PMP and PMF Revaluations after Typhoon Morakot by Considering Combined Effect of Typhoon and Monsoon – A Case Study for Four Reservoirs in Taiwan

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Abstract

Typhoon Morakot in 2009 hit Taiwan, which brought the southern Taiwan a 48-hr heavy rainfall close to the Probable Maximum Precipitation (PMP) in the catchment of Tsengwen Reservoir as well as the world record. Such an extreme rainfall event, which resulted from the combined (co-movement) effect of two climate systems (i.e., typhoon and southwesterly monsoon), caused several collapses and heavy sedimentation in the watersheds. Therefore, the PMP estimation for each reservoir should be reevaluated by considering the combined effect of typhoon and southwesterly flow (under the similar scenario of Typhoon Morakot) to ensure the safety of each reservoir after Typhoon Morakot, especially for the important reservoirs in Taiwan. Moreover, climate change will affect precipitation and flood regimes. It is anticipated that the PMP and Probable Maximum Flood (PMF) will be modified in a changing climate.

In order to reevaluate the PMP estimation for the important reservoirs in Taiwan, this study reviews of PMP and PMF methods for suggesting the most suitable methods and proposes the PMP estimation models which consider the combined effect of typhoon and monsoon. Four reservoirs (i.e., Tseng-Wen, Li-Yu-Tan, Shih-Men, and Fei-Tsui) are chosen as the study areas for estimating the PMP and PMF during the baseline period (1980~1999) and the future period (2020~2039) under the emission scenarios of IPCC AR4. The results show that the mean change percentages of PMP estimation (60-hours duration) at Tseng-Wen, Li-Yu-Tan, Shih-Men, and Fei-Tsui Reservoir are about 8%, 8%, 3%, and -3%, respectively, from the baseline period to the future period. Based on the above PMP estimations, the mean change percentages of PMF by using the dimensionless synthetic unit hydrograph are 7%, 8%, 3% -3% , respectively. It should be noted that these potential increases of PMF under climate change scenarios may increase the vulnerabilities of reservoir safety and function. Suitable adaptation strategies (e.g., flood and sediment management using a bypass tunnel) have to be proposed for coping with the aforemtioned problem and sustanable operation of resevoir.

Keywords: probable maximum precipitation, probable maximum flood, combined effect, typhoon, monsoon.

1 Introduction

PMP is an important input of rainfall-runoff model for estimating PMF which is the key design criterion for hydraulic features of a reservoir. World Meteorological Organization (WMO) defines PMP as the greatest depth of precipitation for a given duration meteorologically possible for 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 1986).

Typhoon Morakot caused great damage to Taiwan in August 2009 (Li et al. 2014), disaster statistics show that 675 people died, 54 people were injured or missing, 1,626 houses collapsed, and the product losses amounted to 6.07 billion US dollars, in addition to inestimable loss of facilities and properties (Hsieh et al. 2010). The mechanism of why Typhoon Morakot brought such an extreme rainfall amount has been analyzed and concluded that the combined effect of typhoon and southwesterly flow, and the terrain effect in southwestern Taiwan were the key factors which lead to tremendous rainfall due to the moisture supplement from the southwesterly flow to the typhoon (Liu et al. 2016). During Typhoon Morakot, the observed 24-hr rainfall in the catchment of Renyitan Reservoir (1191 mm) is larger than the 24-hr PMP of Renyitan Reservoir (1086 mm) and the observed 24-hr rainfall in the catchment of Nanhua Reservoir (1201 mm) approaches to the 24-hr PMP of Nanhua Reservoir (1474 mm). Therefore, the PMP estimation for each reservoir should be reevaluated by considering the combined effect of typhoon and southwesterly flow (under the similar scenario of Typhoon Morakot) to ensure the safety of each reservoir after Typhoon Morakot, especially for the most important reservoir in Taiwan.

This work reviews of PMP and PMF methods for suggesting the most suitable methods and proposes the PMP estimation models which consider the combined effect of typhoon and monsoon. Four important reservoirs (i.e., Tseng-Wen, Li-Yu-Tan, Shih-Men, and Fei-Tsui) are chosen as the study areas for estimating the PMP and PMF during the baseline period (1980~1999) and the future period (2020~2039) under the emission scenarios of IPCC AR4.

