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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.

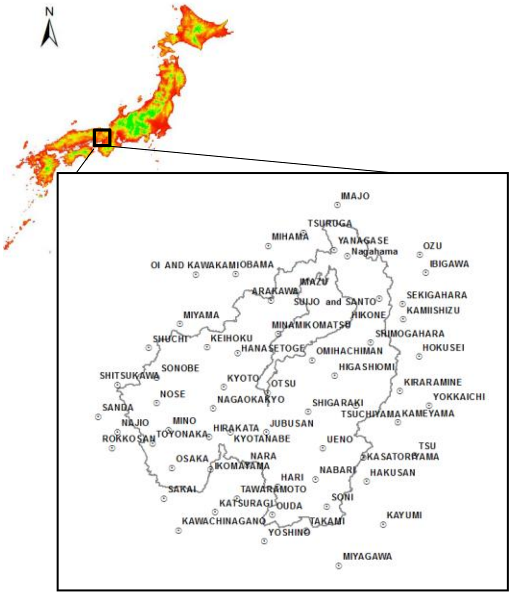

Fig. 1 Locations of the Yodo river basin and AMeDAS stations selected for the statistical analysis and PMP estimation

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.

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

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

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 (Bloschl and Grayson, 2000).

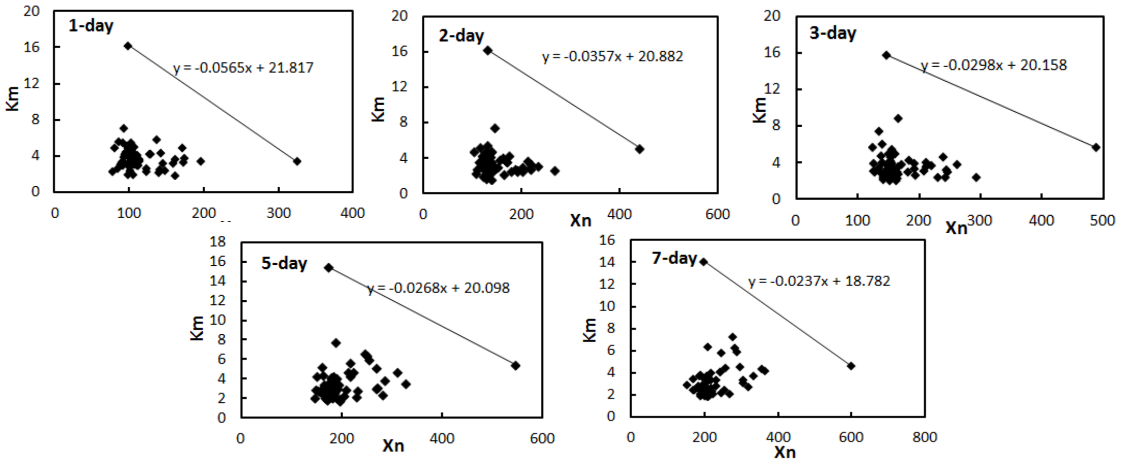

Fig. 2 Km distribution of the 24-hr PMP for Yodo river basin

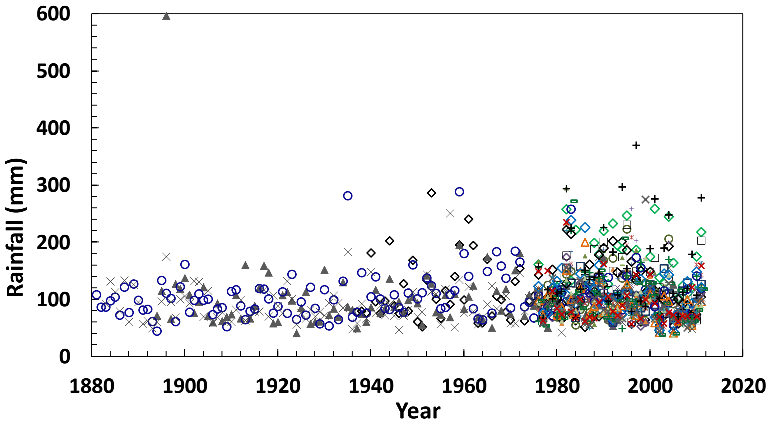

Fig. 3 Distribution of the annual maximum 24-hour rainfall observation in the Yodo river basin.

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_{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).

