Managing the Bharathapuzha River Basin of Kerala for Sustainable Water and Flood Management

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ABSTRACT
The Bharathapuzha River, Kerala's second-longest river, is a critical water source for three districts, with its catchment spanning diverse topographies from the Western Ghats to coastal plains. The region faces increasing extreme events, exacerbated by climate change, variability, and anthropogenic activities, leading to significant land-use changes and a lowering water table. The river's flow is highly regulated by thirteen major hydraulic structures, necessitating an efficient river basin management plan to sustain life and agriculture. This study aims to develop a decision support framework for flood management in the Bharathapuzha basin, focusing on assessing current conditions, establishing ecological flows, and conducting historical drought assessments. Additionally, it explores optimal reservoir operations, considering flood cushions and mapping floodplains for selected design hydrographs. The study concludes with the operationalization of an optimized reservoir operation plan, ensuring synchronous management of all major reservoirs for effective flood control. This comprehensive approach is essential for addressing the region's water management challenges and sustaining the basin's ecosystem and communities.

1. INTRODUCTION

The Bharathapuzha River, Kerala's second longest river, stretches 209 km from its source in the Anaimalai Hills in the Western Ghats to its mouth at the Arabian Sea in Ponnani. Covering a basin area of approximately 6186 km², over 70% of this area lies within Kerala, with the remainder in Tamil Nadu. The river is a vital water source for the districts of Palakkad, Thrissur, and Malappuram. Its catchment, predominantly agricultural and forested, includes major tributaries such as Kannadipuzha, Kalpathipuzha, Gayathripuzha, and Thuthapuzha. Thirteen major hydraulic structures are currently in place along the river (John et al., 2019).

The basin's varied topography, from hilly regions in the Western Ghats to low-lying coastal plains, results in significant rainfall variations, with the Kerala region receiving 967 mm to 3000 mm annually (Drissia, 2019). Most rainfall occurs during the South West monsoon (June to September), followed by the North East monsoon (October to December), characterized by thunderstorms. The basin experiences a tropical climate, with annual temperatures ranging from 23.3°C to 32.3°C (John et al., 2019; Magesh et al., 2013).

2. MATERIAL AND METHODS

2.1. Study Area

Figure 1 illustrates the downstream area of the Bharathapuzha River basin, a perennial river that has experienced significant changes in recent decades. Once consistently flowing, the river now often runs dry in many sections during the summer months. This alarming shift is primarily attributed to extreme climatic events and human activities, such as the construction of regulatory structures along the river and unchecked sand mining from the riverbed. These changes pose a serious threat to the many towns and villages that rely on the Bharathapuzha for their water needs. Figure 2 provides a map of the basin, highlighting the study area.

Figure 1. View of downstream area of Bharathapuzhariver basin (source: USGS earth explorer)

Over the past two decades, the Bharathapuzha River basin has faced anomalies in rainfall patterns and surface temperatures (Raj and Azeez, 2010). There has been a notable increase in the frequency of extreme events in the region, with recent studies by Jose and Athira (2020) indicating the presence of both climate change and climate variability signals. These environmental challenges have been exacerbated by anthropogenic activities, leading to significant disturbances in the basin's natural ecosystem. Land-use changes, as documented by John et al. (2019), have contributed to a marked reduction in water availability at the basin level.

The water table in the region has also declined significantly over time, with some areas classified as overexploited according to the Central Groundwater Board (2017). The river's flow is heavily regulated by 13 major man-made structures and numerous minor irrigation systems. The increased frequency of extreme events highlights the crucial role of these reservoirs in the basin's water management. To sustain life and agricultural activities in the Bharathapuzha River basin, an efficient river basin management plan is urgently needed.