2 PMP Estimation Method

Choosing a suitable method for PMP estimation depends on the availability of meteorological, hydrological, and geological data in the study area. Based on the literatures on PMP estimation and the reservoir safety evaluation reports, these commonly used PMP estimation methods include (1) Storm Transposition-Dewpoint Adjustment Method, (2) Typhoon Model Method, or called Typhoon Separation Method, (3) WMO Statistical Method, and (4) Maximum Envelop Method (WRA 2016).

Typhoon rainfalls are the main source of extreme precipitations in Taiwan. The combined effect of typhoon and monsoon is a key factor that leads to tremendous rainfall in Taiwan.

Therefore, considering the combined effect of typhoon and monsoon for PMP estimation is essential and necessary. The Independent System (IS) approach based on the moisture continuity equation is proposed for considering the combined effect of typhoon and monsoon into PMP estimation. The assumption of IS approach is that typhoon and monsoon are considered as two independent systems. Based on this assumption, typhoon events used in the IS approach have no interaction with monsoon, which are called “pure” typhoon events hereafter. The PMP considering the combined effect of typhoon and monsoon by the IS approach is estimated by summing up the PMP for pure typhoon and the probable maximum monsoon precipitation (PMMP) which is estimated by the Monsoon Precipitation Regression Model.

According to the applicability evaluation of PMP estimation methods through different aspects (i.e., data accessibility, extension under climate change, operational simplicity, and description of physical mechanism) in Table 1, it reveals that the two proposed methods, i.e., (1) STMPR Method: Storm Transposition-Dewpoint Adjustment (ST-DA) Method coupled with Monsoon Precipitation Regression Method and (2)TMMPR Method: Typhoon Model Method (TMM) coupled with Monsoon Precipitation Regression Method, are more suitable for Taiwan’s rainfall characteristics. Moreover, the STMPR and TMMPR Methods are the best ones due to their applicability under climate change and more comprehensive physical mechanisms. The two proposed methods were constructed for PMP estimations hereafter.

Tab. 1: Applicability evaluation of PMP estimation methods through different aspects

Method	Data accessibility	Extension under climate change	Operational simplicity	Description of physical mechanism	Adoption in the study
ST-DA	H	H	L	H	-
TMM	H	H	M	H	-
WMO Statistical	H	L	M	L	-
Max. Envelop	H	L	M	L	-
STMPR	M	H	L	H	Y
TMMPR	M	H	M	H	Y

Note: H: high; M: middle; L: low; Y: Yes.

Due to the complicated topography of the Central Mountain Range, the regions affected by monsoon are delineated based on the rainfall data greater than a threshold at 195 automatic raingauges over Taiwan. The “monsoon effected area” and the “monsoon non-effected area” are delineated for users to judge whether the study area is affected by monsoon or not. If the study area is located in the monsoon effected area (of southwesterly flow or northeasterly monsoon), the monsoon precipitation regression equation (of southwesterly flow or northeasterly monsoon) has to be utilized for PMMP estimation.

The monsoon precipitation regression equations for estimating PMMPs of southwesterly flow and northeasterly monsoon are developed at Alishan station and Ilan station, respectively. For application of the monsoon precipitation regression equations for different locations, the rainfall ratio maps are provided as shown in Figure 1 for the monsoon effect areas of southwesterly flow (Figure 1(a)) and northeasterly monsoon (Figure 1(b)).

