 7-day rain were developed. The paper describes the methodology used to produce the spatial PMP and discuss on the PMP distributions over the basin area. Comparison between the spatial PMP and previous flood historical records were also conducted. Good agreement were observe from the comparison confirming reasonable spatial PMP distribution were constructed.

Keywords: Probable maximum precipitation, Hershfield statistical method, extreme rainfall, spatial distribution

1. Introduction

Global warming have been claimed to produce higher intensity and long period of rainfall across the globe. This includes Japan. Lying on prone typhoon area, exposed to the Pacific Ocean on the East and located near to the Siberian land mass on the West, heavy rainfalls are regularly expected especially during the summer (Jun to August). The rains are observe to becoming more intense and frequent. In order to understand the extreme rainfall, an upper boundary or limit of possible extreme rainfall could be estimated. The estimates is called the probable maximum precipitation (PMP). The PMP estimates can be use for flood disaster management (hazard map, dam operation, flood control, irrigation, etc.). World Meteorological Organization (WMO, 2009) defines the PMP as "the greatest depth of precipitation for a given duration meteorologically possible over a given size storm area at a particular location at a particular time of the year, with no allowance made for long-term climatic trends"(WMO, 2009). Previously, research on PMP are not very popular in Japan probably due to PMP estimates are usually used for dam designs. However, more research are currently being conducted and of high interest. Huge dams are usually constructed for hydro-electricity projects, whereas Japan uses hydro-electricity powers about 10%, 30% from nuclear power plant (before the Fukushima nuclear plant incident) and mainly from coal.

This research conducts PMP estimation for one of the river basins in the Kansai region of Japan, the Yodo river basin. The Yodo river basin extends over six prefectures of Mie, Shiga, Kyoto, Osaka,
Hyogo and Nara with an area of 8,240 km$^2$. It is the largest river basin in the Kansai region. The basin area includes Lake Biwa and several main rivers (Katsura, Seta-Uji, Kizu and Yodo rivers) which flow towards the Osaka bay. The population in the basin has been increased since the Edo period (1700) to Taisho period (1925), from 2 million to 4.73 million people. In 2002 the population have reached 14 million (Shiga Prefectural Government, 2007; Kinki Regional Development Bureau, 2002).

Various hydrological studies have been conducted within the Yodo river basin before. Luo et al. (2012) analyzed land use change under the paleo-environment (1843 to 1976) to explore the effects of human activities on hydrologic response. Kim et al. (2008) developed a numerical model for hydrological and climate change analysis. Combination of the Global Climate Model (GCM) and a hydrological model investigated the possible impacts of climate change from the hydrological viewpoint. Other researches were more focused towards the water quality analysis and water resources management especially in the Lake Biwa of Yodo river basin. Even though, several statistical researches have been conducted using data from stations within the Yodo river basin (Takara and Tosa, 1999; Takara and Stedinger, 1994; Takasao et al., 1986), extreme rainfall analysis and PMP estimates using whole data of the basin has yet to be conducted.

The objective of this paper is to analyze the extreme rainfall in term of the PMP estimates for the Yodo River basin. The PMP are estimated using the Hershfield statistical method. Since the method uses statistical approaches, long recorded data available in Japan were able to be fully utilized. A limitation by using the Hershfield statistical method is that only point PMP are estimated. To obtain an aerial PMP estimates, depth area duration curve is needed. This paper however will not discuss on the areal PMP. Using the point PMP estimates, a spatial PMP of 1-day, 2-day, 3-day, 5-day, and 7-day rain could be generated. The paper will describe the methodology used to produce the spatial PMP using 1-day rainfall.

2. Study site and data

62 stations were chosen for the extreme rainfall analysis and PMP estimation. 31 stations inside the Yodo river basin and 31 stations outside of the basin boundary. The stations outside the Yodo river basin were considered as additional margin for the PMP estimation and spatial distribution analysis for the Yodo river basin. The data were obtained from the Japan Meteorological Agency (JMA). Long historical data (1880 - 2012) belongs to the surface weather observation network, while the rest are from the Automated Meteorological Data Acquisition System (AMeDAS) (1976 - 2012) of JMA. Fig.1 shows the locations of stations selected for the analysis. Distances among each station are about 20 to 30 km.