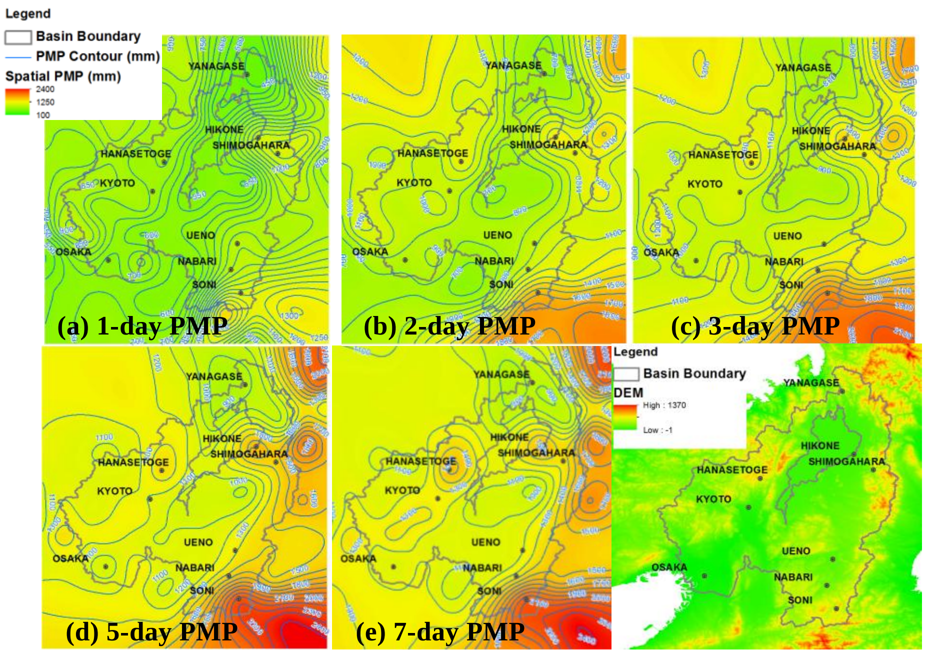

Fig. 4 Spatial PMP (a) 1-day (b) 2-day (c) 3-day (d) 5-day (e) 7-day and (f) DEM for the Yodo river basin

Table 1 Statistical properties of the annual maximum 24-hour rainfall and PMP values (mm) of the selected 62 stations.

No	***Stations(Years)***	X_n ***(1-d)***	X_{max} ***(1-d)***	***PMP***				
				1-d	***2-d***	***3-d***	***5-d***	***7-d***
1	Arakawa(28)	111	223	796	1089	1060	1161	1141
2	Hakusan (34)	145	324	1018	1173	1282	1411	1513
3	Hanasetoge(34)	123	215	757	1185	1244	1363	1526
4	Hari(37)	98	220	630	801	1147	1194	1172
5	Higashiomi(37)	91	174	555	738	818	992	975
6	Hikone(119)	98	597	1004	1273	1378	1567	1512
7	Hirakata(34)	91	172	599	868	968	1142	1153
8	Hokusei(37)	141	310	807	1045	1166	1538	1673
9	Ibigawa(34)	160	354	975	1141	1165	1266	1274
10	Ikomayama(37)	93	275	761	920	1165	1271	1214
11	Imajo(37)	97	141	473	701	776	1011	1117
12	Imazu(37)	91	164	529	812	849	913	946
13	Jubusan(34)	93	204	671	855	1039	1131	1138
14	Kameyama(37)	138	242	833	1035	1140	1384	1522
15	Kamiishizu(37)	141	290	1042	1403	1535	1902	1849
16	Kasatoriyama(37)	161	259	849	1161	1274	1411	1497
17	Katsuragi(31)	85	196	573	759	1114	1231	1242
18	Kawachinagano(37)	93	213	678	874	1163	1290	1242
19	Kayumi(37)	195	498	1297	1765	1975	2322	2325
20	Keihoku(37)	104	209	717	957	1029	1158	1133
21	Kiraramine(32)	170	394	918	1247	1293	1611	1805
22	Kyotanabe(37)	93	200	605	851	955	1094	1120
23	Kyoto(132)	105	289	734	956	1027	1191	1253
24	Mihama(37)	104	269	863	1098	1078	1096	1114
25	Minamikomatsu(36)	110	188	571	832	914	1121	1205
26	Mino(34)	102	259	746	945	1009	1257	1331
27	Miyagawa(35)	324	764	870	1628	1914	2060	1934
28	Miyama(37)	104	269	863	1098	1078	1096	1114
29	Nabari(37)	105	295	904	1073	1358	1446	1361
30	Nagahama(37)	78	120	419	707	838	934	893
31	Nagaokakyo(37)	113	239	758	1029	1076	1245	1309
32	Najio(30)	110	269	870	1090	1198	1341	1339
33	Nara(60)	90	182	602	723	956	1129	1109
34	Nose(37)	103	221	720	916	966	1120	1159
35	Obama(37)	99	232	765	1068	1089	1192	1114
36	Oi(37)	113	261	886	1277	1263	1278	1156
37	Omihachiman(37)	99	183	629	770	891	1119	1150
38	Osaka(130)	91	251	631	847	933	1042	1115
39	Otsu(37)	104	158	548	688	805	1016	1038
40	Ouda(37)	95	235	741	920	1249	1397	1354
41	Ozu(26)	173	421	1173	1513	1598	1852	1914
42	Rokkosan(30)	100	175	648	861	1016	1218	1297
43	Sakai(37)	83	163	641	769	1043	1196	1219
44	Sanda(37)	88	188	698	898	934	1064	1087
45	Sekigahara(37)	147	265	857	1259	1376	1657	1620
46	Shigaraki(37)	102	235	704	808	988	1110	1110
47	Shimogahara(30)	128	341	1066	1165	1228	1452	1351
48	Shitsukawa(37)	108	232	813	1039	1076	1187	1207
49	Shuchi(31)	98	206	714	980	996	1116	1097
50	Soni(37)	158	370	1134	1576	1830	2134	2066
51	Sonobe(34)	112	259	854	1045	1055	1139	1124
52	Suijo(37)	103	249	757	931	1020	1081	1044
53	Takami(29)	172	449	1382	1706	1859	1926	1941
54	Tawaramoto(37)	79	191	591	635	978	1085	1064
55	Toyonaka(34)	96	272	853	1022	1055	1183	1197
56	Tsu(124)	136	427	938	1197	1246	1396	1415
57	Tsuchiyama(37)	122	231	790	967	974	1340	1331
58	Tsuruga(25)	88	165	580	763	741	839	864
59	Ueno(76)	105	287	886	983	1095	1289	1201
60	Yanagase(37)	99	157	445	700	799	860	918
61	Yokkaichi(37)	126	295	849	1069	1246	1475	1561
62	Yoshino(22)	106	226	769	1338	1433	1485	1406