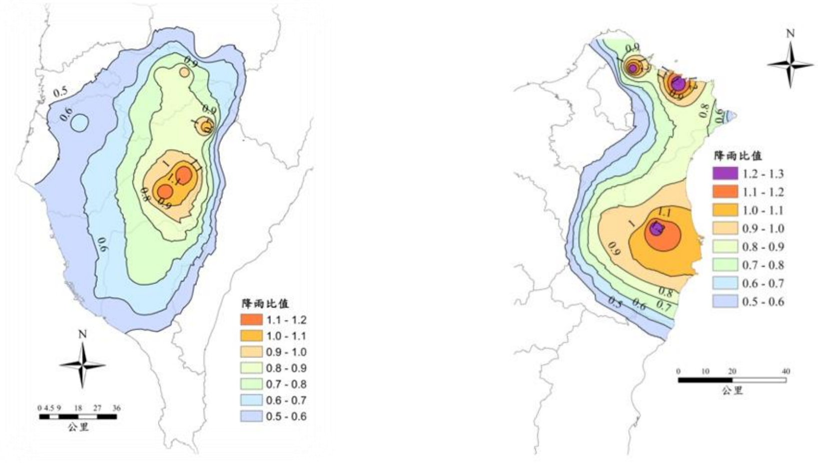


Fig. 1: Rainfall ratio maps for the monsoon effected area of southwesterly flow (left) and northeasterly monsoon (right).

With the delineation of monsoon effect areas and the rainfall ratio maps, the PMP considering the combined effect can be estimated by summing up the PMP (via ST-DA Method or TMM) for pure typhoon and the PMMP estimated by the monsoon precipitation regression equation. Figure 2 displays the procedure for guiding users to choose suitable PMP estimation methods (with or without consideration of the monsoon effect) for their study area.

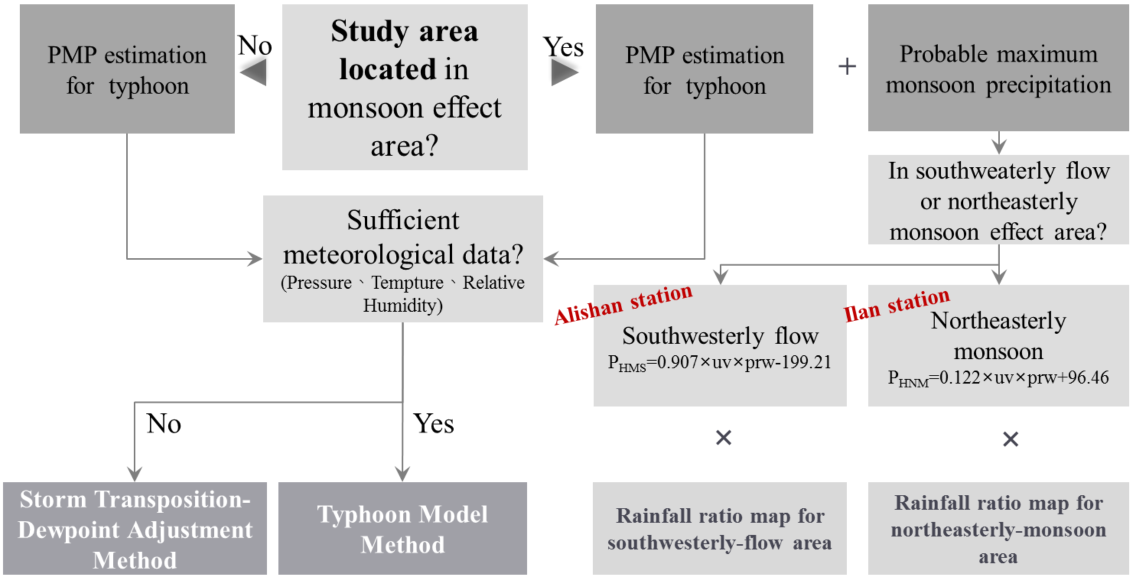


Fig. 2: Procedure for choosing suitable PMP estimation methods

3 PMF Estimation Method

PMF is calculated through a rainfall-runoff model (RRM) by using PMP as input. Due to there are many kinds of rainfall-runoff models, comparing all kinds of models is laborious. Therefore, the current study chosen seven commonly used RRMs adopted in the reservoir safety evaluation reports and basin governance planning reports. The seven commonly used RRMs include (1) traditional unit hydrograph, (2) triangle synthetic unit hydrograph which commonly adopted in basin governance planning reports, (3) dimensionless synthetic unit hydrograph which is used for Shih-Men, Li-Yu-Tan, and Tseng-Wen reservoirs, and the four models ((4) storage function model, (5) tank model, (6) semi-distributed parallel linear reservoir model, and (7) instant unit hydrograph) applied in Fei-Tsui reservoir.