3. Method

The 1-day rainfall obtained by JMA was used to derived the 2-day, 3-day, 5-day and 7-day rainfall using Fortran codes developed by the writers. To obtain the rainfall data directly from JMA are time consuming and costly since 62 station were used, thus a Fortran program was written to generate the 2-day, 3-day, 5-day and 7-day data. From there, the annual maximums of all the periods were extracted also using the same Fortran program. The
2-day, 3-day, 5-day and 7-day rainfall of one of the stations were compared with the data from JMA for validation. Similar rainfall data were obtained, thus assuring the quality of the derived rainfalls (2-day, 3-day, 5-day and 7-day annual maximums).

Using the annual maximums of the rainfalls, Hershfield statistical method was used for estimating the PMPs. Hershfield method is being used widely (Deshpande et al., 2008; Koutsoyiannis, 1999; Durbude, 2008; Desa et al., 2001; Desa et al., 2007). It was considered in the manual on estimation of probable maximum precipitation by the World Meteorological Agency (WMO, 2009) after it had been modified and developed by Hershfield (Hershfield, 1961a; Hershfield 1961b). It is also believed to be closely comparable to those obtained by the conventional moisture maximization and storm transposition methods (Deshpande et al., 2008). More comparison between the statistical method and hydro-meteorological method however are still needed. The essence of the Hershfield statistical method is storm transposition, but instead of transposing the specific rainfall amount of one storm, an abstracted statistic $K_m$ is transposed (WMO, 2009). The Hershfield method for estimating the PMP value for a station uses the following equations.

$$X_{PMP} = X_n + S_n \times K_m$$  \hspace{1cm} (1)

$$K_m = \frac{X_{max} - X_{n-1}}{S_{n-1}}$$  \hspace{1cm} (2)

where, $X_{PMP}$ is the PMP estimates for a station, $X_n$ is the mean of the annual extreme series, $S_n$ is the standard deviation of the annual extreme series, $K_m$ is the frequency factor which depends on the availability of data period, $X_{max}$ is the highest rainfall value at the station, $X_{n-1}$ is the mean of the annual extreme series without the largest value, and $S_{n-1}$ is the standard deviation of the annual extreme series without the largest value.

First, the parameters $X_n$, $S_n$ and $K_m$ are calculated. Then, $K_m$ values for all stations are plotted against the $X_n$ values respectively and an envelope curve is drawn (Fig.2). The new $K_m$ value is picked up from the envelope line for each station's $X_n$. Finally, the PMP values for each station is calculated using Eq.1 by replacing $K_m$ with the new value.

According to the WMO (2009) envelopment is a process for selecting the largest value from any set of data. Several researchers applied similar envelopment technique currently used for this paper (Desa et al., 2007; Metreata, 2006). Fig.2 shows the $K_m$ plots against $X_n$ and its envelope lines. All the $K_m$ values despite various rainfall periods have $K_m$ values less than 20. It was mentioned by Hershfield that the maximum values of $K_m$ obtained using 2700 stations (most stations were in the US) used for previous climatological observation programme is 20 (WMO, 2009). In this study, the average values of the transposed $K_m$ are around 13 to 15. It was stated by Hershfield also that for areas of heavy rainfalls the value of 15 could be too high and too low for arid areas. This study however found that the value 15 was obtained for an area of high rainfalls, contributing to the information for the $K_m$ according to its climate characteristics. The two extreme $K_m$ values comes from Hikone and Miyagawa. A more smooth an accurate envelope could be obtained if longer records and higher number of extreme rainfalls were recorded.