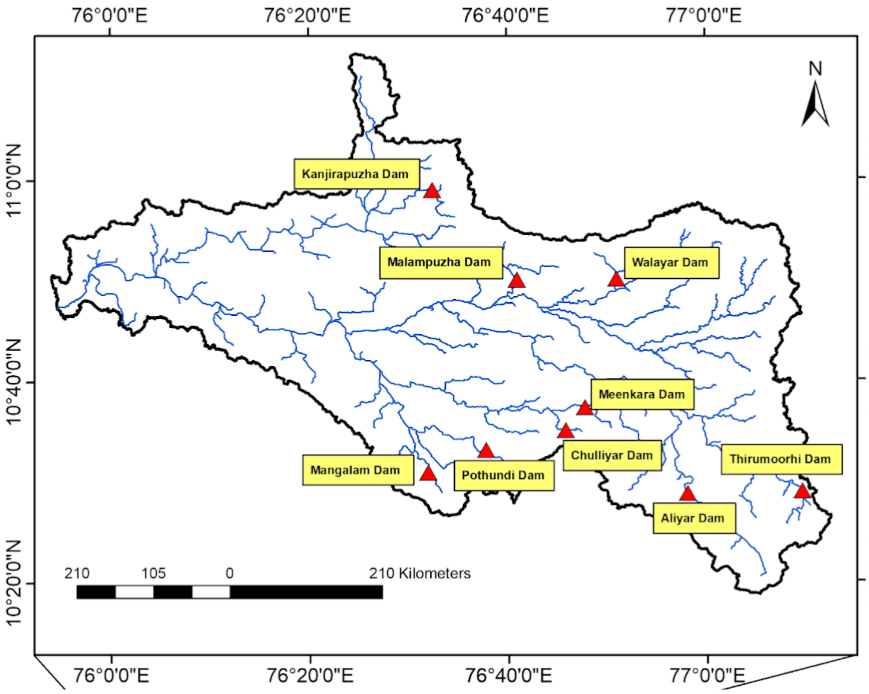

Figure 2. Location of Bharathapuzha river basin

2.2 Data Availability

The hydro-meteorological data necessary for historical assessment and flood management were sourced from various agencies. Rainfall and streamflow data were provided by the Irrigation Development and Research Board (IDRB) of the Government of Kerala. Additional data for the project were obtained from the official websites of the Kerala Irrigation Department, the Food and Agricultural Organization (FAO) of the United Nations, USGS Earth Data, and the Environmental Systems Research Institute (ESRI). Furthermore, data were collected from the Indian Meteorological Department (IMD), the Central Water Commission (CWC), the National Centre for Environmental Prediction (NCEP), and the European Centre for Medium-Range Weather Forecasts (ECMWF).

3. HYDROLOGICAL MODELLING

3.1. HEC-HMS Hydrological Model

Numerous hydrological models, each with unique and shared characteristics, are being developed continuously (Wang et al., 1996). Given these variations, classifying hydrological models is essential to accurately identify their capabilities and limitations. The key inputs required for hydrological models include climatic variables such as precipitation, maximum and minimum air temperatures, relative humidity, wind speed, and atmospheric pressure. Other critical inputs are watershed characteristics, including drainage networks, topography, groundwater aquifer properties, spatio-temporal groundwater level data, hydraulic structures, soil properties, moisture content, vegetative cover, and water quality parameters.

In this study, the HEC-HMS model version 4.11 was employed to simulate rainfall and runoff and generate flood hydrographs. Model inputs were identified using specific methods within the model. The SMA loss method was used to convert rainfall data into runoff. Vegetation maps, hydrologic soil groups, and land use data were integrated using GIS and ArcView software to prepare modeling parameters. Given the presence of multiple reservoirs in the Bharathapuzha basin, reservoir simulation was conducted in HEC-HMS using the specified reservoir routing method. Continuous calibration and validation of the model were performed at regional stations.

The spatial distribution of rainfall was analyzed using the IDW method in GIS, while the temporal precipitation pattern for each sub-basin was determined using data from the nearest registered station. After calibrating and validating the model, optimal parameters were extracted, and precipitation for return periods of 10, 20, 50, and 100 years was derived from the intensity, duration, and frequency (IDF) curves of the basin's synoptic station and input into the model. Flood hydrographs for various return periods were then computed using HEC-RAS software. To determine the average reach velocity, a spatial harmonic mean travel time was calculated. Additionally, the HEC-HMS model was utilized to generate unimpaired flows in the basin. Figure 3 depicts the Bharathapuzha River basin with hydro-meteorological locations, and precipitation data, observed streamflow data, and various basin characteristics (land use/cover, soil data, and slope) were incorporated from the HEC-Geo HMS tool.

