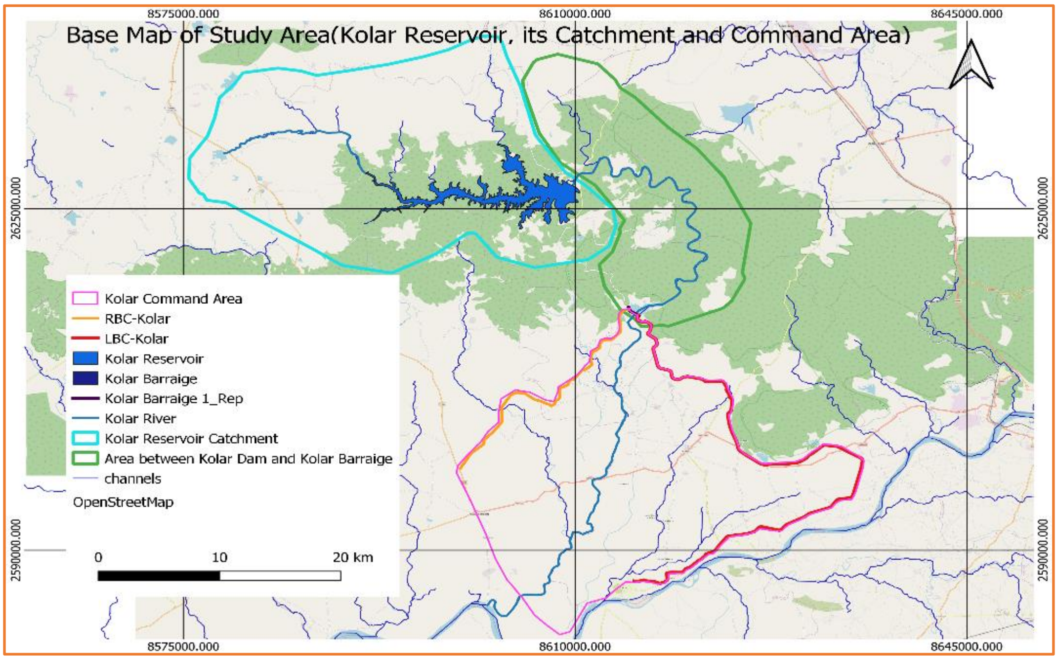
Report No. -------

Development of Reservoir Operation Plan under Climate Change Scenarios for Kolar Reservoir in Madhya Pradesh

(Final Report)



NATIONAL INSTITUTE OF HYDROLOGY

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Development of Reservoir Operation Plan under Climate Change Scenarios for Kolar Reservoir

Study type:	**In-house study**
Duration of the project:	**3 Years**
Lead Organisation:	**National Institute of Hydrology, Central India Hydrology Regional Centre, Bhopal**
Study Team:	
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PREFACE

A number of reservoirs have been planned and constructed in India for the conservation and utilization of the water resources for deriving various benefits. Kolar Dam, a major masonry dam, is located about 35 km away from Bhopal, near Lawakhari village in Sehore District. Constructed across the Kolar, a tributary of the Narmada on the right bank, the dam is about 45 m high. The catchment area up to the dam site is 508 sq km. The management of any reservoir system from planning to operation is quite challenging as it deals with diverse complex variables and uncertainties viz., inflows, return flows, storages, diversions, inter/intra-basin water transfers, irrigation demands, hydropower demands, industrial demands and municipal water supply demands (Rani & Moreira, 2010). The reservoir management strategies should be based on the hydrological response of the catchment as well as the water utilization pattern in the command areas.

Kolar reservoir is an important source of potable water supply for the city. As per an agreement with the Water Resources Department, 56.6 MCM is reserved for drinking water supplies. The Kolar project was proposed to irrigate 45,078 ha of area, but only 31,000 ha is being irrigated presently due to water shortage. Therefore, the Sip Kolar project is proposed to divert water into the existing Kolar project for augmenting water and irrigating an area of 6,100 ha, which is found to be a deficit area of the existing command of the Kolar project. As the Sip-Kolar link project is underway to add/divert 35 MCM water to Kolar dam to irrigate the deficit area of 6100 ha and bring its capacity to FRL, which was not attained in previous years. Looking into the deficit in reservoir storage in the past year, a study titled “Development of Reservoir Operation Plan under Climate change scenarios for Kolar reservoir”, is envisaged to assess scenarios based demand demand-supply analysis and management options for optimal use of water in Kolar reservoir. Different scenarios of Sip-Kolar link, efficiency management (incorporation of drip& sprinkler and canal lining for reduction in agricultural water use), population growth, etc., will be analysed, and a suitable management plan will be prepared. Lastly, the development of reservoir operation policy under a changed scenario would be suggested for better water management practices. Looking into the climate change-related impacts and uncertainties in the future, the management of the available water resources, including the management and operation of the Kolar reservoir, should be challenging as well as an interesting case study for devising targeted adaptation plans for the various stakeholders. In such an uncertain futuristic scenario, the assessment of the impacts of climate change on the water availability in the reservoir and the subsequent impacts on meeting the committed demands for the domestic, industrial, and agricultural sectors is necessary. The study shall address these issues and explore the possibilities of formulating revised reservoir operation policies to address the altered future supply-demand scenario in the basin. The crop water requirement and irrigation scheduling of Rabi Crops using CROPWAT 8.0 in the Kolar command area is estimated. The estimation of water balance of Kolar reservoir has been accomplished by using a mathematical approach for 15 years (2009-2024) to determine inflow on a daily basis for the water year (June 01 to May 31 next year) and to understand the present and future supply demands scenario of Kolar reservoir. The trend analysis of annual and seasonal precipitation and maximum temperature was done in order to identify the trend points for climate change, and the rainfall-runoff relationship has been of the Kolar basin was carried out to determine the 5% and 10% increase in inflow from the present inflow data series estimation. Lastly, the rule curves have been derived for the conservation operation of Kolar reservoir using NIHReSyP 2018 for different scenarios I to V. Different Scenarios are (i)Rule curves for present demand(ii) future demand (iii)inflow increase to 5%(iv) inflow increase to 10%(v) Cropping pattern change.

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ABSTRACT

The management of any reservoir system from planning to operation is quite challenging as it deals with diverse complex variables and uncertainties, viz., inflows, return flows, storages diversions, inter/intra-basin water transfers, irrigation demands, hydropower demands, industrial demands and municipal water supply demands (Rani & Moreira, 2010). The reservoir management strategies should be based on the hydrological response of the catchment as well as the water utilization pattern in the command areas. Kolar River is a right bank tributary of the Narmada River, and Kolar reservoir is a multi-purpose project located on it. It flows for a total length of 101 km, all of which is in the state of Madhya Pradesh. The Kolar River arises in the Vindhya Range of Sehore district and flows in a south-westerly direction to meet the Narmada at village Neelkanth near Nasrullahganj in the Sehore district of Madhya Pradesh.

Kolar reservoir is an important source of potable water supply for the city. As per an agreement with the Water Resources Department, 56.6 MCM is reserved for drinking water supplies. The Kolar project was proposed to irrigate 45,078 ha of area, but only 35,000 ha is being irrigated presently due to water shortage. Therefore, the Sip Kolar project is proposed to divert water into the existing Kolar project for augmenting water and irrigating an area of 6,100 ha, which is found to be a deficit area of the existing command of the Kolar project. As the Sip-Kolar link project is underway to add/divert 35 MCM water to Kolar dam to irrigate the deficit area of 6100 ha and bring its capacity to FRL, which was not attained in previous years. Looking into the deficit in reservoir storage in the past year, a study titled "Development of Reservoir Operation Plan under Climate change scenarios for Kolar reservoir", is envisaged to assess scenarios based demand demand-supply analysis and management options for optimal use of water in Kolar reservoir.

The present study has, therefore, been undertaken with the objectives: (i) Assessment of present and future supply-demand scenario of Kolar dam, (ii) Development of rainfall-runoff relationship for assessment of reservoir inflows. (iii) Scenario development for climate, demography, and water resources management aspects. (iv) Development of Reservoir Operation Policy under different scenarios. The output of the study would develop a revised reservoir operation policy under different scenarios for better water management practices.

The Crop water requirement and Irrigation Scheduling of Rabi Crops have been carried out using CROPWAT 8.0 using the average climatic data of 26 years (1996-2021) for the Kolar reservoir command area. The net irrigation requirement for Rabi crops is 273 mm/year, obtained by the addition of the net irrigation requirement during January to December. The gross irrigation

water requirement for Rabi crops has been estimated as 462.71 mm/year, consisting of an irrigation efficiency of 59%. The entire command area of 35040 ha (370.13 sq. km) requires 151 MCM of water for Rabi crops. However, during the Rabi season, the Kolar Dam Authority, on average, releases 145.52 MCM of water over the period of 15 years for irrigation of Rabi crops, which implies that the dam does not fill to its full capacity of 270 MCM. Therefore, the result shows that the dam cannot conveniently supply the water required for the irrigation of Rabi crops in the command area, and there is a need for proper management of water resources. Therefore, the Sip–Kolar link project is initiated (operational since 2022) whereby diversion of 35 MCM water from the Sip River to Kolar dam during June to October to augment the storage shortfall in Kolar dam to meet the irrigation demands (151 MCM) as well as the domestic demands (71 MCM). The Water Balance of Kolar Reservoir has been carried out on a 1-daily basis for a period of 15 years from 2009-2024. Results indicate that the quantum of harvested runoff water depends largely on the annual/ monsoon rainfall (1217 mm) falling in the catchment as well as inflow calculated was used for deriving the rainfall-runoff relationship for different scenarios i.e (i) present, (ii) increase in inflow 5% (iii) increase in inflow 10%. Trend analysis of annual and seasonal precipitation and maximum temperature using Mann-Kendall and Sen’s Slope estimator has been done for the period of 26 years (1996-2021). Sen’s Slope estimator revealed a significant rising trend in annual precipitation with a value of 8.77, whereas seasonally winter and post-monsoon seasons show a slight declining trend in rainfall. The temperature trend is not significant for the Kolar basin.

Lastly, the rule curves have been derived for the conservation operation of Kolar reservoir using NIHReSyP 2018 for different scenarios I to V. Different Scenarios are (i)Rule curves for present demand(ii) future demand (iii)inflow increase to 5%(iv) inflow increase to 10%(v) Cropping pattern change. This operation policy tries to distribute the deficit equitably in advance so that the reduced supply can be maintained throughout the demand period. The dam has a gross storage capacity of 270 MCM and a live storage capacity of 265 MCM, and after catering to Rabi irrigation (151 MCM), and domestic supplies to Bhopal City (71 MCM) the dam is not operated to its optimum limit due to a shortfall in attaining FRL in previous years. Kolar dam authority has added 19.73 Sq. Km to the Kolar Command Area to be irrigated through a micro irrigation system for catering to Rabi crops at present, and another 21 sq. Km of extension in the Kolar command area through micro irrigation is in planning for the future since the operationalization of the Sip-Kolar link project in 2022. In these years (2009-2024), after releasing water for irrigation of Rabi crops as well as catering to water supply demand to Bhopal,

the final water storage at the end of the water year is on average 62.5 MCM, which emphasizes the need for its optimum utilization.

The study contributed immensely in understanding the water resources system in Kolar basin through assessment of present water availability, trend analysis of annual and seasonal precipitation and maximum temperature, Cropwat analysis as well as future water availability and demand was also evaluated and seen that Kolar reservoir could cater to future demands of irrigation and water supply as well though critical failure months' increases. The study suggested the revised reservoir operation policies (rule curve levels) based on present and future demands, as well as different scenarios of a 5%, 10% increase in inflow and a cropping pattern change. As the inflow increases to 5%, 10%, there is a reduction in critical failure months simultaneously, as well as time and volume reliability of irrigation also shows significant improvement (increase) respectively. The revised reservoir operation policies would help WRD, Hoshangabad, to operate the reservoir to its optimum use according to the changes in future demand (2050) and future changes in cropping patterns in the Kolar command.

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1. INTRODUCTION

In many semi-arid regions of the world, surface water provides a major source of water supply for meeting the various demands. River runoff occurring during the rainy season is stored in surface reservoirs to sustain human, agricultural, and industrial water use during the dry season (Andreas Güntner et al., 2005). The water resources management in semi-arid regions of Madhya Pradesh is often characterized by reservoirs ranging from large impoundments to small farm ponds/check dams in rural areas for short-term local use. The integrated management of water resources is required to secure water availability in water-scarce semi-arid regions of Madhya Pradesh (Gaiser *et al*., 2003).

Kolar dam is situated near the village Birpur in the district Sehore and at a distance of about 30 KM from Bhopal. Its latitude is 220 -51’-00” N and its longitude is 770 -24’-00’’ E. It is located in the Narmada Basin. The project has an annual irrigation potential of 45040ha, a Cultivable Command Area of 45087 ha, an Area Irrigated during Rabi is 35040 ha, and a Gross Command Area of 62752 ha. It is an earthen embankment dam built across the Kolar River and also provides 61 MCM of water to Bhopal city for drinking purposes, which constitutes about 70% of Bhopal's drinking water, and also provides for irrigation and inland fisheries. This reservoir has multiple purposes, including irrigation and water supply.

The Kolar basin is believed to be a water-deficient basin based on the present supply-demand scenario. Kolar reservoir is an important source of potable water supply for the city. As per an agreement with the Water Resources Department, 61 MCM is reserved for drinking water supplies. The Kolar project was proposed to irrigate 45,078 ha of area, but only 31,000 ha is being irrigated presently due to water shortage. Therefore, the Sip Kolar project is proposed to divert water into the existing Kolar project for augmenting water and irrigating an area of 6,100 ha, which is found to be a deficit area of the existing command of the Kolar project. As the Sip-Kolar link project is underway to add/divert 35 MCM water to Kolar dam to irrigate the deficit area of 6100 ha and bring its capacity to FRL, which was not attained in previous years. Looking into the deficit in reservoir storage in the past year, a study titled “Development of Reservoir Operation Plan under Climate change scenarios for Kolar reservoir”, is envisaged to assess scenarios based demand demand-supply analysis and management options for optimal use of water in Kolar reservoir.

Looking into the changing cropping pattern, particularly paddy crop being now practiced in monsoon season and population growth, the management of the available water resources is a key area of research to cope with the altered changes and study the future water availability scenario. As such, it is imperative to assess the present supply-demand scenario and frame the reservoir operation policy being practiced at present, to revise it according to the future changes scenario. The future water demands as well as the future water availability have to be assessed so that the policy makers can frame appropriate policies for the judicial use of the available water resources while maintaining the range of hydrologic variation necessary to preserve the ecological integrity of the basin. The water balance of the Kolar reservoir and rainfall-runoff relationship of Kolar catchment need to be carried out for the assessment of present supply-demand scenario, assessment of the inflows into the reservoir as well as derivation of the changed scenarios namely increase of inflow to 5% and 10% respectively, which was thereafter used for formulation of reservoir operation policy for the optimal utilisation of the available water both for the present and future time horizons.

The present study has, therefore, been undertaken with the objectives: (i) Assessment of present and future supply-demand scenario of Kolar dam, (ii) Development of rainfall-runoff relationship for assessment of reservoir inflows. (iii) Scenario development for climate, demography, and water resources management aspects. (iv) Development of Reservoir Operation Policy under different scenarios. The output of the study would develop a revised reservoir operation policy under different scenarios for better water management practices.

2. REVIEW OF LITERATURE

2.1 Based on the estimation of crop water requirement

Thimme Gowda P. *et al.* (2013) experimented to determine the water requirement of maize (Zea mays L.) for under rain-fed conditions at Dharwad district, Karnataka. The study was conducted during the kharif season of 2011 in the field having deep black soil at the Main Agricultural Research Station, Dharwad. The field experimental data were collected and analysed at two dates of sowing of maize, i.e., June 16, 2010, and July 30, 2010. The calculated total water requirement of maize sown at an early date was 116.0 mm, and that of sown later was 183.8 mm. As a result, the crop water requirement was higher for later-sown maize compared to early sown maize. Hence, the water requirement of maize varied with planting dates.

2.1 A) Irrigation scheduling/ Irrigation management

For efficient and cost-effective use of water for irrigating crops, good management of irrigation is required. Irrigation scheduling depends upon the availability of water and on the design, maintenance, and operation of an irrigation system. The decision-making process for determining when to irrigate and how much to irrigate the field for each irrigation turn is a major element of any irrigation management program. This process of decision-making is termed as irrigation scheduling.

Haque *et al.* (2004) generated an irrigation water delivery scheduling model to enhance the irrigation efficiency for a large-scale irrigation project for rice in Malaysia. They mainly developed irrigation water delivery schedules during the main season and off-season of the rice-based project. For irrigation scheduling, the water balance approach was used in which rainfall was considered as a stochastic variable. A total saving of 19% and 11% of irrigation water in the main season and off season, respectively, was achieved with the model when compared with the traditional irrigation schedules.

Husam *et al.* (2011) evaluated the irrigation water needs for the common cultivated crops (citrus, almonds, date palms, grapes) in the Gaza Strip and compared the outcomes with the farmers' irrigation practices. The model outcomes demonstrate that the reference evapotranspiration results in 1451 ± 5 mm/year. Hence, the irrigation water system necessities are assessed to be 763, 722, 1083, 591 mm/year on average for Citrus, Almonds, Date palm, Grapes, respectively. The existing farmer irrigation practices exceed the irrigation water need by 30%. With the help of GIS techniques, the spatial distribution of irrigation water requirements in the entire area of the Gaza Strip is shown on maps based on data from eight meteorological stations. Irrigation water quality isn't ideal in the Gaza Strip; chemical analysis of irrigation wells indicates high salinity and SAR ratio. The obtained outcomes from the model could be a good organizing tool for the planners and decision makers to limit the overexploitation of the groundwater and to build reasonable and strict regulations to optimize the water use in the agricultural sector in the Gaza Strip, which is categorized as a semi-arid region.

Patil et al. (2014) conducted irrigation scheduling using the FAO CROPWAT and CRIWAR models for the command area of the Wadi Adampur distribution of the Wan River Project. After analysis, the results revealed that the actual water applied between the years 2006-07 and 2010-11, except for 2009-10, varied from 2.56 to 16.93 m^3. On average, 9.23 m^3 of water was applied annually. The irrigation schedules were developed using the CRIWAR and CROPWAT software. The calculated water requirement with CLIMWAT and CROPWAT fluctuated between 4.89 and 6.92 m^3 and 9.80 and 12.90 m^3, respectively, in the command area. The discharge requirement was evaluated as 2.05 lps per hectare and 4.59 lps per hectare using the CROPWAT and CRIWAR models. It is concluded that the average actual water application, when compared with the CROPWAT and CRIWAR models, was found to be 53.06% more and 14.77% less, respectively. Although the average actual water applied in CROPWAT is higher than estimated, the average irrigated area is smaller, at only 730 hectares. The CROPWAT model developed a schedule for less water, allowing for significantly more area, approximately 1111.88 hectares, to be irrigated. Considering the above outcomes, the CROPWAT-developed irrigation schedule is recommended for effective irrigation scheduling.

Vellidis *et al.* (2016) the study aimed to compare three different irrigation scheduling strategies in two different tillage systems (i.e., conservation and conventional). The three irrigation scheduling strategies were the University of Georgia Check Book Method for cotton, the University of Georgia Smart Sensor Array (UGA SSA), and the Smart Irrigation Cotton App. The investigation was conducted during the 2015 growing season at the University of Georgia's Stripling Irrigation Research Park near Camellia. The growing stage was examined in unusually wet conditions with rain higher than 23 inches. On comparison with irrigation plots, rain-fed plots had the highest yield and highest water use efficiency.

For proper irrigation management in agriculture, it is necessary to determine crop water requirements at the field level is necessary. In order to take into account the effect of crops on evapotranspiration (ET_O) was introduced (Allen *et al.*, 1998). Evaporation and transpiration occur concurrently, and it is hard to separate these two processes. Thornthwaite first introduced the concept of evapotranspiration in 1948. An accurate estimation of ET_o includes integration of a number of factors such as crop characteristics and development stage, weather parameters, environmental conditions, and management practices (**Kjaersgaard et al., 2008**). **Thimme Gowda P. *et al.* (2013)** experimented to determine the water requirement of maize (Zea mays L.) for under rainfed conditions at Dharwad district, Karnataka. The crop water requirement was higher for later-sown maize compared to early sown maize. Hence, the water requirement of maize varied with planting dates. **Husam *et al*. (2011)** evaluated the irrigation water needs for the common cultivated crops (citrus, almonds, date palms, grapes) in the Gaza Strip and compared the outcomes with the farmers' irrigation practices. The existing farmer irrigation practices exceeded the irrigation water need by 30%. The obtained outcomes from the model could be a good organizing tool for the planners and decision makers to limit the overexploitation of the groundwater and to build reasonable and strict regulations to optimize the water use in the agricultural sector in the Gaza Strip, which is categorized as a semi-arid region. **Pawar *et al.* (2014)** did irrigation scheduling using the FAO CROPWAT and CRIWAR models for the study area command area of Wadi Adampur distribution of the Wan River Project. CROPWAT model developed a schedule for less water, significantly more area, about 1111.88 ha is to be irrigated. Considering the above outcomes, the CROPWAT developed irrigation schedule is suggested for proper irrigation scheduling. Similarly, for Kolar Command the assessment of crop water requirement through CROPWAT 8 model would serve the purpose to assess how much water is needed for irrigation by the different crops sown in the Kolar command and to determine if Kolar Dam Authority is supplying the water for irrigation in excess to what is required or accurately and sufficient to the crop requirement in Command.

2.2 Water Balance of Reservoir

Assessment of the Water Balance of the Barekese Reservoir in Kumasi, Ghana (Domfeh et al, 2015). A 10-year water balance has been assessed for the Barekese Reservoir using an integrated Remote Sensing and GIS approach for estimation of surface runoff based on the Soil Conservation Service Curve Number (SCS-CN). The SCS-CN model was calibrated against observed discharges recorded at the Office located 10.3 km upstream from Barekese, and the result of the calibration was used to simulate runoff into the reservoir. The SCS-CN model produced an R2 value of 0.84 and an efficiency of 82.68%. Monthly observed reservoir levels were used for the calibration and validation of the water balance model. The water balance model produced an R2 value of 0.84 and an efficiency of 81.9%. The monthly water budget revealed that total catchment runoff and direct precipitation, respectively, constituted 94.32% and 5.68% of the inflows, while spilled water, water withdrawal, and evaporation, respectively, amounted to 72.19%, 20.85%, and 6.96% of the outflows. This result reveals that the reservoir is being underutilized. The current average production of treated water is 109,000m3/day, but the reservoir can safely yield the design capacity of 220,000m3/day and an additional average hydropower of 368.6kW in six months during the rainy season, provided the economic analysis for the hydropower generation is found to be justifiable.

Characterizing the Water Balance of the Sooke Reservoir, British Columbia over the Last Century (Werner et al, 2015) The main objectives of this study are to better understand the characteristics of the SR through an in-depth assessment of the contemporary water balance when the basin was intensively monitored (1996–2005), to use standardized runoff to select the best timescale to compute the Standard Precipitation (SPI) and Standard Precipitation Evaporation Indices (SPEI) to estimate trends in water availability over 1919 to 2005. Estimates of runoff and evaporation were validated by comparing the simulated change in storage, computed by adding inputs and subtracting outputs from the known water levels by month, to the observed change in storage. Water balance closure was within ±11% of the monthly change in storage on average when excluding months with spill pre-2002. The highest evaporation, dry season (1998), and lowest precipitation, wet season (2000/2001) from the intensively monitored period were used to construct a worst-case scenario to determine the resilience of the SR to drought. Under such conditions, the SR could support Greater Victoria until the start of the third wet season.

Evaporation from a small water reservoir: Direct measurements and estimates (Tanny et al, 2007). Measurements of net radiation, air temperature, humidity, and water temperature enabled estimation of other energy balance components. Several models and energy balance closures were evaluated. In addition, evaporation from a class-A pan was measured at the site. EC evaporation measurements for 21 days averaged 5.48 mm day_1. Best model predictions were obtained with two combined flux-gradient and energy balance models (Penman–Monteith– Unsworth and

Penman–Brutsaert), which, with the water heat flux term, gave similar daily average evaporation rates that were up to 3% smaller than the corresponding EC values. The ratio between daily pan and EC evaporation varied from 0.96 to 1.94. The bulk mass transfer coefficient was estimated using a model based on measurements of water surface temperature, evaporation rate, and absolute humidity at 0.9 and 2.9 m above the water surface, and using two theoretical approaches.

Modeling Evaporation-Seepage Losses for Reservoir Water Balance in Semi-Arid Regions (Sivapragasam, 2009). It is demonstrated in the study by a case study in the optimal scheduling of the Pilavakkal reservoir system in the Vaipar basin of Tamil Nadu, India. For modeling reservoir losses, many models are available, of which, Penman combination model is most commonly used. In this study, an alternative approach based on Genetic Programming (GP) is proposed. The results of the GP and Penman model for both evaporation loss estimation and reservoir scheduling are compared. It is found that while the GP and Penman combination model performs equally well for estimating evaporation losses, GP is also able to model seepage losses (or other losses from the reservoir) to a much better degree. It is also shown that the reservoir scheduling does get influenced based on how the reservoir losses are modelled in the reservoir water balance equation.

Simple water balance modeling of surface reservoir systems in a large data-scarce semiarid region (Guntner et al, 2004). For the State of Ceará in semiarid Northeast Brazil, which has several thousand reservoirs, a simple deterministic water balance model is presented. Using a cascade-type approach, the reservoirs are grouped into six classes based on storage capacity, rules for flow routing between reservoirs of different sizes are defined, and water withdrawal and return flow due to human water use are considered. While large uncertainties exist in model applications, particularly regarding reservoir operation rules, model validation against observed reservoir storage volumes indicates that the approach is a reasonable simplification for assessing surface water availability in large river basins. The results demonstrate the significant impact of reservoir storage on downstream flow and underscore the need for a coupled simulation of runoff generation, network redistribution, and water use.

2.3 Reservoir Operation

Since the 1960s, water resources management policy and practice have shifted to a greater reliance on improving water use efficiency. Water research teams in many countries have conclusively demonstrated the value of adopting the modern tool of operations research or systems analysis for assisting in the development, operation, planning, and management of water resources projects.

Yeh (1985), Wurbs (1996), and McKinney (1999), in their state-of-the-art review, discussed different optimization techniques that are used in water resources system analysis at the basin level and reservoir operation. A reservoir-system regulation plan, operating procedure, or release policy is a set of rules for determining the quantities of water to be stored or released or withdrawn from a reservoir, or a system of several reservoirs, under various conditions (Wurbs, 1993). The main task is to decide how much water must be stored and/or released, without creating any water shortage in the long term due to emergency releases during floods. Although several studies are focused on weather prediction and accordingly stream flow forecasting (Anderson et al., 2002; Fleming & Neary, 2004; Lim et al., 2010), the operation of reservoir systems studies is rather limited to optimization or simulation model applications.

According to Yeh (1985), the techniques commonly used by the researchers can be broadly classified into linear programming (LP), non-linear programming (NLP), dynamic programming (DP), discrete differential DP (DDDP), differential DP (DDP), successive approximation DP (SADP), stochastic DP (SDP) and genetic algorithms (GA). The most relevant research carried out in the last two decades in the optimization of reservoir operation is summarized under the following subheadings, viz., a) reservoir simulation and b) reservoir operation under climate change. The mass curve techniques used to design the reservoir capacity are considered to be the first simulation model used in water resources planning and management. Yeh (1985) suggested that simulation models can be used to evaluate the consequences of variations in certain model inputs.

Applications of optimization techniques to derive reservoir operating rules have been described by many researchers (e.g., Oliveira and Loucks 1997; Sharif and Wardlaw, 2000; Tu et. 2003). Christensen et al. (2004) suggested that statistically insignificant changes in the inflows would have large impacts on reservoir storage, and therefore, the reservoir operation procedures are likely to be impacted. Minville et al., (2010) evaluated the impacts of climate change on medium-term reservoir operations for the Peribonka water resource system and reported an increase in spills and tendency for reduction in mean annual hydropower production, despite an increase in the annual average inflow to the reservoirs, partly attributed to the impacts of climate change. Report on Simulation of Hirakud Reservoir to study Conservation of Water (Dhal, Soumya Ranjan; 2012). Experimental models were made and observed, which led to results of different levels of water in different months, so that the water supply made is enough to meet the requirements. Further, these models were used to predict water requirements for Irrigation and Hydropower so that failure of crops and power scarcity can be eradicated to some extent. Thus, these small models or simulation operations on reservoirs have completely revolutionized the world with their effective results by successfully helping in predicting the water requirement and availability so that further initiatives can be taken to have a supply of water in downstream areas, as well as for high-priority demands throughout the year. Report on 5-Development of Simulation Models for Multi-reservoir System Operation and Canal System Operation at NIH (Goel M.K., Jain, Sharad K., 2003). Recognizing the utility of simulation models in analysing the performance of complex water systems and in developing their operation procedures, two simulation models have been developed in the National Institute of Hydrology (N.I.H.), Roorkee. First model [Software for Reservoir Analysis (SRA)] pertains to the simulation of a multi-purpose multi-reservoir system for conservation and flood control purposes while the second model [Simulation of Integrated Network of Channels for Irrigation (SINCHAI)] simulates the operation of a canal system and can be used for real-time operation of canals in irrigation commands is also to be referred to Develop Reservoir Operation Policy of Kolar Reservoir.

3. STUDY AREA AND DATA USED:

The Kolar River is a right bank tributary of the Narmada River. It flows for a total length of 101 km, all of which is in the state of Madhya Pradesh. The Kolar River arises in the Vindhya Range of Sehore district and flows in a southwesterly direction to meet the Narmada at village Neelkanth near Nasrullahganj in the Sehore district of Madhya Pradesh.

3.1 Kolar Basin:

The Kolar River total drainage area is 1,347 km^2, is spread across the two districts. The upper part of the river basin lies at an elevation of 350 to 600 metres, and much of it is under tropical deciduous forest. The river debouches into the plains near Jholiapur. Much of the upper basin has poor soils, and agriculture here is largely of wheat and gram. The lower basin has better soils and a flatter slope and has been extensively bunded, allowing for impounding water during the monsoons.

3.2 Kolar Dam:

Kolar dam is situated near the village Birpur in the district Sehore and at a distance of about 30 KM from Bhopal. Its latitude is 220 -51’-00” N and its longitude is 770 -24’-00’’ E. It is located in the Narmada Basin. The project has an annual irrigation potential of 45040ha, a Cultivable Command Area of 45087 ha, and a Gross Command Area of 62752 ha. It is an earthen embankment dam built across the Kolar River and also provides 61 MCM of water to Bhopal city for drinking purposes, which constitutes about 70% of Bhopal's drinking water, and also provides for irrigation and inland fisheries.