Spline interpolation method in ArcGIS 10 Spatial analyst tool box were used for the interpolation of the point PMP. The method was chosen due to its low interpolation error and its approach in preserving the point value whereby the interpolated surface goes through the data points. The Spline technique is considered as a deterministic and global method where a continuously differentiable surface is fitted to all the data. The technique used to interpolate the data assumes that the data are error free and hence the interpolated data goes through the data points. Spline technique is one of the interpolation technique that are generally recommended for hydrologic applications since it is robust, operationally straightforward to use and represents quite well the spatial distributions of hydrological parameters (Bloschil and Grayson, 2000).
4. Results and discussions

4.1 Maximum 24-hour rainfall time series

Fig. 3 illustrates the annual maximum 24-hour rainfall distribution of stations within the Yodo river basin from 1880 to 2012. The observed data ranges from 29 years to 132 years. The longest observation data were obtained from Kyoto, Osaka and Hikone stations which have 132, 130 and 119 years of observation respectively, while the others have only up to 37 years. This corresponds to the commencing of AMeDAS in 1974. Information of each station’s data and the parameters for the PMP estimation are presented in Table 1.

4.2 Probable maximum precipitation (PMP) estimates

Table 1 shows the PMP estimates and its rainfall statistical properties ($X_n$ and $X_{max}$) of each station. The results show stations with higher $X_{max}$ values tends to has higher PMP estimates indicating good correspondence between them.

The Hershfield statistical method uses a transposed frequency factor Km for its PMP estimation; which considers the average maximum rainfall, $X_n$ of one station instead of just the largest maximum rainfall, $X_{max}$. Thus, for this case Soni station has the highest estimated PMP value due to its high $X_n$ even though Hikone’s $X_{max}$ is much higher. Hikone station has 118 years data compared to Soni station with 36 years data, resulting into Hikone’s $X_n$ being much less than Soni’s. Therefore, the PMP value in Soni is overestimated due to its less numbers of observations. More accurate PMP estimates could be obtained from longer data records.

Generally, both highest range of PMP value and maximum rainfalls are observed at Soni, Hikone and Shimogahara (PMP values higher than 1000 mm, and $X_{max}$ higher than 300 mm for the 1-day
rainfall case), followed by Nabari, Ueno, Kasatorayama and Toyonaka (PMP values higher than 800 and $X_{\text{max}}$ higher than 250 mm).

4.3 Spatial probable maximum precipitation (PMP)

A spatial PMP for the Yodo river basin is presented in Fig. 4. The PMP spatial distributions presented include 100-mm interval isohyetal lines. PMP values at any point in the river basin could be estimated from the isohyetal lines. The isohyetal lines clearly show the range of PMP values. The highest PMP observed is around the Hikone and Shimogahara stations which are from 900 to 1040 mm (1-day PMP), while the lowest is at the north side of Lake Biwa around Yanagase and Torahime where the isohyetal lines are less than 500 mm. At the south-east of the basin, areas around Soni, Nabari Ouda and Ueno also show quite high PMP values (800 to 1300 mm). In general, similar distribution of the high and low PMP estimates are observed for all periods (2-day, 3-day, 5-day and 7-day rainfall). In addition, the PMP estimates areas around Hanasetogi seems to increase and become significant as the rainfall period increase from 1-day to 7-day. This could show that Hanasetogi has higher risk of extreme rainfall for storms with longer period.

By comparing the PMP distribution against the DEM (Fig.4f) of the basin, we could see that areas located at the foot of the mountainous lines (ex: Hanasetoge, Ktoto, Soni, Shimogahara) have higher PMP distributions. This show the orographic effects taking place in those areas. Orographic barriers tend to enhance rainfalls. In the case of Hikone and Shimogahara (North East of the basin) areas which have the highest PMP distributions, additional moisture sources could come from winds blowing through the Lake Biwa thus contributing high PMP distribution. From records, maximum winds recorded in Hikone and Shimogahara stations are mostly from the North-West directions.

