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Hydrological Safety of Vaturu Dam by Evaluating Spillway Adequacy

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Abstract: Probable Maximum Flood is considered as one of the most adopted inflow design floods in assessing the adequacy of dam structure in current practices. It is the largest flood that could conceivably occur at a particular location and frequently estimated from Probable Maximum Precipitation (PMP). This study incorporates hydrological modelling using HEC-HMS to simulate the outflow providing the results used in the catchment procedure of translation of PMP to PMFs for a 24 to 168-hour duration. The adequacy of Vaturu Water Supply Dams (CA= 40 km2) which is located in Fiji will be assessed in the context of extreme meteorological events of the PMP/PMF magnitude. The flood rise during these events should not exceed or overtop the dam crest level. Vaturu dam is a domestic water supply embankment dam built in the 1980s to cater for the water supply needs of the Nadi and Lautoka supply zones. A conventional reservoir routing procedure using the Goodrich method is then carried out for all PMP/PMF durations, i.e., 24 to 168 hours. During this period, flood rise levels were noted to be restricted to the Dam Crest level of +532 m ASL. The results and its analysis validated the safety of the Vaturu Dam and the ability of the dam to discharge the onslaught of PMP/PMF safely.

Keywords: Rainfall-runoff, HEC-HMS, Vaturu Dam, PMP/PMF routing

Introduction

Failures of dam structures due overtopping raise the importance of undertaking an accurate assessment of the dams' safety features in terms of their emergency action and implementation plan in the event of probable catastrophic events (Sidek et. al., 2013; Tingsanchali et al., 2012). One of these measures is the hydrological inspection and evaluation that plays a part in the overall inspection program in terms of assessing the overtopping probability of the dam/reservoir considering an extreme meteorological event, i.e., during a probable maximum precipitation (PMP) scenario. The PMP as defined by the World Meteorological Organization is “the greatest depth precipitation for a given duration meteorologically possible for a given size storm area at a particular location at a particular time of year” (WMO, 2009). The PMF derived from PMP is the largest flood that could conceivably occur at a particular location (Graham, 2009). The PMF values are useful in dam design by reviewing the adequacy of the current spillway capacities of the existing dams (Hwee, 2013).

Over the past decade, Vaturu dam have been operating and discharge the floodwater over its spillway. However, its spillway had never been evaluated in terms of its ability to discharge extreme storm events safely. Where it is

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crucial to highlight essential outcomes such as the dams' water level and the discharge over the spillway during critical storm events, which will be compared against the safe dam operating level (Dam crest level) and the design discharge capacity of the spillway (Nathan, 2001). Thus, the objective of this paper is to simulate the rainfall-runoff relationship of Vaturu dam for the period from January 2007 to December 2019 by HEC-HMS software and to evaluate the spillway capacity adequacy of Vaturu Dam using Probable Maximum Precipitation (PMP) and Probable Maximum Flood (PMF) using the Goodrich method.

Study Area

The Fiji Islands are an archipelago of volcanic islands comprising of 2 major islands, namely Viti Levu and Vanua Levu, and 300 islands spread over 1.3 million square kilometers in the Pacific Ocean. The two large mountainous islands of Viti Levu (10,400km2) and Vanua Levu (5,540km2) comprise 87% of the total land area. On the world map, as shown in Figure 1, Fiji is located in the Southern Hemisphere at latitude 15-22 degrees south and 177 degrees west to 175 degrees east. Surrounded by the South Pacific Ocean, the Fiji group lies 5,100 km southwest of Hawaii and 3150 km northeast of Sydney, Australia, and has the 180th-degree meridian line over it.