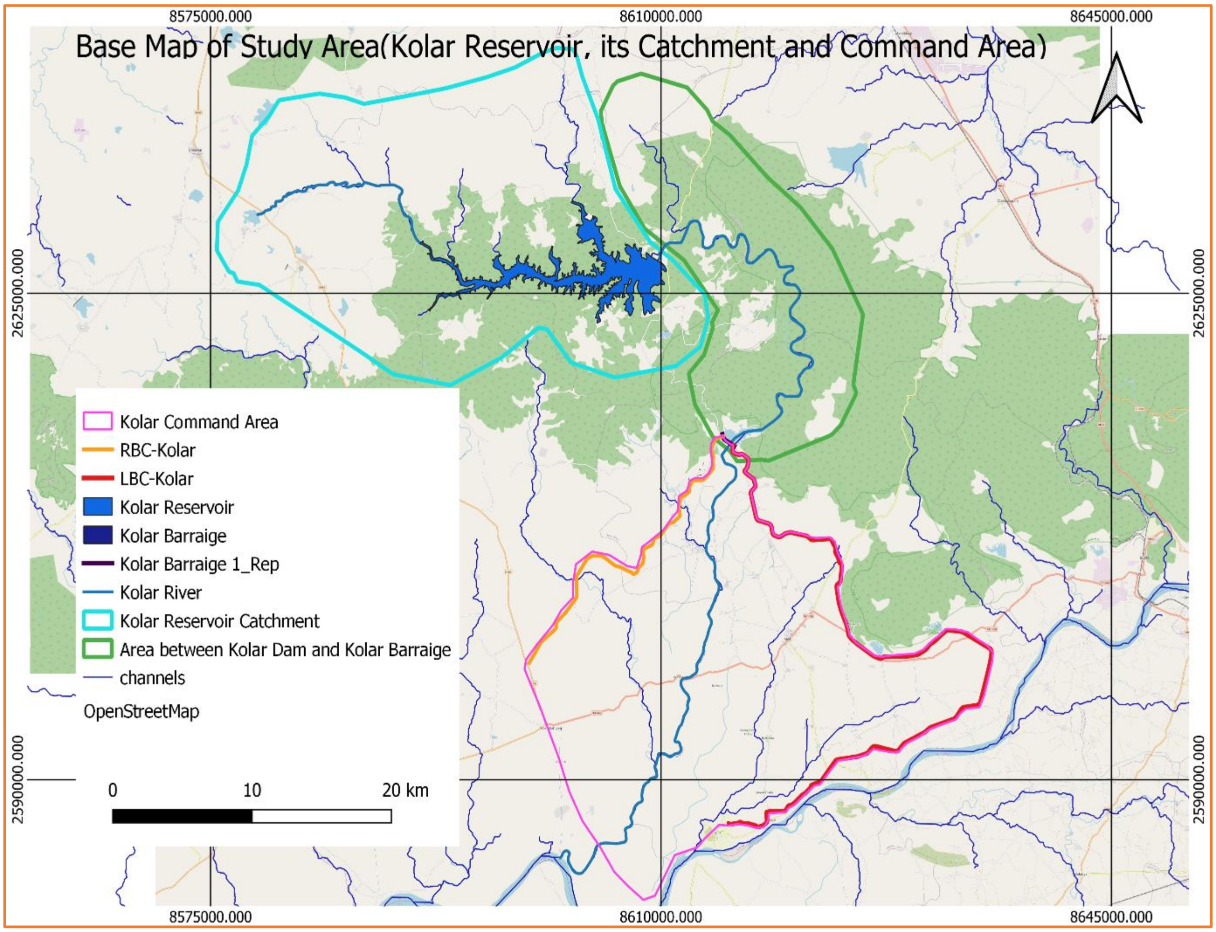


Figure 1. Study Area of Kolar Dam, its Catchment and Command Area.

3.3 Description of the dam:

Kolar dam is a homogeneous earthen embankment dam having a length of 1242m with a maximum height of 45 M with a gross capacity of 270 MCM & live storage of 265 MCM. The length of the concrete spillway at the right flank of the dam is 141 m. Its height up to crest is 14.70 m. 8 radial gates are provided of size 15 (wide) m X 8.5 (high) m for releasing the flood discharge of 8605 cumec. The height of the dam above the deepest foundation level is 45 m. The spillway crest has an ogee shape. A sluice has been provided in the earthen dam at RD 360 m for releasing water to the Public Health Engineering Department for supplying to Bhopal town for drinking purposes. Water for irrigation is released through a spillway in the river itself to the Jholiapur barrage, from where canals start.

3.4 Digital Elevation Model of Study Area:

A Digital Elevation Model (DEM) is a specialized database that represents the surface relief between points of known elevation. By interpolating known elevation data from sources such as ground surveys and photogrammetric data capture, a rectangular grid for the digital elevation model can be created. GIS software can utilize digital elevation models for 3D surface visualization, generating contours, and conducting viewshed visibility analysis.

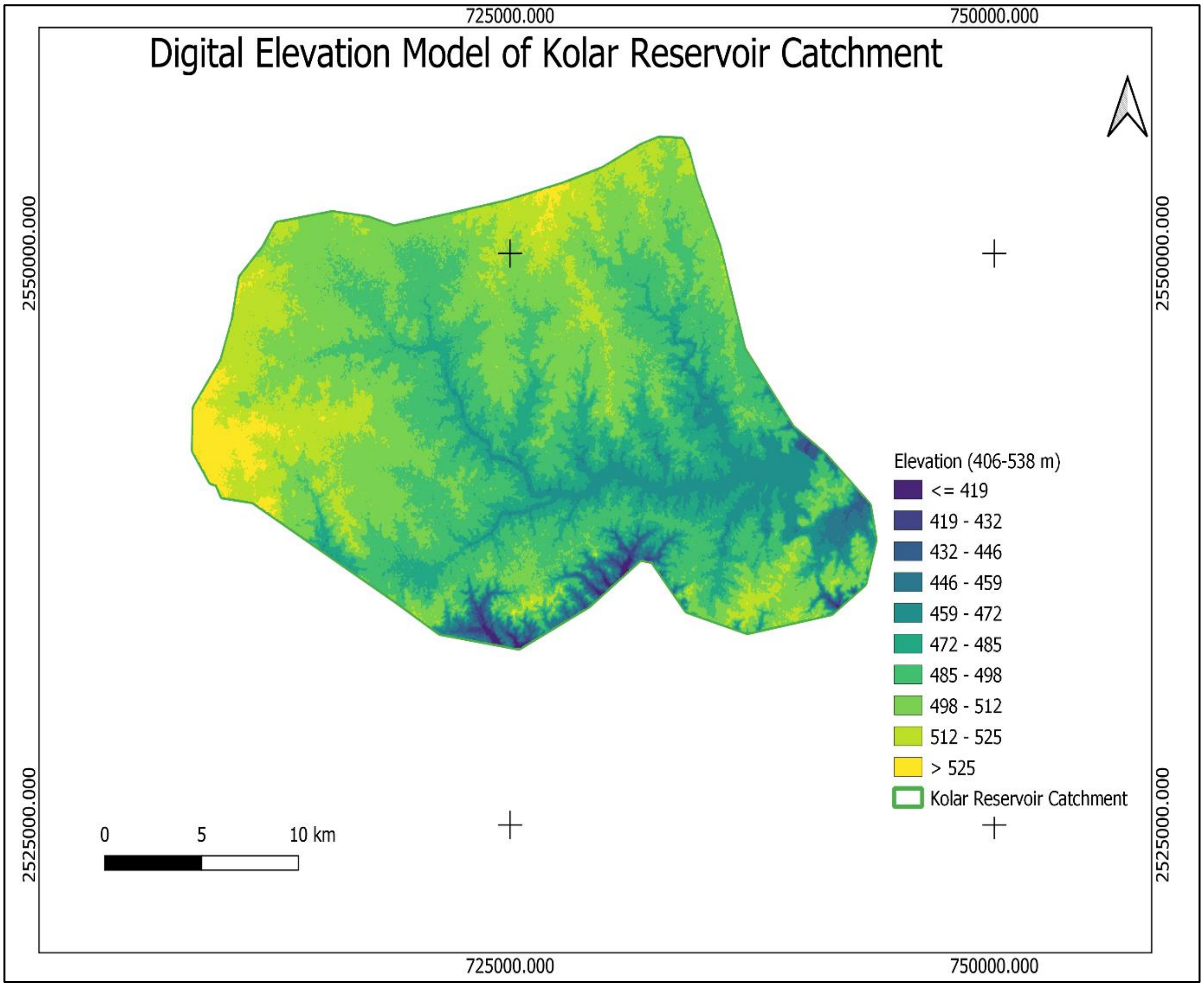


Figure 2. Digital Elevation Model of Kolar Reservoir Catchment (508 Sq.Km)

Digital Elevation Model (DEM) is the digital representation of the land surface elevation concerning any reference datum. DEM is frequently used to refer to any digital representation of a topographic surface. DEMs are used to determine terrain attributes such as elevation at any point, slope, and aspect. Figure 2 shows a DEM of the Kolar catchment, where the lowest elevation of the Kolar catchment is 419 m and the highest elevation is 525 m.

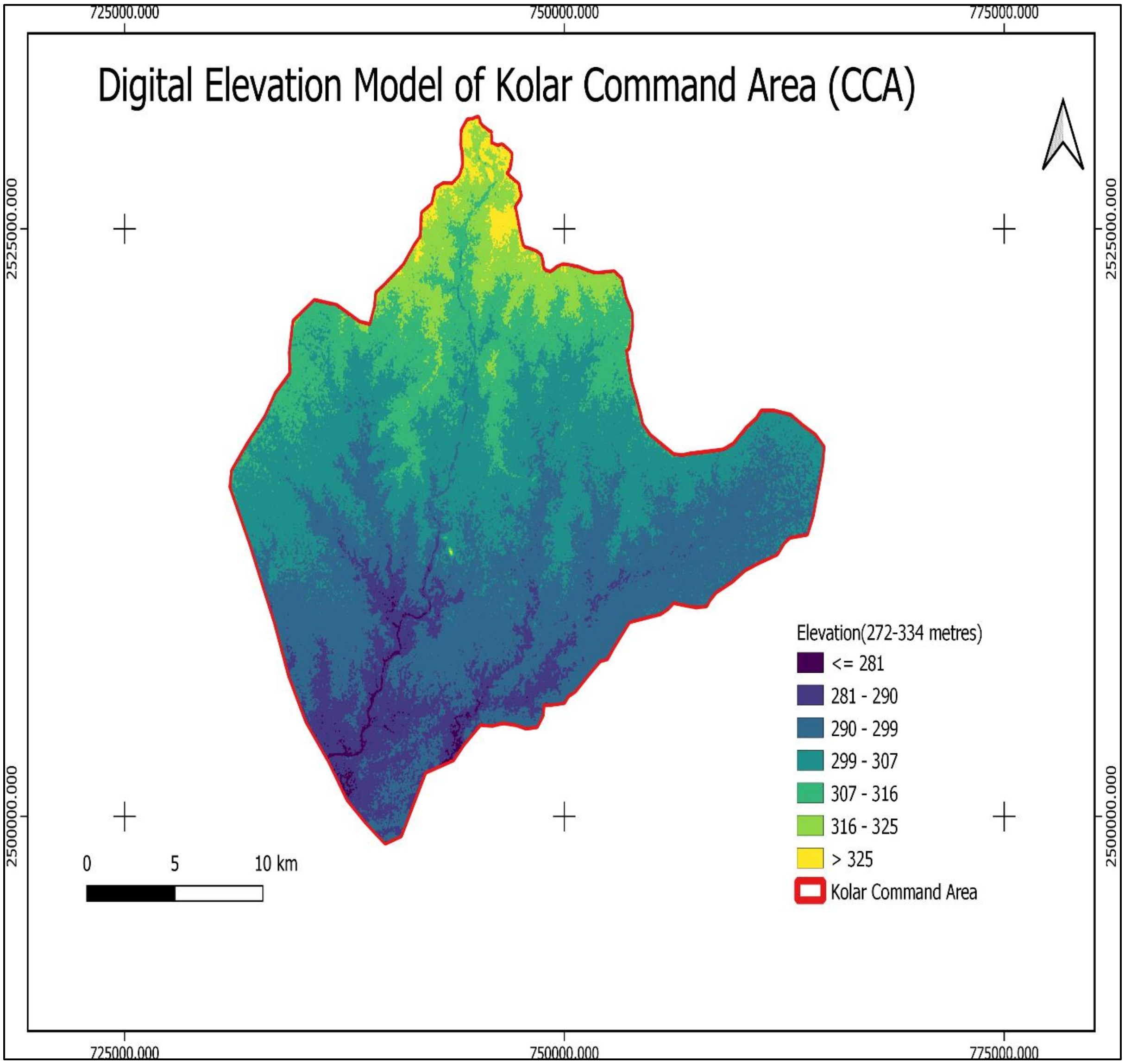


Figure 3. Digital Elevation Model of Kolar Command Area

DEM of Kolar Command area is shown in Figure 3, where the lowest elevation of Kolar Command is 281 m and the highest elevation is 325 m.

3.5 Soil of the study area:

The Soil map of the study area was collected from the National Bureau of Soil Survey and Land Use Planning (ICAR) – Nagpur, and thematic maps of soil were prepared for Kolar catchment and Kolar command area using the details therein, in QGIS 2.6.1. (Figures 4 and 5). The soil map is classified according to three categories based on soil depth, drainage, and erosion into various categories. In terms of depth of soil, it is classified into various categories such as shallow, very shallow, extremely shallow, slightly deep, moderate deep, and deep. In terms of drainage, soil is classified into 2 categories such as well well-drained and moderately well-drained. Based on erosion, the classes are categorized viz gently slope with moderate erosion, moderate erosion, moderate slope with moderate erosion, and severe erosion.

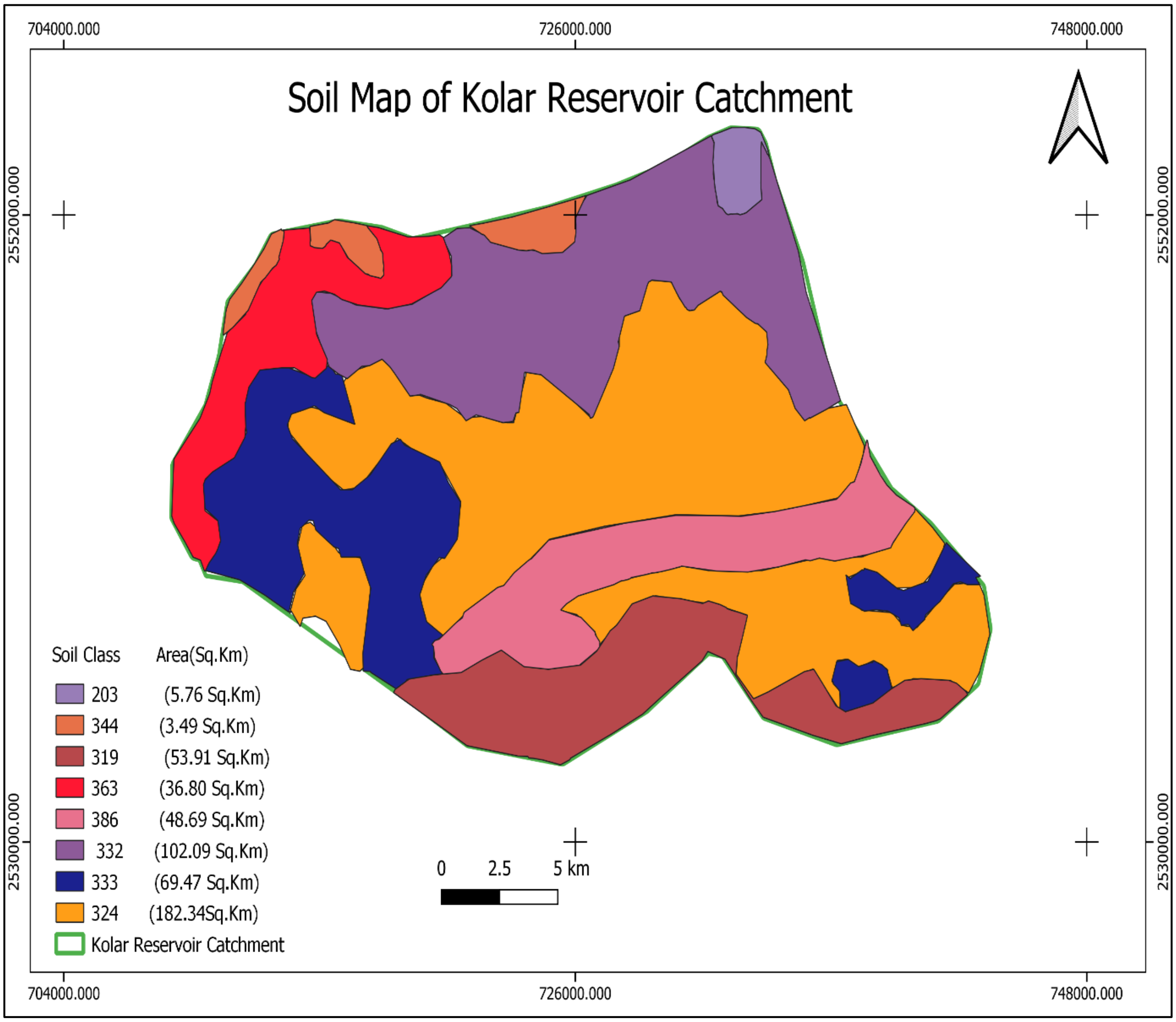


Figure 4. Soil Map of Kolar Reservoir Catchment

Table 1. Soil Classification of Kolar Catchment (NBSS)

Soil Class for Kolar Reservoir Catchment	
Soil-Type	Soil-Classification
324	Very shallow, somewhat excessively drained loamy soil on moderately sloping hilly terrain (highly dissected) with very severe erosion and slightly stony
333	Deep, moderately well-drained calcareous clayey soils on a very gently sloping undulating plateau with moderate erosion.
332	Shallow well well-drained clayey soils on a very gently sloping undulating plateau with moderate erosion and moderately stony
386	Deep, moderately well-drained clayey soils on a very gently sloping undulating plain with moderate erosion
363	Deep, moderately well-drained clayey soils on a very gently sloping plateau, moderately dissected with moderate erosion
319	Very shallow, somewhat excessively drained loamy soil on moderately sloping hills with escarpments, with very severe erosion and slightly stony
344	Extremely shallow, somewhat excessively drained loamy soils on a moderately sloping plateau with severe erosion
203	Shallow well well-drained, clayey soils on very gently sloping hills with escarpments, with severe erosion and moderately stony

In Figure 4. Soil classes are classified into 8 Categories by numbers. The maximum area is covered by 324 (Loamy Soil) in Kolar Catchment, which occupies 36%.

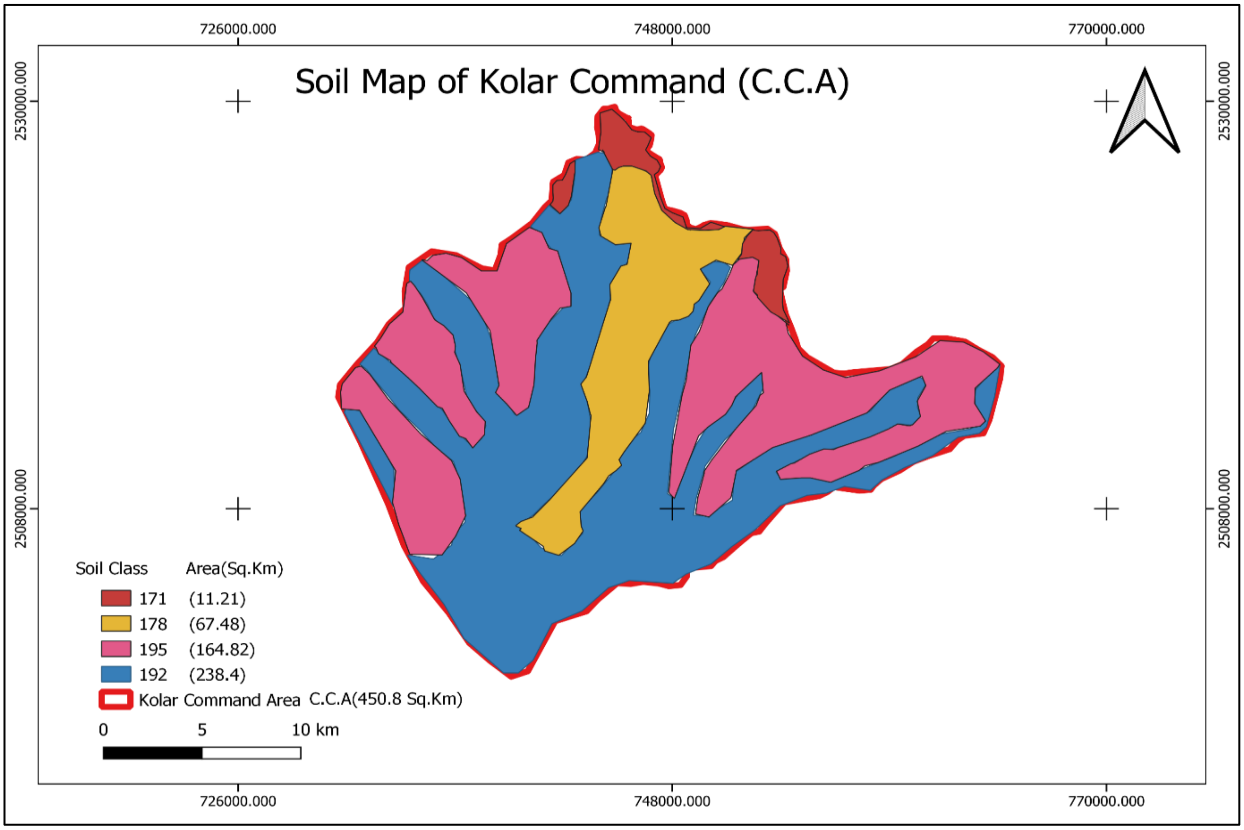
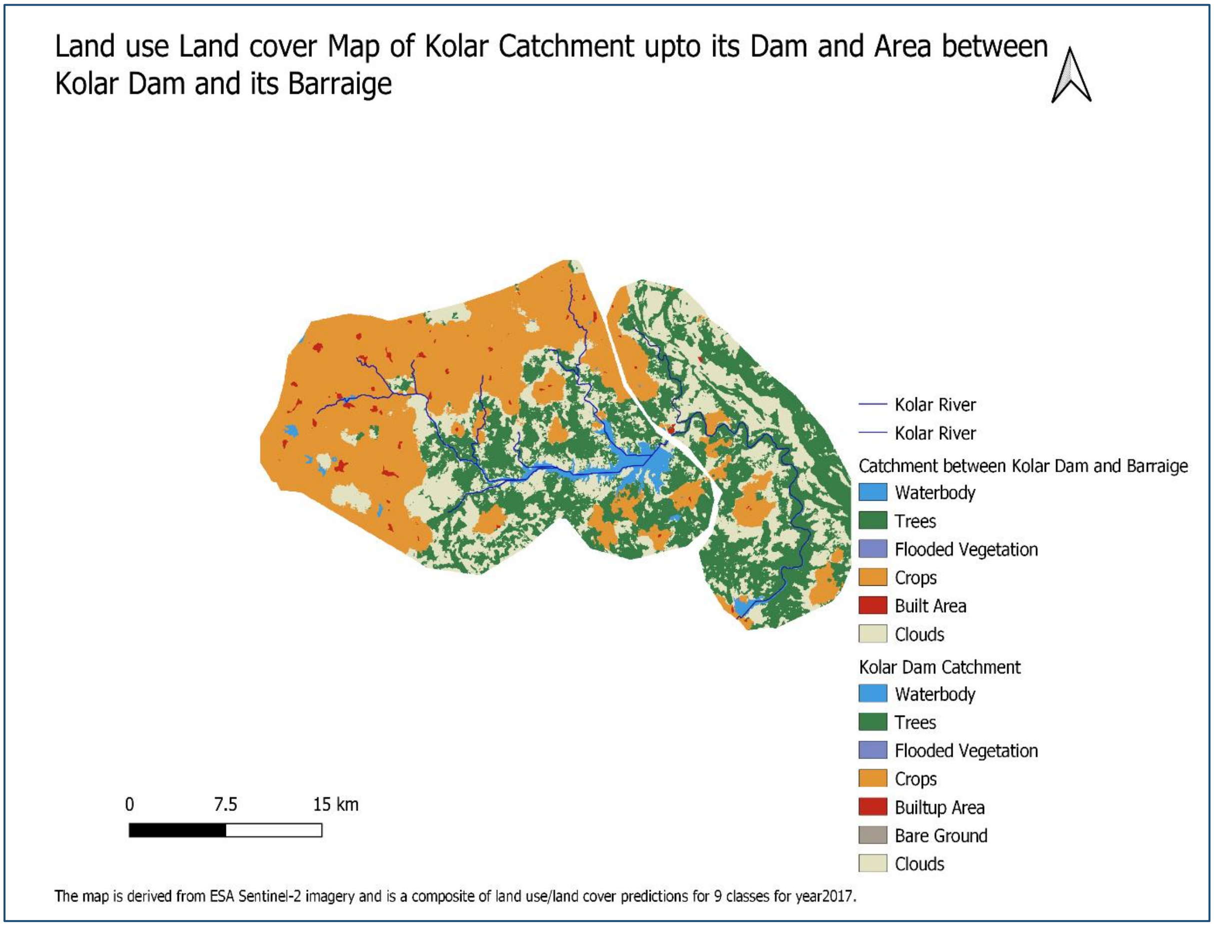


Figure 5. Soil Map of Kolar Command Area.

Table 2. Soil Classification of Kolar Command area (NBSS)

	Soil Class for Kolar Command
Soil-Type	Soil-Classification
192	Clayey Soil (Deep, Moderately well drained, Calcareous, Very Gently Sloping with Moderate Erosion)
195	Clayey Soil (Deep, Moderately well drained, Gently Sloping with Moderate Erosion)
178	Deep, moderately well-drained clayey soils on very gently sloping plain land with moderate erosion
171	Deep, moderately well-drained calcareous clayey soils on very gently sloping undulating plains with moderate erosion

In Figure 5, the maximum area covered by soil (192-Clayey Soil (deep, moderately well drained, calcareous, very gently sloping with moderate erosion) in the command area. This occupies 53% of the total command area.



The map is derived from ESA Sentinel-2 imagery and is a composite of land use/land cover predictions for 9 classes for year2017.

Figure 6. Land Use Cover Map of Kolar Dam Catchment and Catchment between Kolar Dam and Jholiapur Barrage.

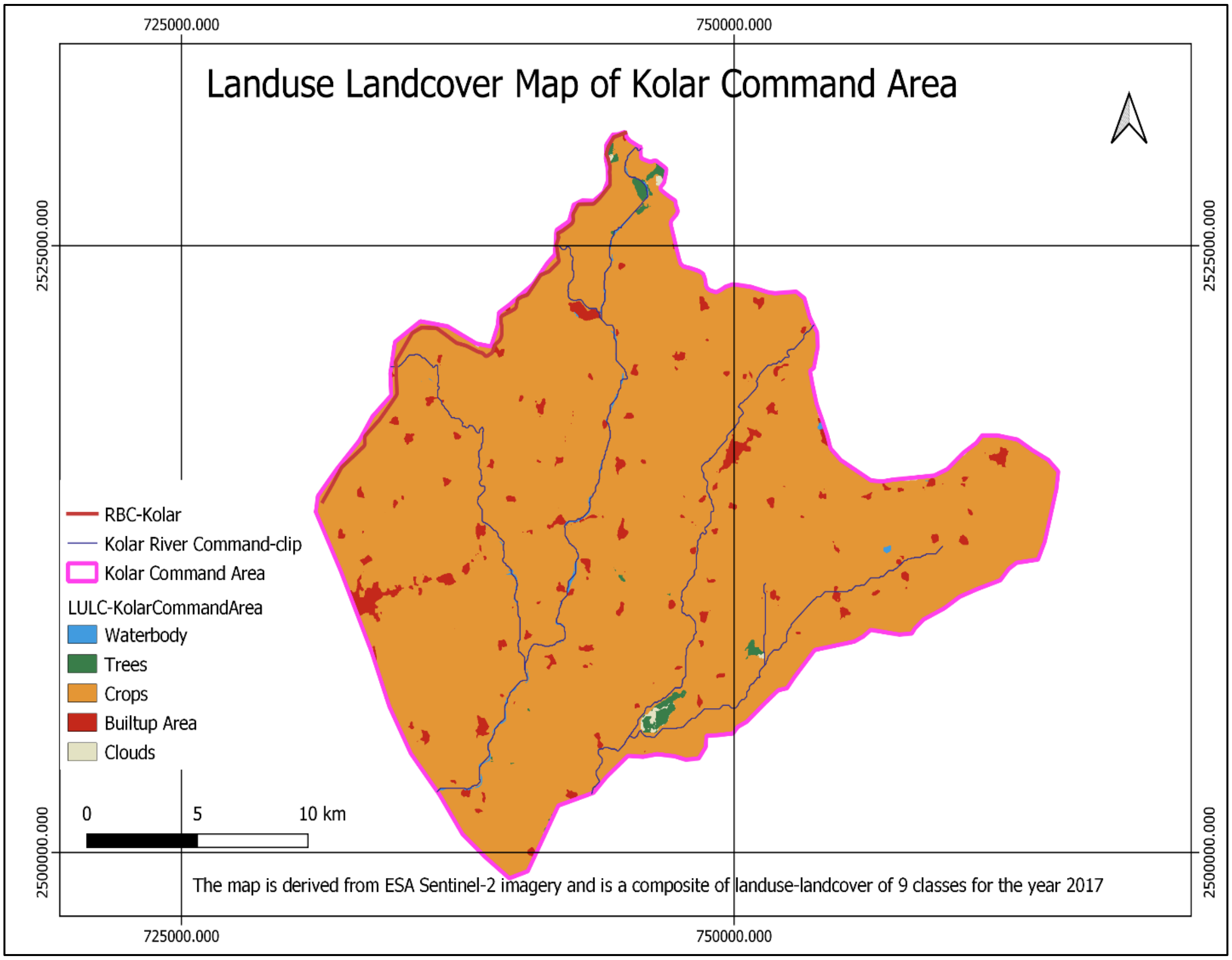


Figure 7. Landuse/Landcover Map of Kolar Command.

4. RAINFALL AND CLIMATE

4.1 Climatology

The Climate of the Sehore district can be divided into four seasons. The winter season commences from the end of November and lasts till the end of February. The period from March to about the middle of June is the hot season. The south west monsoon season from the middle of June to the end of September, October & end of November constitutes the post monsoon or retreating monsoon season.