4.4 Comparison of PMP with historical flood events

Extreme rainfalls have been proven to influence the discharge within the Yodo river basin (Luo et al., 2012), therefore the spatial PMP distribution of the Yodo river basin is compared with previous flood records. Table 2 presents flood disasters in the Yodo river basin according to the main rivers’ maximum flow and the Yodo river's maximum water level. During every flood event the Kizu river frequently has the largest maximum flow compared to Katsura and Uji rivers. Generally, this agrees with the estimated spatial PMP distribution in Fig.5 which shows areas around Kizu river having higher PMP range (800 mm to 1300 mm) compared to areas around Katsura and Uji rivers (600 mm to 800 mm).
Table 1 Statistical properties of the annual maximum 24-hour rainfall and PMP values (mm) of the selected 62 stations.

| No | Stations (Years) | $X_{\text{max}}$ (1-d) | PMP
<table>
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<tr>
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<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>$X_{\text{max}}$ (1-d)</td>
<td>2-d</td>
</tr>
<tr>
<td>1</td>
<td>Arakawa(28)</td>
<td>111</td>
<td>1246</td>
</tr>
<tr>
<td>2</td>
<td>Hamazawa(34)</td>
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<td>1084</td>
</tr>
<tr>
<td>3</td>
<td>Nasu(37)</td>
<td>98</td>
<td>602</td>
</tr>
<tr>
<td>4</td>
<td>Higashino(36)</td>
<td>91</td>
<td>1513</td>
</tr>
<tr>
<td>5</td>
<td>Hikone(39)</td>
<td>98</td>
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<td>91</td>
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<td>12</td>
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<td>99</td>
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Table 2 Flood disasters in the Yodo river basin (Shiga Prefectural Government, 2007)

<table>
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<tr>
<th>Date</th>
<th>Maximum flow (m^3/s)</th>
<th>Max. water level (m)</th>
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<tbody>
<tr>
<td>25/09/1952</td>
<td>5800</td>
<td>7800</td>
</tr>
<tr>
<td>27/09/1955</td>
<td>3850</td>
<td>4160</td>
</tr>
<tr>
<td>27/09/1957</td>
<td>3650</td>
<td>4050</td>
</tr>
<tr>
<td>14/08/1958</td>
<td>3900</td>
<td>6800</td>
</tr>
<tr>
<td>27/09/1959</td>
<td>6200</td>
<td>7200</td>
</tr>
<tr>
<td>30/08/1960</td>
<td>770</td>
<td>3840</td>
</tr>
<tr>
<td>29/07/1961</td>
<td>5220</td>
<td>7800</td>
</tr>
<tr>
<td>17/09/1965</td>
<td>5170</td>
<td>6870</td>
</tr>
<tr>
<td>17/09/1972</td>
<td>3250</td>
<td>5230</td>
</tr>
<tr>
<td>02/08/1982</td>
<td>3980</td>
<td>9260</td>
</tr>
</tbody>
</table>

5. Summary and Conclusions

The PMP estimated using the statistical Hershfield methods corresponds reasonably for storms with longer period since the PMP estimates becomes significantly higher as the rain period increases.

In term of comparison with historical flood records, The PMP illustrate a good correspondence with the previous flood events. It is estimated that the area around Ueno, Nabaki and along the Uji river has a high 1-day PMP value (800 mm to 1300 mm) compared to areas around Katsura and Uji river (600 mm to 800 mm) corresponding well to areas with the highest river discharge.

Generally, the paper highlights one of the methodology that can be used to estimate the PMP values and producing a spatial PMP estimates. Since Japan has long rainfall records, the statistical methods are appropriate and fully utilizes the records. Spatial distribution of the PMP presented in this paper will be useful as a background material in identifying area with the most extreme rainfall possible to occur in the Yodo river basin with a period of 1-day, 2-day, 3-day, 5-day and 7-day. Comparisons as well as inputs to numerical models can also be conducted using the results obtained. PMP studies are one of the steps to determine the probable maximum flood (PMF). PMF studies are crucial for basins with high exposure and exposed to various kinds of natural disasters.
Acknowledgements

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References


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