University
of Ljubljana
Faculty
for Civil and Geodetic Engineering

PAVAN KUMAR YEDITHA

MODELLING THE IMPACTS OF RESERVOIR OPERATION ON RIVER FLOODS:
A CASE STUDY OF CAUVERY BASIN IN INDIA

MASTER'S THESIS

MASTER STUDY PROGRAMME FLOOD RISK MANAGEMENT

Univerza *v Ljubljani*

Ljubljana, 2022

University
of Ljubljana
Faculty
for Civil and Geodetic
Engineering

Candidate

PAVAN KUMAR YEDITHA

MODELLING THE IMPACTS OF RESERVOIR OPERATION ON RIVER FLOODS:

A CASE STUDY OF CAUVERY BASIN IN INDIA

Master's thesis no .: 504.61:556.166(540)(043.3)

Mentor:
Dr. Sanjay Giri, PhD
Specialized consultant, river basin and reservoirs
Deltares, Netherlands

Co-mentor:
Assoc. Prof. Dr Biswa Bhattacharya, PhD
IHE Delft Institute for Water Education
Netherlands

Commission member:
Assoc. Prof. Dr.Biswa Bhattacharya, PhD

Chairman of the Commission:
Prof. Dr. Simon Rusjan, PhD

Supervisor:
Prof. Dr. Matjaž Mikoš, PhD

Delft, 29 August 2022

Univerza *v Ljubljani*

I, PAVAN KUMAR YEDITHA, registration number 26125065, author of the written thesis of the study entitled**: Modelling the impacts of reservoir operation on river floods: A case study of Cauvery basin in India.**

I DECLARE

1. Circle one of variants a) or b)
   a) that the written final work of the study is the result of my independent work;

   b) that the written final work of the study is the result of the own work of several candidates and meets the conditions set out in the UL Statute for joint final work of the study and is in the required proportion the result of my independent work;

2. that the printed form of the written final part of the study is identical to the electronic form of the written final part of the study;

3. that I have obtained all the necessary permissions for the use of data and copyrighted works in the written final part of the study and clearly marked them in the written final part of the study.

4. that in preparing the written final part of the study I acted in accordance with ethical principles and, where necessary, obtained the consent of the ethics commission for the research.

5. I agree that the electronic form of the written final part of the study is used to check the similarity of the content with other parts with the software for checking the similarity of the content related to the study information system of the member;

6. to transfer to UL free of charge, non-exclusively, spatially and indefinitely the right to store the author's work in electronic form, the right to reproduce and the right to make the written final part of the study available to the public on the World Wide Web through the UL Repository;

7. dissertations. UL consents enable free, non-exclusive, space and time unlimited storage of the author's work in electronic form and reproduction and making the dissertation available to the public on the World Wide Web through the UL Repository;

8. that I allow the publication of my personal data, which are stated in the written final part of the study and this statement, together with the publication of the written final part of the study.

V / Na:

Date: 29/08/22

YPavan

Student's signature / -to:

"This page is intentionally blank"

ERRATA

Error page	Error bar	Instead	Let it be

ACKNOWLEDGEMENTS

This research work is a collaborative effort of many individuals without whose support and guidance this research would not have been materialized. First, I would like to offer my special thanks to my mentor Dr Sanjay Giri for accepting me to Deltares to pursue my thesis research and seamlessly supervising me throughout my thesis period. I am thankful for providing me all the necessary data needed for the successful completion of the thesis, reserving his time for me to clarify all my doubts, responding to my messages at odd hours of the day and correcting my approach toward the thesis, reports and also giving me value advice related to my future goals in life as a student as well as a professional.

Special thanks to the River and Inland shipping department for their warm and welcoming environment, which seamlessly helped me interact with everyone and gain immense knowledge from them. I would especially thank Dr Amgad and Dr Victor, who have helped me throughout my thesis by sparing their valuable time and knowledge to clear my doubts.

Dr Biswa Bhattacharya's guidance and support during the whole period of my master's and especially during the thesis period has helped me overcome all the difficulties that came my way. This continuous support motivated me and made me curious to learn new things throughout this master and thesis.

I am grateful to Matjaž Mikoš, my supervisor, for sparing his time and giving me valuable feedback and suggestions for putting forward my thesis more scientifically.