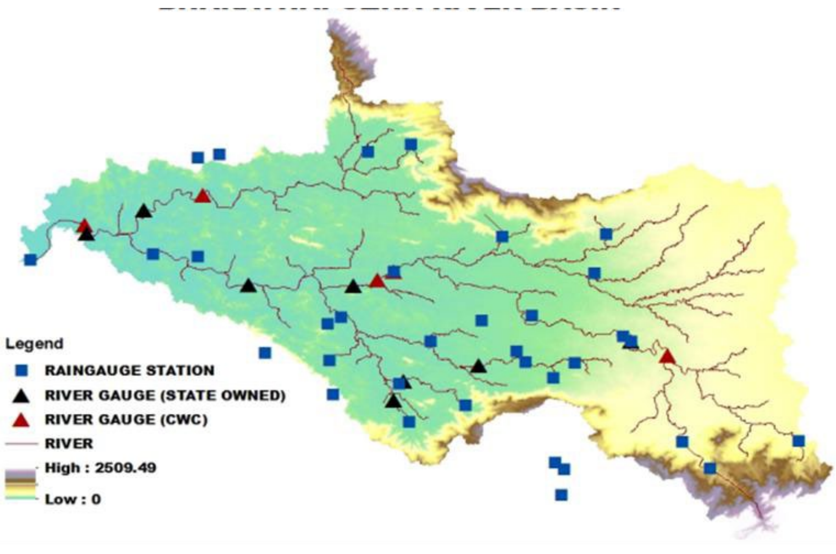

Figure 3. Spatial map of hydro-meteorological stations in the basin

The HEC-HMS model was implemented to simulate all nine reservoirs in the Bharathapuzha basin. A simulation run was created by integrating the basin model, meteorological model, and control specification model. The basin model included key elements such as subbasins, reservoirs, diversions, and reaches, with pre-determined parameters assigned to each subbasin. The meteorological model specified precipitation using a 'specified hyetograph' for each subbasin and evaporation as 'specified evapotranspiration.' These inputs were managed as gauges through the time-series data manager. The simulation period was set for the years 2000 to 2020 within the control specification module. Key computational locations, including reservoirs, regulators, and river gauge stations, were identified to manage the complexity of simulating all reservoirs in a single model. Separate models were developed for each reservoir, requiring pre-processing of reservoir data. The rainfall-inflow patterns for all reservoirs were plotted to detect any outliers. While the sub-basin area remained constant, various parameters were calibrated by adjusting their values to achieve a satisfactory match between the predicted hydrograph and the observed or historical hydrograph. The HEC-HMS model simulates runoff using rainfall data; we have the rainfall data at the reservoir sites. Understanding the data constraints, the data are corrected and generated using available resources. For example, wherever the inflow to reservoirs is there but rainfall is nil, we separate that inflow and add it to the model as additional sources for equating the water balance. The data constraints are solved using many manual techniques.

3.2. Sensitivity Analysis

Sensitivity analysis is a crucial aspect of rainfall-runoff modeling, used to identify the most influential parameters within the model. In this study, a sensitivity check was performed to determine the most sensitive parameter of the Soil Moisture Accounting (SMA) method by analyzing changes in volume. The sensitivity analysis was conducted separately for the early-wet and wet periods of a water year. The SMA parameters for the basin model were initialized using the soil database and streamflow data. The analysis involved varying each initial parameter individually, both increasing and decreasing it by increments ranging from -50% to 50%, and observing the resulting changes in output volume. The percentage change in output volume relative to the initial parameters was then tabulated and plotted to assess the sensitivity of the study area. This analysis is particularly useful for model calibration, as it allows for ranking the parameters based on their sensitivity. The most sensitive parameters were ranked first, followed by those with lower sensitivity.