4.2 Rainfall

There are five rain gauge stations in Sehore district, namely Astha, Ichhawar, Nasrullaganj, Budhni, and Sehore itself. The normal rainfall of Sehore district is 1217.7 mm. The highest rainfall, i.e., 1412.3mm received at Sehore, and the minimum at Astha, i.e., 1054.9 mm. July is the wettest month of the year, and about 36% of the annual rainfall takes place during this month only. About 92.4% of the annual rainfall takes place during the southwest monsoon period, i.e., between June to September. About 6.2% and 1.4% of rainfall was received during winter and summer seasons, respectively. Hence, only 7.6% of the annual rainfall takes place from October to May. `

4.3 Temperature

There is no meteorological observatory in the Sehore district. The nearest meteorological observatory is at Bairagarh, where similar conditions prevail. The winter season starts from the end of November & ends by the last week of February. January is the coldest month of the year. The average normal minimum temperature during the month is about 10.4%. The individual day temperature comes as low as 1 or 20ºC. From March onwards, the temperature starts rising, and the maximum temperature is observed during May. The average normal maximum temperature is 40.70ºC. The individual day temperature can be as high as 45 or 460ºC. On the arrival of the monsoon, the weather became pleasant. In October, with the retreating of the monsoon, the temperature rises slightly during the daytime, and nights become pleasant. The average annual normal temperature of the Sehore district is 31.40ºC. During the southwest monsoon, the relative humidity is generally high, exceeding about 88% in August. Humidity decreases in the post-monsoon season. In the cold season, it is fairly good over the district. The driest part of the year is the summer season, with the humidity going down to 26% or less. The annual normal relative humidity of the district is 57%. Winds are generally light to moderate in the district, with some slight strengthening in force during the monsoon season. The wind velocity in the post-monsoon or during the winter season is, in general, low as compared to the Pre-monsoon or summer season. The normal average and wind velocity of the district is about 8.3 Km/hr.

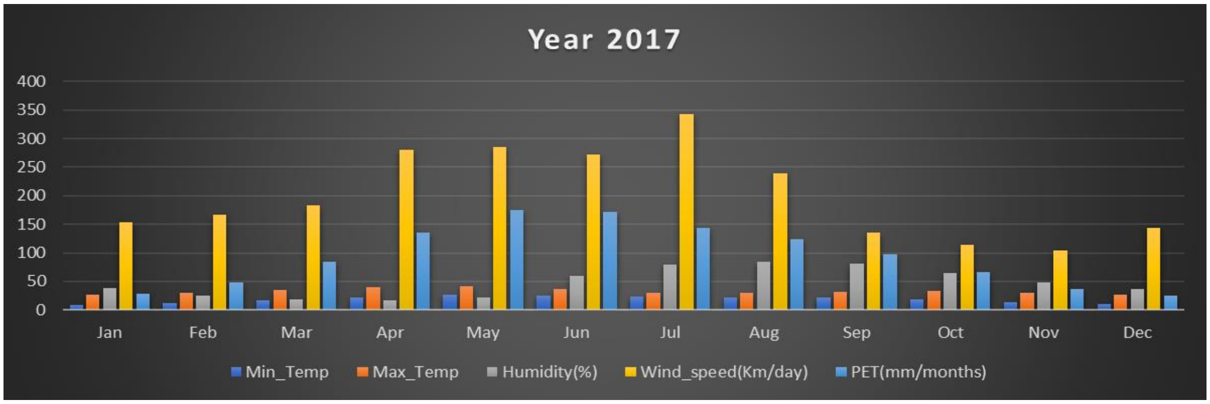


Figure 8. Climate of the study area year 2017

4.4 Geology

Geologically, the entire Kolar basin comprises different lithological formations, which include Deccan trap formations that occupy over 85% of the total area of the district. The general flow is characteristic of lava flows of basalt in the area the most of the flows are of 'Aa' type in nature, being disposed in a three-fold system along a vertical column. Each flow normally consists of an upper fragmentary zone, a middle massive part, and a persistent thin layer of basalt clinkers. The fragmentary top zone presents a brecciated look. It is very often highly vesicular and amygdular. The vesicles are generally sub-rounded to irregular in shape. The middle part comprises massive basalt, which is aphanite to highly porphyritic.

About 12 flows of Deccan trap can be identified in the district between the altitudes 435 and 533 m above MSL. In general, the thickness of the individual flows ranges between 5 and 10m. However, the older flows seem to have more thickness compared to the younger ones, as indicated by flow numbers 0 and 1.

4.5 Description of rocks and their water-bearing properties (Hydrogeology)

The Kolar Basin consists of Deccan trap formations, which also occupy about 85% of the total area of the district. The main aquifer systems in the formation are the weathered, vesicular flow contacts, jointed, fractured zones, etc. The groundwater occurs mainly under phreatic conditions, the red bole horizon generally confined conditions the red bole horizon generally acts as a semi-confining and confining layer in the deep aquifers. The yield of wells in this formation varies from 1 to 5 LPS.

4.6 Irrigation

The project has an annual irrigation potential of 45040ha, a Cultivable Command Area of 45087 ha, and a Gross Command Area of 62752 ha. It is an earthen embankment dam built across the Kolar River and also provides 61 MCM of water to Bhopal city for drinking purposes, which constitutes about 70% of Bhopal's drinking water, and also provides for irrigation and inland fisheries.

4.7 Change in Cropping Pattern

In the last few decades, the cropping pattern in the Sehore district has changed substantially. In some parts of the district, the farmers have started multi-crop cultivation due to profitability, which will cause extensive development of groundwater resources. There is a need to change the cropping pattern in the area and adopt cultivation of those crops that require less irrigation. More water-intensive crops would be sown in the future, looking into the starting trend of multi-crop cultivation by farmers. Therefore crop water requirement of the changed cropping pattern crops sown in the Rabi season has been assessed using Cropwat 8.0. The water-intensive Rabi crops considered for analysis are Spring Wheat, Potato, Small Vegetables, and Pulses.

4.8 Data Collection

Secondary data of the study area includes hydrological information like, reservoir water levels (2009-2024), Reservoir Water level data(yearly-1989-2021), spill discharge, canal releases data (2009-2024), ground water data, meteorological data, dam details, Current operation rules, DPR and other information collected from Kolar Irrigation Project office, Kolar dam control room, and Water Resources Department, Hoshangabad shown in table 3.

Table 3. Details of data collection in the Study Area

Category	Information
Kolar Reservoir data	DPR of Kolar Reservoir, Elevation Area Capacity table for Kolar Reservoir, Elevation Area Capacity table for Kolar Barraige, Monthly Evaporation losses of Sehore District, Yearly Canal releases from RBC and LBC of Kolar Barraige for Irrigation(2009-2020), Reservoir Water level data(2017-2021)-10 daily, Reservoir Water level data(yearly-1989-2021), Canal releases LBC(Monthly,2017-2022), Canal releases RBC(Monthly,2020-2022).
Climate data	Yearly Rainfall data(1989-2021),
GIS data	SRTM data(30m)2020, ESA Sentinel 2 imagery data 2017,2020,2021(10m), LANDSAT8,9 data(2022)
Crop data	Rabi crops data(2020)
Literature	Livestock data (2012), Industrial Demand and Population census (2011)

4.9 Field Visit

Field visits were undertaken as it is important to understand the irrigation mechanism, operational policies, physical status, peculiarities, and associated problems to proceed with the objectives of hydrological modelling of Kolar Catchment, development of reservoir operation policies, and one-to-one discussions with field officers and executives for the collection of relevant information. Various hydrological, meteorological, agricultural, and livestock data were obtained from several field visits to the Kolar Catchment and Command area.

4.10 Physical Characteristics of the Kolar Dam

The data of physical characteristics (Catchment area, spread area, Max Rainfall in the Catchment, River Bed Level, FRL, and Capacity) of Kolar Dam were obtained from the Kolar Irrigation Project office, and Kolar Dam Control room is shown in Table 4.

Table 4. Physical Characteristics of the Kolar Dam.

S.No.	**Hydrology and Reservoir Data**	
1.	Catchment Area up to the Dam site	508 Km^2
2.	Max Rainfall in the Catchment	1230.50 mm
3.	Spread area at FRL	270 Msqm
4.	River Bed Level	429.30 m
5.	Minimum Drawdown Level	432.93m
6.	Full Reservoir Level	462.20 m
7.	Gross Capacity at FRL	270Mm^3
8.	Live Capacity at FRL	265Mm^3

By the system is 61 M Cum to provide for 70% of Bhopal drinking purposes. The rainfall data for 2 major rain gauge stations, namely Birpur and Brijeshpur, are being used for average annual rainfall calculations. The average annual rainfall values are available from 2009-2024. The daily and monthly inflow values were estimated from the water balance of Kolar Reservoir for 2009-2024(15 years).

Figure 9. Field visit to Kolar Dam and Kolar Irrigation Project office, Birpur Village.

Latest Design Inflow Flood and Flood Routing Studies:

In terms of the Indian Standard IS 11223:1985 classification criteria, Kolar Dam is classified as a "Large Dam" and, therefore, qualifies for PMF (Probable Maximum Flood) as the design flood. The design flood studies submitted to CWC and PMF, examined for the project by the Hydrology (DSR) Directorate, CWC, are 8605 cumec, for which the project was designed is found to be safe, and there is no need for revision. Flood routing studies were carried out by the State DSO. (O&M Manual Kolar Dam)

4.11 Target Demands from the Dam

The Kolar reservoir project is mainly operated to meet the irrigation demands of LBC and RBC, and the drinking water supply demands for the city. This reservoir is not operated for flood control. There is no power generation from the reservoir. Various demands that are met from the reservoir are detailed in the following section.

a) **Water Supply Demands for Domestic Purposes**

Kolar reservoir is an important source of potable water supply for the city. As per an agreement with the Water Resources Department, 61 MCM is reserved for drinking water supplies, which constitute about 70% of Bhopal's drinking water supply and have been considered for developing the operating policy of the reservoir.

b) **Irrigation Use Demands**

The Kolar reservoir is constructed to provide irrigation through its Left Bank Canal and Right Bank Canal Systems. The gross command area, cultivable command area, and irrigated command area under LBC and RBC combined are 62752 ha, 45040 ha, and 35040 ha, respectively. The annual irrigation demands on an average to be met by the LBC and RBC are 66 M Cum and 61 M Cum respectively. The command area lies in the Sehore district of Madhya Pradesh. The 75% dependable yield at dam site is 194.65 M Cum and balance available for use at Dam site is 194.65 M Cum (EAP, 2021).

5. METHODOLOGY

5.1 Crop Water Requirement and Irrigation Scheduling of Rabi crops cultivated in Kolar Command area.

5.1.1 Data collection and software used

Four types of data are required for using the CROPWAT software, namely, rainfall data, climatic data, soil data, and crop data (Muñoz, G.; Grieser, J., 2006). Climatic data for thirty years (1970–2000) were gathered for the Sehore and Hoshangabad Meteorological Station (Table 5), obtained from the CLIMWAT 2.0 which is a climatic database to be used in association with the CROPWAT program and which allows the calculation of IRs for different crops for a range of climatological stations around the world (www.fao.org) as well as Rainfall, Temperature(min and max), Relative Humidity, Wind Speed, Sunshine hours were downloaded from IMD, Pune. The river drainage network and topographic, land use/cover data, and soil map were developed using ArcGIS 10.4 software. The soil type existing in the Kolar command area is clayey soil and calcareous, with moderate erosion.

Table 5. Climate characteristics, rainfalls, and ET0 of Kolar area (average for 1970–2000 period) obtained using the CLIMWAT tool attached to the CROPWAT software

Months	**Min Temp (^{0}C)**	**Max Temp (^{0}C)**	**Humidity**	**Wind**	**Sun**	**Rad**	**ET**	**Rain**	**Eff rain**
			%	**Km/ day**	**hours**	**MJ/m^2/ day**	**mm/ day**	**mm**	**mm**
January	12.7	26.6	47	69	7.8	15.5	2.7	14	13.7
February	14.3	29.8	34	69	8.6	18.5	3.38	6	5.9
March	18.6	34.9	24	78	8.8	21	4.43	8	7.9
April	23.5	39.3	19	86	8.8	22.7	5.43	2	2
May	27.6	42	22	104	9	23.4	6.48	6	5.9
June	26.6	37.6	47	121	6.6	19.9	5.86	122	98.2
July	24	30.2	80	104	4	15.8	3.76	429	167.9
August	23.5	29.2	83	86	3.9	15.3	3.37	390	164
September	23.2	30.7	76	78	5.6	16.9	3.7	240	147.8
October	19.5	32.1	57	52	8	18.3	3.71	25	24
November	14.5	29.3	47	52	8.4	16.6	2.97	10	9.8
December	12.3	27.1	47	61	7.8	15	2.56	9	8.9
Average	**20**	**32.4**	**48**	**80**	**7.3**	**18.3**	**4.03**	**1261**	**656.1**

5.1.2 Crop data

Crop data were collected from the agriculture department, Nashrullaganj, for the years 2016, 2017, and 2018. Based on the above crop data, the cropping pattern and their respective coverage were determined; the major cultivated crops in the study area in the Rabi season were Wheat, Gram, and Mustard. Crop coefficient values (Kc) were taken from available published data for initial, mid, and late growth stages.

The FAO CROPWAT 8.0 model yielded soil metrics such as total available moisture content, initial moisture depletion, maximum rain infiltration rate, and maximum rooting depth, which provide precise information on the soil near the climatic station. The soil conservation (S.C.) approach of the United States Department of Agriculture (USDA) was employed in this investigation. (FAO, 2018)

5.1.3 Estimating reference evapotranspiration

Cropwat 8.0 software was used for estimating reference evapotranspiration by the FAO Penman-Monteith method from meteorological data.

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1)$$

where, ETo: reference crop evapotranspiration, mm/d; *Rn*: net radiation at the crop surface, MJ/(m^2·d); *G*: soilheat flux, MJ/(m^2·d); *T*: average air temperature,^{0}C; *U*2: wind speed measured at 2 m height, m/s; es =Saturation vapour pressure [kPa], ea =Actual vapour pressure [kPa], (e_a–e_d): vapor pressure deficit, kPa; Δ: slope of the vapour pressure curve, kPa/^{o}C; γ: psychrometric constant, kPa/^{0}C;900: conversion factor.

5.1.4 Crop Coefficient

The crop coefficient (Kc) value for any particular crop is of utmost importance for estimating the crop water requirement. Based on this, suitable irrigation planning is adopted to render the impact resulted due to water stress conditions. Kc values for different crops are different and vary with crop growth stages, as shown in Figure 10.

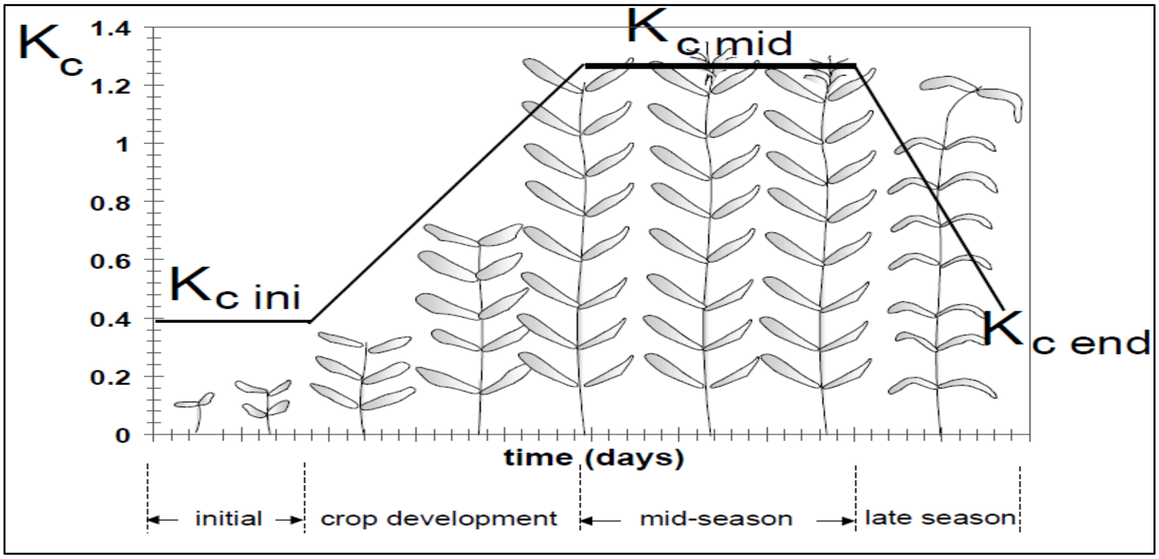


Figure 10. The variation in Kc for crops as influenced by weather factors and crop development (Pereira, 2015)

The crop coefficient value is affected by various parameters, mainly crop characteristics, crop planting or sowing date, rate of crop development, length of growing season, and climatic conditions, and by different stages of growth.

The Kc_{ini} value given in FAO-56 was used as such, and no correction was applied due to the unavailability of data like the time interval between wetting events of soil and the magnitude of wetting events. Crop coefficient (Kc) values for the developmental stage and late season stage for each of the crops were calculated by linear interpolation. The Kc_{mid} and Kc_{end} values were corrected by using the given formula(Allen et al., 2005)

5.1.5 Crop evapotranspiration (ETc) or Crop Water Requirement

The crop water requirement is the amount of water equal to what is lost from a cropped field by the ET and is expressed by the rate of ET in mm/day (Ewaid et al., 2019). ETo is multiplied by an empirical crop coefficient (Kc) to produce an estimate of crop evapotranspiration (ETc) or CWR.

$$ETc = Kc \cdot ETo \qquad (2)$$

Where, ETc is a crop evapotranspiration; Kc is a crop coefficient; ETo is a reference crop evapotranspiration.

5.2 Methodology and Data Collection for Trend Analysis of Hydro-meteorological Parameters

The non-parametric Mann-Kendall (MK) trend test and Sen’s slope estimate were employed to find the existence of rainfall and temperature trends, and their significance level in the Kolar basin. Gridded Rainfall and Temperature datasets were downloaded from the Indian Meteorological Department, Pune, for the Kolar basin from 1981-2022 (42 years) at a resolution of $0.25^{o} \times 0.25^{o}$ and 1990-2022 (33 Years) at a resolution of $1^{o} \times 1^{o,}$ respectively. Rainfall and Temperature trends are analyzed for 42 and 33 years, respectively. The statistical significance of the seasonal distributions is analyzed using the Mann-Kendall (MK) Test (Mann, 1945; Kendall, 1948), while the magnitude of the seasonal time series is determined through the nonparametric method, Sen's estimator (Sen, 1968).

5.3 Rainfall-Runoff relationship for assessment of water availability

Rainfall-runoff relationships refer to the relationship between the amount of rainfall that occurs in a particular area and the resulting runoff that occurs as a consequence of this rainfall. It helps in understanding how rainfall contributes to the flow of water in rivers, streams, and other water bodies. Through the analysis of historical data of rainfall and runoff for the period from 2010 to 2023 in the Kolar basin, and by studying the patterns and characteristics of rainfall events and the corresponding runoff derivation equations are generated in Excel to estimate the expected runoff for a given amount of rainfall. Rainfall-runoff relationship has been derived using the historical data of rainfall and runoff for the period from 2010 to 2023. Based on the historical derivation of the rainfall-runoff relationship 5%, 10% increase in rainfall and its corresponding runoff is derived as a future scenario for 25 years, i.e, 2025 to 2050. Hence, from the historical datasets (2010-2023) for the present average annual rainfall and its corresponding runoff (i.e, inflow to the Kolar reservoir) is calculated to be 641.1 MCM and 240.62 MCM, respectively. Similarly, for a 5%, 10% increase in rainfall, i.e, 673.15 and 705.21 MCM, its corresponding runoff is calculated to be 252.43 MCM and 264.45 MCM, respectively. Therefore, for future scenarios of 5% and 10% increase in rainfall, their corresponding runoff, i.e, inflow to the Kolar Reservoir, is derived for the future period of 25 years, i.e, 2025 to 2050-2060.

5.4 Method used in Estimation of Water Balance of Kolar Reservoir

The water balance equation is a basic formula to quantitatively study hydrology and water resources. (Vörösmarty et al., 1998; Li &Wang, 2012).

This study used a water balance equation to calculate the variability of inflow available for Kolar Dam, such that Inflow to the dam –Outflow from the dam = Rise in the water surface of the dam, which is an increase in the storage of the dam in a time interval (Dawidek & Ferencz, 2014).

The water balance of a large reservoir, *RL*, was calculated on a 1-day basis for years 2009-2024 according to the equation given below:

$$V = V_{t-1} + Q_{in} - Q_{out} - U_{RL} + (P-E-S) * A_{RL}$$

Where *Vt* is the reservoir storage volume (m3) at day *t*, (10-daily), *Q*in is the inflow from all other upstream sub-basins via the river network, *Q*out is the outflow from the large reservoir, *URL* is water withdrawal (all variables in m3), *P*, *E* (m) S (m) are precipitation to and evaporation, seepage from the reservoir water surface, *ARL* (m2) –Area. The value of *E* was calculated with the Penman-Monteith approach (Shuttleworth, 1992). Losses by seepage into the bedrock were not accounted for because no information on their magnitude was available. The outflow, *Q*out, is composed of (a) uncontrolled outflow over the spillway if *V*max is exceeded by storage plus inflow and (b) controlled outflow by reservoir operation, *Q*control. Exact operation rules for reservoir outflow as a function of actual storage volume and water demand were not available. Instead, simple rules summarizing the common practice of reservoir management in the study area were applied. 1- Daily reservoir water levels were obtained for the years 2009-2024.

5.5 Methodology for Reservoir operation for optimal utilization of water resources

The National Institute of Hydrology (NIH), Roorkee developed a generalized software named "SRA – Software for Reservoir Analysis" for reservoir analysis for carrying out various kind of reservoir analysis such as capacity computation, storage yield analysis, hydropower simulation, reservoir routing, elevation-area-capacity (EAC) interpolation, inflow estimation using rate of rise method, initial rule curve derivation, and operation of a system of multiple reservoirs for conservation purposes. Subsequently, a GUI, named "NIH_ReSyP – Reservoir Systems Package", has been developed in the Visual BASIC platform to provide a user-friendly environment for carrying out various hydrological analyses related to reservoirs (Goel M.K, 2018). In this study NIH_ReSyP 2018 Software is used for the development of reservoir operation policy. The main module used is "Conservation Operation," which entails the following submodules:

(i) Probable Flow Estimation

(ii) Initial Rule Curve Derivation

(iii) Conservation Operation

5.5.1 Probable Flow Estimation

Derivation of initial rule curves for a reservoir requires probable inflows corresponding to different reliabilities (say 50%, 75%, and 90%) for different months. This module is used to compute the probable monthly inflow values using a statistical approach. The computations are made with the original data series as per rank analysis, log-transformed series, and power-transformed series. The input data for this module includes the long-term inflow series for the month under consideration, and the output is the probable flow values in the month corresponding to six specified reliability levels. In this study, a power-transformed series of reliable flows is used.

5.5.2 Initial Rule Curve Derivation

A rule curve or a rule level specifies the storage or space to be maintained in a reservoir during different times of the year, assuming that a reservoir can best satisfy its purposes if the storage specified by the rule curve is maintained at different times. This module computes the initial rule curve levels for various purposes (irrigation, hydropower, domestic supply, etc.), which are specified in the operation analysis of a reservoir and which are fine-tuned for deriving optimum operation policy. The computations for deriving various rule curve levels are made using the monthly inflow series for different probability levels (computed in the module under section 5.5.1) along with the average monthly demands. In India, the reservoirs are constructed to serve conservation purposes like water supply for domestic and industrial use, irrigation, hydropower generation, and minimum downstream flow requirements. Kolar reservoir mainly caters to conservation purposes like water supply for domestic and industrial use, irrigation, whereas hydropower generation is incidental. Therefore, in this study present module, a provision has been made to derive three rule curves: a) Upper rule curve, b) Rule curve for Irrigation, c) Rule curve for Water supply. The upper rule level represents a level in the reservoir such that if it is maintained throughout the year, all the demands can be met in full. The rule curve for irrigation/hydropower is calculated for the case when water is scarce in the reservoir and it is not possible to meet all the demands in full throughout the year. Rule curve for domestic supply is calculated for the case when the scarcity of water is so severe that even after cutting supply for other lesser priority 51 demands (say, irrigation and hydropower), the supply for meeting full domestic water demands can hardly be made throughout the year. Using these initial trial rule curve levels, a number of simulation runs are taken for a reservoir to evaluate the performance of the reservoir if it is operated by these trial rule curve levels. Based on the results of the simulation, the rule curves are modified till optimum operation is achieved. Input data requirement of this module includes general details of the reservoir such as FRL, DSL, EAC table, normal monthly evaporation depths, target monthly demands for different purposes, monthly inflow sequence corresponding to different reliabilities, and hydropower details (if any) such as capacity of power plant, tail water level, minimum level for power generation, and efficiency of plants.

5.5.3 Conservation Operation

This module is used to simulate the operation of a multi-purpose multi-reservoir system for conservation operation. The various conservation purposes considered in the module include water supply for domestic and industrial purposes, irrigation, hydropower generation, and minimum flow in the downstream river reach. The highest priority is given to the water supply demand for domestic and industrial purposes, and the minimum downstream flow demands, while priority between hydropower and irrigation is user-specified and may change from one period to another. The model can simulate the operation of a system either for monthly operation or for ten-day operation. For each period (monthly/ten-daily), total water demands and availability at each hydraulic structure are computed. The amount of water required for hydropower depends on the available head of water, which keeps changing. This amount is calculated based on the mean elevation of water during a period. The release policy for meeting various demands depends on the specified operation policy (in terms of rule curve levels for various purposes derived using the initial rule curve derivation module). Four rule curve levels, namely, the upper rule level, the first middle rule level, the second middle rule level (applicable if hydropower is also a demand in addition to the irrigation and domestic supply demand) and the lower rule level need to be specified for all the periods (monthly/ten-daily). If the reservoir level rises above the upper rule curve level in any month, the extra water is spilled, and the reservoir is brought back to the upper rule curve level. Above the middle rule curve levels, full demands are met for all purposes during a period. If the reservoir level falls below middle rule curve levels, supply for lower priority demands is curtailed by a specified percent to meet reduced demands for the full water year. If the reservoir reduces below the lower rule curve level, supply for lower priority demands is stopped, and supply is made only for domestic demands and minimum flow requirements. The data requirements of the model are quite modest, and such types of data are generally available with the operating authorities at the dam sites. Some data pertain to the information about each structure viz. full reservoir level, dead storage level, elevation-area-capacity table, various conservation demands from the reservoir like water supply for domestic and industrial purposes, irrigation, hydropower demands and minimum flow requirements in the downstream channel, evaporation depths and local inflow from the intermediate/free catchment area. The model operates each storage reservoir in the system in accordance with the given trial rule curves. Each diversion structure is operated by the inflow availability and diversion demands. Based on the trial rule curve levels, it calculates the monthly time and volume reliability for each structure. In addition, it also calculates the total number of failure months, irrigation or power failure, and water supply failure. It also calculates the number of months when the release from the reservoir is less than a specified percentage of the total demands and thus calculates the "Critical Failure" months. In addition to calculating the reliability, a detailed operation table for each structure is optionally prepared. For each period, the table gives the year, month and period of operation, the initial storage, flow from upstream structure (if any), flow from intermediate catchment, evaporation, irrigation demand, water supply demand, hydropower and downstream demands, actual release made for these demands, level of failure (if any), power generated, spill from the structure, and end level. Based on the observations from the tabular presentation, rule curve levels can be fine-tuned till the best operation performance is achieved. It is also possible to simulate scenarios for inter-basin water transfer or water transfer among various hydraulic structures within the system.

6. RESULT AND DISCUSSION

6.1 Crop Water Requirement and Irrigation Scheduling of Rabi Crops using CROPWAT 8.0 Model in Kolar Command Area

The CROPWAT 8.0 was used for irrigation and crop water requirement for the Rabi season for 2017-18. Effective rainfall was estimated as 52.03% of the rainfall, i.e, 656.1 mm per annum out of the total average annual rainfall of 1261 mm for the Kolar River basin. Table 6 shows that the average monthly rainfall with maximum effective rainfall occurred in July (167.9mm), followed by August (164mm), September (147.8 mm), and June (98.2 mm).

Table 6. Climate characteristics, rainfalls, and ET0 of Kolar area (average for 1970–2000 period) obtained using the CLIMWAT tool attached to the CROPWAT software

Months	**Min Temp (^{0}C)**	**Max Temp (^{0}C)**	**Humidity**	**Wind**	**Sun**	**Rad**	**ET**	**Rain**	**Eff rain**
			%	**Km/ day**	**hours**	**MJ/m^2/ day**	**mm/ day**	**mm**	**mm**
January	12.7	26.6	47	69	7.8	15.5	2.7	14	13.7
February	14.3	29.8	34	69	8.6	18.5	3.38	6	5.9
March	18.6	34.9	24	78	8.8	21	4.43	8	7.9
April	23.5	39.3	19	86	8.8	22.7	5.43	2	2
May	27.6	42	22	104	9	23.4	6.48	6	5.9
June	26.6	37.6	47	121	6.6	19.9	5.86	122	98.2
July	24	30.2	80	104	4	15.8	3.76	429	167.9
August	23.5	29.2	83	86	3.9	15.3	3.37	390	164
September	23.2	30.7	76	78	5.6	16.9	3.7	240	147.8
October	19.5	32.1	57	52	8	18.3	3.71	25	24
November	14.5	29.3	47	52	8.4	16.6	2.97	10	9.8

December	12.3	27.1	47	61	7.8	15	2.56	9	8.9
Average	**20**	**32.4**	**48**	**80**	**7.3**	**18.3**	**4.03**	**1261**	**656.1**

6.2 Calculation of Reference Evapotranspiration and Effective Rainfall Estimation

Transpiration (water lost from the plant surface) and evaporation (water lost from the soil surface) occur at the same time and, when combined, are referred to as evapotranspiration (ET). The rate of ET from a hypothetical crop with a height of 0.12 m, albedo (0.23), and fixed canopy resistance (70 sm−1) is called the reference evapotranspiration. (Allen et al., 1998)

The Kolar Command mean annual reference evapotranspiration (ET_0) is estimated at 4.03 mm/day. Table 6 shows the Monthly Climate/ET_0 of the Kolar Command Area. Results of the study show that the average peak monthly ET_0 was observed to be 6.68 mm/day in May and followed by 5.43 mm/day in April due to the high temperatures during the months. Whereas, average minimum ET_0 were observed as 2.56 and 2.7 mm/day in the months of December and January, respectively, due to the cool winter months (Table 6)**.**

6.3 Calculation of Actual Evapotranspiration (ETc)

The crop evapotranspiration (ETc) for Rabi crops sown in Kolar Command Area are as follows: wheat is 325.2 mm/season, gram is 254.4 mm/season, mustard is 249.1 mm/season, and pulses are 263.2 mm/season (season-1 year) respectively (Fig. 11).