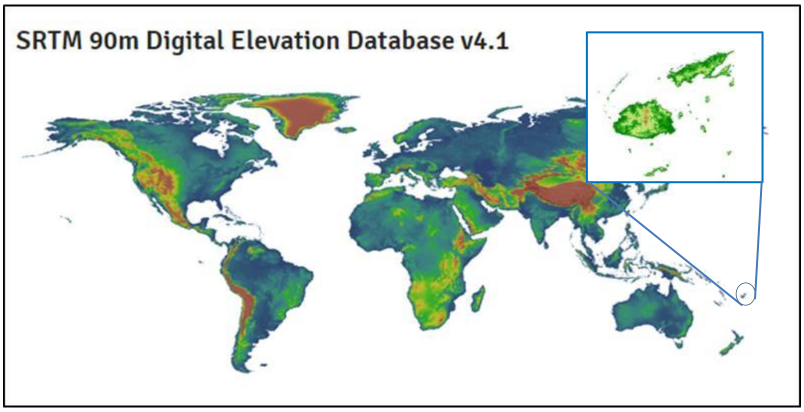

Figure 1. Location of Fiji islands

Vaturu dam is located on the western part of Viti Levu at 16° 35' 23" S Latitude and 179° 24' 22" E Longitude, 30 km upstream of Nadi town and is at an elevation of 528m above sea level (ASL). It is the primary water supply source for residents of the Nadi and Lautoka regional water supply systems, meeting the demand of 180,000 residents. The main inflow into Vaturu Dam are Nadi River and Viti River. It has a storage capacity of 70MCM and is the main water supply for Nadi Irrigation Scheme. The main characteristic of the dam is as shown in Table 1 and Figure 2 presents the Level, Area ,Volume Curve for Vaturu Dam (2020).

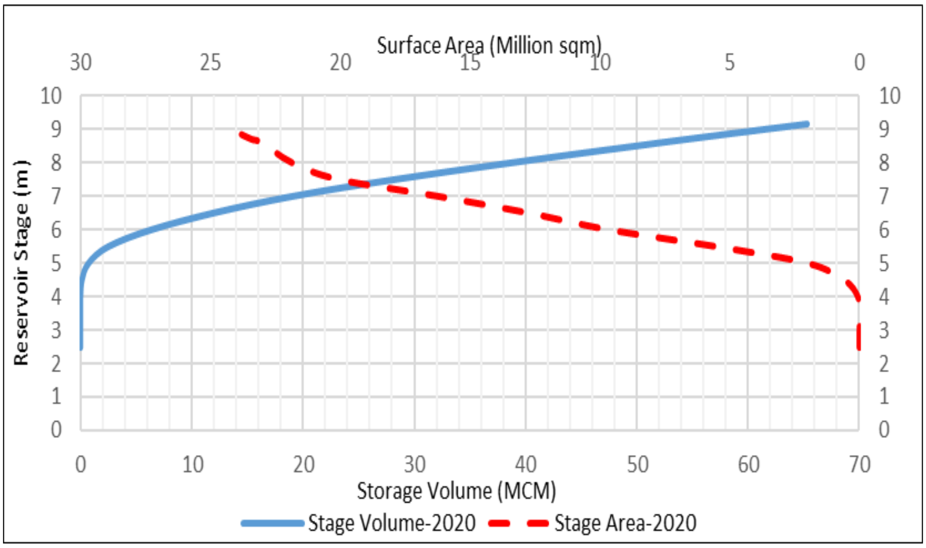

Figure 2. Level, area, volume curve for Vaturu Dam (2020)

Table 1. Properties and description of Vaturu Dam

Properties	Description
Dam Type	Clay core with earth and rockfill shoulders with spillway excavated through saddle.
Dam Crest Level	RL 532 m
Full Supply Level	RL 527 m
Minimum Operating Level	RL 502 m
Maximum Flood Level	RL 528.8 m
Critical Level	RL 510 m
Dam height	54 m
Maximum Depth	37 m
Crest width	10 m
Crest Length	297m
Surface Area	200 ha
Catchment Area	40 km^2

The rainfall data obtained for the Vaturu dam study was obtained from the Water Authority of Fiji, Water Resource Management Department (WRMD) from January 2007 to December 2019. The relationship between rainfall and the outflow of Vaturu Dam was analysed based on ten years of daily observation data. HEC HMS were used to simulate the outflow and the goodness of the outflow data was then tested using Nash Sutcliffe Coefficient, correlation, and the mean average error (Faiza et al., 2022; Güntner et al., 2004; Kaatz, 2014). The collected data was processed and screened accordingly. All missing and unreliable input data was replaced and corrected based on the neighbouring stations (Khalifeloo, 2015). The digital elevation maps of the watershed were obtained and downloaded from The Consortium for Spatial Information (CSI) for Constative Group for International Agricultural Research (CGIR) website, which provides the Shutter Radar Topography Mission (SRTM) data.