To quantify sensitivity, the elastic ratio (e) was employed, which measures the relative change in the dependent variable (output volume) concerning the independent variable (parameter value). Parameters with a higher elasticity ratio were identified as the most sensitive, and therefore, were ranked accordingly from most to least sensitive. Figure 4 shows the sensitivity analysis plot.

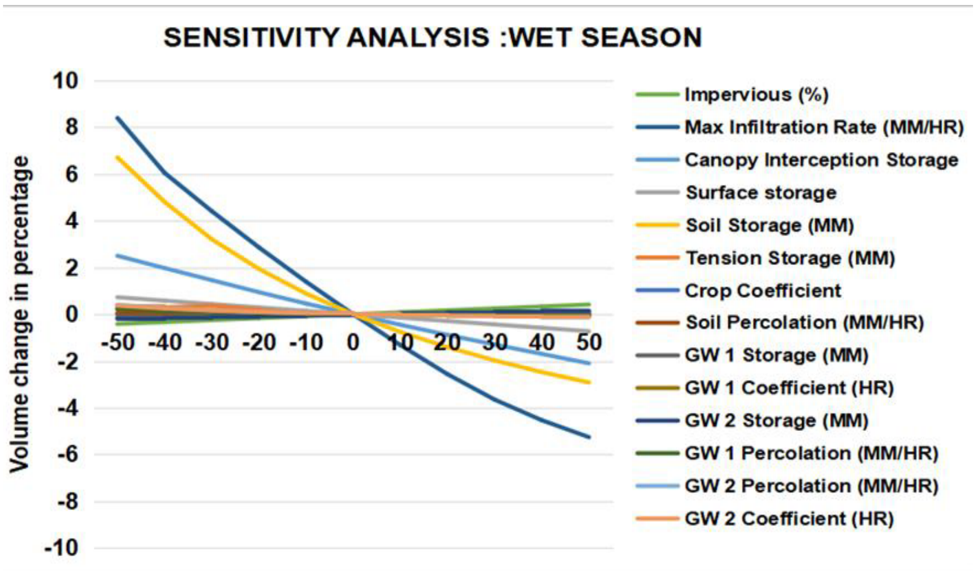

Figure 4. Sensitivity Analysis

The sub-basin area was 64 km2. The sub-basin is calibrated using inflow to the reservoirs. The reservoir water level is also compared. Figure 5 shows the scatter plot representing the observed discharge and the predicted discharge during the calibration phase. The coefficient of determination (R2) for the calibration phase was 0.86, which depicts satisfactory performance. The Nash-Sutcliff Efficiency (NSE) during the calibration phase was 0.87, respectively, thus depicting the capability of the proposed model in adequately predicting the observed discharges in the subbasin.