The crop water need is the amount (or depth) of water that equals the water loss by ET. Crops have different water requirements depending upon the place, climate, soil type, cultivation method, effective rain, etc., and the total water required for crop growth is not equally distributed over its whole life span (P.V.Azevedo, et al., 2007) The irrigation water requirements (IRs) for the four crops included in this study are in the following order according to the (mm/season) unit for Kolar Command Area as shown in table 7 to10.

Kolar Command Area-Wheat (286.9) > Pulses (other crops) (229.2) > Gram (214.9) > Mustard (211)

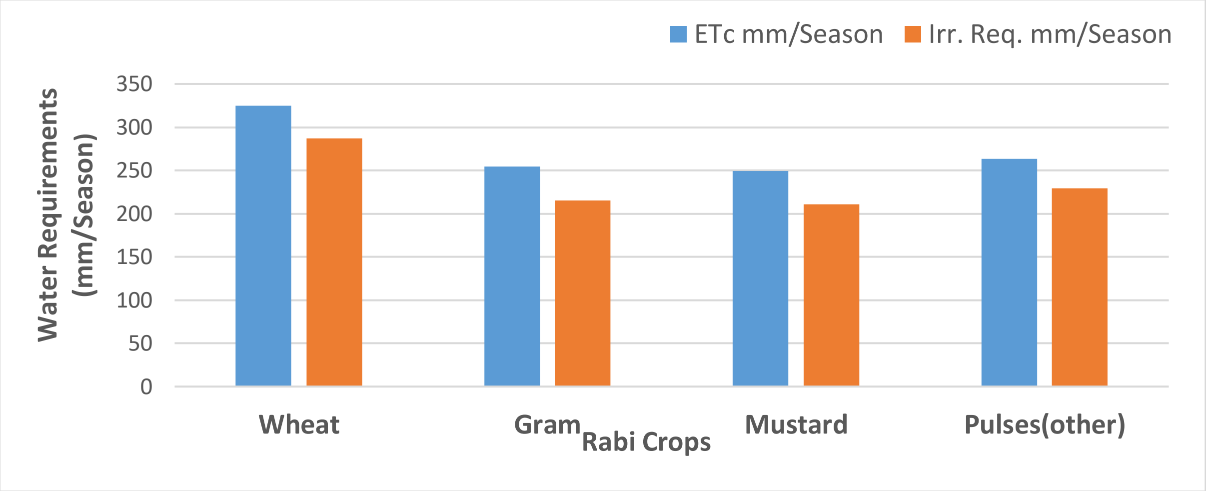


Figure 11. Crop Evapotranspiration and Irrigation Requirements of Rabi Crops/Season in Kolar Command Area.

Table 7. Crop Water Requirement for Wheat (Rabi)

Wheat crop water requirement and Net Irrigation Required							
Month	**Decade**	**Stage**	**Kc**	**ETc**	**ETc**	**Eff rain**	**Irr. Req.**
			coeff	**mm/day**	**mm/dec**	**mm/dec**	**mm/dec**
Nov	2	Init	0.44	1.31	7.8	1.6	6.5
Nov	3	Init	0.44	1.25	12.5	2.8	9.7
Dec	1	Deve	0.46	1.24	12.4	2.9	9.5
Dec	2	Deve	0.7	1.8	18	2.7	15.3
Dec	3	Mid	1.02	2.67	29.3	3.3	26
Jan	1	Mid	1.13	2.98	29.8	4.4	25.4
Jan	2	Mid	1.13	3.04	30.4	5.1	25.2
Jan	3	Mid	1.13	3.29	36.2	4.1	32.2
Feb	1	Late	1.12	3.53	35.3	2.6	32.8
Feb	2	Late	1	3.38	33.8	1.6	32.2
Feb	3	Late	0.85	3.17	25.4	1.9	23.4
Mar	1	Late	0.7	2.86	28.6	2.6	25.9
Mar	2	Late	0.53	2.36	23.6	3	20.6
Mar	3	Late	0.44	2.1	2.1	0.2	2.1
					325.2	38.8	**286.9**

Table 8. Crop Water Requirement for Gram (Rabi)

	Gram Crop Water Requirement and Net Irrigation Requirement						
Month	**Decade**	**Stage**	**Kc**	**ETc**	**ETc**	**Eff rain**	**Irr. Req.**
			coeff	**mm/day**	**mm/dec**	**mm/dec**	**mm/dec**

Oct	1	Init	0.4	1.48	1.5	1.8	1.5
Oct	2	Init	0.4	1.48	14.8	2.8	12
Oct	3	Init	0.4	1.38	15.2	3	12.3
Nov	1	Deve	0.46	1.47	14.7	4.5	10.2
Nov	2	Deve	0.65	1.94	19.4	2.7	16.7
Nov	3	Deve	0.85	2.42	24.2	2.8	21.4
Dec	1	Mid	1	2.7	27	2.9	24.1
Dec	2	Mid	1.01	2.57	25.7	2.7	23
Dec	3	Mid	1.01	2.62	28.8	3.3	25.5
Jan	1	Late	1	2.64	26.4	4.4	22
Jan	2	Late	0.88	2.37	23.7	5.1	18.6
Jan	3	Late	0.72	2.12	23.3	4.1	19.2
Feb	1	Late	0.6	1.91	9.5	1.3	8.3
					254.4	41.3	**214.9**

Table 9. Crop Water Requirement for Mustard (Rabi)

	Mustard	**Crop Water Requirement and Net Irrigation Requirement**					
Month	**Decade**	**Stage**	**Kc**	**ETc**	**ETc**	**Eff rain**	**Irr. Req.**
			coeff	**mm/day**	**mm/dec**	**mm/dec**	**mm/dec**
Oct	1	Init	0.41	1.52	1.5	1.8	1.5
Oct	2	Init	0.41	1.52	15.2	2.8	12.4
Oct	3	Init	0.41	1.42	15.6	3	12.7
Nov	1	Deve	0.47	1.5	15	4.5	10.6
Nov	2	Deve	0.66	1.97	19.7	2.7	17.1
Nov	3	Deve	0.87	2.46	24.6	2.8	21.8
Dec	1	Mid	1.01	2.73	27.3	2.9	24.4
Dec	2	Mid	1.02	2.61	26.1	2.7	23.4
Dec	3	Mid	1.02	2.66	29.2	3.3	25.9
Jan	1	Late	1.01	2.68	26.8	4.4	22.4
Jan	2	Late	0.88	2.37	23.7	5.1	18.5
Jan	3	Late	0.7	2.05	22.5	4.1	18.5
Feb	1	Late	0.6	1.89	1.9	0.3	1.9
					249.1	40.3	**211**

Table 10. Crop Water Requirement for Pulses (Rabi)

Month	**Decade**	**Stage**	**Kc**	**ETc**	**ETc**	**Eff rain**	**Irr. Req.**
			coeff	**mm/day**	**mm/dec**	**mm/dec**	**mm/dec**
Nov	2	Init	0.4	1.19	10.7	2.4	8

Nov	3	Init	0.4	1.13	11.3	2.8	8.6
Dec	1	Dev	0.51	1.37	13.7	2.9	10.8
Dec	2	Dev	0.75	1.93	19.3	2.7	16.6
Dec	3	Dev	1.01	2.63	28.9	3.3	25.6
Jan	1	Mid	1.13	3	30	4.4	25.6
Jan	2	Mid	1.13	3.05	30.5	5.1	25.4
Jan	3	Mid	1.13	3.31	36.4	4.1	32.3
Feb	1	Late	1.13	3.56	35.6	2.6	33
Feb	2	Late	0.88	2.97	29.7	1.6	28.1
Feb	3	Late	0.53	1.96	15.7	1.9	13.8
Mar	1	Late	0.35	1.43	1.4	0.3	1.4
					263.2	34	**229.2**

6.4 Net Irrigation Requirement (NIR) and Irrigation Schedule

Field irrigation management is enhanced by an understanding of crop irrigation water requirements and irrigation schedules. The goal of irrigation water management is to efficiently and deliberately regulate the amount, time, and rate of irrigation. Determining when and how much water to apply to the field is called irrigation scheduling. Good scheduling is the use of the right time and the right amount of water for production. Ineffective scheduling hurts yield, quantity, and nutrient use. The efficiency of water in agricultural production is generally low. Only 40 to 60% of the water is effectively used by the crop; the rest of the water is lost in the system or on the farm either through evaporation, runoff, or percolation into the groundwater. Irrigation scheduling, if properly managed, can offer a good solution to improve water efficiency in the farm. Tables and Figures illustrate the field crop irrigation schedules for the wheat, Gram, Mustard, and Pulses.

The total gross irrigation mean and the total net irrigation mean are 193.8 and 135.6 for wheat, 207.1 mm and 145 mm for Gram, 206.5mm and 144.6 mm for Mustard, and 170.4 mm and 119.3 mm for Pulses in Kolar Command Area. There are four irrigation schedules for Wheat, four for Gram, four for Mustard, and three for Pulses.

It is found that for the semi-arid type of climate, the crops sown and net irrigation requirement are similar in their water needs as well as irrigation scheduling.

To avoid water crop water stress, rainfall and irrigation must be sufficient to meet the crop's ET requirement. This means that for any period during the crop growing season, the net irrigation requirement (NIR) is the amount of water that is not effectively provided by rainfall:

NIR= ET - ERAIN (3)

where NIR net irrigation requirement,

ET= evapotranspiration,

and ERAIN = effective rainfall.

NIR is irrigation water that is delivered to the field and available for the crop to use. This is primarily water, which is stored in soil in the crop root zone, although some of the water that is evaporated from water, soil, and plant surfaces during application also effectively reduces climate demand. (A.G. Smajstrla and F.S. Zazueta., 2002). Operations, such as leaching, transplantation, and land preparation, require certain amounts of water. Thus, CWR includes ET, losses during the application of water needed for these purposes, as in Equation (3). Irrigation Schedules of major crops sown during Rabi season are illustrated in detail from Tables 11 to 14 and Figure 12 to 15.

Table 11. Irrigation Schedules for Wheat

Irrigation Scheduling		**Wheat-Kolar**									
Date	**Day**	**Stage**	**Rain**	**Ks**	**Eta**	**Depl**	**Net Irr**	**Deficit**	**Loss**	**Gr. Irr**	**Flow**
			mm	**fract.**	**%**	**%**	**mm**	**mm**	**mm**	**mm**	**l/s/ha**
18-Nov	4	Init	0	1	100	55	42.1	0	0	60.1	1.74
25-Dec	41	Dev	0	1	100	55	124.3	0	0	177.6	0.56
10-Feb	88	End	0	1	100	57	135.6	0	0	193.8	0.48
21-Mar	End	End	0	1	0	43					

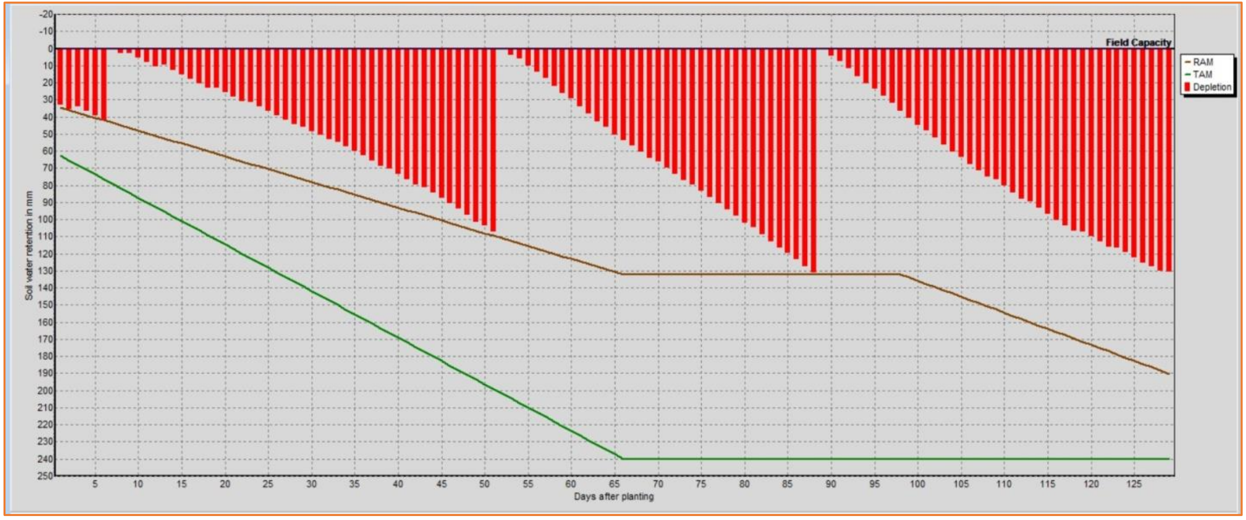


Figure 12. Irrigation Schedules for Wheat

Table 12. Irrigation Schedules for Gram

Date	**Day**	**Stage**	**Rain (mm)**	**Ks (fraction)**	**Eta (%)**	**Depl (%)**	**Net Irr(mm)**	**Deficit (mm)**	**Loss (mm)**	**Gr.Irr (mm)**	**Flow (L/s/ha)**
15-Oct	1	Ini	0	1	100	52	33.2	0	0	47.4	5.48
30-Nov	47	Dev	0	1	100	58	123.2	0	0	175.9	0.44
01-Feb	110	Mid	0	1	100	67	161.7	0	0	231	0.42
10-Feb	End	End	0	1	0	7					

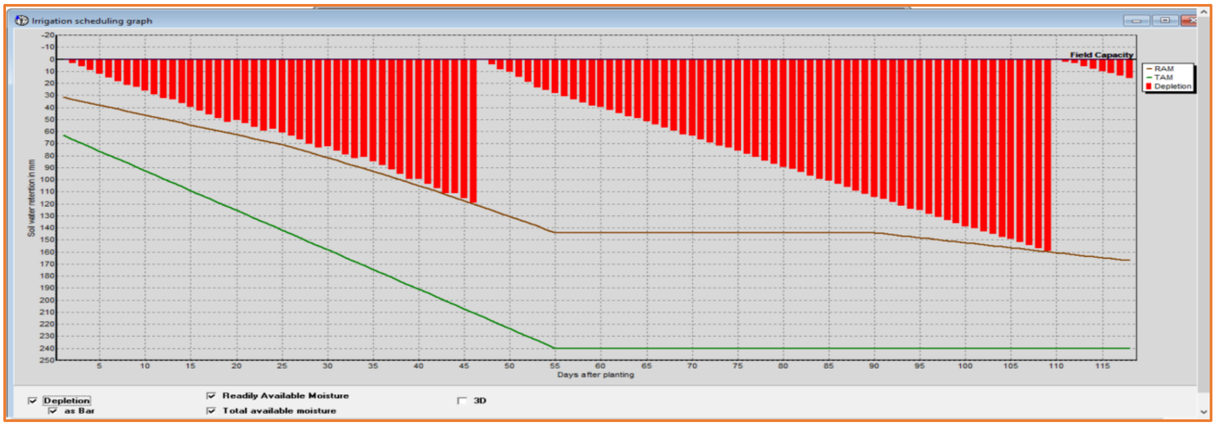
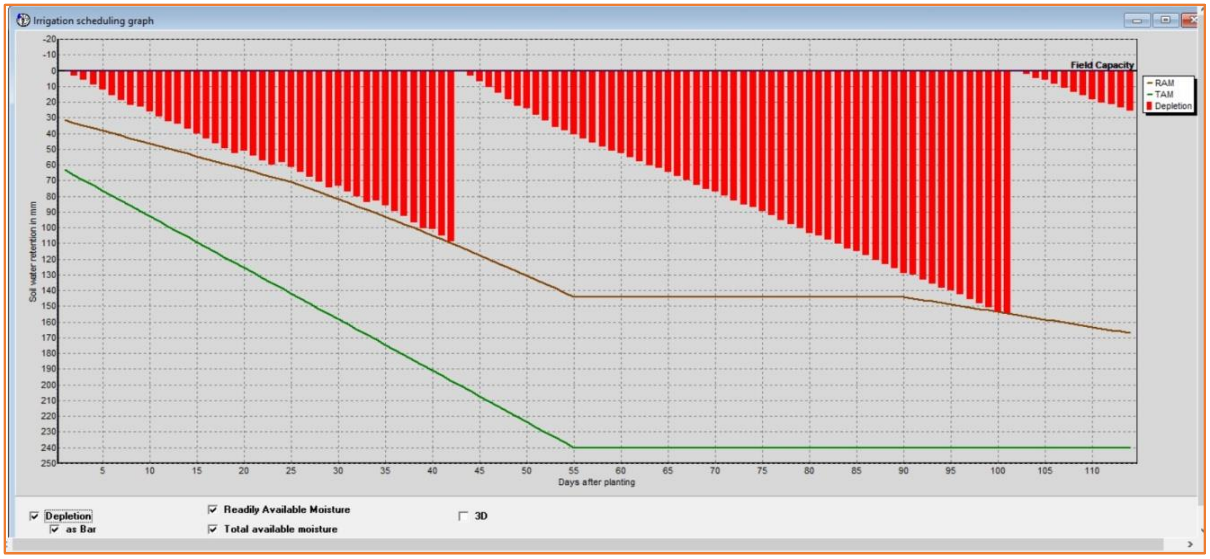


Figure 13. Irrigation Schedules for Gram

Table 13. Irrigation Schedules of Mustard

Date	**Day**	**Stage**	**Rain (mm)**	**Ks (fraction)**	**Eta(%)**	**Depl (%)**	**Net Irr(mm)**	**Deficit (mm)**	**Loss (mm)**	**Gr.Irr (mm)**	**Flow (L/s/ha)**
15-Oct	1	Ini	0	1	100	52	33.2	0	0	47.4	5.49
26-Nov	43	Dev	0	1	100	56	112.7	0	0	161	0.44
24-Jan	102	Mid	0	1	100	65	156.8	0	0	224.1	0.44
06-Feb	End	End	0	1	0	11					



☑ Depletion
☑ as Bar
☑ Readily Available Moisture
☑ Total available moisture
☐ 3D

Figure 14. Irrigation Schedules for Mustard

Table 14. Irrigation Schedules for Pulses

Date	Day	Stage	Rain (mm)	Ks (fraction)	Eta (%)	Depl (%)	Net Irr(mm)	Deficit (mm)	Loss (mm)	Gr.Irr (mm)	Flow (L/s/ha)
20-Oct	6	Ini	0	1	100	61	47.2	0	0	47.4	5.49
02-Dec	49	Dev	0	1	100	60	119.3	0	0	161	0.44
01-Feb	End	End	0	1	100	76					

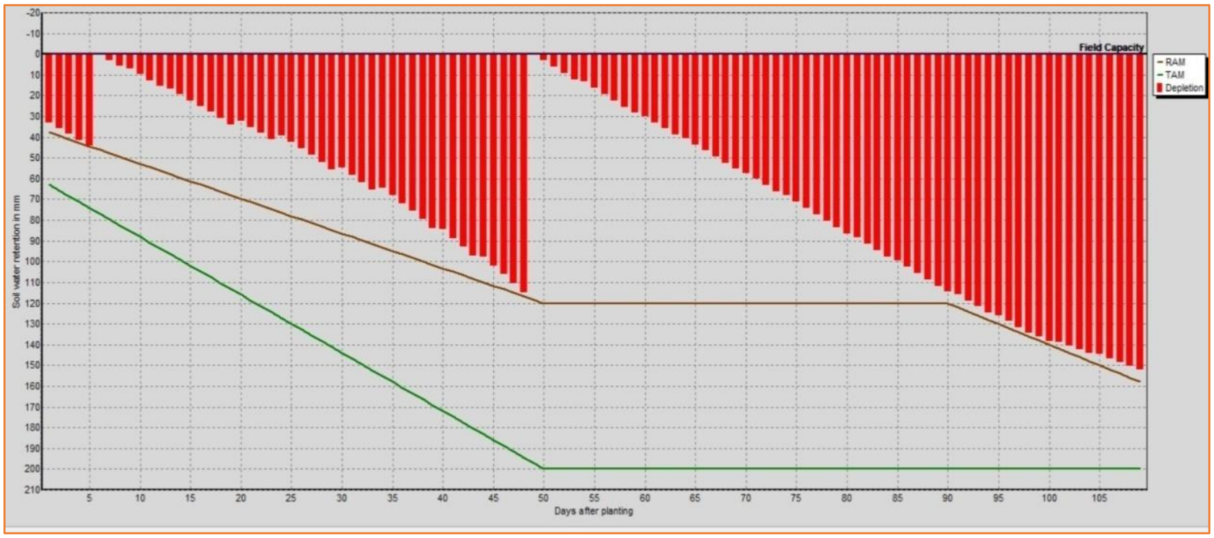


Figure 15. Irrigation Schedules for Pulses

In the above figures 12 to 15, (TAM) is the total available moisture or the total amount of water available to the crop. The (RAM) is the readily available water or the portion of (TAM) that the plant can get from the root zone without facing water stress. (Some, L.; et.al, 2006).

Table 15. Kolar Irrigation Scheduling

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wheat	82.8	88.4	48.6	0	0	0	0	0	0	0	16.2	50.8
Gram	60.1	8.4	0	0	0	0	0	0	0	25.8	48.4	72.6
Mustard	59.4	1.9	0	0	0	0	0	0	0	26.6	49.4	73.7
Pulses												
in mm/day (NIR 1)	2.5	2.8	1.4	0	0	0	0	0	0	0.1	0.6	1.7
in mm/month (NIR 2)	78.6	77.6	42.3	0	0	0	0	0	0	2.9	19.4	52.2
in l/s/h (NIR 3)	0.29	0.32	0.16	0	0	0	0	0	0	0.01	0.08	0.19
Irrigated area(% of total area)	98	98	87	0	0	0	0	0	0	11	98	98
Irr.req. For the actual area	0.3	0.33	0.18	0	0	0	0	0	0	0.1	0.08	0.2

6.5 Results of CWR and Irrigation Scheduling in Kolar Command Area

The estimation of the actual irrigation requirement of the Kolar command area during the Rabi season was carried out (Table 15). This is the summation of the NIR2 values from January to December. Using the scheme irrigation efficiency (59%), the gross water requirement of 462.71 mm/year was obtained for Rabi crops. Therefore, the entire command area of 35040 ha or 350.40 Sq km will require 151 M Cum as per the Rabi crops demands {canal irrigation(145.52MCM) + micro irrigation(5.56MCM)}. During Rabi season the Kolar Dam Authority releases 145 M Cum water for irrigation of Rabi crops according to availability of water in Kolar Dam. The water conveyance efficiency and water application efficiency were calculated in the Kolar command area as 84 and 70, respectively (According to field conditions). The Scheme irrigation efficiency and total losses calculated through the canal is 59% and 51 M Cum. Therefore, the Kolar dam authority can look towards reducing the losses and increasing the irrigation efficiency of the Kolar dam. As per Cropwat the crop water requirement of Rabi crops in Kolar Command Area is 111 M Cum whereas Kolar dam authority, on an average released 145.52 M Cum (15years) according to water availability in dam.

1. Therefore, the entire command area of 35040 ha requires 151 M Cum, water for Rabi crops. It is seen that on average, the Kolar dam releases 145.52 MCum water over the period of 15 years, which implies that the dam does not fill to its full capacity of 270 MCum. Therefore, the result shows that the dam cannot conveniently supply the water required for

the irrigation of Rabi crops in the command area, and there is a need for proper management of water resources.

2. The dam has a Gross Storage Capacity of 270 MCum and a live storage capacity of 265 MCum, and after catering to Rabi Irrigation (151 MCum), PHED supply to Bhopal for drinking and domestic uses according to present demand, i.e, 71 MCum. At present, the dam is not being operated to its optimum limit due to a shortfall in full storage of 270 MCM of Kolar dam. Therefore, the Sip–Kolar link project is initiated (operational since 2021) whereby diversion of 35 MCM water from the Sip River to Kolar dam during June to October to augment the storage shortfall in Kolar dam so as to meet the irrigation demands as well as the domestic demands.

6.6 Water Balance of Kolar Reservoir

An Excel worksheet was used to conduct the water balance of Kolar reservoir. The daily inflow for the water year (June 1 to May 31 of the following year) was calculated using reservoir levels, outflows, spills, evaporation losses, and seepage. In Figure 16, the annual water balance and its many components are displayed. The difference between total inflows, outflows, and changes in storage based on volumes on the beginning and last days of the water year has been used to calculate the percentage of mistakes for each water year. The inflow calculated from the water balance of Kolar reservoir can be utilized for rainfall–runoff modelling. The investigation revealed that the percentage errors in water balance varied between 6.87 and 5.04% and evaporation losses were found to be well within the range (less than 10% of inflow). The two main losses from Kolar reservoirs are evaporation and seepage, which are dependent on the water spread and contact area, respectively. The results of water balance for reservoirs indicated average annual inflow may be 190±50 MCM from Kolar Reservoir.

It is seen that over the period (15 years) through water balance of Kolar reservoir (2009-2024) the water availability in the dam is not sufficient, i.e only for 5 years the reservoir has attained Full Reservoir Level (462.20 m), i.e. 270 MCM with inflow ranges more than 230 MCM. The water availability in the dam based on last 15 years inflow data indicates that inflow has not been sufficient (<230 MCM) does not meet the irrigation demands in full in most of the years considered for the simulation i.e 72% to 77% of volume reliability for irrigation is seen, except during 4 years i.e., 2012-13(inflow of 289.86 Mm^3), 2013-14 (inflow of 291.98 Mm^3), 2016-17 (inflow of 236.20 Mm^3) and 2019-20 (inflow of 294.34 Mm^3). In the years 2013-2014 and 2016-

2017, the Kolar reservoir attained its FRL, and gates were operated to release the excess flood water. Also, on average, the storage remaining in the reservoir at the end of the water year is generally around 62.659 MCM, which emphasises the need for its optimum utilization. Accordingly, the MP WRD has developed an additional command area of 19.73 sq. km for which the irrigation water demand is 5.56 MCM (Table 30).

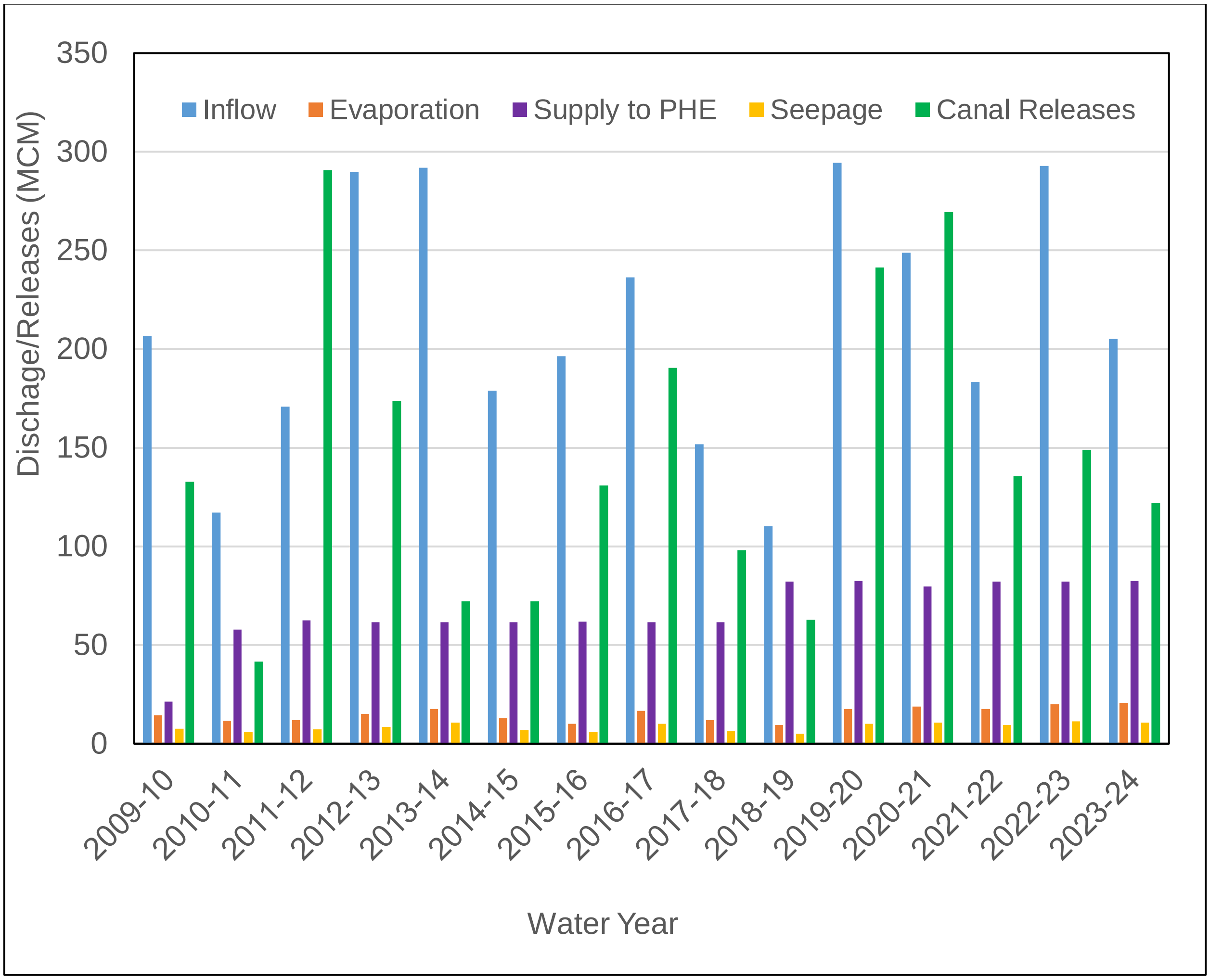


Figure 16. Water Balance of Kolar Reservoir for the period 2009 to 2024.