Methodology

The HEC-HMS model is a physically based and conceptually semi-distributed model designed to simulate rainfall-runoff processes such as precipitation, evapotranspiration, infiltration, interflow, overland flow, percolation, baseflow, recharge of aquifers, and streamflow. However, some of the processes were simplified. In this study, the catchment was divided into seven subbasins, as shown in Figure 3. The HEC-HMS model provide option for manual input of watershed characteristics data such as SCS curve number, lag time, and precipitation in the basin model category. The model is calibrated and validated for the extreme historical events used for calibration are considered in order to obtain the appropriate values for the parameters.

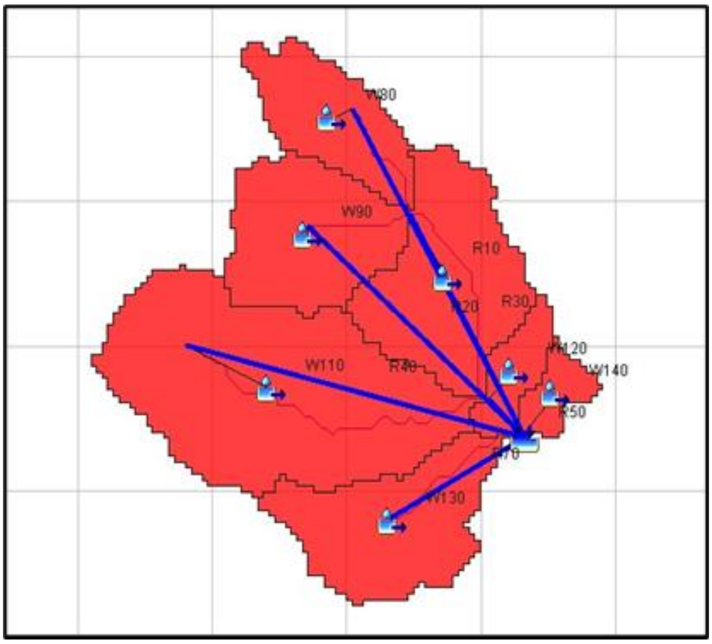

Figure 3. Vaturu Dam catchment – HEC HMS setup

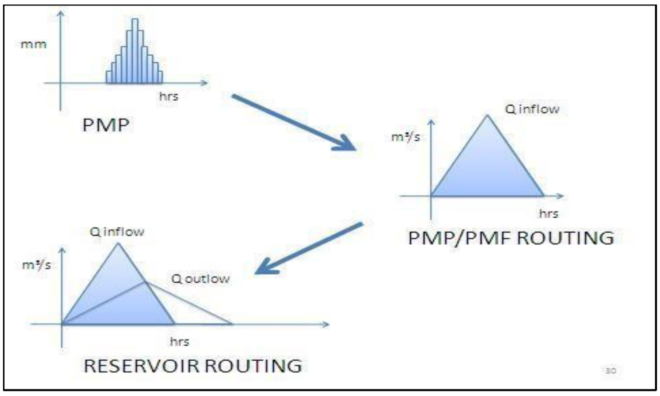

Figure 4. Reservoir routing flowchart

Figure 4 shows the reservoir routing chart where the primary function of reservoir routing is to determine the outflow of the PMP/PMF developed by Hershfield (1961,1965) as they pass through the particular location and reservoir. The freeboard or flood rise height is also estimated using the Reservoir level and change in Storage + Flow relationship.