Since this thesis report is the last piece of work for my Master's degree, I would like to gratefully acknowledge The European Commission for awarding me the scholarship to follow this Erasmus Mundus Programme in Flood Risk Management (EM-FRM). I am thankful t the lecturers and support staff of the four institutes/universities- IHE Delft, Technical University of Dresden (TUD), Polytechnical University of Catalonia (UPC) and the University of Ljublijana. My special thanks to Dr Biswa Bhattacharya for his continuous support as program coordinator and Mrs Ineke Melis for all her help and support throughout the period.

I am grateful to the FRM family for their cherished memories, friendship, and encouragement they have given me during these two years.

I thank my mentors, Dr Maheswaram Rathinasamy and Dr Ankit Agarwal, without whom I would not have realised my life path and achieved this scholarship to move forward towards my future goals. I thank my friends who have supported and helped me to come to Europe to start this master's and complete it successfully.

Last but not least, my sincere thanks to my family, who have been by my side and provided me with the strength to overcome all the challenges I faced regardless of distance. Their unconditional love, support and encouragement brought me up to this extent.

Delft Pavan Kumar Yeditha
August 2022

BIBLIOGRAPHIC-DOCUMENTALISTIC INFORMATION AND ABSTRACT

UDC:	**504.61:556.166(540)(043.3)**
Author:	**Yeditha Pavan Kumar**
Supervisor:	**Dr Sanjay Giri, Dr Biswa Bhattacharya**
Co-supervisor:	**Dr. Matjaž Mikoš**
Title:	**Modelling the impacts of reservoir operation on river floods: A case study of Cauvery basin in India.**
Document type:	**Master thesis**
Notes:	**89 pg., 8 tab., 60 fig., 2 eq., 1 ap**
Keywords:	**Floods, Cauvery river basin, Real-time control (RTC), flood control, reservoir analysis.**

Abstract

Floods are one of the most devastating natural disasters, affecting millions of people around the world. Extreme events have increased considerably due to climate change, which has increased the occurrence of floods in many major river basins around the world. India is a country with multiple monsoon-based rivers and extreme weather events. The occurrence of large-scale floods has increased noticeably. The socioeconomic impact of these floods is immense since they occur in such short periods. The Cauvery River basin is one of the key river basins identified as prone to flooding each year. There are numerous dams and barrages in the basin. The prevalence of floods in this basin is attributed to the basin's severe short-term and flashy rainfall pattern, according to reports and news stories. Furthermore, considering their primary aim of agriculture and drinking water supply, the dams do not appear to consider flood management. To better understand the occurrence of floods and the impact of dams on floods in the basin, comprehensive research was conducted utilizing process-based numerical modelling methods in conjunction with data analysis, emphasising the 2018 flood event. Following the knowledge of the processes in the basin connected to the occurrence of floods and dam operation, one-dimensional (1D) process-based hydrodynamic models (Delft3D-FM) paired with a Real-Time Control (RTC) tool for dam operation were built for the main Cauvery river, including some major branches including Kabini and Bhavani. Based on observable data, the model was initially calibrated and validated. It was then used to simulate the real-world system and understand the propagation of the 2018 flood. According to the results study, the dams in the basin did not produce any additional floods to the river other than passing through the arriving flood peaks. However, the dams may be utilised to mitigate the consequences of the flood. As a result, several dam operation scenarios were explored to determine whether the existing dams are suitable for flood management. To that end, a series of model simulation scenarios were created and tested to determine whether dams can be utilized to collect flood peaks and under what conditions they can be used for flood management. Based on an understanding of the flooded areas, the Mettur reservoir in the main Cauvery river was used for scenario simulations to assess the effects of the reservoir operation. Based on the reservoir analysis, it was found that the reservoir is not capable of capturing floods with its current specifications. To capture the impending flood peaks, two main scenarios were simulated: lowering the spillway crest level (i.e. increasing flow capacity) and raising the dam height (i.e. increasing reservoir storage). The findings of the simulation and analysis demonstrated that the reservoirs could capture the flood peaks in both scenarios. Even though these scenarios appear to help improve the flood management functions of the Mettur reservoir, other technical, economic, social, and environmental factors must be addressed when picking solutions for the real-world situation. This study successfully replicates and reveals some essential features linked to the consequences of dams on flood propagation in the Cauvery river, as well as the importance of reservoir storage and spillage capacity in conjunction with an efficient reservoir operation strategy.