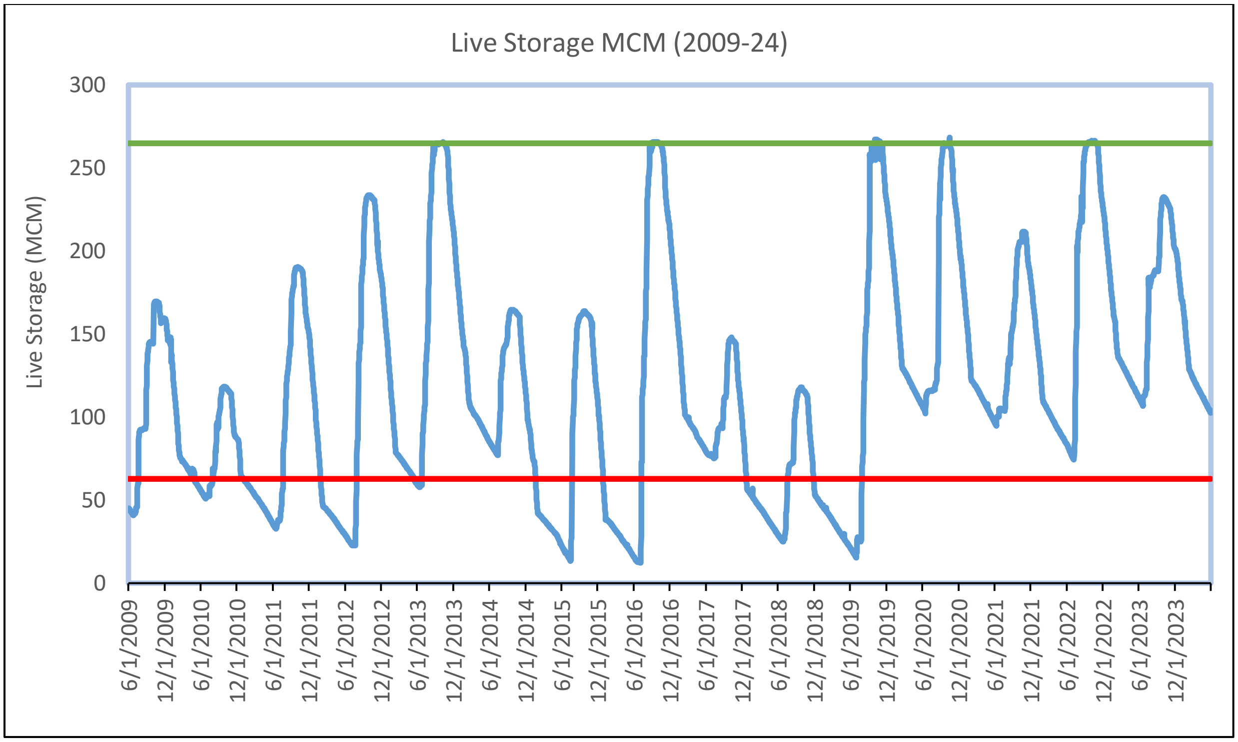


Figure 17. Live Storage Capacity of Kolar Reservoir (Average storage at end of May is 62.659 MCM)

6.7 Trend Analysis of annual and seasonal precipitation and maximum, minimum temperatures using Mann-Kendall and Sen's Slope estimator.

Mann-Kendall trend test and Sen's slope estimate provide insight into the data's seasonal distribution and yearly trends using 30 years' precipitation data (1981-2021) and 26 years' temperature datasets (1996-2021). The distribution for mean seasonal and yearly precipitation is shown in Table 16. There is an increase in monsoon precipitation (1.18 mm per year) and a slight increase of 0.06 mm in winter months, while pre-monsoon and post-monsoon months witnessed a slight decrease in rainfall over the years, i.e., -0.44 and -0.61 mm respectively (Table 16). Due to an increase in monsoon precipitation, the yearly trend has also increased over time, with an average rise of 0.96 mm per year, but there is no significant trend in the annual rainfall at a 95% confidence level. However, the annual rainfall has increased with an average rise of 0.508 mm/year. Sen's estimator, which calculates seasonal precipitation volume, was found to be 0.0, 5.80, -0.479, and -0.00, respectively, for the pre-monsoon seasons, monsoon, post-monsoon, and winter; and corroborates the abovementioned findings. There is no significant trend in the monsoon rainfall at a 95% confidence level. The monsoon rainfall has increased at a much higher rate of 5.80 mm/year, whereas there is a marginal decrease in the post-monsoon rainfall at a rate of -0.479 mm/year shown in Table 17. This trend indicated that rainfall exhibited downward and upward trends over the study period (Panda and Sahu, 2019). Temperature evidenced a warming trend, indicating a potential shift in the local climate.

Table 16. Mann-Kendall test (mm/year) for seasonal and annual distribution of rainfall values in bold text indicates a confidence level greater than 95% as per the Mann-Kendall test.

Winter	Pre-Monsoon	Monsoon	Post-Monsoon	Annual
+0.06	--0.44	+1.18	-0.61	+0.96

#Z-value for seasonal and annual distribution of rainfall values in bold text indicates a confidence level greater than 95% as per the Mann-Kendall test.

Table 17. Sen's slope (mm/year) for seasonal and annual distribution of rainfall values in bold text indicates a confidence level greater than 95% as per the Mann-Kendall test.

Winter	Pre-Monsoon	Monsoon	Post-Monsoon	Annual
-0.00	0.00	+5.80	-0.479	0.508

#Sen's slope (mm/year) for seasonal and annual distribution of rainfall values in bold text indicates a confidence level greater than 95% as per the Mann-Kendall test.

Table 18. Mann-Kendall test (mm/year) for monthly distribution of rainfall values in bold text indicates a confidence level greater than 95% as per the Mann-Kendall test.

Months	MK-Z	Months	MK-Z	Months	MK-Z
January	-0.090	May	-0.113	September	0.060
February	-0.090	June	0.074	October	-0.103
March	0.153	July	0.201	November	-0.183
April	0.071	August	-0.050	December	0.016

Table 19. Sen's slope (mm/year) for the monthly distribution of rainfall values in bold text indicates a confidence level greater than 95% as per the Mann-Kendall test.

Months	Sen's Slope	Months	Sen's Slope	Months	Sen's Slope
January	-0.203	May	-0.329	September	0.909
February	-0.176	June	0.698	October	-0.422
March	0.045	July	4.018	November	0
April	0.000	August	-5.270	December	0

Tables 18 and 19 show monthly trends of precipitation. No significant trends have been observed in monthly rainfall for any of the months at a 95% confidence level. March, June, July, and Sep witnessed increased precipitation. However, August witnessed the steepest decline with -5.270 mm/year.

In addition to precipitation, this finding demonstrates how well the study's approach to climate change has significantly influenced local climate during the past 33 years. The study area’s annual maximum temperatures (33-year mean) were determined to be 32.83 °C, with the summer season(37.99°C) witnessing the highest temperature. It has also been noted that the seasonal mean maximum temperature experienced during the winter season(27.33°C) was the lowest, closely followed by the post-monsoon(31.04°C), pre-monsoon(30.45°C), and monsoon(31.51°C) periods. The annual mean minimum temperature is determined to be 18.95°C, with the average value for each season (summer, monsoon, post-monsoon, and winter) being 22.54°C,22.41°C,14.24°C, and 10.78°C, respectively. The study area has its lowest temperature in the winter season, followed by the post-monsoon and pre-monsoon seasons. The annual mean of average temperature was determined to be 25.12°C, with the values for pre-monsoon, monsoon, post-monsoon, and winter being 30.52°C, 26.93°C, 22.53°C, and 19.04 °C, respectively. The highest average temperature is found to be summer season, followed by the monsoon, post-monsoon, and winter seasons, respectively, with the latter being the coldest.

Mann-Kendall Z-Statistic (MK-Z) and Sen’s slope (β) for Temperature Parameter

Table 20. Mann-Kendall Z-Statistic (MK-Z) and Sen’s slope (β) of the seasonal and annual trends of minimum and maximum temperatures.

Temperature	**Winter**		**Pre-Monsoon/Summer**		**Monsoon**		**Post-Monsoon**		**Annual**	
	MK-Z	ß	MK-Z	ß	MK-Z	ß	MK-Z	ß	MK-Z	ß
Minimum Temperature	0.23	0.004	**5.07**	0.095	**-3.92**	-0.040	**-5.00**	-0.124	-0.64	-0.004
Maximum Temperature	-0.91	-0.020	**2.09**	0.037	0.79	0.009	0.82	0.015	0.76	0.008

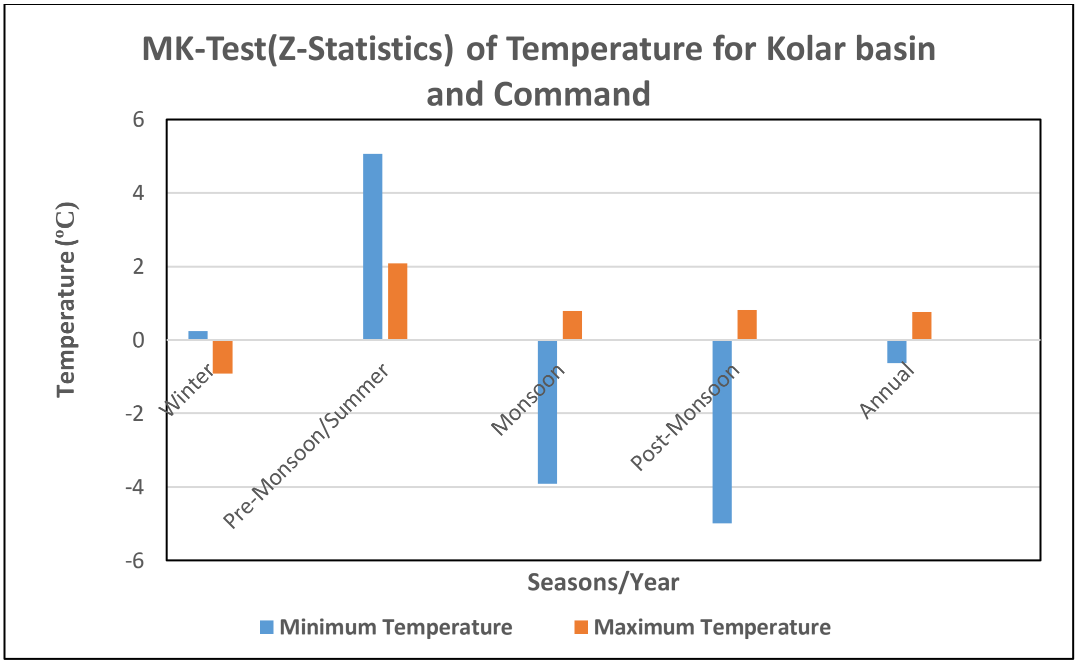


Figure 18. MK-Z statistics of minimum and maximum temperatures for the Kolar basin and its command

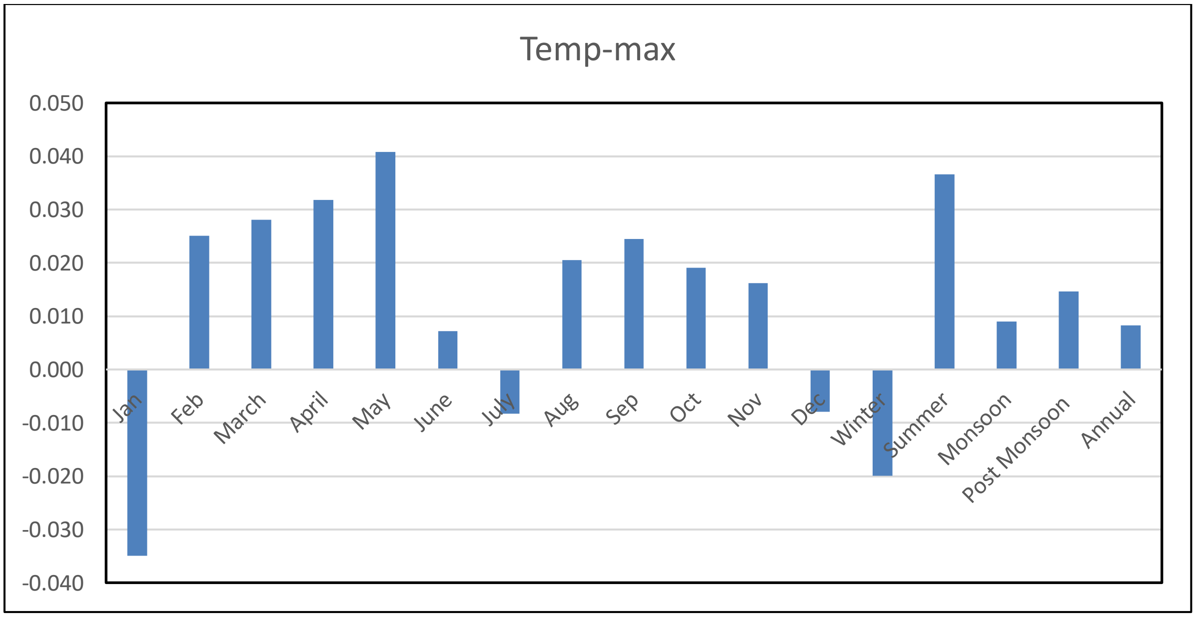


Figure 19. Sen’s slope for the maximum temperature of the Kolar basin and its command

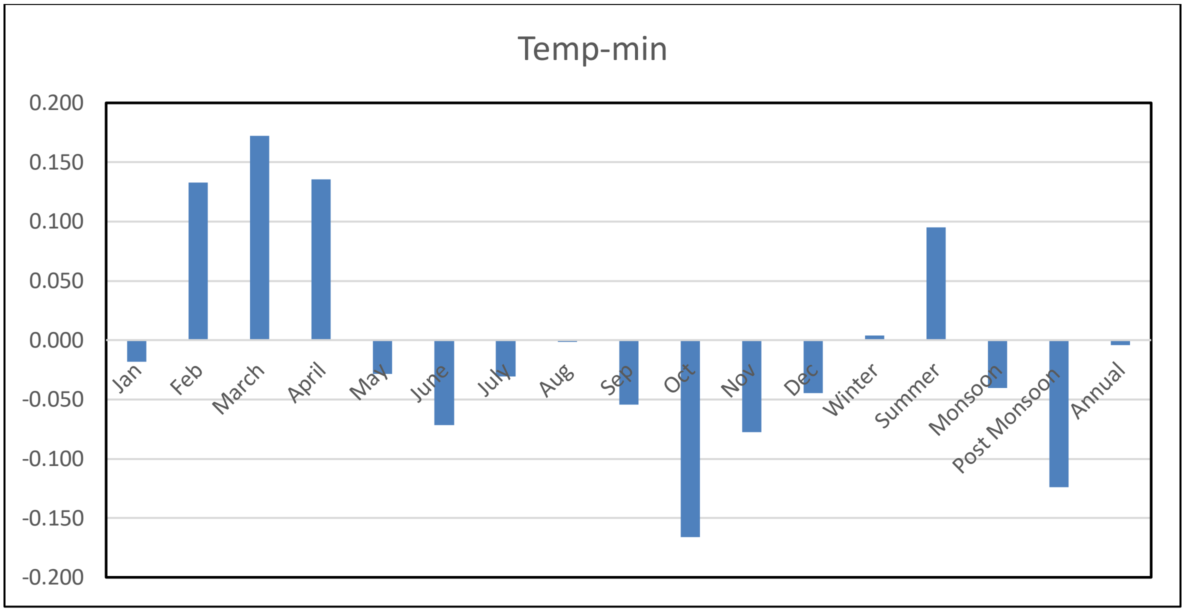


Figure 20. Sen's slope for the minimum temperature of the Kolar basin and its command

Table 20 and Figure 18 provide an overview of the seasonal and annual trends of minimum and maximum temperatures. The inferences drawn from Table 20 are as follows.

(i)Annual average minimum temperature showed marginal decreasing trends, though not significant at the 95% confidence level.

(ii)Annual average maximum temperature showed marginal increasing trends, though not significant at the 95% confidence level.

(iii)Seasonal average minimum temperature shows a statistically significant decreasing trend during monsoon and post-monsoon seasons and a statistically significant increasing trend during the summer season at a 95% confidence level.

(iv)Meanwhile, the corresponding seasonal maximum temperatures Kolar basin also showed upward trends, in most of the months, but significant only in the Pre-monsoon/Summer season at a 95% confidence level.

Results of the regression analysis for annual maximum temperatures, seasonal summer minimum and maximum temperature data, and minimum temperatures of monsoonal and post-monsoonal are shown in Figs. 21 to 23. The slope coefficient demonstrates the rate of a temperature attribute. In particular, a positive sign denotes an increasing tendency, whereas a negative sign denotes a decreasing trend in the rainfall amount (Tali et al., 2021). It is observed from the figure that during summer months, the maximum and minimum temperatures are increasing, thus showing the strongest trends. Temperature evidenced a warming trend, indicating a potential shift in the local climate.

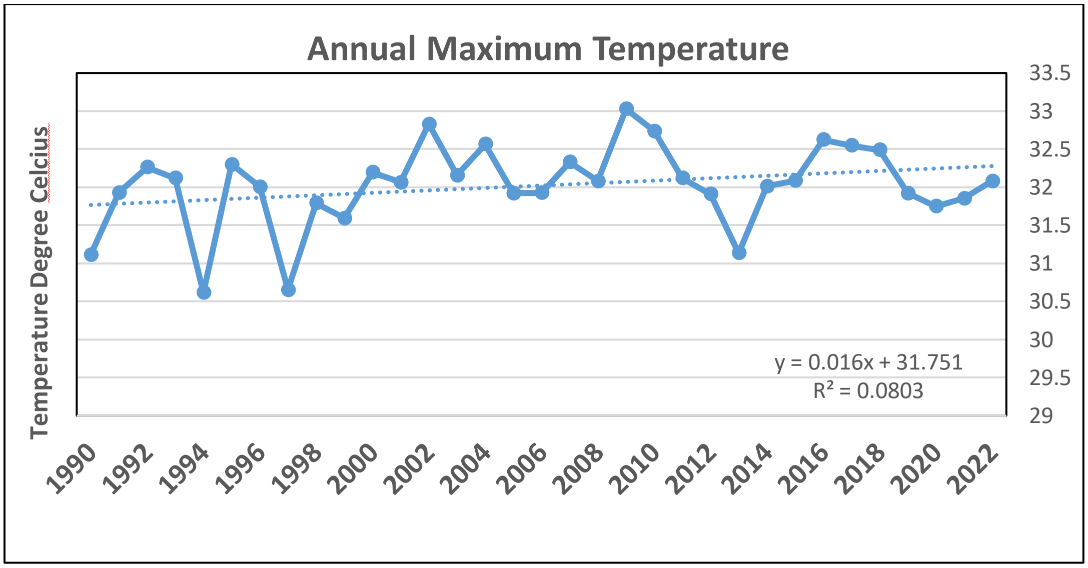


Figure 21. Regression analysis for the Annual maximum temperature of the Kolar basin and its command area

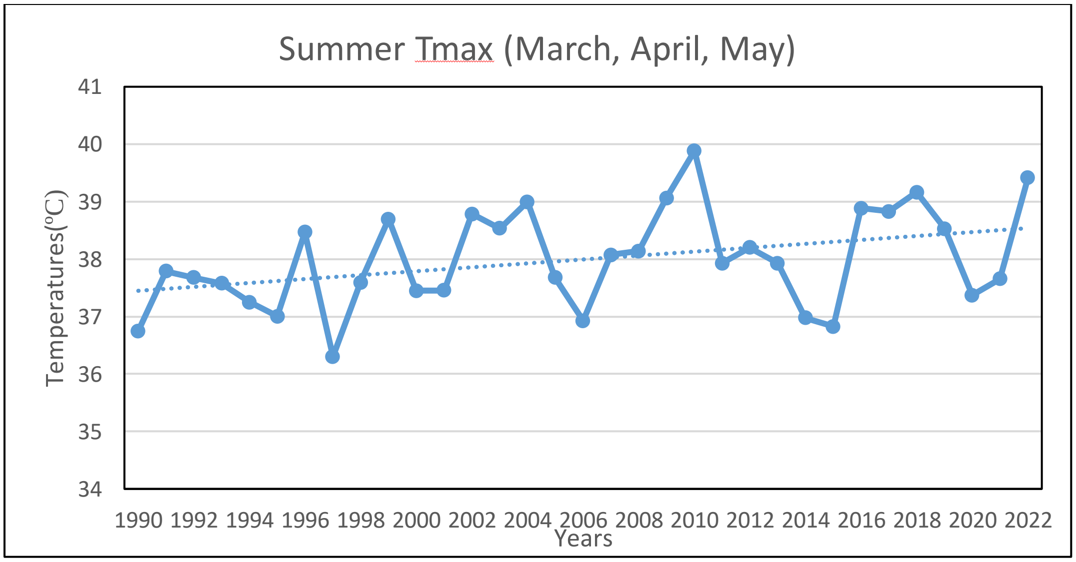


Figure 22. Regression analysis for the summer maximum temperature of the Kolar basin and its command area

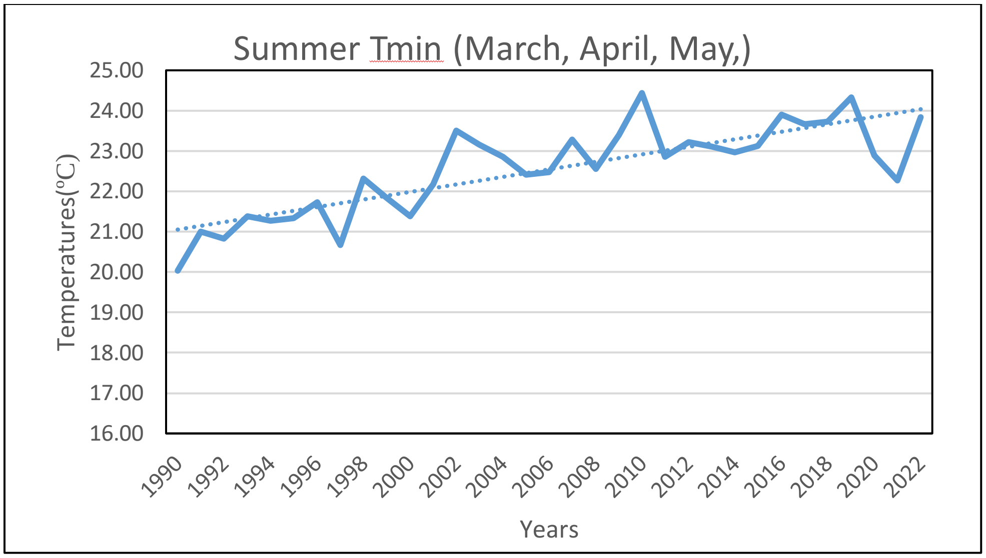


Figure 23. Regression analysis for the summer minimum temperature of the Kolar basin and its command area

Table 21 shows MK (Z-statistics) and Sen's slope for monthly minimum and maximum temperatures and it is evident from it that statistically significant upward trend has been observed for monthly minimum temperature during February, March and April months signifying rising temperatures during these months whereas statistically significant downward trends has been observed during June, July, October, November and December months at 95% confidence level.

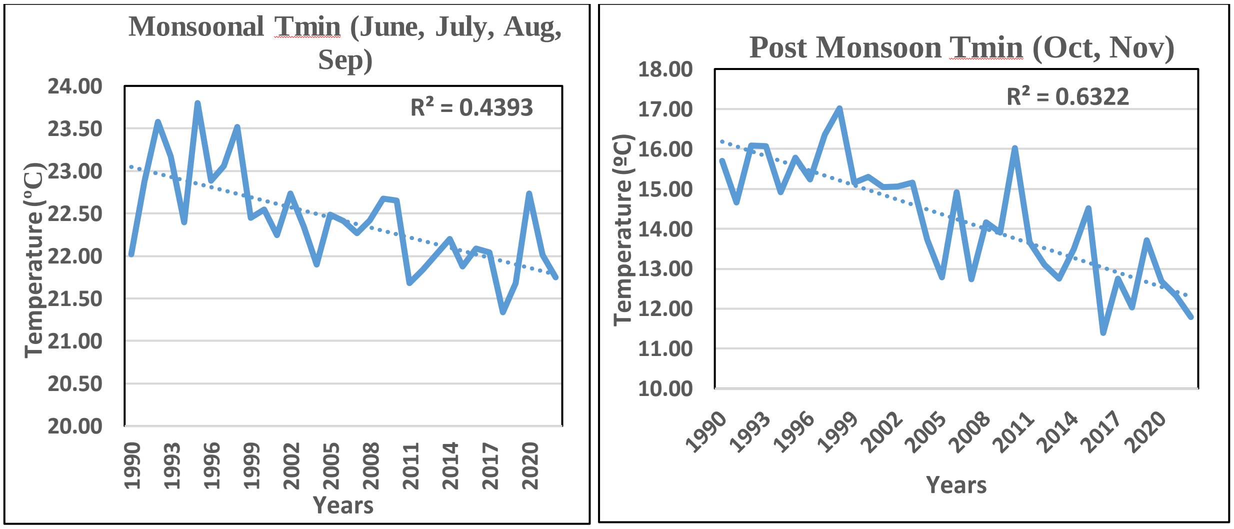


Figure 24.Regression analysis for monsoonal and post-monsoon minimum temperature of Kolar basin and its command area

Table 21. MK(Z-statistics) for minimum and maximum monthly temperatures of the Kolar basin and its command area

Temperatures	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Minimum Temperature	-0.85	**4.73**	**6.28**	**4.82**	-1.16	**-4.08**	**-2.34**	-0.17	**-4.03**	**-4.93**	**-3.80**	**-2.12**
Maximum Temperature	-1.04	0.88	0.85	1.38	1.63	0.26	-0.39	1.26	1.04	0.73	1.22	-0.23

Table 22. Sen's Slope minimum and maximum monthly temperatures of the Kolar basin and its command area

Temperatures	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec
Minimum Temperature	-0.018	0.133	0.172	0.135	-0.028	-0.072	-0.030	-0.002	-0.054	-0.166	-0.078	-0.045
Maximum Temperature	-0.035	0.025	0.028	0.032	0.041	0.007	-0.008	0.021	0.024	0.019	0.016	-0.008

6.8 Rainfall-runoff relationship for Kolar Basin for assessment of water availability in Kolar Reservoir.

Rainfall-runoff relationships refer to the relationship between the amount of rainfall that occurs in a particular area and the resulting runoff that occurs as a consequence of this rainfall. It helps in understanding how rainfall contributes to the flow of water in rivers, streams, and other water bodies. Through the analysis of historical data of rainfall and runoff for the period from 2010 to 2023 in the Kolar basin, and by studying the patterns and characteristics of rainfall events and the corresponding runoff derivation equations are generated in Excel to estimate the expected runoff for a given amount of rainfall. Rainfall-runoff relationship has been derived using the historical data of rainfall and runoff for the period from 2010 to 2023. Based on the historical derivation of the rainfall-runoff relationship 5%, 10% increase in rainfall and its corresponding runoff is derived as a future scenario for 25 years, i.e, 2025 to 2050. Hence, from the historical datasets (2010-2023) for the present average annual rainfall and its corresponding runoff (i.e, inflow to the Kolar reservoir) is calculated to be 641.1 MCM and 240.62 MCM, respectively. Similarly, for a 5%, 10% increase in rainfall, i.e, 673.15 and 705.21 MCM, its corresponding runoff is calculated to be 252.43 MCM and 264.45 MCM, respectively. Therefore, for future scenarios of 5% and 10% increase in rainfall, their corresponding runoff, i.e, inflow to the Kolar Reservoir, is derived for the future period of 25 years, i.e, 2025 to 2050-2060.

6.9 Development of Operation Policy for Kolar Reservoir

6.9.1 Present Operation Policy of Kolar Reservoir

From the working table (2009-2024) of the reservoir, prepared by the Kolar reservoir authority, it is noted that top priority is given for meeting full water supply demand (61 MCM annually) while next higher priority is given for meeting irrigation demand by Right Bank Canal (on an average 61.23Mm^3). The irrigation water demand of the Left Bank Canal is met for water more than above mentioned demands. If the water is in excess of all demands, the extra water is spilled after filling the reservoir up to the FRL. The failures for LBC, as noted from the working table and as given by the project authority, are for the years, 2010-11(117Mm^3), 2011-12(170.80Mm^3), 2014-15(179.02Mm^3) 2015-16(196.24Mm^3), 2017-18(151.893Mm^3), 2018-19(110.098Mm^3), 2021-22(183.31Mm^3), i.e.,7 years in 15 years and it amounts to 46.66 percent. It is noted that the total annual inflow is less than 150 Mm^3 for drought years.

6.9.2 Aspect considered for Policy Development.

In the present study, the reservoir operation for the Kolar reservoir has been developed for the conservation demands like water supply for domestic use purposes to Bhopal city, and irrigation. Hydropower generation is nil. The policy development does not include flood protection, as this reservoir is not operated for flood control.

6.9.3 Data used for the Development of Operation Policy for Kolar Reservoir

The monthly inflow series (in million cubic meters) at the Kolar reservoir for the period 2010 to 2023 has been considered for the policy development as shown in Figure 25. The Elevation-Area-Capacity table has been prepared based on information obtained from the DPR of Kolar dam (May 2021) as well as interpolating the in-between values, which have been used for the operation study, and the same is given in Table 24. It is noted from the survey that the reduction in storage capacity at DSL is 7%, and the reduction in storage capacity at FRL is 8%. The normal values of monthly evaporation for the reservoir are presented in Table 23.

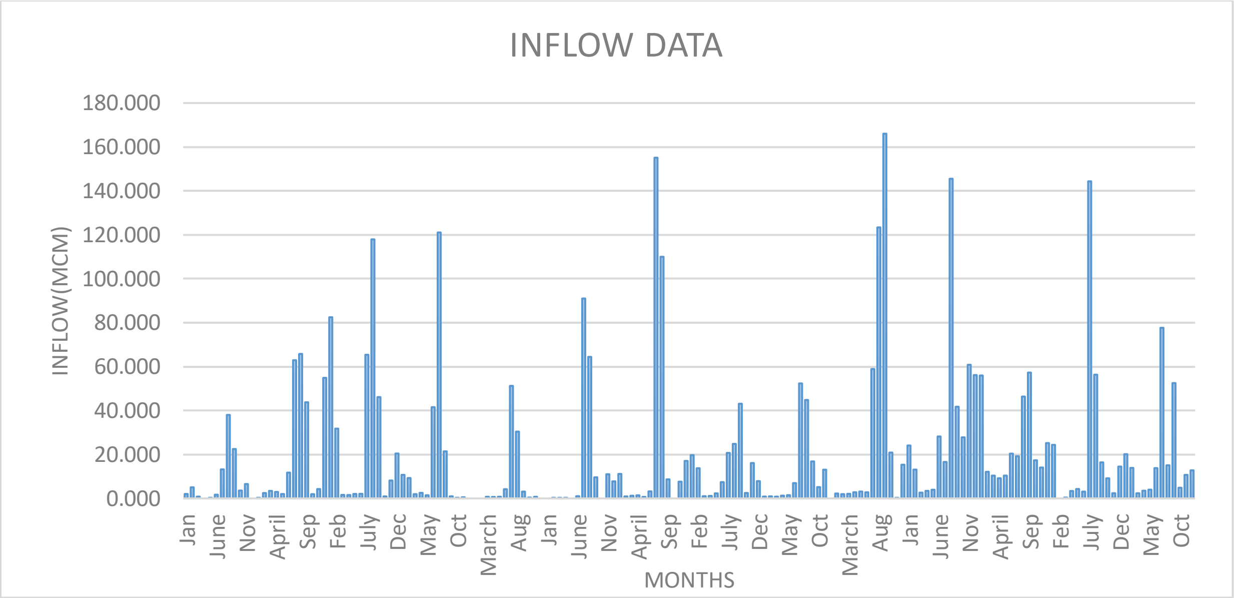


Figure 25. Monthly Inflow series, at the Kolar Reservoir for the period (2010-2023)

The Elevation- Area–Capacity curve for this reservoir has been plotted in Figure 28 based on the Emergency Action Plan (May 2021). The average monthly irrigation demand has been calculated from details collected from the project authority. Various demands from the reservoir are given in Table 25.