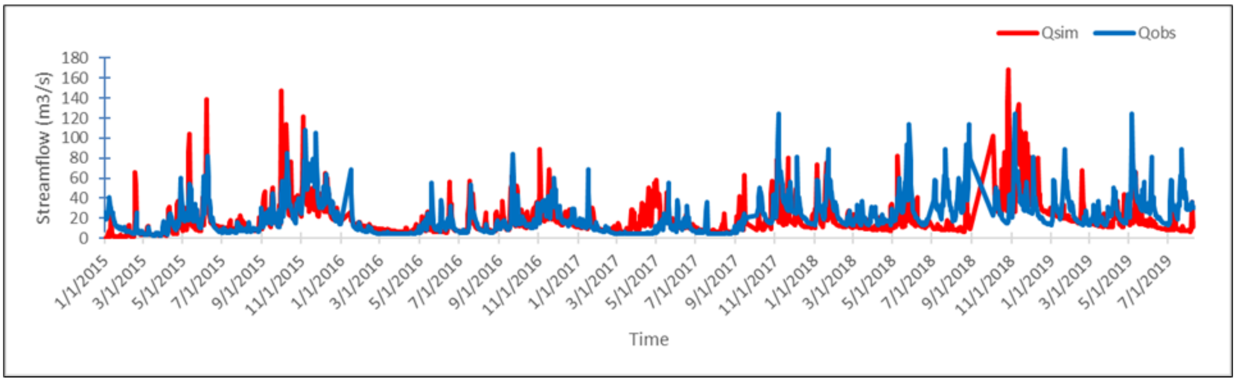

Figure 5. Simulated and observed hydrograph of Vaturu during calibration

As shown in Figure 5, the model shows a reasonable fit between the simulated and observed with Nash Sutcliff coefficient of 0.5 and correlation value of 0.57 confirm an agreeable linear relationship. Table 2 summarized the goodness of fit between the observed flow and the simulated flow for the Vaturu dam.

Table 2. Goodness of fit of the calibrated HEC-HMS

Objective Functions	Values
Nash Sutcliff Coefficient	0.51
Correlation	0.57
MAE	1.24
RMSE	1.54

Reservoir Routing (Goodrich Method)

The main function of reservoir routing is to determine the outflow of the PMP/PMF as they pass through any reservoir. The height of the freeboard or flood rise is also estimated using the reservoir level and change in storage and flow relationship. Rainfall-runoff data from 2007 to 2019 was assembled to study the weather pattern on a daily basis to study the significant trend. It can be noted that there are periods of high rainfall during the wet seasons, mainly November to April, while there were few days in the dry season where moderate precipitation occurred in the years 2011 and 2013. As observed in Figure 5, the most notable critical storm events were the floods that happened in 2013 and 2019, and this study aimed to evaluate the dam by overtopping during the 2016 floods caused by Cyclone Winston.

Figure 6 shows the PMP/PMF translation graph for the period January 2007 to December 2016, it is clear that maximum precipitation and flooding occurred from the 20th to the 25th of February 2015. The maximum rainfall recorded on the 21st of February was 628mm. This event coincided with the arrival of a category five cyclone (Cyclone Winston) that made landfall in Fiji and claimed 44 lives. This storm event was analyzed for various durations, from 24 to 168 hours.

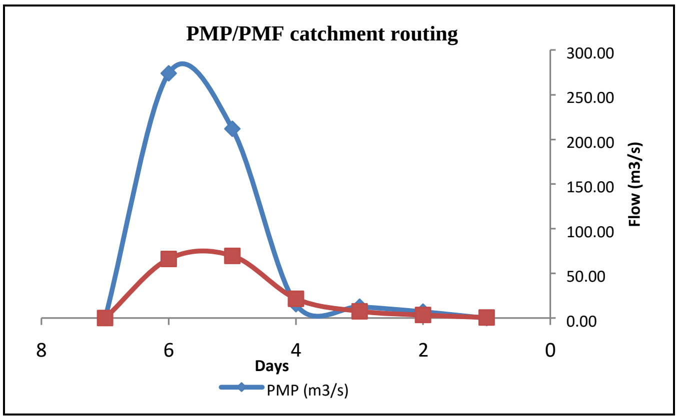

Figure 6. Flood hydrographs obtained from HEC-HMS models using the 16 h 100-year, PMP