BIBLIOGRAFSKO – DOKUMENTACIJSKA STRAN IN IZVLEČEK

UDK:	**504.61:556.166(540)(043.3)**
Avtor:	**Yeditha Pavan Kumar**
Mentor:	**Dr. Sanjay Giri, Dr. Biswa Bhattacharya**
Somentor:	**Dr. Matjaž Mikoš**
Naslov:	**Modeliranje vplivov delovanja akumulacije na rečne poplave: študija primera bazena Cauvery v Indiji.**
Tip dokumenta:	**magistrsko delo**
Obseg in oprema:	**89 str., 8 pregl., 60 sl., 2 eq., 1 pril.**
Ključne besede:	**Poplave, porečje reke Cauvery, nadzor v realnem času (RTC), nadzor poplav, analiza rezervoarja**

Izvleček:

Poplave so ena najbolj uničujočih naravnih nesreč, ki prizadene milijone ljudi po vsem svetu. Ekstremni dogodki so se znatno povečali zaradi podnebnih sprememb, ki so povečale pojav poplav v mnogih večjih porečjih po svetu. Indija je država z več monsunskimi rekami in ekstremnimi vremenskimi pojavi. Pojav večjih poplav se je opazno povečal. Družbeno-ekonomski vpliv teh poplav je ogromen, saj se zgodijo v tako kratkih obdobjih. Povodje reke Cauvery je eno od ključnih porečij, ki so vsako leto izpostavljena poplavam. V porečju so številni jezovi in jezovi. Glede na poročila in novice se razširjenost poplav v tem porečju pripisuje močnemu kratkotrajnemu in bliskovitemu vzorcu padavin. Poleg tega se zdi, da glede na njihov glavni cilj kmetijstva in oskrbe s pitno vodo jezovi ne upoštevajo obvladovanja poplav. Za boljše razumevanje pojavljanja poplav in vpliva jezov na poplave v porečju je bila izvedena obsežna raziskava z uporabo procesnih metod numeričnega modeliranja v povezavi z analizo podatkov, s poudarkom na poplavnem dogodku leta 2018. Po poznavanju procesov v bazenu, povezanih s pojavom poplav in delovanjem jezov, so bili izdelani enodimenzionalni (1D) procesni hidrodinamični modeli (Delft3D-FM) v povezavi z orodjem za nadzor v realnem času (RTC) za delovanje jezov. zgrajena za glavno reko Cauvery, vključno z nekaterimi večjimi vejami, vključno s Kabinijem in Bhavanijem. Na podlagi opazovanih podatkov je bil model prvotno umerjen in validiran. Nato je bil uporabljen za simulacijo resničnega sistema in razumevanje širjenja poplave leta 2018. Glede na študijo rezultatov jezovi v porečju niso povzročili nobenih dodatnih poplav v reki, razen prehoda skozi prihajajoče poplavne vrhove. Jezovi pa se lahko uporabijo za ublažitev posledic poplave. Posledično je bilo raziskanih več scenarijev obratovanja jezov, da bi ugotovili, ali so obstoječi jezovi primerni za obvladovanje poplav. V ta namen je bila ustvarjena in preizkušena vrsta modelnih simulacijskih scenarijev, da bi ugotovili, ali je jezove mogoče uporabiti za zbiranje poplavnih konic in pod kakšnimi pogoji jih je mogoče uporabiti za obvladovanje poplav. Na podlagi razumevanja poplavljenih območij je bil rezervoar Mettur v glavni reki Cauvery uporabljen za simulacije scenarijev za oceno učinkov delovanja rezervoarja. Na podlagi analize zadrževalnika je bilo ugotovljeno, da zadrževalnik s trenutnimi specifikacijami ni sposoben zajemati poplav. Za zajem bližajočih se konic poplav sta bila simulirana dva glavna scenarija: znižanje vrha preliva (tj. povečanje zmogljivosti pretoka) in dvig višine jezu (tj. povečanje zadrževanja rezervoarja). Ugotovitve simulacije in analize so pokazale, da lahko akumulacije zajamejo konice poplav v obeh scenarijih. Čeprav se zdi, da ti scenariji pomagajo izboljšati funkcije obvladovanja poplav zadrževalnika Mettur, je treba pri izbiri rešitev za dejansko stanje upoštevati druge tehnične, ekonomske, socialne in okoljske dejavnike. Ta študija uspešno posnema in razkriva nekatere bistvene značilnosti, povezane s posledicami jezov na širjenje poplav v reki Cauvery, kot tudi pomen skladiščenja rezervoarja in zmogljivosti razlitja v povezavi z učinkovito strategijo delovanja rezervoarja.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

