Cupola-Based Flood Risk Assessment at Tarbela Dam, Pakistan

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ABSTRACT

Floods pose a big challenge for water systems in dams like Tarbela, where water levels change with the seasons and often without notice. To build strong structures, we need exact flood models. Unlike single-variable models, copula-based multi-variable methods capture the complex links between flood features, leading to a deeper risk review. This study addresses a crucial problem and enhances flood risk evaluation by applying a multi-variable probability-based method. The research will zero in on grasping the links among various flood characteristics like peak, volume, and duration. This work sets out to examine the relationship between peak flow, volume, and duration to build a foundation for maintaining Tarbela Dam's water infrastructure.

Keywords: Copula, Flood Risk, Tarbela Dam, MOM, MLE.

INTRODUCTION

Flood risk management is essential because of the Tarbela Dam in Pakistan's vulnerability to multiple major flood occurrences in the past and shifting storage conditions. Effective flood control requires accurate modelling of the interplay between peak flow, volume, and duration, while standard univariate approaches fall short of capturing these relationships. Due to the copula-based multivariate technique used in this work, joint behaviours across flood variables may be thoroughly investigated under low, medium, and high storage conditions. Copula models have been demonstrated to be successful in capturing interactions across hydrological variables in earlier studies (Ganguli and Reddy 2013) (Xu *et al*., 2017), which provides a strong basis for the methodology employed in this work. Furthermore, the methodology employed in this work is supported by previous applications of the copula method in multivariate flood frequency research, such as (Villalobos-Herrera *et al*., 2021) which demonstrate how well it gauges the relationship between flood components. Recent fieldwork that has improved our understanding of copula identifiability and estimation accuracy has demonstrated the viability of using copula in hydrologic research (Derumigny and Fermanian, 2022).

OBJECTIVE

The primary goal of this study is to determine the joint interdependence of peak flow, volume, and duration at Tarbela Dam under various storage conditions (low, medium, and high). The study's goal is to provide insights into the flood risk profiles unique to each storage level by identifying appropriate copula models for each scenario.

METHODOLOGY

This research employed several copula models, including Clayton, Ali Mikhail, Frank, Joe, Normal, Student t, and Gumbel, to measure the dependence of flood characteristics. To confirm the Copula's appropriate fitting, which was done through Maximum Likelihood Estimation (MLE) and Method of Moments, the Copula fit was validated using Cramér-von Mises (CvM). Choosing the correct copula to capture the dependencies between the combinations of peak flow, volume, and duration, i.e., peak flow and Volume (P-V), peak flow and Duration (P-D), Volume and Duration (V-D).

Depending upon the water level in the dam, the storage conditions have been classified as low, medium, and high. To elucidate flood risks further, the joint return periods were computed under AND (conjunctive) and

OR (disjunctive) scenarios. In the AND scenario, the probability of exceedance of two given variables at the same time was assessed, while in the OR scenario, the probability of exceedance of one variable at least in a given condition was considered. The return period analysis was a very inspective analysis, which readily shows the recurrence intervals.

Each copula model was selected according to its effectiveness in modelling specific storage conditions and their respective dependency structures. MLE and MOM made the fitting process very flexible, and this made possible the evaluation of the model about flood causal factors. This detailed approach to the modelling process makes it possible not to ignore the distinguishing features of every storage level, enhancing the results in real-life flood control scenarios.

More recently, parameter estimation methods based on L-moment, which can accommodate outliers, have been devised to complement MLE and MOM to obtain better reliability results in certain applications. This study specifically used MLE and MOM due to their flexibility and compatability with the following characteristics of the data, (Aminuddin Jafry *et al*. 2024) validated that L-moment methods show better performance in scenarios with extreme flood values than traditional techniques. It means that their findings validate that selection of parameter estimation methods is dataset and modeling goal specific, in line with the rigor in this study.

These findings, however, are important in understanding how different types of storage capacities affect flood risk and have an operational application in making flood risk management decisions in Tarbela Dam.

CONCLUSION/RESULT

The use of a copula in assessing the risk of flooding yields revealing information regarding the risk associated with the various storage levels in the Tarbela Dam. In the case of low storage, the Frank, Clayton, and Normal copulas were most effective; in the case of medium storage, the Joe and Gumble copulas outperformed; while in the case of high storage, the Gumble and Joe dominated in that order with the P-V, P-D and V-D respectively. In addition, for almost all storage capacities, the copulas gave the best results with the MLE approach. Lower RMSE values were also recorded for P-V in all the spans of storage capacity. The study displays that moderate storage has the advantage of proportionate risk mitigation while coping with the AND situations of high inflow and flooding occurrence with low-frequency periods. While high storage safety level circumstances are the most protective covering a long period, which allows for extremes to happen without the danger of them occurring at the same time. For instance, the Gumbel copula can be used for such conditions. These results are in line with the results of more recent works by (Xu *et al*., 2017) that argue for the application of multivariate analysis techniques in flood damage assessment. So, the information provided in this research makes it possible to construct portions of the Tarbela dam flood control systems that take into consideration the very dependable operational regime of the hydraulic structures.

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