Time (daily), precipitation discharge (m3/s), water surface elevation (m), flood discharge (m3/s), and the change in volume storage (m3) are calculated. These fields are necessary to calculate twice the difference in storage with respect to time added to the discharge at the outlet. The tabulated calculations by the formula 2S/t + Q are summarized in Table 3.

Table 3. Catchment routing using goodrich routing method

Time,t (hrs.)	Discharge,I (m^3/ sec)	Water Surface Elevation EL	Outflow Discharge, Q (m^3/ sec)	Storage,S x 10^6 (m^3)	$2S/\Delta t + Q$
0	0.00	521.15	0	19.78	916
24	274.12	528.18	66.2	19.84	985
48	211.84	528.06	69.7	25.74	1261
72	15.62	527.96	21.7	25.65	1209
96	12.81	527.86	7.7	25.42	1185
120	7.21	527.76	3.4	25.19	1170
168	0.00	527.66	0.7	24.97	1157

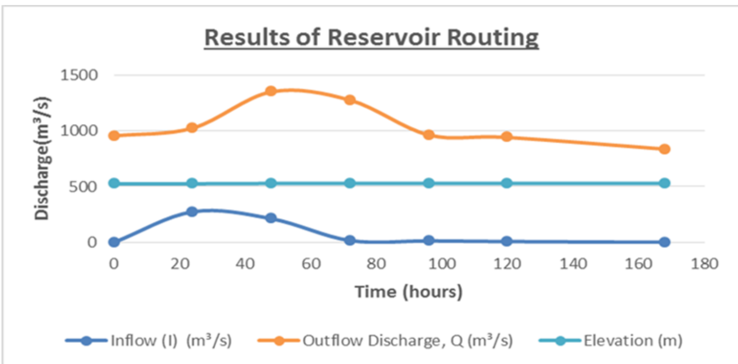

Figure 7. Goodrich method storage routing

Analysis from the flood routing table is then represented on the Goodrich Method Storage routing graph to determine the freeboard height and its corresponding flow over the spillway. As shown in Figure 7, nodes on the 2S/t + Q graph represent each day of study duration. When projected vertically to the axis above, its flow over the spillway is determined. And the value of the water level in the dam can be calculated by projecting it horizontally to the left of the axis. Finally, these values are compared to the design limitations, such as dam level should not exceed 532m (dam crest level) and the maximum spillway discharge of 1800m^3/s. The results from the graphical representation are highlighted in Table 4 below.

Table 4. Results from Goodrich method graph

Time (h)	Inflow (l) (m/sec)	Elevation (m)	Outflow Discharge Q (m^3/sec)
0	0.00	521.15	955.00
24	274.12	528.18	1025.00
48	211.84	528.06	1350.00
72	15.62	527.96	1275.00
96	12.81	527.86	963.00
120	7.21	527.76	941.00
168	0	527.66	836.00

Spillway Adequacy Analysis

Figure 8, denoting the relationship between inflow, outflow and the dam level is plotted to validate the observations made. It shows the reservoir routing procedure for the peak outflows and corresponding flood rises for a 24–168-hour duration. It can be observed that as the rainfall intensifies, the flood level rises. An almost constant water level at the dam is maintained and at its peak flood observation, the dam level rose to 528. 18m.It shows the dam with its free overspill concrete-lined crump weir is able to successfully allow safe discharge of flood events of PMP/PMF magnitude for the research period. At the highest measured flood, the dam rises to a level of 528.06m ASL, which is less than the elevation of the Dam Crest level of 532m ASL. As a result, the water level over the spillway rose by 1.06m. During this time, the flow over the spillway was 1350m3/sec. The flood rise is confined to the dam crest level; therefore, the Vaturu Dam is safe from overtopping from the onslaught of a PMP/PMF event.