Based on the applicability evaluation of PMF estimation methods through different aspects (i.e., model complexity**,** extension under climate change, etc.), it reveals that the unit hydrograph methods (traditional unit hydrograph, triangle synthetic unit hydrograph, dimensionless synthetic unit hydrograph, and instant unit hydrograph) with low model complexity are easier to be applied than the conceptual rainfall-runoff models (storage function model, tank model, and semi-distributed parallel linear reservoir model). Among the unit hydrograph methods, triangle synthetic unit hydrograph (TSUH) is generally used at ungauged sites and the dimensionless synthetic unit hydrograph (DSUH) is more convenient to change its rainfall duration than the traditional unit hydrograph (TUH). Therefore, the DSUH is suggested for PMF estimation hereafter.

In the reservoir safety evaluation reports, the DSUH developed at the reservoir design and planning stage was usually used for PMF estimation. For evaluating the suitability of the previous DSUH at the reservoir design and planning stage, the DSUHs for each reservoir are constructed by using the recent storm events. For each reservoir, (1) the mean DSUH of the recent storm events, (2) the DSUH with the largest peak among the recent storm events, and (3) the previous DSUH at the reservoir design and planning stage are compared. The proposed procedure for choosing the suitable DSUH is shown in Figure 3.

The results show that, for Tseng-Wen reservoir, the DSHU constructed by Typhoon Kalmaegi has the largest peak that is greater than the peak of the previous DSHU (Figure 4(a)). Therefore, the aforementioned two DSHUs were used for estimating PMFs. Then, the DSHU with the larger PMF was chosen as the suitable one. The same procedure was performed for evaluating the suitability of the previous DSHUs for the other three reservoirs. The comparisons of the three DSHUs at Shih-Men, Li-Yu-Tan, and Fei-Tsui reservoirs are shown in Figures 4(b), 4(c) and 4(d), respectively. For Shih-Men reservoir, the DSHU constructed by Typhoon Krosa is greater than the peak of the previous DSHU and the PMFs calculated by the two DSHUs should be further compared. For Li-Yu-Tan and Fei-Tsui reservoirs, the previous DSHUs were suggested to be used. However, for

Fei-Tsui reservoir, the DSHU was not adopted. For Fei-Tsui reservoir, the storage function model, tank model, and semi-distributed parallel linear reservoir model were adpted for the 2nd reservoir safety evaluation and the instant unit hydrograph was added for the 4th reservoir safety evaluation.