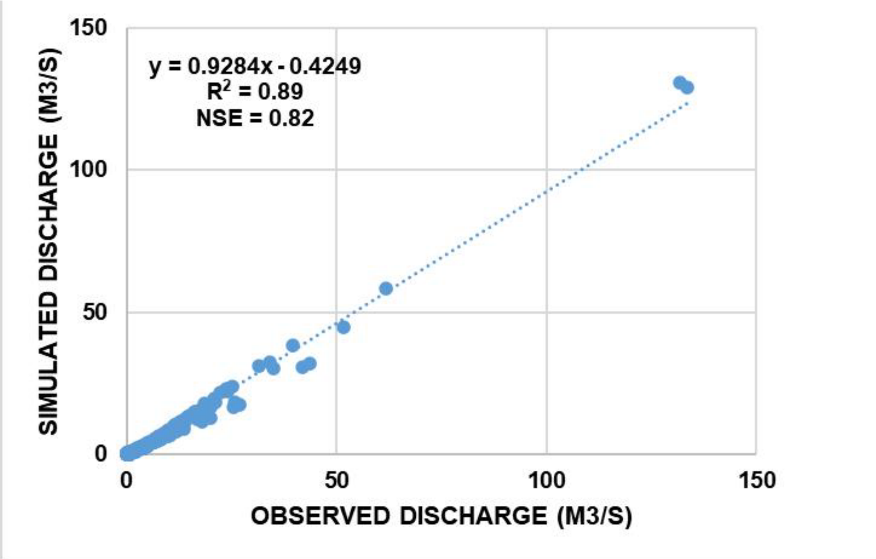

Figure 5. Scatter plot of observed and simulated flows in Aliyar subbasin

3.4. Reconstruction of Historic Unimpaired Streamflows

The natural extremity in flows, also known as the virgin flow condition, was generated through continuous simulation using the HEC-HMS model. This non-structural condition represents the flow without any human-made interventions such as reservoirs. However, since the reservoir module within HEC-HMS is not entirely suitable for simulating historic reservoir operations, the model was coupled with the HEC-ResSim module for more accurate reservoir simulation. The primary objective of the continuous flow simulation in HEC-HMS was to generate a long-term streamflow time series data covering the period from 2000 to 2020. This data is essential for computing flood magnitudes for different return periods. In flood frequency analysis, accounting for reservoir regulations can obscure the capture of extreme high peaks in the computed flows. Therefore, virgin flow conditions, which represent the natural flow without reservoir influence, were preferred for this analysis. To ensure accuracy in the continuous simulation, the Soil Moisture Accounting (SMA) loss method was adopted. This method is particularly well-suited for continuous time series simulation, as supported by previous research (Chu and Steinman, 2009). The comparison of impaired and unimpaired stream flows is shown in Table 1.

Table 1. Comparison of impaired and unimpaired streamflow

River gauge locations	Impaired Flow (m^3/s)		Unimpaired Flow(m^3/s)		Difference (%)	
	Peak discharge	Total discharge	Peak discharge	Total discharge	Peak discharge	Total discharge
Ambarampalayam	974.9	34577.9	1119.3	36116	14.81	4.45
Manakkadavu	1006.5	35638.5	1151.7	37179.3	14.43	4.32
Pambady	2986.7	84391.9	3669.5	90854.5	22.86	7.66
Cheruthuruthy	5955.5	152425.2	6645.4	158114.4	11.58	3.73
Thiruvegapura	1655.4	57971.7	1748.8	55537.3	5.64	4.38
Kumbidi	8234.7	239086.3	8959.1	247332.1	8.80	3.45

A comparison between impaired and unimpaired streamflows reveals that both peak discharge and annual discharge are higher in the unimpaired flows. Specifically, peak discharge shows an increase of 14.81%, 14.43%, 22.86%, 11.58%, 5.64%, and 8.80% for the natural streamflow compared to the impaired flow at the Ambarampalayam, Manakkadavu, Pambady, Cheruthuruthy, Thiruvegapura, and Kumbidi stations, respectively. Similarly, the total annual discharge for these stations increased by 4.45%, 4.32%, 7.66%, 3.73%, 4.38%, and 3.45%, respectively.

4. CONCLUSIONS

Analysis of various freely available Digital Elevation Models (DEMs) identified the COPERNICUS FAB DEM as the most effective for representing the stream network in the Bharathapuzha basin. Examination of land use and land cover maps from 2015 to 2020 revealed a decrease in agricultural land, with increases in urban and forest areas. Soil maps from the National Bureau of Soil Survey (NBSS) indicated that sandy clay loam and clay loam are the predominant soil types in the basin. Challenges were encountered with the reservoir water level and storage time series data, which contained outliers and errors, hindering accurate estimation of inflows due to missing data on seepage and evaporation losses. Skill assessment of hindcast data from IITM, GEFS, and ECMWF, using metrics like RMSE, BSS, and MAE, demonstrated that ECMWF hindcasts performed better for most grid points in the study area. The HEC-HMS model successfully captured the trend and shape of the observed hydrograph, achieving R^2 values of 0.63 and 0.43 during calibration and validation, respectively. Sensitivity analysis of Soil Moisture Accounting parameters highlighted soil storage, maximum infiltration, and tension storage as the most sensitive parameters.

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