Table 23. Normal Monthly Evaporation Depths (m) (revised) for Kolar Reservoir.

Months	Elevation Depth m
January	**0.089**
February	**0.108**
March	**0.191**
April	**0.284**
May	**0.33**
June	**0.484**
July	**0.108**
August	**0.083**
September	**0.108**
October	**0.108**
November	**0.089**
December	**0.088**

Table 24. Elevation -Area-Capacity for Kolar Reservoir (Based on EAP 2021)

Elevation **m**	**Area** M, Sq.m	**Capacity** M Cum
433	1.275	5
434	1.575	7.8
435	1.9	9.8
436	2.235	12.2
437	2.6	14.75
438	3.05	17.5
439	3.525	20.5
440	3.995	24.25
441	4.525	28.5
442	5.125	33.5
443	5.725	38.75
444	6.375	45
446	7.75	59.25
447	8.45	67.25
448	9.225	76.5
449	10.05	85.75
450	10.9	95.75
451	11.75	106.75
452	12.72	118.25
453	13.7	130
454	14.7	142
455	15.7	154.25
456	16.69	166.75
457	17.68	179.5
458	18.68	193.5
459	19.68	208
460	20.68	224.5
461	21.68	241.5
462	22.7	265
463	23.66	295.03
463.5	24.44	325

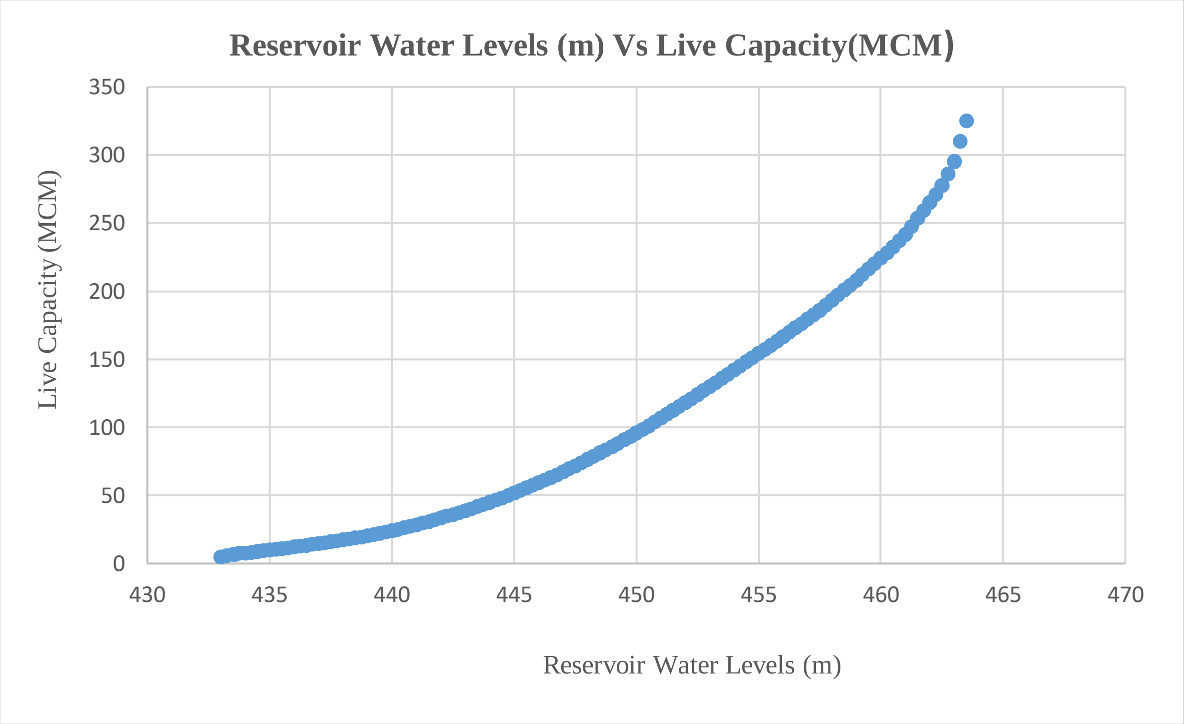


Figure 26. Graphical representation of between Reservoir Water Elevation (m) and Live Capacity (MCM) of Kolar Reservoir

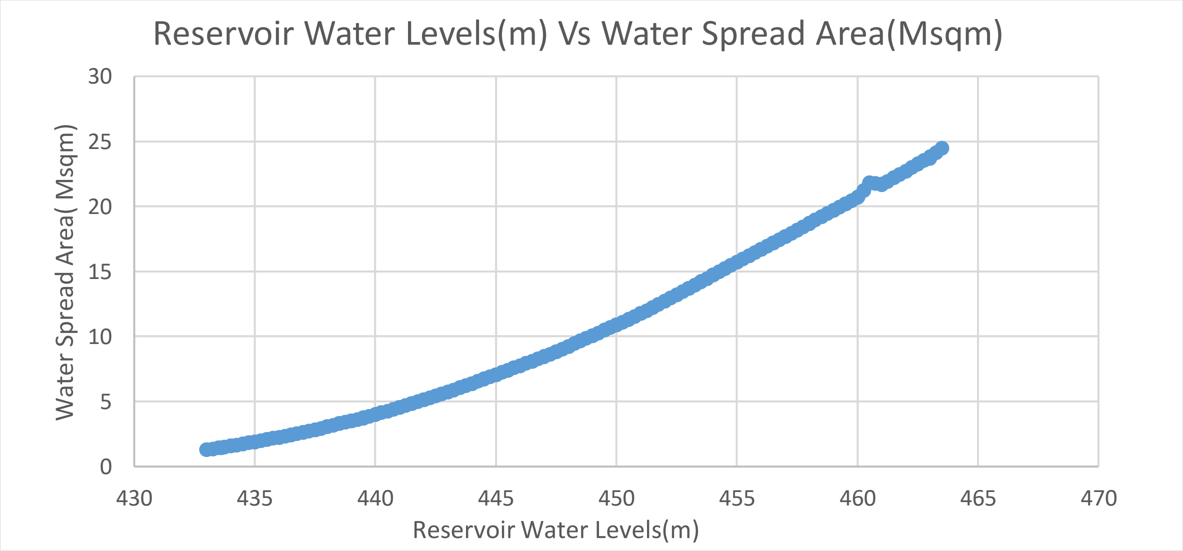


Figure 27. Graphical representation of Spread Area (Sq.Km) and Reservoir Water Elevation (m) of Kolar Reservoir

Full Reservoir Level of Kolar Dam is 462.20 m where whereas in FRL the spread area is 22.8 M Sq. m

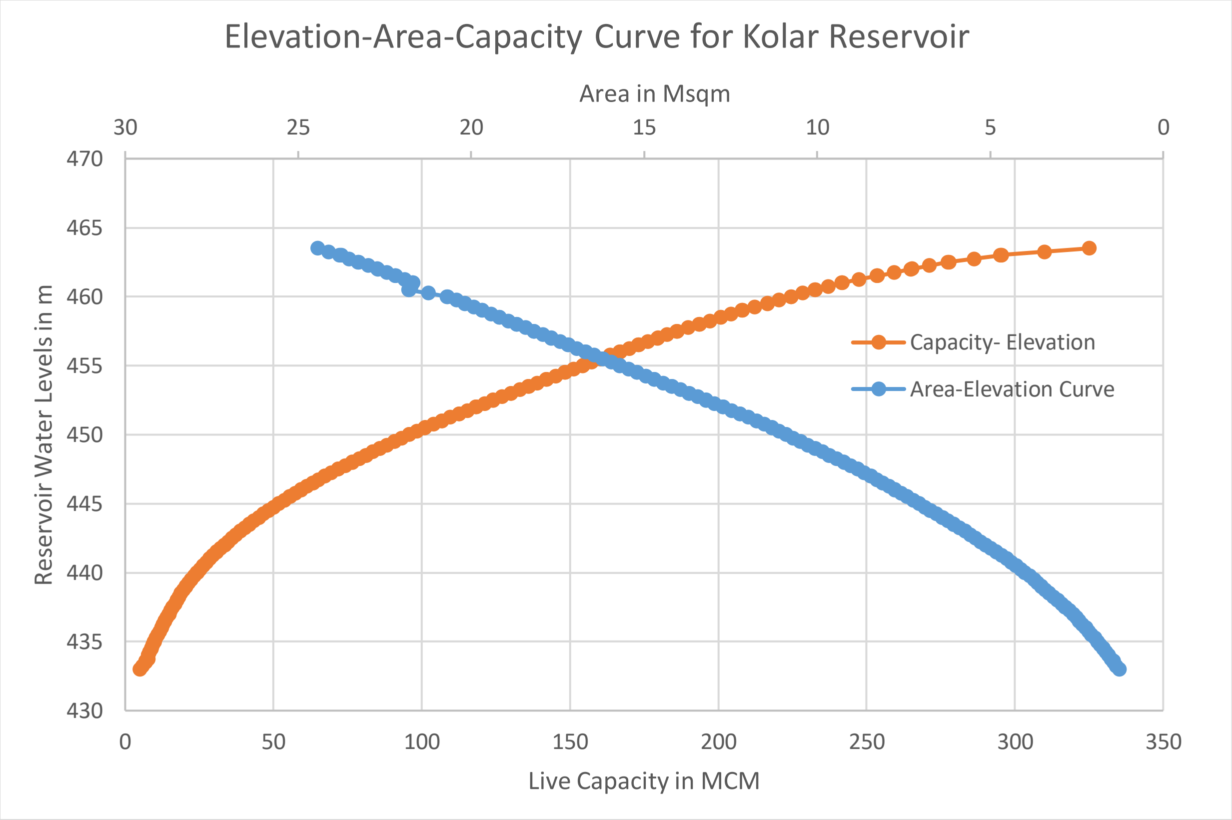


Figure 28. Elevation- Area-Capacity Curve for Kolar Reservoir (as per EAP 2021)

Table 25. Target Monthly Demands from the Kolar Reservoir

Month	P1-WS Demand(MCM)	P2-Env Demand(MCM)	Irrigation Demand bypass PP(MCM)
Jan	6.11	0.80	**38.60**
Feb	5.57	0.80	**14.45**
March	6.11	0.80	**0.00**
April	5.91	0.80	**0.00**
May	6.11	0.80	**0.00**
June	5.91	0.80	**0.00**
July	6.11	0.80	**0.00**
August	6.11	0.80	**0.00**
September	5.91	0.80	**9.47**
Oct	5.86	0.80	**3.87**
Nov	5.86	0.80	**42.16**
Dec	6.11	0.80	**42.39**
MCM	**71.70**	**9.60**	**150.94**

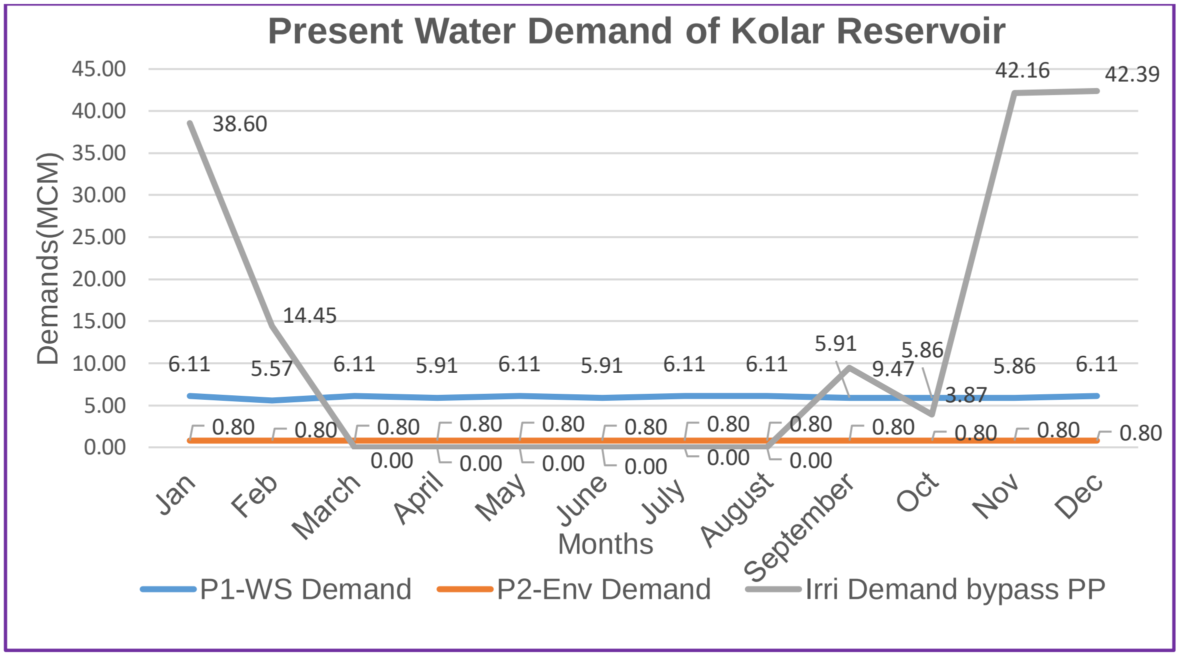


Figure 29. Target Monthly Demands from the Kolar Reservoir

6.9.4 The Solution Strategy Adopted

The rule curves based policy has been adopted for the conservation regulation of Kolar reservoir. This policy tries to distribute the deficit equitably in advance so that the reduced supply can be maintained throughout the demand period. Based on the number, nature, and priority of demands, three initial rule curves have been derived for this reservoir.

The methodology of simulation has been adopted for refining the rule curves. Simulation, in essence, is to duplicate the system behaviour under given hydrologic conditions. Though this approach is not useful for deriving any operational policy directly, it helps in policy evaluation. Simulation is one of the important techniques that can represent the true behaviour of a system. The analysis has been carried out for the monthly time interval. The results of the simulation have been used to refine the policy so as to achieve the maximum possible benefits from the available resources.

The module MULTIRESERVOIR SIMULATION of the Conservation Operation tool of NIH_ReSyP 2018 has been used to simulate the monthly operation of this reservoir for Conservation regulation. For each time step, the module calculates the release to be made for each demand accordance to the trial policy, spill (if any), and the actual evaporation losses at the prevailing water spread area, total release, end level, upper rule level, etc. In the end, the module calculates the number of months when the release is less than the demand and thus calculates the monthly time reliability of the reservoir for the trial policy as well as the volumetric reliability. In addition, it also calculates the number of months of critical failure when the release is less than 75% of the target demand.

Initially, three trial rule curve levels have been derived for the reservoir using various scenarios of reservoir inflows and levels of demands. The upper rule curve provides empty storage space in the reservoir for flood absorption. The middle rule curve is critical for irrigation demands, and the lower rule curve is critical for water supply demands. An exhaustive reservoir operation simulation study has been undertaken using these rule curves. The rule curves have been refined as long as the monthly time reliability of the reservoir could be increased without increasing the number of critical failure (supply less than 75 percent of the demand) months. The detailed operation table of the simulation has been utilized for this purpose. The operation policy, which has met the objectives of the conservation storage regulation, has finally been recommended for adoption. Monthly reservoir inflows of different probabilities have been considered in deriving different rule levels. The derivation of inflows of different probabilities is explained in the following section.

6.10.4(a) Probable Flow Estimation

Derivation of initial rule curves for a reservoir requires probable inflows corresponding to different reliabilities (say 50%, 75%, and 90%) for different months. This module is used to compute the probable monthly inflow values using a statistical approach. The monthly inflow series for the reservoir has been analysed using the statistical approach. For Kolar reservoir, inflow data are available for 14 14-year inflow series (2010-2023), and different reliable inflows have been arrived at the dam site using the available inflow series. The power transformation approach has been used for this purpose. This approach is a standard technique and is being extensively used in hydrological analysis. The monthly inflows for the reservoir have been estimated for 50%, 60%, 70%, 75%, 80%, and 90% probabilities using this approach. The results of this analysis for the 12 months have been presented in Table 27 and Figure 30. The report on NIHReSyP 2018 can be consulted to know more about the power transformation approach.

Table 26. Monthly Yield Estimation for Kolar Reservoir from 2009-2024

Months	**50%**	**75%**	**80%**

January	8.681	1.609	0.855
February	4.633	1.111	0.647
March	1.387	0.770	0.669
April	1.978	0.800	0.586
May	2.046	0.837	0.626
June	5.055	2.612	2.249
July	57.597	33.280	28.494
August	49.488	31.023	27.659
September	25.424	10.800	8.443
October	3.779	0.705	0.380
November	7.083	2.523	1.862
December	11.158	2.784	1.572

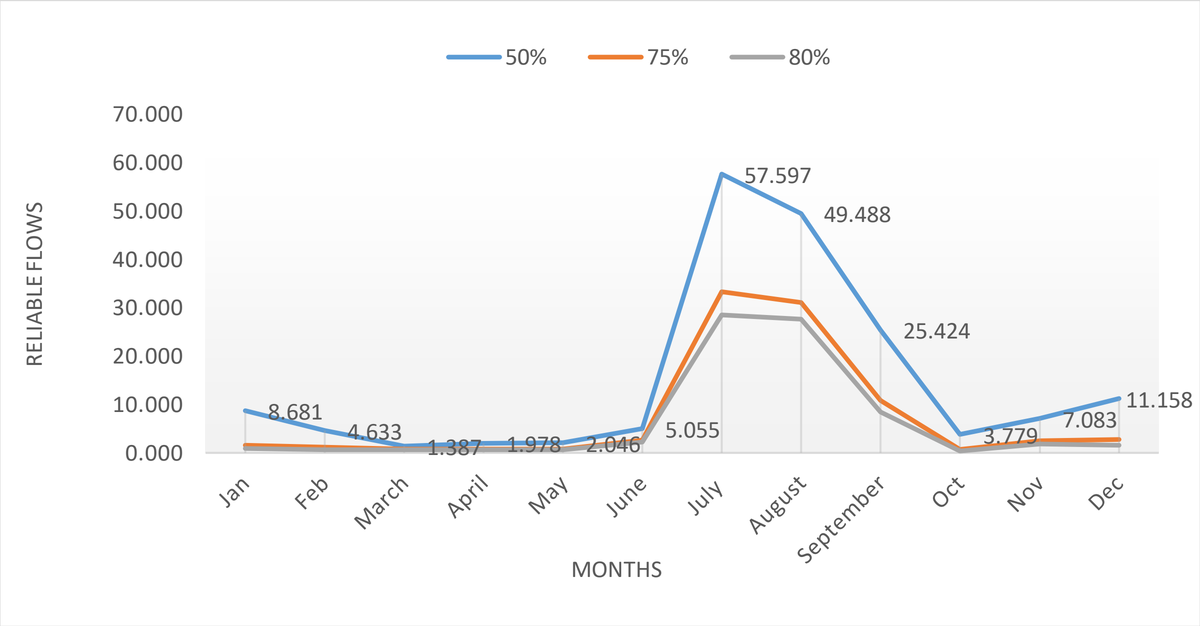


Figure 30. Kolar Dam Probable Flow at 50%, 75%, and 80%

6.9.4(b) Derivation of Initial Rule Curve

A rule curve or a rule level specifies the storage or space to be maintained in a reservoir during different times of the year, assuming that a reservoir can best satisfy its purposes if the storage specified by the rule curve is maintained at different times. This module computes the initial rule curve levels for various purposes (irrigation, hydropower, domestic supply, etc.), which can be specified in the operation analysis of a reservoir and which can be fine-tuned for deriving an optimum operation policy. The computations for deriving various rule curve levels are made using the monthly inflow series for different probability levels (computed in the module under section 3.3) along with the average monthly demands.

The computations for deriving various rule curve levels have been made using the monthly inflow series for different probability levels along with the average monthly demands. Using the monthly dependable inflow series, the water availability has been assumed to correspond to a particular monthly inflow series. Computations of end–of end-of-month reservoir levels have been made for 12 months after allowing for water demands in full or partial, and the evaporation losses from the reservoir surface. The Elevation-Area-Capacity table has been used, and the intermediate values have been linearly interpolated whenever required. The evaporation losses have been considered at a normal monthly rate over the surface area of the reservoir corresponding to a particular elevation.

The module Initial Rule Curve Derivation of NIH_ReSyP 2018 has been used to derive the initial trial rule curves. Since the Kolar reservoir is meant to serve for irrigation, water supply for domestic and industrial use, it has been considered appropriate to derive three rule levels for this reservoir. First, the upper rule level up to which the reservoir should be filled if there is sufficient inflow in the reservoir and all the demands are met in full. Secondly, the irrigation rule (middle rule level), below which the supply for irrigation demands should be curtailed so that the reduced supply can be maintained for a longer duration. Thirdly, the water supply level, below which the supply will be made to meet the domestic and industrial water supply demand. The report on NIHReSyP 2018 can be consulted to know the procedure adopted to derive the initial trial rule curves. The initial trial rule curve is presented in Table 27 and Figure 31.

Table 27. Initial Rule Curve for Levels (m) for Kolar Reservoir

	Upper Rule Curve	Irrigation Rule Curve	Water Supply Rule Curve
Month	**URC(A)**	**MRC(B)**	**LRC (C)**
Jan	453.84	449.65	443.33
Feb	452.35	444.65	442.15
March	451.67	440.9	440.9
April	450.96	439.18	439.18
May	450.17	436.83	436.83
June	462.2	456.37	439.68
July	462.2	457.21	441.74
Aug	462.2	458.05	443.8
Sep	462.2	458.9	445.85
Oct	461.86	458.38	445.98
Nov	459.62	457.55	445.99
Dec	456.91	453.8	444.24

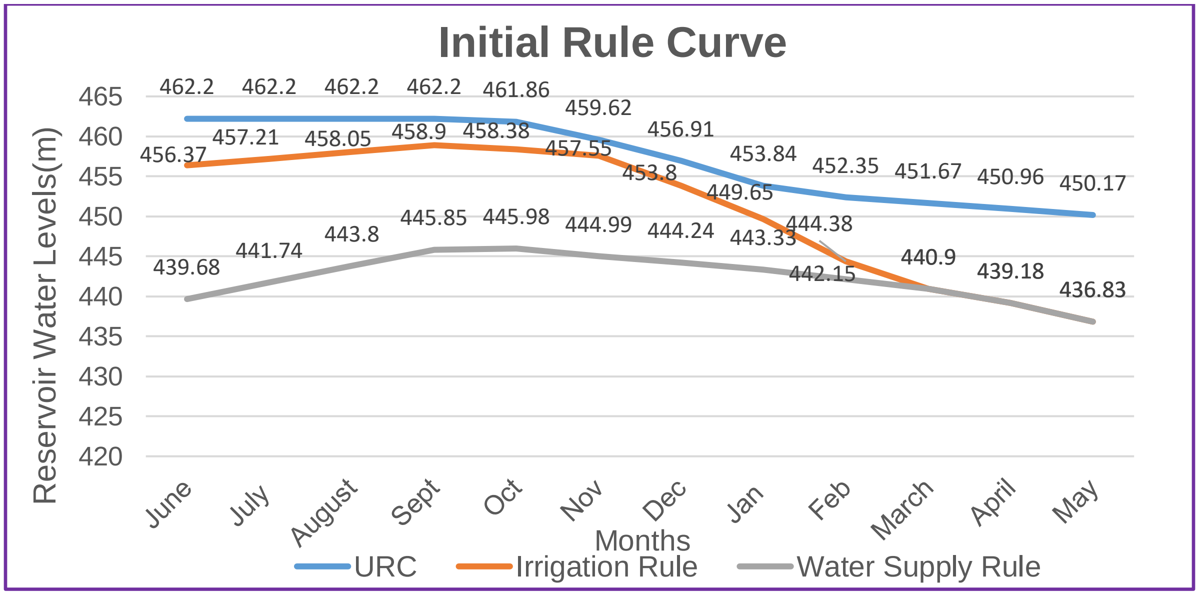


Figure 31 Initial Rule Curve Levels (m) for Kolar Reservoir

6.9.4(c) Simulation of Monthly Operation of the Reservoir

The module MULTIRESERVOIR SIMULATION of the NIH_ReSyp package has been used to simulate the monthly operation of the reservoir. The monthly inflow data, target monthly domestic and industrial water supply demand (M Cum), irrigation demand (M Cum), storage details and the normal values of evaporation details are input to the program. Various trial rule levels derived earlier are also input into the program. The module simulates the operation of the reservoir by the policy. A detailed working table for the reservoir operation is prepared.

1. Initial storage (M Cum) in the reservoir at the start of each time step (monthly in the present case)
2. Actual evaporation losses (M Cum) from the reservoir based on the initial and final water spread area. This is calculated iteratively till sufficient accuracy is achieved.
3. The total demand in the month (M Cum) for all the purposes.
4. Release of water from the reservoir for different purposes, like domestic and industrial demand, irrigation demand, based on the policy.
5. The amount of incidental power produced (M kWh) in different months.
6. The spill (M Cum) from the reservoir, if any.
7. End level (m) in the reservoir after each time step.

In addition, some ratios are also calculated, and if a ratio is less than a specified target, letters signifying different failures are indicated. These are indicated below.

1. Total release for irrigation/ Total irrigation demand. If this ratio is less than 1.00, “I” appears after the Tot_Rel column, indicating that it is a failure month for irrigation.
2. Total Release for water supply and upstream use/Total domestic & industrial water demand. If this ratio is less than 1.00, “W” appears after the Tot_Rel column, indicating that it is a water supply failure month.
3. Total release for all demands/Total of all demands. If this ratio is less than 0.75, “C” appears in the column instead of “I,” indicating that it is a critical failure month.

   In the end, the module calculates the total number of failure months when the supply is less than the total of the target demand for all purposes, and hence calculates the monthly time reliability of the reservoir for the test policy. It also calculates the total number of critical failure months when the supply is less than 75% of the demand, and hence, the monthly time reliability for critical failure. The module also calculates the total volumetric demand and supply from the reservoir and hence, the volumetric reliability of the reservoir.

An exhaustive operation simulation study for the Kolar reservoir has been undertaken using the initial trial rule curve levels. The results of the simulation analysis have been compared using the above performance indices. The policy has been refined using the detailed operation simulation table of the reservoir. The operation policy that best met the objectives of the conservation storage has finally been recommended for adoption. The recommended operation policy has been given for the present demand as well as foreseeing the future demand.

6.10 Development of Reservoir Operation Rule Curves for Different Scenarios I to V.

It is noted from research articles on climate change in Narmada basin and Central India that central India will experience a wetter and warmer climate up to the mid-21st century, albeit highly spatially variable, as projected by the majority of models within the CMIP5 GCM ensemble do, which is the current consensus amongst other bodies of work. (Mishra, S.K. et.al, 2017; Shah, S. et.al, 2020; Sperber, K.R. et.al, 2013). According to Rickards, N., Thomas, T. et.al, 2020, GCMs project a warmer, wetter climate in the Narmada basin, driving increased monsoon flows and annual mean flows. As Kolar basin is only 508Sq.km and only 1 grid is encompassing the whole area, the climate in a single grid point can be influenced by local factors, which may not be representative of the broader climate trends and patterns in a region or globally hence Kolar River, being a right bank tributary of Narmada River it is likely to experience the same climate; hence increase in inflow to the range of 5% to 10 % (Richards et.al 2020; Mishra et.al, 2017; Shah et.al, 2020; Sperber et.al, 2013) has been taken to represent the likely changes in inflow for the future period 2050.

To represent the impact of Climate change on the Kolar basin, hypothetical scenarios III and IV, i.e increase in inflow to 5% and an increase in inflow to 10%, has been considered based on the Climate Change studies of the Narmada basin (Richards et.al 2020; Mishra et.al, 2017; Shah et.al, 2020; Sperber et.al, 2013). Different Scenario (I to V) based rule curves have been derived for the operation of Kolar Reservoir (Table 28). It is noted from research articles on climate change in Narmada basin and Central India that central India will experience a wetter and warmer climate up to the mid-21st century, albeit highly spatially variable, as projected by the majority of models within the CMIP5 GCM ensemble do, which is the current consensus amongst other bodies of work. (Mishra, S.K. et.al, 2017; Shah, S. et.al, 2020; Sperber, K.R. et.al, 2013). According to Rickards, N., Thomas, T. et.al, 2020, GCMs project a warmer, wetter climate in the Narmada basin, driving increased monsoon flows and annual mean flows. Therefore, Kolar River, being a right bank tributary of Narmada River it is likely to experience the same climate; hence increase in inflow to the range of 5% to 10 % has been taken for the future period 2050.

The Kolar reservoirs' initial rule levels have been determined using the NIH_ReSyP Software module for present and future demands, i.e, near future 25 years (2050). Using these rule levels, a thorough simulation study of reservoir operation has been conducted. The rule curves have been refined as long as it was possible to raise the reservoir's monthly time reliability without also raising the months with a catastrophic failure rate (supply falling short of 75% of demand). Trial rule curves are adjusted by the observation from the simulation table until the best outcomes are obtained. Different Scenario (I to V) based rule curves have been derived for the operation of Kolar Reservoir (Table 28). The following table 28 summarizes the different scenarios for the derivation of Operation Rule Curves of Kolar Reservoir. Scenario III and IV, i.e increase in inflow to 5% and 10% respectively, have been considered for simulation of rule curves for assessing the future period (2050) changes, looking into the aspect of climate change in the Kolar basin. The simulated rule curve levels for the Kolar reservoirs for the present (scenario I) and future demands (scenario II) are displayed in Tables 35 and 36, respectively. The represented rule curve diagram for the Kolar reservoir for present demands and future demands is displayed in Figures 32 and 33.

Table 28. Different Scenario for Derivation of Operation Rule Curves of Kolar Reservoir

Scenario I	Rule Curves for Present Demand (222 MCM)
Scenario II	Rule Curves for Future Demand(232 MCM)
Scenario III	Inflow Increase 5 %(due to Rainfall increase to 5%)
Scenario IV	Inflow Increase 10 %(due to Rainfall increase to 10%)
Scenario V	Changed the Cropping pattern, then Demand increased (239 MCM)

6.10.1 Target Demands from the Dam

Kolar reservoir (a multipurpose project) is an important source of potable water supply for the city. As per the Agreement between PHED, Bhopal, and the Water Resources Department, 61.0 MCM is reserved for the Domestic supply to Bhopal city.