Table 2 Flood disasters in the Yodo river basin (Shiga Prefectural Government, 2007)

Date	Maximum flow (m^3/sec)				Max. water level (m)
	Kizu River	Katsura River	Uji River	Yodo River	Yodo River
25/09/1952	5800	2700	1780	7800	6.97
27/09/1955	3850	810	670	4610	5.49
27/08/1957	3650	790	525	4030	5.07
14/08/1958	3900	2500	1270	6800	6.5
27/09/1959	6200	1700	885	7200	6.69
30/08/1960	770	2600	310	3840	4.7
28/10/1961	5220	2100	1000	7800	6.95
17/09/1965	5170	2500	900	6870	6.75
17/09/1972	3250	2320	810	5230	4.64
02/08/1982	3980	1950	990	6260	4.65

5. Summary and Conclusions

The PMP estimated using the statistical Hershfield methods corresponds reasonably with the X_{max} of each stations respectively. Generally the highest ranges of PMP value and maximum rainfalls are observed around Soni, Hikone, Shimogahara, Nabari and Ueno with a 1-day PMP value around 1000 mm . However, PMP value in Soni is overestimated due to its few numbers of observations. More accurate PMP estimates could be obtained from longer data records.

From the PMP spatial distribution and isohyetal lines the highest observed PMP is around the Hikone and Shimogahara stations which are from 900 to 1040 mm, while the least is around the Yamagase and Torahime stations. However areas near Hanasetogi has higher risk of extreme rainfall 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 Kizu 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 population and exposed to various kinds of water related natural disasters.

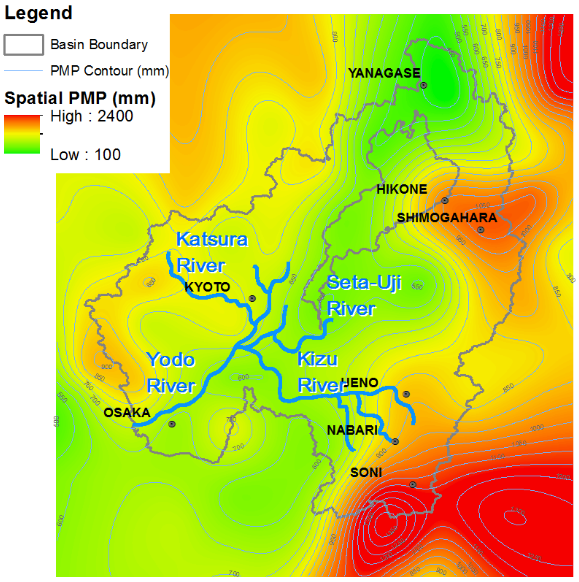

Fig. 5 Yodo river basin main rivers and spatial 1-day PMP.

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