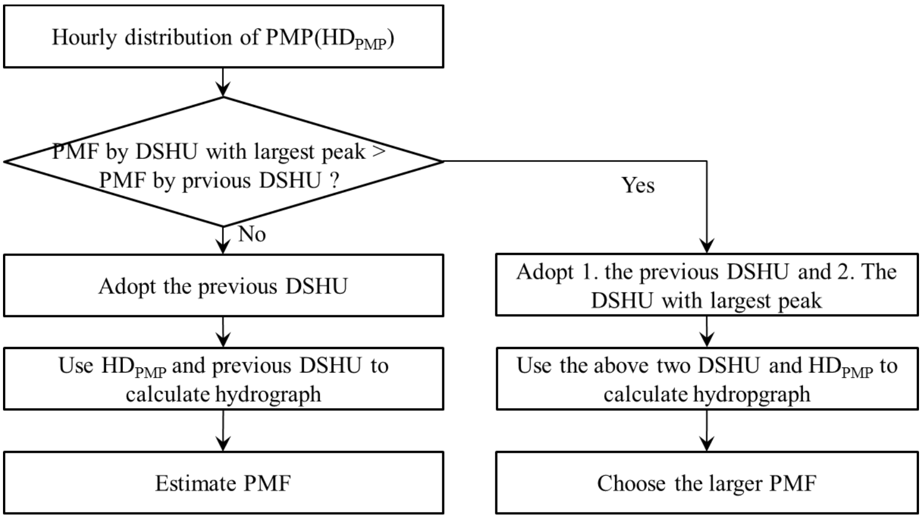
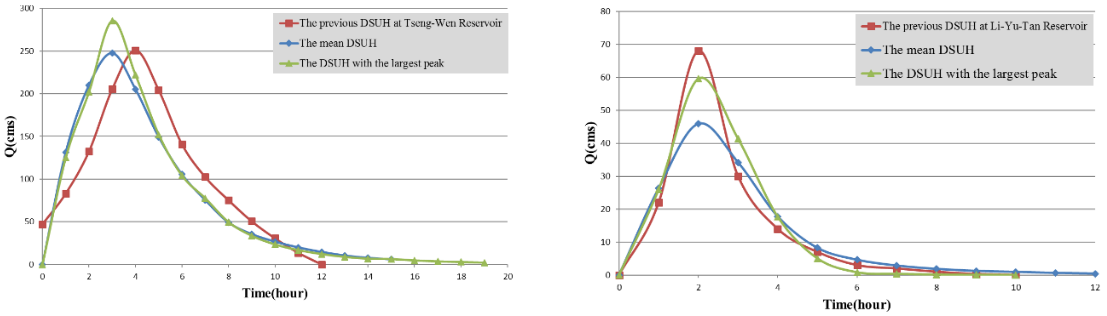
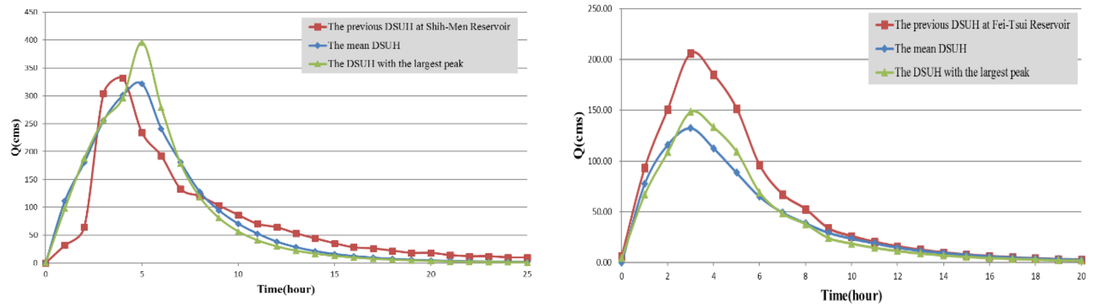


Fig. 3: The proposed procedure for choosing the suitable DSUH for PMF estimation



(a) Tseng-Wen Reservoir (b) Li-Yu-Tan Reservoir



(c) Shih-Men Reservoir (d) Fei-Tsui Reservoir

Fig. 4: The mean DSUH, the DSUH with the largest peak, and the previous DSUH for (a) Tseng-Wen Reservoir, (b) Li-Yu-Tan Reservoir, (c) Shih-Men Reservoir, and (d) Fei-Tsui Reservoir.

4 Case Studies

4.1 Climate Change Scenarios

The current work investigates the variations (changes) of the three variables (i.e., uv×prw, uv, and prw) in the monsoon significant areas from the baseline period (1980~1999) to the future period (2020~2039) by using the output data of 7 GCMs under A1B emission scenario provided by IPCC AR4. The three variables (i.e., uv×prw, uv, and prw) are the key variables in the PMP estimation methods and the monsoon precipitation regression equations for PMMP estimation, which may change under climate change.

4.2 PMP estimation under Climate Change

Based on the change percentages of the three variables (i.e., uv×prw, uv, and prw) from the baseline period to the future period under the A1B emission scenario for the 7 GCMs, the PMP estimations for the reservoirs can be obtained, which are shown in Table 2. The recent safety evaluation report's PMP, the PMP during the baseline period, and the PMP design value are also included in the table. From the table, it reveals that most of the PMP values during the baseline period (calculated by the proposed methods) are close to the values of safety evaluation reports.