The Kolar reservoir project is mainly operated to meet the irrigation demands of LBC and RBC, water supply demands for the PHED, Bhopal. This reservoir is not operated for flood control. Various demands that are met from the reservoir are detailed in the following section.

6.10.1a Water Supply Demands for Domestic Purposes

The agreement between the Water Resource Department, Government of Madhya Pradesh, and PHED, Bhopal Kolar dam, is to supply water for domestic purposes at a rate of 0.1689 cusec daily. This amounts to 61 M Cum annually and has been considered for developing the operating policy of the reservoir.

6.10.1b Irrigation Use Demands

- The Kolar reservoir is constructed to provide irrigation through its Left Bank Canal and Right Bank Canal Systems. The project has an annual irrigation potential of 45040ha, a

Cultivable Command Area of 45087 ha, and a Gross Command Area of 62752 ha. The command area lies in the district of Sehore and Nasrullaganj. The annual requirement of the irrigation system is estimated to be around 151 M Cum to irrigate an area of 370.13 Sq.Km.

- The Kolar project proposed to irrigate **45,078 ha** (cultivable area) of area but only **35,000 ha** is being irrigated presently due to water shortage.
- As the Sip-Kolar link project is underway to add/divert **35 MCM** water to Kolar dam to irrigate the deficit area of **6100 ha** and bring its capacity to FRL, which was not attained in previous years.

6.10.2 Evaluation of Future Demand and Supply

It is seen that over the period (15 years) through water balance of Kolar reservoir (2009-2024) the water availability in dam is not sufficient i.e only for 5 years the reservoir has attained Full Reservoir Level (462.20 m), i.e., 270 MCM, with inflow ranges more than 230 MCM. The water availability in the dam based on last 15 years inflow data indicates that inflow has not been sufficient (<230 MCM) does not meet the irrigation demands in full(100%) in most of the years considered for the simulation, i.e. 72% to 77% of volume reliability for irrigation is seen, except during 4 years i.e., 2012-13(inflow of 289.86 Mm^3), 2013-14 (inflow of 291.98 Mm^3), 2016-17 (inflow of 236.20 Mm^3) and 2019-20 (inflow of 294.34 Mm^3). Also, on average, the storage remaining in the reservoir at the end of the water year is generally around 62.659 MCM, which emphasises the need for its optimum utilization. Accordingly, the MP WRD has developed an additional command area of 19.73 sq. km for which the irrigation water demand is 5.56 MCM (Table 30).

Table 29. shows the evaluated future demand in near future i.e next 25-year period, whereby for new command area (21 Sq. Km micro irrigation) is proposed to be added for which the additional demand is 7 MCM, additional population of 11179420 crores (projected growth) in 2051 for which the additional demand is 3 MCM (domestic 2 MCM and provision of industrial demand being 1 MCM). Therefore, the total additional water demand anticipated for the future is 10 MCM, and as such, the total water demand shall be 232 MCM to satisfy all future demands shown in Table 30.
Table 29. Total additional water demand anticipated for the future (25-year period, i.e, 2050)

Water Demand for the future		Projected Growth(2051)	Values in MCM
1.	Additional Command Area(21Sq.Km) Demand		7
2.	Population Demand Growth	11179420 crore	2MCM(Domestic)
3.	Industrial Demand Growth		1 MCM(Industrial)
		Total	10 MCM

Table 30. Evaluation of Present and Future Water Demands

Particulars	Area (Sq.km)	Canal Irrigation (Rabi-Wheat) (MCM)	Micro-Irrigation (Rabi-Wheat) (MCM)	Total Irrigation Demand (Present) (MCM)	Domestic Water Supply (MCM)
Present Demand	350.40 **(Canal)** 19.73 **(Micro)**	145.52	5.56	**151.08**	**71**
Total Present Water Demand (Irrigation + Domestic Water Supply)					**222 MCM**
Future Demand (Additional Command proposed)	21 **(Micro Irrigation)**		7		
Additional Population Demand(Year 2051)	11179420 (Crore)				**2**(Domestic) **1**(Industrial)
Additional Water Demand in the future					**10 MCM**
Total Future Water Demand (Irrigation + Domestic Water Supply)					**232 MCM**

Kolar Dam Authority is supplying 145.52 MCM for irrigation of Kolar command through L.B.C and R.B.C to meet all present demands, including the losses (i.e., evaporation and conveyance), which amounts to 151 MCM as shown in Table 30. Reservoir operation has been carried out using NIHReSyP based on the present inflows and water demands, and optimum rule curves have been developed for the optimal operation of the reservoir. In the recommended policy for present demand, the monthly time reliability for the water supply and irrigation comes out to be 100% and 78.6%. The volume reliability for irrigation comes out to be 77.4%. Out of 168 months, several critical failures (when the release is less than 75% of the total demand) occurred 16 times. Table 31 shows the abstract of the simulation run for the Kolar Reservoir for present demands. (The working table generated in NIHReSyP 2018 is shown in Table 42 as a sample for the present demand simulation.)

Table 31. Abstract of the simulation run for the Kolar Reservoir for present demands

Number of Failures for WS=0	Time and Vol. Reliability =1.000
Number of Failures for irrigation: 12	Time and Vol. Reliability =0.786 0.774
Number of Critical(Release < 0.75* Demand) Irrigation Failures =16	
Resi for WS Irrigation Power 0 0.333 0	
Vul for WS Irrigation Power 0 0.799 0	

Table 32 shows the abstract of the simulation run for the Kolar Reservoir for future demands.

Number of Failures for WS=0	Time and Vol. Reliability =1.00 1.00
Number of Failures for irrigation: 21	Time and Vol. Reliability =0.75 0.756
Number of Critical(Release < 0.75* Demand) Irrigation Failures = 18	
Resi for WS Irrigation Power 0 0.333 0	
Vul for WS Irrigation Power 0 0.781 0	

Similarly, the reservoir simulation has been carried out separately based on the future water demands of 232 MCM, and the optimum rule curves have been developed. It has been assumed that the inflow pattern will continue to remain the same in the future as well, as the reservoir has not filled to its gross capacity in most of the years since its commissioning. In the recommended policy for future demand, the monthly time reliability for the water supply and irrigation comes out to be 100% and 75%. The volume reliability for irrigation comes out to be 75.6%. Out of 168 months, there are 21 critical failure months (when the release is less than 75% of the total demand). Therefore, it can be observed that the reservoir can still meet the anticipated future demand, depending on whether it is operated based on the optimal rule curves developed for the future. Simulation runs for the Kolar Reservoir recommended policy based on present and future demands are presented in Tables 34 and 35, respectively. The results of the simulation run for the present policy and the recommended policy based on present demand and future demand are shown below in Table 33.

Table 32. Results of the simulation runs for the recommended policy based on present demand and future demand.

S.No	Items	Recommended Policy based on present demand	Recommended Policy based on future demand
1.	Number of failures for the water supply	0	0
2.	Time reliability for water supply	1	1
3.	Number of failures for irrigation	12	21
4.	Time reliability for irrigation	0.786	0.75
5.	Number of critical failures	16	18
6.	Volume reliability for irrigation	0.774	0.756

In the current operation policy, the demands for water supply for domestic and industrial use are met fully in all periods. The demands for RBC and LBC are met to the possible extent based on the rainfall scenarios and inflow to the dam. The months in which the release for irrigation is less than 75% of the total demand are treated as critical failure months. For the present demand, the recommended operation policy for the present from the simulation table is that the monthly time reliability for water supply and irrigation is 100% and 78.6%, respectively. The volume reliability for irrigation comes out to be 77.4%. Out of the 168 months, there are 16 critical failure months (when the total release is less than 75% of the total demand). From the working table using the current operating policy, the average annual release for irrigation is 145.5 M Cum. Later number of simulation runs have been taken considering various rule curve levels, and the refinement has been made till the reliability of the reservoir for various demands could be improved and the unnecessary spill water could be reduced. In the recommended policy based on the present demand, it has been assumed that for the reservoir level above the irrigation rule level, all the demands will be satisfied in full. If the water level falls below the irrigation rule level, then the water supply demand will be satisfied in full, while the irrigation demand will be curtailed to 75%. If the reservoir levels fall below water supply demands, the demands will be met for as longer the duration as possible. Based on this policy, in recommended rule levels for present demand, the monthly time reliability for the water supply and irrigation comes out to be 100% and 78.6%. The volume reliability for irrigation comes out to be 77.4%. Out of the 168 months, there are 16 critical failure months (when the total release is less than 75% of the total demand). In the recommended policy for future demand, the monthly time reliability for the water supply and irrigation comes out to be 100% and 75%. The volume reliability for irrigation comes out to be 75.6%. Out of the 168 months there are 18 critical failure months (when the total release is less than 75% of the total demand) From the Working operation table, water lost through evaporation per year is around 15.11 M Cum. Thus, roughly 237 M Cum of water is required annually. From the inflow data and working table, it is observed that during the years 2009-2011, 2014,2015, 2017,2018, 2021 and 2023 were years with annual inflow less than 210 M Cum. From the operation table, it can be seen that most of the irrigation (critical) failure months happen to fall in these drought years (2010, 2014, 2018). So the recommended policy for present and future demands tries to distribute the deficit equitably in all the months. As soon as a shortage of water is anticipated, the supply is curtailed well in advance so that the reduced supply can be maintained throughout the year. The recommended policy for present demand improves the volume reliability for irrigation and water supply by 1% over the current operation policy. The recommended policy for present and future demands also improves the average annual release for irrigation i.e. 222 and 232 M Cum respectively. On observation, it is seen that the recommended policy for present demand and the recommended policy for future it is observed that the recommended operating policy for present demand and future demand reduces the spill considerably, so the recommended policy gives the optimum upper rule level which gives the storage space for flood absorption without affecting conservation demands. Three rule curves have been provided in the recommended policy. The upper rule curve has been termed as Curve A(Upper Rule Curve), the irrigation rule curve as Curve B (Middle Rule Curve), and the water supply rule curve as Curve C(Lower Rule Curve). These have been plotted in Figures 32 and 33, and their respective tables are in Tables 34 & 35.

6.10.3 Scenario-I (Present Demand) & Scenario-II (Future Demand): Final Rule Curve Derivation

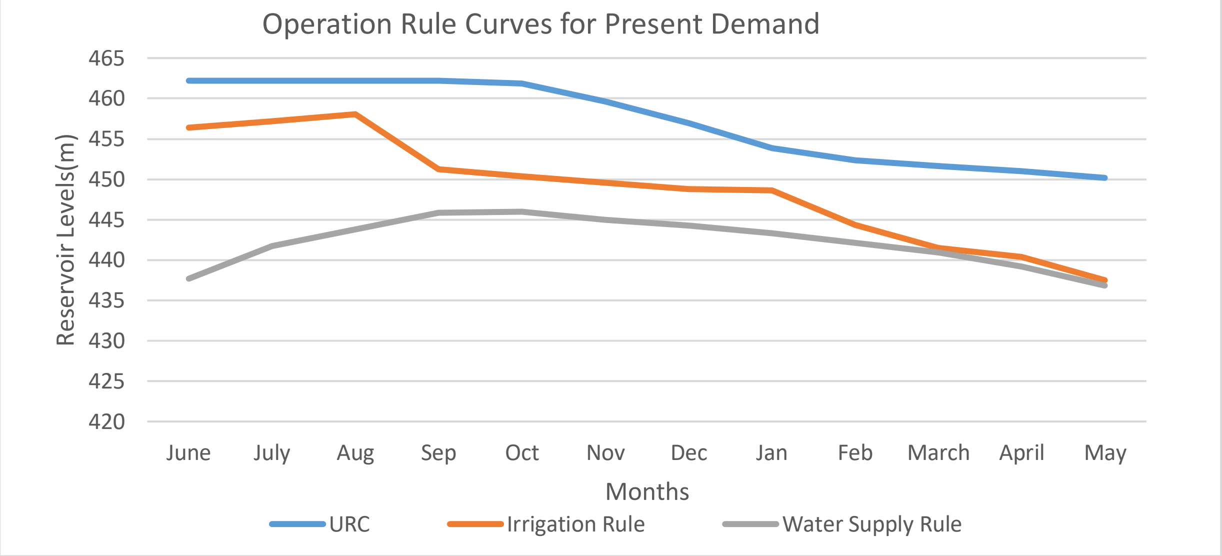


Figure 32. Recommended Rule Curve Levels for Present Demand

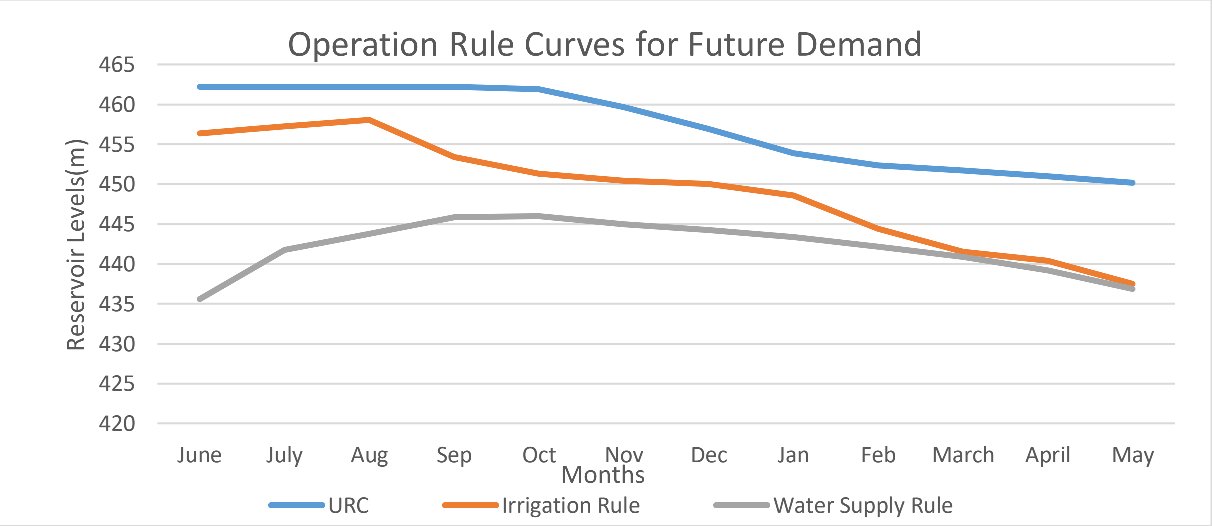


Figure 33. Recommended Rule Curve Levels for Future Demand

Table 33. Recommended Rule Curve for Present Demand

	Upper Rule Curve	Irrigation Rule Curve	Water Supply Rule Curve
Month	**URC(A)**	**MRC(B)**	**LRC (C)**
Jan	453.84	448.59	443.33
Feb	452.35	444.38	442.15
March	451.67	441.5	440.9
April	450.96	440.4	439.18
May	450.17	437.5	436.83

June	462.2	456.37	437.68
July	462.2	457.21	441.74
Aug	462.2	458.05	443.8
Sep	462.2	451.25	445.85
Oct	461.86	450.38	445.98
Nov	459.62	449.55	444.99
Dec	456.91	448.8	444.24

Table 34. Recommended Rule Curve for Future Demand

	Upper Rule Curve	Irrigation Rule Curve	Water Supply Rule Curve
Month	**URC(A)**	**MRC(B)**	**LRC (C)**
Jan	453.84	448.59	443.33
Feb	452.35	444.38	442.15
March	451.67	441.5	440.9
April	450.96	440.4	439.18
May	450.17	437.5	436.83
June	462.2	456.37	435.59
July	462.2	457.21	441.74
Aug	462.2	458.05	443.8
Sep	462.2	453.38	445.85
Oct	461.86	451.31	445.98
Nov	459.62	450.43	444.99
Dec	456.91	449.99	444.24

6.10.4 Scenario III Inflow Increase to 5%

By increasing the inflow to 5% and demand kept at 232 MCM, the reservoir operation rule curves have been developed for scenario III. In the recommended policy for scenario III, the monthly time reliability for the water supply and irrigation comes out to be 100% and 76.2%. The volume reliability for irrigation comes out to be 77.5%. Out of 168 months, there are 18 critical failure months (when the release is less than 75% of the total demand). Therefore, it can be observed that the reservoir can still meet the anticipated water demand, depending on whether it is operated based on the optimal rule curves developed for scenario IV. Table 36 and Fig. 34 show the abstract simulation run for the Kolar Reservoir and recommended rule curves for scenario III, respectively. As the inflow increases to 5%, 10%, there is a reduction in critical failure months simultaneously, as well as time and volume reliability of irrigation also shows significant improvement (increase) respectively.

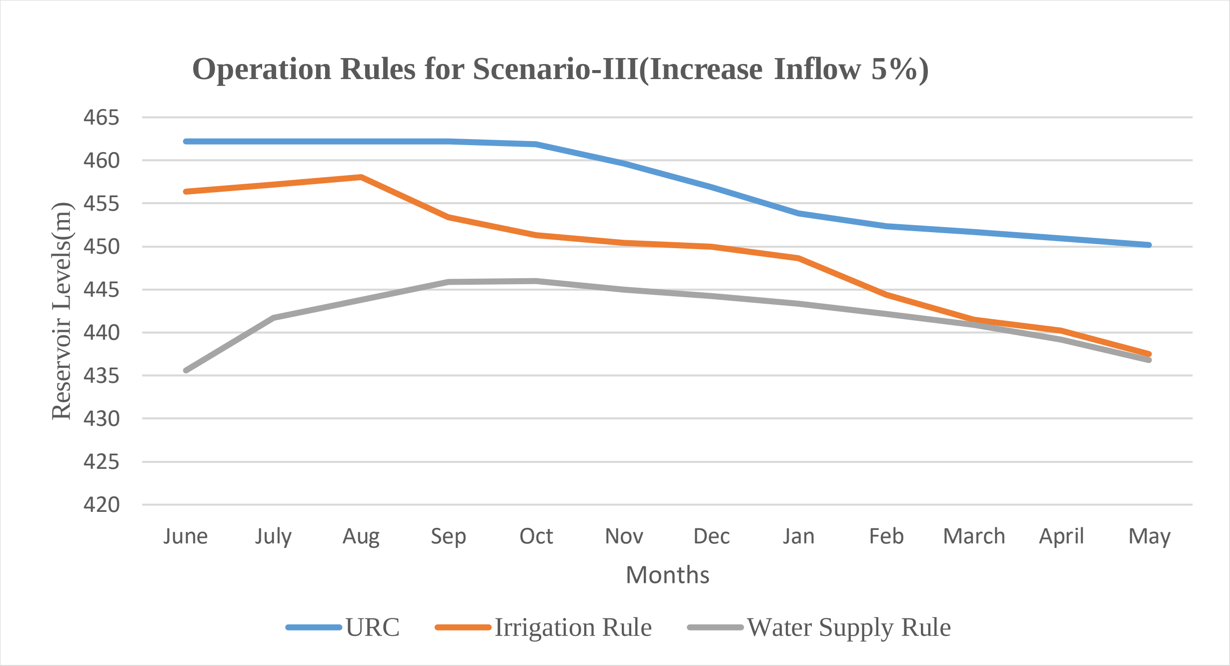


Figure 34. Recommended Rule Curve Levels for Scenario-III Inflow Increase 5%

Simulation of Final Rule Curves for 5% increase in inflow
Number of Failures for WS=0, Time and Vol Reliability= 1.000 1.000
Number of Failures for Irr= 20, Time and Vol Reliability=.762 .775
Number of Critical(Release<0.75 * Demand) Irrigation Failures= 18

Table 35. Recommended Rule Curve for Inflow Increase 5%

	Upper Rule Curve	Irrigation Rule Curve	Water Supply Rule Curve
Month	**URC(A)**	**MRC(B)**	**LRC (C)**
Jan	453.84	448.59	443.33
Feb	452.35	444.38	442.15
March	451.67	441.5	440.9
April	450.96	440.2	439.18
May	450.17	437.5	436.83
June	462.2	456.37	435.59
July	462.2	457.21	441.74
Aug	462.2	458.05	443.8
Sep	462.2	453.38	445.85
Oct	461.86	451.31	445.98
Nov	459.62	450.43	444.99
Dec	456.91	449.99	444.24

6.10.5 Scenario IV Inflow Increase to 10%

Similarly, by increasing the inflow to 10% and the demand kept at 232 MCM, the reservoir operation rule curves have been developed for scenario IV. In the recommended policy for scenario IV, the monthly time reliability for the water supply and irrigation comes out to be 100% and 78.6%. The volume reliability for irrigation comes out to be 79.3%. Out of 168 months, there are 17 critical failure months (when the release is less than 75% of the total demand). Therefore, it can be observed that the reservoir can still meet the anticipated water demand, depending on whether it is operated based on the optimal rule curves developed for scenario IV. Table 37 and Fig. 35 show the abstract of the simulation run for the Kolar Reservoir and recommended rule curves for scenario IV, respectively. As the inflow increases to 5%, 10%, there is a reduction in critical failure months simultaneously, as well as time and volume reliability of irrigation also shows significant improvement (increase) respectively.

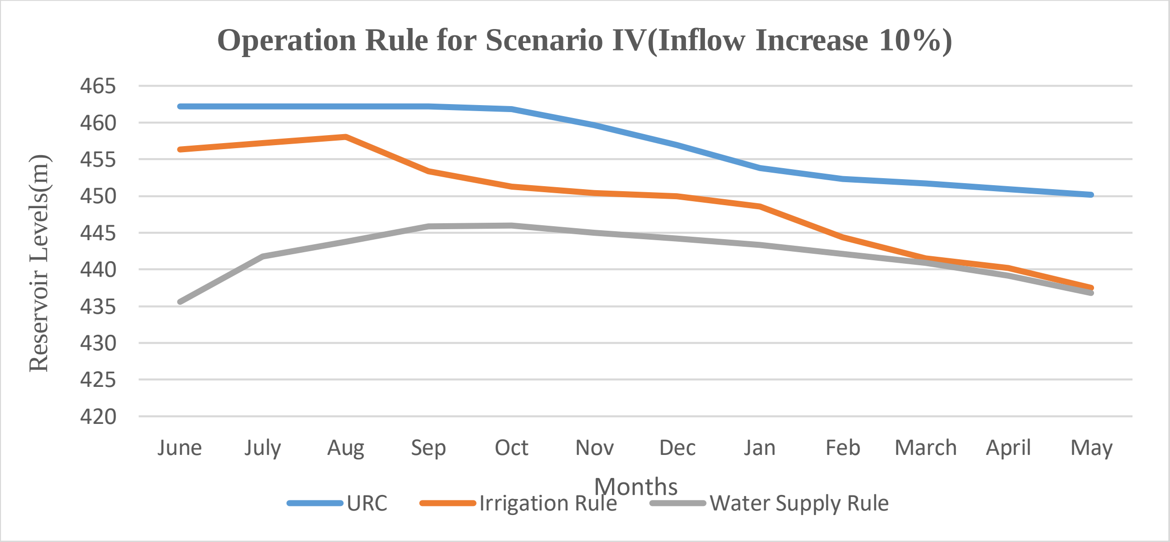


Figure 35. Recommended Rule Curve Levels for Scenario-IV Inflow Increase 10%

Simulation of Final Rule Curves for 10% increase in inflow

Number of Failures for WS=0, Time and Vol Reliability= 1.000 1.000

Number of Failures for Irr= 18, Time and Vol Reliability=.786 .793

Number of Critical(Release<0.75 * Demand) Irrigation Failures= 17

Table 36. Recommended Rule Curve for Inflow Increase 10%

	Upper Rule Curve	Irrigation Rule Curve	Water Supply Rule Curve
Month	**URC(A)**	**MRC(B)**	**LRC (C)**
Jan	453.84	448.59	443.33
Feb	452.35	444.38	442.15
March	451.67	441.5	440.9
April	450.96	440.2	439.18
May	450.17	437.5	436.83
June	462.2	456.37	435.59
July	462.2	457.21	441.74
Aug	462.2	458.05	443.8
Sep	462.2	453.38	445.85
Oct	461.86	451.31	445.98
Nov	459.62	450.43	444.99
Dec	456.91	449.99	444.24

6.10.6 Scenario V Simulation of Final Rule Curves for changed cropping pattern

Cropping pattern has been changed for the Kolar command area, looking into the future demand for water-intensive crops as irrigation supplies are increasing due to the effective choice of irrigation systems, such as micro irrigation. Therefore, the following crops are suggested for the future, based on future cropping pattern change: Spring Wheat, Potato, Small Vegetables, and Pulses to be sown during the Rabi season. The Crop Water Requirement and Irrigation Requirement for the above crops are shown in Table 38.

Table 37. Crop Water Requirement and Irrigation Requirement for Crops Sown under

Rabi Crops(Changed Cropping Pattern)	Crop Water Requirement(ETc) mm/Season	Irrigation Requirement mm/Season
Spring Wheat	350	311
Potato	400	360.5
Small Vegetables	380	340.9
Pulses	225	191

Changed Cropping Pattern

Crop Water Requirement of Rabi crops (changed cropping pattern) for the Irrigated Command area is 129 MCM.

Table 38. Increase Demand for Rabi Crops under Changed Cropping Pattern-Scenario V

	Increase Demand for Rabi Crops(changed cropping pattern)Area 370.13 Sq. Km	**Domestic Demand**	**Total Demand under the changed cropping pattern**
Scenario V	177.17 MCM	71MCM	**248.17 MCM**

Similarly, the reservoir simulation has been carried out separately based on the Changed Cropping Pattern water demands of 248.17 MCM, and the optimum rule curves have been developed as shown in Table 39. It has been assumed that the inflow pattern will increase in the range of 5% to 10% in future according to review of literature in semi-arid regions of central India i.e Madhya Pradesh, though due to Sip-Kolar Link project operationalization additional water of 32 MCM from Sip River joins Kolar dam thereby attaining its full reservoir capacity in last few years i.e in 2022 and 2024. Therefore, the renewed inflow of an increase of 5% has been used to derive the operation rule curves for scenario V. In the recommended policy for Changed Cropping Pattern water demand, i.e, scenario V, the monthly time reliability for the water supply and irrigation comes out to be 100% and 72.6%. The volume reliability for irrigation comes out to be 73.8%. Out of 168 months, there are 23 critical failure months (when the release is less than 75% of the total demand). Therefore, it can be observed that the reservoir can still meet the anticipated Changed Cropping pattern water demand, depending on whether it is operated based on the optimal rule curves developed for the Changed Cropping pattern demand. Table 40, Figure 36, and Table 41 show the abstract of the simulation run for the Kolar Reservoir for the Changed Cropping pattern demands and the recommended rule curve for the Changed Cropping pattern demands.

Table 39. Abstract of the simulation run for the Kolar Reservoir for the Changed Cropping pattern demands

Number of Failures for WS=0	Time and Vol. Reliability =1.00 1.00
Number of Failures for irrigation: 23	Time and Vol. Reliability =0.726 0.738
Number of Critical(Release < 0.75* Demand) Irrigation Failures = 19	
Resi for WS Irrigation Power 0 0.333 0	
Vul for WS Irrigation Power 0 0.781 0	

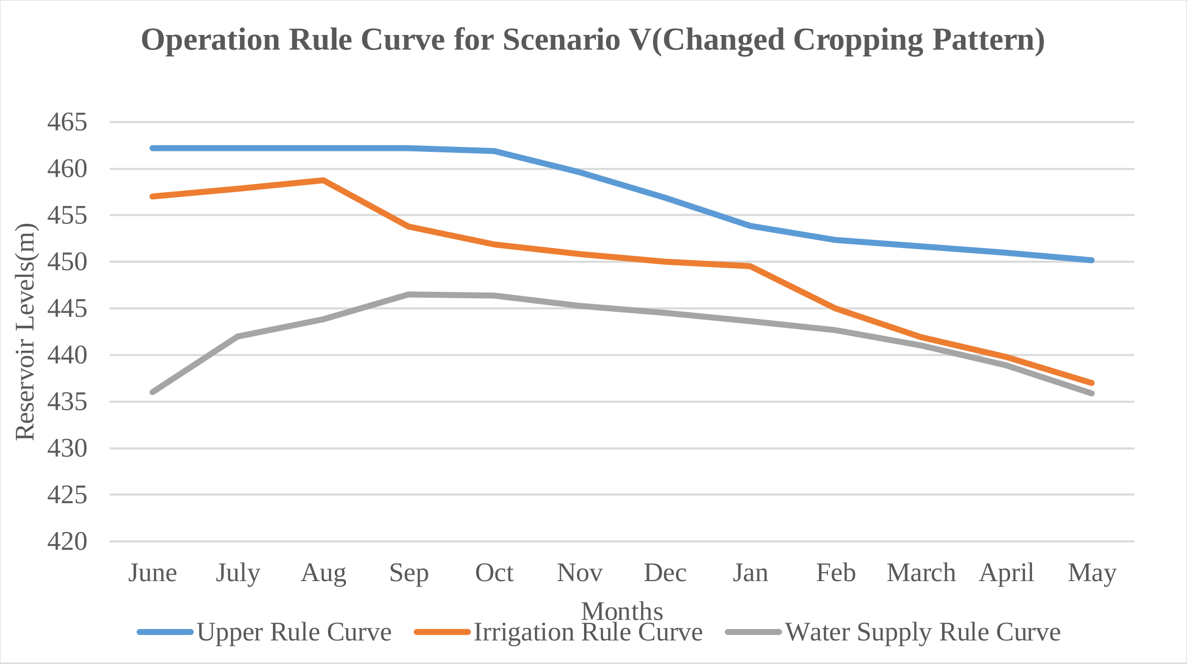


Figure 36. Recommended Rule Curve Levels for Scenario-IV Inflow Increase 10%

Table 40. Recommended Rule Curve for Changed Cropping Pattern Demand

	Upper Rule Curve	Irrigation Rule Curve	Water Supply Rule Curve
Month	**URC(A)**	**MRC(B)**	**LRC (C)**
Jan	453.84	449.5	443.66
Feb	452.35	444.99	442.64
March	451.67	441.5	441.45
April	450.96	439.5	439.25
May	450.17	436.99	436.89
June	462.2	456.99	435.99
July	462.2	457.86	441.99
Aug	462.2	458.75	443.85
Sep	462.2	453.77	446.5
Oct	461.86	451.88	446.35
Nov	459.62	450.84	445.25
Dec	456.91	450	444.55

6.10.7 RECOMMENDED CONSERVATION OPERATION PROCEDURE FOR THE KOLAR RESERVOIR

The recommended procedure for conservation operation of the Kolar reservoir using the three rule curves A (Upper Rule Level), B (Middle Rule Level), and C (Lower Rule Level) is as follows:

For a particular month:

1. Try to maintain the reservoir at rule level A (Upper Rule Level-URL) while meeting all the demands in full. If the reservoir level overtops the rule level A (URL), spill the excess water and bring the reservoir level back to level A (URL).
2. If it is not possible to maintain the reservoir level at A (URL), meet all the demands as long as the reservoir is at or above level B (Middle Rule Level).
3. If it is likely that the reservoir level will go below level B (Middle Rule Level- MRL), it will meet 75% of the target irrigation demands.
4. If the reservoir is at or below rule level C (Lower Rule Level-LRL), make the release to meet only full water supply demand for as long a duration as possible. In this case, stop supplying for irrigation demands completely.
5. It is advisable to periodically review the situation within a month and modify the previous decision (for the remaining duration of that month) and follow steps (1) to (4) to operate the reservoir. Figures 34 and 35 show the final recommended rule levels for meeting the present and future demand for the conservation operation of Kolar dam.