Conclusion

A general approach to the determination of the spillway adequacy of the Vaturu Dam indicated that the existing spillway has the ability to discharge the probable maximum flood period safely. These observations were made over the period of one week during the storm event of Cyclone Winston. This category five cyclone caused widespread flooding over the Fiji Group, claiming 44 victims. The highest inflow discharge rate derived from the maximum daily precipitation was 274.12 m3/s, and the observed maximum reservoir level during this period was 528.06m. Discharge over the spillway yielded a flow of 1350m3/s. It is vital to compare these parameters to ensure that they are confined to the limit state per Dam Design. The Dam crest level of 532m ASL and maximum spillway discharge capacity of 1800m3/s threshold were confirmed to have not been exceeded for the storm event of Cyclone Winston.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

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References

Faiza, N., Tai, V. C., & Mohammad, M. (2022). Trend analysis of river flow in Langat River Basin using Swat model. *Journal of Engineering & Technological Advances, 7*(1), 13-22.

Graham, W. J. (2009). Major US dam failures: their cause, resultant losses, and impact on dam safety programs and engineering practice. In *Great Rivers History: Proceedings and Invited Papers for the EWRI Congress and History Symposium* (pp. 52-60).

Güntner, A., Krol, M. S., Araújo, J. C. D., & Bronstert, A. (2004). Simple water balance modelling of surface reservoir systems in a large data-scarce semiarid region, *Hydrological Sciences Journal, 49*(5). https://doi.org/ 10.1623/hysj.49.5.901.55139.

Hershfield, D. M. (1961). Estimating the probable maximum precipitation. *Journal of the Hydraulics Division*, *87*(5), 99-116.

Hershfield, D. M. (1965). Method for estimating probable maximum rainfall. *Journal-American Water Works Association*, *57*(8), 965-972.

Hwee, H.H., & Poon, H.C. (2013). Risk assessment scenario of Machap Dam overtopping using new PMP Malaysian series. *Jordan J. Civil Eng. 159*(701), 1–10

Kaatz, J. A. (2014). *Development of a HEC-HMS model to inform river gauge placement for a flood early warning system in Uganda* (Doctoral dissertation), Massachusetts Institute of Technology.

Khalifeloo, M. H., Mohammad, M., & Heydari, M. (2015). Multiple imputation for hydrological missing data by using a regression method (Klang river basin). *International Journal of Research Engineering and Technology*, *4*(6), 519-524.

Mohammad, M., Faiza, N., Low, Y.K.., & Shariff, M.S. (2020), Rainfall runoff modelling of sungai pahang by using hydrologic modeling system (HEC-HMS). *Journal of Mechanics of Continua and Mathematical Sciences, 9*, 171-180. https://doi.org/10.26782/jmcms.spl.9/2020.05.00017

Nathan, R., & Merz, S. K. (2001). Estimation of extreme hydrologic events in Australia: Current practice and research needs. In *Proceedings of a Workshop on Hydrologic Research Needs for Dam Safety* (pp. 69-77).

Sidek, L. M., Nor, M. M., Rakhecha, P. R., Basri, H., Jayothisa, W., Muda, R. S., ... & Razad, A. A. (2013, June). Probable maximum precipitation (PMP) over mountainous region of cameron highlands-batang Padang catchment of Malaysia. In *IOP Conference Series: Earth and Environmental Science 16*(1): 012049. https://doi.org/10.1088/1755-1315/16/1/012049

Tingsanchali, T., & Tanmanee, S. (2012). Assessment of hydrological safety of Mae Sruai Dam, Thailand. *Procedia Engineering*, *32*, 1198-1204.

WMO (World Meteorological Organization). (2009). *Manual on estimation of probable maximum precipitation (PMP*), WMO-No.1045, Geneva, Switzerland.

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