Tab. 2: PMP estimations of 60-hour duration for each reservoir

Reservoir	Climate change Yes/No	PMP Estimations (mm)	Recent safety evaluation report's value (mm)	PMP design value (mm)
Tseng-Wen	No	3,283	3,572	3,087
	Yes	3,214~4,013 (Avg：3,543)	-	-
Li-Yu-Tan	No	3,100	3,100	3,100
	Yes	3,272~3,481 (Avg：3,361)	-	-
Shih-Men	No	2,232	2,050	2,050
	Yes	2,195~2,470 (Avg：2,303)	-	-
Fei-Tsui	No	3,142	2,866	2,921
	Yes	2,863~3,240 (Avg：3,061)	-	-

Using the TMMPR Method at Tseng-Wen Reservior (in the monsoon effected area), the PMP estimations of 60-hour duration for the 7 GCMs range from 3,214 mm to 4,013 mm. The mean change percentage of PMP estimation is about 8% from the baseline period to the future period. Using the ST-DA Method at Li-Yu-Tan Reservior (in the monsoon non-effected area), the PMP estimations of 60-hour duration for the 7 GCMs range from 3,272 mm to 3,481 mm. The mean change percentage of PMP estimation is about 8% from the baseline period to the future period. Using the TMM at Shih-Men Reservior (in the monsoon non-effected area), the PMP estimations of 60-hour duration for the 7 GCMs range from 2,195 mm to 2,470 mm. The mean change percentage of PMP estimation is about 3% from the baseline period to the future period. The analysis for Fei-Tsui Reservoir (in the monsoon effected area) by using the TMMPR Method show that the

PMP estimations of 60-hour duration for the 7 GCMs range from 2,863 mm to 3,240 mm. The mean change percentage of PMP estimation is about -3 % from the baseline period to the future period. (The 60-hour duration adopted herein is mainly for comparison with the original design value of PMP.)

4.3 PMF estimation under Climate Change

Based on the above PMP estimations, the current work further calculates the PMFs by using the DSUH. The results are shown in Table 3. The PMF estimations at Tseng-Wen Reservior using the previous DSUH for the 7 GCMs range from 11,523 cms to 14,075 cms. The mean change percentage of PMF estimation is about 7% from the baseline period (11,744 cms) to the future period (mean=12,573 cms). The PMF estimations at Li-Yu-Tan Reservior using the previous DSUH for the 7 GCMs range from 3,332 CMS to 3,545 cms. The mean change percentage of PMF estimation is about 8% from the baseline period (3,157 cms) to the future period (mean=3,423 cms). The PMF estimations at Shih-Men Reservior using the DSHU constructed by Typhoon Krosa for the 7 GCMs range from 15,915 cms to 18,089 cms. The mean change percentage of PMF estimation is about 3% from the baseline period (16,195 cms) to the future period (mean=16,729 cms). The PMF estimations at Fei-Tsui Reservoir using the previous DSUH for the 7 GCMs range from 8,416 cms to 9,583 cms. The mean change percentage of PMF estimation is about -3% from the baseline period (9,277 cms) to the future period (mean=9,033 cms).

Tab. 3: PMF estimations of 60-hour duration for each reservoir

Reservoir	Climate change Yes/No	Estimations in the current work (cms)	Estimations of recent safety evaluation report (cms)	Reservoir design value (cms)
Tseng-Wen	No	11,744	12,958	12,430
	Yes	11,523~14,075 (Avg：12,573)	-	-
Li-Yu-Tan	No	3,157	3,183	3,027
	Yes	3,332~3,545 (Avg：3,423)	-	-
Shih-Men	No	16195	14,500	10,900
	Yes	15,915~18,089 (Avg：16,729)	-	-
Fei-Tsui	No	9,277	10,310	10,500
	Yes	8,416~9,583 (Avg：9,033)	-	-

5 Conclusions

In order to reevaluate the PMP estimation for the important reservoirs in Taiwan afer Typhoon Morakot, this work proposes the PMP estimation models which consider the combined effect of typhoon and monsoon. The results show that the PMP (60-hours duration) and PMF estimations at Tseng-Wen, Li-Yu-Tan, and Shih-Men Reservoir increase from the baseline period to the future period. It should be noted that these potential increases of PMF under climate change scenarios may increase the vulnerabilities of reservoir safety and function. Suitable adaptation strategies (e.g., flood and sediment management using a bypass tunnel) have to be proposed for coping with the aforemtioned problem and sustanable operation of resevoir.

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