Table 41. Simulation of Kolar Reservoir with Recommended Operation Policy for Present Demand (Working Table generated in NIHReSyP)

Table 42. Simulation of Kolar Reservoir with Recommended Operation Policy for Present (Working Table generated in NIHReSyP)

YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	
	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2010-01-0	147.3	2	1.2	38.6	0.8	38.6	6.1	45.5	0	0	450.62	448.59	453.84	A
2010-02-0	102.6	5.1	1.2	14.4	0.8	14.4	5.6	20.8	0	0	448.99	444.38	452.35	A
2010-03-0	85.7	0.8	1.9	0	0.8	0	6.1	6.9	0	0	448.13	440.9	451.67	A
2010-04-0	77.7	0	2.5	0	0.8	0	5.9	6.7	0	0	447.13	439.18	450.96	A
2010-05-0	68.5	0.2	2.7	0	0.8	0	6.1	6.9	0	0	445.98	436.83	450.17	A
2010-06-0	59.1	1.7	3.7	0	0.8	0	5.9	5.9	0	0	444.87	456.37	462.2	B
2010-07-0	51.2	13.2	0.8	0	0.8	0	6.1	6.1	0	0	445.75	457.21	462.2	B
2010-08-0	57.5	38	0.8	0	0.8	0	6.1	6.1	0	0	449.29	458.05	462.2	B
2010-09-0	88.6	22.5	1.2	9.5	0.8	0	5.9	5.9C	0	0	450.75	451.25	462.2	F
2010-10-0	104	3.6	1.2	3.9	0.8	2.9	5.9	9.6I	0	0	450.1	450.38	461.86	F
2010-11-0	96.8	6.6	0.9	42.2	0.8	11.2	5.9	17.8C	0	0	448.87	449.55	459.62	F
2010-12-0	84.6	0	0.9	42.4	0.8	0	6.1	6.1C	0	0	448.12	448.8	456.91	F
YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	
	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2011-01-0	77.6	0.2	0.8	38.6	0.8	0	6.1	6.1C	0	0	447.39	448.59	453.84	F
2011-02-0	70.9	2.5	0.9	14.4	0.8	14.4	5.6	20.8	0	0	444.93	444.38	452.35	A
2011-03-0	51.6	3.4	1.3	0	0.8	0	6.1	6.9	0	0	444.26	440.9	451.67	A
2011-04-0	46.9	3	1.8	0	0.8	0	5.9	6.7	0	0	443.41	439.18	450.96	A
2011-05-0	41.3	2	1.9	0	0.8	0	6.1	6.9	0	0	442.2	436.83	450.17	A
2011-06-0	34.5	11.8	2.8	0	0.8	0	5.9	5.9	0	0	442.78	456.37	462.2	B
2011-07-0	37.6	62.9	0.9	0	0.8	0	6.1	6.1	0	0	449.78	457.21	462.2	B
2011-08-0	93.5	65.8	1.1	0	0.8	0	6.1	6.1	0	0	454.82	458.05	462.2	B
2011-09-0	152.1	43.8	1.8	9.5	0.8	9.5	5.9	16.2	0	0	456.87	451.25	462.2	A
2011-10-0	177.9	1.9	1.9	3.9	0.8	3.9	5.9	10.5	0	0	456.05	450.38	461.86	A

2011-11-0	167.4	4.3	1.3	42.2	0.8	42.2	5.9	48.8	0	0	452.28	449.55	459.62	A
2011-12-0	121.5	54.9	1.2	42.4	0.8	42.4	6.1	49.3	0	0	452.66	448.8	456.91	A
YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	
	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2012-01-0	126	82.5	1.2	38.6	0.8	38.6	6.1	45.5	0	22	453.84	448.59	453.84	I
2012-02-0	140.1	31.8	1.5	14.4	0.8	14.4	5.6	20.8	0	27	452.35	444.38	452.35	I
2012-03-0	122.4	1.6	2.4	0	0.8	0	6.1	6.9	0	0	451.67	440.9	451.67	I
2012-04-0	114.5	1.5	3.4	0	0.8	0	5.9	6.7	0	0	450.92	439.18	450.96	A
2012-05-0	105.9	2	3.7	0	0.8	0	6.1	6.9	0	0	450.14	436.83	450.17	A
2012-06-0	97.2	2.1	5.3	0	0.8	0	5.9	5.9	0	0	449.24	456.37	462.2	B
2012-07-0	88.2	65.4	1.4	0	0.8	0	6.1	6.1	0	0	454.33	457.21	462.2	B
2012-08-0	146	117.9	1.5	0	0.8	0	6.1	6.9	0	0	461.6	458.05	462.2	B
2012-09-0	255.5	46.1	2.4	9.5	0.8	9.5	5.9	16.2	0	13	462.17	451.25	462.2	I
2012-10-0	270	0.9	2.4	3.9	0.8	3.9	5.9	10.5	0	0	461.7	450.38	461.86	A
2012-11-0	257.9	8.2	1.9	42.2	0.8	42.2	5.9	48.8	0	0	459.45	449.55	459.62	A
2012-12-0	215.4	20.5	1.7	42.4	0.8	42.4	6.1	49.3	0	7	456.91	448.8	456.91	I
YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	
	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2013-01-0	178.4	10.7	1.4	38.6	0.8	38.6	6.1	45.5	0	2	453.84	448.59	453.84	I
2013-02-0	140.1	9.3	1.5	14.4	0.8	14.4	5.6	20.8	0	5	452.35	444.38	452.35	I
2013-03-0	122.4	2	2.4	0	0.8	0	6.1	6.9	0	1	451.67	440.9	451.67	I
2013-04-0	114.5	2.5	3.4	0	0.8	0	5.9	6.7	0	1	450.96	439.18	450.96	I
2013-05-0	106.3	1.4	3.7	0	0.8	0	6.1	6.9	0	0	450.12	436.83	450.17	A
2013-06-0	97.1	41.6	6	0	0.8	0	5.9	5.9	0	0	452.72	456.37	462.2	B
2013-07-0	126.7	121.1	1.9	0	0.8	0	6.1	6.9	0	0	460.85	457.21	462.2	B
2013-08-0	239	21.4	1.8	0	0.8	0	6.1	6.9	0	0	461.43	458.05	462.2	A
2013-09-0	251.7	1	2.3	9.5	0.8	9.5	5.9	16.2	0	0	460.57	451.25	462.2	A
2013-10-0	234.1	0.3	2.3	3.9	0.8	3.9	5.9	10.5	0	0	459.83	450.38	461.86	A
2013-11-0	221.6	0.5	1.7	42.2	0.8	42.2	5.9	48.8	0	0	456.39	449.55	459.62	A
2013-12-0	171.7	0	1.3	42.4	0.8	42.4	6.1	49.3	0	0	452.24	448.8	456.91	A
YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	

	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2014-01-0	121	0	1	38.6	0.8	31.2	6.1	38.1I	0	0	448.59	448.59	453.84	F
2014-02-0	82	0	0.9	14.4	0.8	14.4	5.6	20.8	0	0	446.12	444.38	452.35	A
2014-03-0	60.2	0.7	1.4	0	0.8	0	6.1	6.9	0	0	445.07	440.9	451.67	A
2014-04-0	52.6	0.7	1.9	0	0.8	0	5.9	6.7	0	0	443.94	439.18	450.96	A
2014-05-0	44.7	0.8	1.9	0	0.8	0	6.1	6.9	0	0	442.58	436.83	450.17	A
2014-06-0	36.5	4.2	2.7	0	0.8	0	5.9	5.9	0	0	441.73	456.37	462.2	B
2014-07-0	32.1	51.2	0.8	0	0.8	0	6.1	6.1	0	0	448	457.21	462.2	B
2014-08-0	76.5	30.4	0.9	0	0.8	0	6.1	6.1	0	0	450.38	458.05	462.2	B
2014-09-0	99.9	3.1	1.2	9.5	0.8	0	5.9	5.9C	0	0	450.01	451.25	462.2	F
2014-10-0	95.9	0.4	1.2	3.9	0.8	0	5.9	5.9C	0	0	449.35	450.38	461.86	F
2014-11-0	89.2	0.7	0.9	42.2	0.8	0	5.9	5.9C	0	0	448.72	449.55	459.62	F
2014-12-0	83.2	0	0.9	42.4	0.8	0	6.1	6.1C	0	0	447.97	448.8	456.91	F
YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	
	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2015-01-0	76.2	0	0.8	38.6	0.8	0	6.1	6.1C	0	0	447.22	448.59	453.84	F
2015-02-0	69.3	0.2	0.8	14.4	0.8	14.4	5.6	20.8	0	0	444.4	444.38	452.35	A
2015-03-0	47.9	0.3	1.2	0	0.8	0	6.1	6.9	0	0	443.2	440.9	451.67	A
2015-04-0	40	0	1.5	0	0.8	0	5.9	6.7	0	0	441.66	439.18	450.96	A
2015-05-0	31.8	0	1.5	0	0.8	0	6.1	6.9	0	0	439.78	436.83	450.17	A
2015-06-0	23.4	1	1.9	0	0.8	0	5.9	5.9	0	0	437.7	456.37	462.2	B
2015-07-0	16.7	91	0.8	0	0.8	0	6.1	6.1	0	0	450.46	457.21	462.2	B
2015-08-0	100.8	64.4	1.2	0	0.8	0	6.1	6.1	0	0	455.3	458.05	462.2	B
2015-09-0	157.9	9.6	1.7	9.5	0.8	9.5	5.9	16.2	0	0	454.63	451.25	462.2	A
2015-10-0	149.7	0	1.6	3.9	0.8	3.9	5.9	10.5	0	0	453.63	450.38	461.86	A
2015-11-0	137.5	11	1.1	42.2	0.8	42.2	5.9	48.8	0	0	450.26	449.55	459.62	A
2015-12-0	98.6	7.8	0.9	42.4	0.8	21.6	6.1	28.5C	0	0	448.05	448.8	456.91	F
YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	
	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2016-01-0	77	11.2	0.8	38.6	0.8	0	6.1	6.1C	0	0	448.51	448.59	453.84	F

2016-02-0	81.2	0.9	0.9	14.4	0.8	14.4	5.6	20.8	0	0	446.14	444.38	452.35	A
2016-03-0	60.3	1.2	1.4	0	0.8	0	6.1	6.9	0	0	445.15	440.9	451.67	A
2016-04-0	53.2	1.4	1.9	0	0.8	0	5.9	6.7	0	0	444.14	439.18	450.96	A
2016-05-0	46	0.7	2	0	0.8	0	6.1	6.9	0	0	442.81	436.83	450.17	A
2016-06-0	37.8	3.2	2.7	0	0.8	0	5.9	5.9	0	0	441.77	456.37	462.2	B
2016-07-0	32.3	155.1	1.2	0	0.8	0	6.1	6.1	0	0	457.04	457.21	462.2	B
2016-08-0	180.1	110	1.7	0	0.8	0	6.1	6.9	0	12	462.17	458.05	462.2	I
2016-09-0	270	8.7	2.4	9.5	0.8	9.5	5.9	16.2	0	0	461.79	451.25	462.2	A
2016-10-0	260	0	2.4	3.9	0.8	3.9	5.9	10.5	0	0	461.24	450.38	461.86	A
2016-11-0	247.1	7.6	1.8	42.2	0.8	42.2	5.9	48.8	0	0	458.73	449.55	459.62	A
2016-12-0	204.1	17.1	1.6	42.4	0.8	42.4	6.1	49.3	0	0	456.28	448.8	456.91	A
YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	
	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2017-01-0	170.3	19.7	1.4	38.6	0.8	38.6	6.1	45.5	0	3	453.84	448.59	453.84	I
2017-02-0	140.1	13.7	1.5	14.4	0.8	14.4	5.6	20.8	0	9	452.35	444.38	452.35	I
2017-03-0	122.4	1	2.4	0	0.8	0	6.1	6.9	0	0	451.63	440.9	451.67	A
2017-04-0	114	1.1	3.4	0	0.8	0	5.9	6.7	0	0	450.85	439.18	450.96	A
2017-05-0	105.1	2.3	3.7	0	0.8	0	6.1	6.9	0	0	450.09	436.83	450.17	A
2017-06-0	96.7	7.4	5.4	0	0.8	0	5.9	5.9	0	0	449.71	456.37	462.2	B
2017-07-0	92.9	20.7	1.2	0	0.8	0	6.1	6.1	0	0	450.96	457.21	462.2	B
2017-08-0	106.3	24.8	1.1	0	0.8	0	6.1	6.1	0	0	452.48	458.05	462.2	B
2017-09-0	123.9	43.1	1.5	9.5	0.8	9.5	5.9	16.2	0	0	454.6	451.25	462.2	A
2017-10-0	149.3	2.5	1.6	3.9	0.8	3.9	5.9	10.5	0	0	453.8	450.38	461.86	A
2017-11-0	139.6	16.1	1.2	42.2	0.8	42.2	5.9	48.8	0	0	450.91	449.55	459.62	A
2017-12-0	105.8	7.9	0.9	42.4	0.8	28.8	6.1	35.7C	0	0	448.05	448.8	456.91	F
YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	
	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2018-01-0	77	0.8	0.8	38.6	0.8	0	6.1	6.1C	0	0	447.39	448.59	453.84	F
2018-02-0	70.9	0.9	0.8	14.4	0.8	14.4	5.6	20.8	0	0	444.73	444.38	452.35	A
2018-03-0	50.2	0.8	1.2	0	0.8	0	6.1	6.9	0	0	443.66	440.9	451.67	A

2018-04-0	42.8	1.3	1.6	0	0.8	0	5.9	6.7	0	0	442.43	439.18	450.96	A
2018-05-0	35.8	1.5	1.6	0	0.8	0	6.1	6.9	0	0	441.04	436.83	450.17	A
2018-06-0	28.7	7	2.3	0	0.8	0	5.9	5.9	0	0	440.75	456.37	462.2	B
2018-07-0	27.4	52.3	0.7	0	0.8	0	6.1	6.1	0	0	447.61	457.21	462.2	B
2018-08-0	72.9	44.8	0.9	0	0.8	0	6.1	6.1	0	0	451.35	458.05	462.2	B
2018-09-0	110.7	16.8	1.3	9.5	0.8	9.5	5.9	16.2	0	0	451.29	451.25	462.2	A
2018-10-0	110.1	5.2	1.3	3.9	0.8	3.9	5.9	10.5	0	0	450.7	450.38	461.86	A
2018-11-0	103.4	13.1	1	42.2	0.8	24.3	5.9	31.0C	0	0	448.87	449.55	459.62	F
2018-12-0	84.6	0	0.9	42.4	0.8	0	6.1	6.1C	0	0	448.12	448.8	456.91	F
YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	
	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2019-01-0	77.6	2.2	0.8	38.6	0.8	0	6.1	6.1C	0	0	447.61	448.59	453.84	F
2019-02-0	72.9	1.9	0.9	14.4	0.8	14.4	5.6	20.8	0	0	445.15	444.38	452.35	A
2019-03-0	53.2	2.1	1.3	0	0.8	0	6.1	6.9	0	0	444.29	440.9	451.67	A
2019-04-0	47	2.8	1.8	0	0.8	0	5.9	6.7	0	0	443.42	439.18	450.96	A
2019-05-0	41.4	3.1	1.9	0	0.8	0	6.1	6.9	0	0	442.42	436.83	450.17	A
2019-06-0	35.7	2.8	2.6	0	0.8	0	5.9	5.9	0	0	441.29	456.37	462.2	B
2019-07-0	30	58.9	0.8	0	0.8	0	6.1	6.1	0	0	448.59	457.21	462.2	B
2019-08-0	82	123.4	1.2	0	0.8	0	6.1	6.9	0	0	458.26	458.05	462.2	B
2019-09-0	197.3	166	2.3	9.5	0.8	9.5	5.9	16.2	0	75	462.17	451.25	462.2	I
2019-10-0	270	20.9	2.5	3.9	0.8	3.9	5.9	10.5	0	16	461.86	450.38	461.86	I
2019-11-0	261.7	0.2	1.9	42.2	0.8	42.2	5.9	48.8	0	0	459.19	449.55	459.62	A
2019-12-0	211.2	15.3	1.6	42.4	0.8	42.4	6.1	49.3	0	0	456.69	448.8	456.91	A
YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	
	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2020-01-0	175.6	24.1	1.4	38.6	0.8	38.6	6.1	45.5	0	13	453.84	448.59	453.84	I
2020-02-0	140.1	13.1	1.5	14.4	0.8	14.4	5.6	20.8	0	9	452.35	444.38	452.35	I
2020-03-0	122.4	2.6	2.4	0	0.8	0	6.1	6.9	0	1	451.67	440.9	451.67	I
2020-04-0	114.5	3.4	3.4	0	0.8	0	5.9	6.7	0	1	450.96	439.18	450.96	I
2020-05-0	106.3	4	3.8	0	0.8	0	6.1	6.9	0	2	450.17	436.83	450.17	I

2020-06-0	97.6	21.6	5.7	0	0.8	0	5.9	5.9	0	0	451.08	456.37	462.2	B
2020-07-0	107.7	9.4	1.3	0	0.8	0	6.1	6.1	0	0	451.25	457.21	462.2	B
2020-08-0	109.7	136.6	1.4	0	0.8	0	6.1	6.9	0	0	460.79	458.05	462.2	B
2020-09-0	238	29.6	2.3	9.5	0.8	9.5	5.9	16.2	0	0	461.32	451.25	462.2	A
2020-10-0	249	15.1	2.4	3.9	0.8	3.9	5.9	10.5	0	0	461.42	450.38	461.86	A
2020-11-0	251.3	49.3	1.9	42.2	0.8	42.2	5.9	48.8	0	32	459.62	449.55	459.62	I
2020-12-0	218.2	45.6	1.7	42.4	0.8	42.4	6.1	49.3	0	35	456.91	448.8	456.91	I
YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	
	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2021-01-0	178.4	47.1	1.4	38.6	0.8	38.6	6.1	45.5	0	38	453.84	448.59	453.84	I
2021-02-0	140.1	5.4	1.5	14.4	0.8	14.4	5.6	20.8	0	1	452.35	444.38	452.35	I
2021-03-0	122.4	3.2	2.4	0	0.8	0	6.1	6.9	0	2	451.67	440.9	451.67	I
2021-04-0	114.5	2.5	3.4	0	0.8	0	5.9	6.7	0	1	450.96	439.18	450.96	I
2021-05-0	106.3	3.9	3.8	0	0.8	0	6.1	6.9	0	2	450.17	436.83	450.17	I
2021-06-0	97.6	20.4	5.6	0	0.8	0	5.9	5.9	0	0	450.97	456.37	462.2	B
2021-07-0	106.5	19.2	1.3	0	0.8	0	6.1	6.1	0	0	452	457.21	462.2	B
2021-08-0	118.2	46.4	1.2	0	0.8	0	6.1	6.1	0	0	455.24	458.05	462.2	B
2021-09-0	157.3	57.3	1.9	9.5	0.8	9.5	5.9	16.2	0	0	458.21	451.25	462.2	A
2021-10-0	196.5	17.4	2.1	3.9	0.8	3.9	5.9	10.5	0	0	458.54	450.38	461.86	A
2021-11-0	201.3	14.1	1.6	42.2	0.8	42.2	5.9	48.8	0	0	455.85	449.55	459.62	A
2021-12-0	164.9	25.2	1.4	42.4	0.8	42.4	6.1	49.3	0	0	453.79	448.8	456.91	A
YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	
	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2022-01-0	139.5	24.4	1.2	38.6	0.8	38.6	6.1	45.5	0	0	451.9	448.59	453.84	A
2022-02-0	117.1	0	1.3	14.4	0.8	14.4	5.6	20.8	0	0	449.93	444.38	452.35	A
2022-03-0	95	0.4	2	0	0.8	0	6.1	6.9	0	0	449.08	440.9	451.67	A
2022-04-0	86.5	3.4	2.8	0	0.8	0	5.9	6.7	0	0	448.42	439.18	450.96	A
2022-05-0	80.4	4.3	3.1	0	0.8	0	6.1	6.9	0	0	447.8	436.83	450.17	A
2022-06-0	74.7	3.1	4.4	0	0.8	0	5.9	5.9	0	0	447.02	456.37	462.2	B
2022-07-0	67.5	144.4	1.5	0	0.8	0	6.1	6.9	0	0	458.68	457.21	462.2	B

2022-08-0	203.4	56.3	1.7	0	0.8	0	6.1	6.9	0	0	461.41	458.05	462.2	A
2022-09-0	251.1	16.4	2.4	9.5	0.8	9.5	5.9	16.2	0	0	461.32	451.25	462.2	A
2022-10-0	249	9.2	2.4	3.9	0.8	3.9	5.9	10.5	0	0	461.16	450.38	461.86	A
2022-11-0	245.2	2.4	1.8	42.2	0.8	42.2	5.9	48.8	0	0	458.24	449.55	459.62	A
2022-12-0	197	14.5	1.5	42.4	0.8	42.4	6.1	49.3	0	0	455.51	448.8	456.91	A
YYYY-Mn-D	Ini_Sto	Loc_Flo	Evapr	Tir_Dem	Tds_Dem	Ir_Rel	Ws_Rel	Tot_Rel	Lin_Dv	Spill	End_Lev	Mdl_Rul	Upr_Rul	
	Mm3	Mm3	m	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	Mm3	m	m	m	
2023-01-0	160.6	20.1	1.3	38.6	0.8	38.6	6.1	45.5	0	0	453.33	448.59	453.84	A
2023-02-0	133.9	13.9	1.5	14.4	0.8	14.4	5.6	20.8	0	3	452.35	444.38	452.35	I
2023-03-0	122.4	2.4	2.4	0	0.8	0	6.1	6.9	0	1	451.67	440.9	451.67	I
2023-04-0	114.5	3.5	3.4	0	0.8	0	5.9	6.7	0	2	450.96	439.18	450.96	I
2023-05-0	106.3	4	3.8	0	0.8	0	6.1	6.9	0	2	450.17	436.83	450.17	I
2023-06-0	97.6	13.8	5.5	0	0.8	0	5.9	5.9	0	0	450.39	456.37	462.2	B
2023-07-0	100	77.7	1.5	0	0.8	0	6.1	6.1	0	0	456.26	457.21	462.2	B
2023-08-0	170	15.1	1.4	0	0.8	0	6.1	6.1	0	0	456.85	458.05	462.2	B
2023-09-0	177.6	52.5	2	9.5	0.8	9.5	5.9	16.2	0	0	459.23	451.25	462.2	A
2023-10-0	211.9	4.9	2.1	3.9	0.8	3.9	5.9	10.5	0	0	458.73	450.38	461.86	A
2023-11-0	204.1	10.7	1.6	42.2	0.8	42.2	5.9	48.8	0	0	455.81	449.55	459.62	A
2023-12-0	164.4	12.8	1.3	42.4	0.8	42.4	6.1	49.3	0	0	452.71	448.8	456.91	A

Number of Failures for WS. = 0, Time and Vol. Reliability = 1 1

Number of Failures for Irr. = 18, Time and Vol. Reliability = 0.786 0.774

Number of Critical (Release < 0.75 * Demand) Irrigation Failures = 16

Resi. for WS, Irr, Pow: 0 0.333 0
Vul. for WS, Irr, Pow: 0 0.799 0

7.0 CONCLUSIONS

7.1 Crop Water Requirement and Irrigation Scheduling

This study was carried out to determine crop water requirement and irrigation scheduling of Rabi and Kharif crops cultivated in the Kolar Command area. The major conclusions which can be drawn are as follows –

(i) The results obtained from this study for average rainfall year can be used by the Water Resource Department for future planning and helps to save water in satisfying crop water requirement and serves as a guide to farmers for selecting the amount and frequency of irrigation water which could be used judiciously for crops especially for Rabi crops.

(ii) The Kolar dam authority supplies irrigation water only during the Rabi Season for Rabi crops, whereas there is no supply of water from it for the irrigation of Kharif crops.

(iii) Therefore, the entire Irrigated command area of 37013 ha requires 151.08 MCM water for Rabi crops and 71 MCM for Domestic Water Supply. On average, the Kolar dam released 145.52 MCM of water over the period of 15 years (2009-2024), which implies that the dam does not fill to its full gross storage capacity of 270 MCM.

(iv) As such, the dam cannot conveniently supply the water demand for Rabi irrigation in the command area, and there is a need for proper management of water resources.

(v) Therefore, the Sip–Kolar link project is initiated (operational since 2022) whereby diversion of 35 MCM water from the Sip River to Kolar dam during June to October to augment the storage shortfall in Kolar dam to meet the irrigation demands as well as the domestic demands.

7.2 Trend Analysis of Hydro-meteorological Parameters

The analysis reveals the evolving trends in rainfall and temperature patterns within the basin, which may impact the reservoir storage and water availability for various uses. Appropriate water allocation strategies need to be devised to meet the committed demands for various water usages, including present and future agricultural demands due to increased consumptive use for crops, as well as to meet the rising domestic water demand for Bhopal city, to the rising water demands of a growing population.

Even though the trends in the annual, seasonal, and monthly rainfall are not significant at the 95% confidence level in the basin, significant trends have been observed in the maximum and minimum temperature in the study area. The increase in the minimum temperature is dominant as compared to the increase in the maximum temperature. The increases in the minimum and maximum temperatures may be attributed to climate change, and calls for adequate planning and management of water resources in the basin.

7.3 Estimation of Water Balance of Kolar Reservoir

The water balance of Kolar reservoir has been carried out in an Excel worksheet where reservoir levels, outflows, spill, losses due to evaporation, and seepage were used to determine inflow daily for the water year (June 01 to May 31 next year). The seepage and evaporation are the major losses from Kolar reservoirs depend on the area of contact and water spread, respectively. The results of water balance for reservoirs indicated average annual inflow may be 200±50 MCM from Kolar Reservoir.

It is seen that over the period (15 years) through water balance of Kolar reservoir (2009-2024), the water availability in the dam is not sufficient, i.e, only for 5 years the reservoir has attained Full Reservoir Level (462.20 m) i.e. 270 MCM with inflow ranges more than 230 MCM. The water availability in the dam based on last 15 years inflow data indicates that inflow has not been sufficient (<230 MCM) does not meet the irrigation demands in full in most of the years considered for the simulation i.e 72% to 77% of volume reliability for irrigation is seen, except during 4 years i.e., 2012-13(inflow of 289.86 Mm^3), 2013-14 (inflow of 291.98 Mm^3), 2016-17 (inflow of 236.20 Mm^3) and 2019-20 (inflow of 294.34 Mm^3).

The reservoir water balance is a preliminary exercise before the reservoir operation, which was carried out to compute the inflow in the Kolar Reservoir over a period of 2009-2024 as well as water storage available in the reservoir at the end of the water year (i.e., May. It also gave a fair idea about the availability of water in the past and present as well as future availability scenario could also be seen based on future changes in water demand. Also this exercise gave a fair idea about the validity of the estimation of seepage and other water balance components.

7.4 Reservoir Operation for Optimal Utilization of Water resources of Kolar Reservoir

As in India there exist uncertain monsoon, hence it becomes imperative to use its limited water resources efficiently. Reservoir operation plays an important role in management of scarce water resources available in the country and water crisis prevalent in many cities and towns. In the present study policy to optimally utilize the conservation storage of Kolar reservoir has been developed for different Scenarios I to V which are as follows (i) present demand (ii) future demand (iii) Inflow increase to 5% (iv) Inflow increase to 10% (v) Cropping pattern change. The operation of Kolar reservoir with the recommended policy has been suggested using 14 years inflow series. Important conclusions for Reservoir operation policy for optimal utilization of conservation storage of Kolar reservoir for present and future demand as well as different scenarios are as follows:

(i) The recommended policy gives the irrigation rule curves to distribute the deficit equitably much in advance for both present and future demand as well as in case of different (iii) to (v) scenarios of Kolar dam.

(ii) In the recommended policy for present demand, the monthly time reliability for the water supply and irrigation comes out to be 100% and 78.6%.The volume reliability for irrigation comes out to be 77.4%.Out of 168 months there are 16 critical failure months (when the release is less than 75% of the total demand).

(iii) In the recommended policy for future demand, the monthly time reliability for the water supply and irrigation comes out to be 100% and 75%.The volume reliability for irrigation comes out to be 75.6%.Out of 168 months there are 18 critical failure months (when the release is less than 75% of the total demand).

(iv) The volume reliability for irrigation for recommended policy for present demands and future demand is 77.4% and 75.6% respectively having a difference of 1.8% which shows improvement in conservation in prior case, whereby the critical failure months is reduced for recommended policy of present demands to 16 critical failure months from 18 critical failure months in future policy while catering to increased demand of 10MCM.

(v) The water availability in the dam based on last 15 years inflow data series indicates that inflow has not been sufficient (<230 MCM) does not meet the irrigation demands in full in most of the years considered for the simulation, i.e 72% to 77% of volume reliability for irrigation is seen, except during 4 years i.e., 2012-13(inflow of 289.86 Mm^3), 2013-14 (inflow of 291.98 Mm^3), 2016-17 (inflow of 236.20 Mm^3) and 2019-20 (inflow of 294.34 Mm^3) which constitutes 26.66%. Hence Sip-Kolar Link project was initiated to divert 35 MCM water from Sip River to Kolar dam and is functional since 2022 in order to bring the Kolar Reservoir to attain its FRL which is successful too as in year 2022 and 2024 Kolar Reservoir was first to fill and attain FRL. From the period of Sip-Kolar link operation in the year 2022 the Kolar reservoir has attain its FRL in 2022 and 2024 respectively.

The Kolar dam mainly caters for irrigation purposes and water supply to Bhopal city. The upper rule curve levels in all the months is kept below FRL to maximum extent possible in order to serve the conservation requirement of the reservoir. It is required to maintain the reservoir at the upper rule level and spill the additional water at rate of inflow so that the reservoir can be kept at this level. The recommended policy for present and future demand is given for Kolar reservoir to operate at optimum limit.

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