KRS	Krishna Raja Sagara
IMD	Indian Meteorological Department
CRB	Cauvery River Basin
HO Station	Hydrological observation station

1 INTRODUCTION

1.1 Background

Rivers are one of the major sources of surface freshwater and the primary water source on this planet, which is why it is essential for life. Rivers carry freshwater that originates from glaciers, rain, or other sources. Their effects on society and the environment vary depending on where they come from and how much volume they carry. According to observations of earlier civilizations, rivers played an important part in their development by supplying crucial resources such as fertile soil for plant growth, freshwater for drinking, and an easy mode of transportation for travel between various places. As a result, several ancient civilizations developed alongside the river's banks. Rivers, the source of life for many civilizations, can pose floods, one of the most catastrophic and costly natural calamities.

Floods have been observed to have consequences other than cost and fatalities throughout history. They have substantial consequences such as community upheaval, dislocation, and societal imbalance. The effective use of flood control techniques is one of the key factors in reducing floods and their effects. Many structures have been built in river systems from ancient times to manage river flows and avert natural calamities such as floods. Along with flood protection, these structures performed other functions such as river water storage and distribution.

A dam is one of the most important constructions built to control and regulate large amounts of water like rivers. Dams are structures made of concrete, wood, earthy materials, steel, and other things. Their main objective is to create a huge barrier containing the water for future use. Dams are used for various functions, including water supply, hydro and tidal power generation, flood protection from river flooding, irrigation, marine defence, recreation, water conservation, debris control, transportation, tourist attractions, and others. Despite the fact that they can be used to protect against floods, dams are only effective up to the design flood for which they were built. Dams cannot regulate extreme occurrences that exceed the limits of dam design.

With extreme events causing severe floods in many basins becoming increasingly common over the last decade, it is critical to design a strong flood management strategy to avoid tragedies caused by these extreme events. One strategy that is commonly utilized nowadays is reservoir operation optimization for flood control. Dams can be used efficiently to optimize the reservoir's discharge and accommodate the peak flow if reliable flood forecasts are available. A reservoir's level of protection is determined by ideal release patterns, lead time, and river section capacity. Reservoir operation for flood control is a complex procedure with many competing interests. Some of them are water releases prior to the arrival of flood peaks, the reservoir's water level during flood events, the reservoir's available free storage during the beginning phases of the inflow flood peak, and ensuring that reservoir releases do not cause flooding in areas downstream of the reservoir. The reservoir operating problem becomes more complicated when a flood-prone river basin includes many reservoir systems. Typically, the decision to operate a reservoir is based on "thumb rules" that consider stage-discharge relations and previous flood events. Due to catastrophic flooding scenarios, the available rules are inapplicable.

1.2 Problem statement

Floods are a major natural calamity that has a global impact on society. Controlling and eradicating floods in a river system is crucial in determining the extent of damage caused by the catastrophic phenomena (Lempérière, 2017). Many countries have suffered significant weather events that have resulted in floods throughout the last decade. Dams, when used properly, are one of the constructions that can aid in flood mitigation. Dams in river systems are large human interventions in river systems with both beneficial and negative consequences (Magilligan and Nislow, 2005). Even if mega-dams are present in a river system, they might inflict more damage than regular flood events if not managed properly. Improper use of these dams may increase the likelihood of floods due to sediment entrapment and downstream alterations induced by diminished sediment mobility (Magilligan and Nislow, 2005; Petkovsek and Roca, 2014). The main feature that defines the reduction in flood component effects and silt transfer downstream is determining the best operation of the dams. Identifying suitable dams and their optimal release patterns is thus a major task in many river basins where dams are either used or not employed for flood control (Richter and Thomas, 2007).

1.3 Literature review

Previous studies focused on the occurrence of floods, impacts of dams and reservoir operation, as well as the best operation of dams to mitigate their effects. Among the few domains that have received attention are:

1.3.1 Dams and their impacts on floods

Fluvial floods are one of the most devastating natural disasters, mostly produced by the effect of rainfall and other changes in the basin over many decades. The impact of dams on river flow and peaks has shifted since the industrial period and the significant growth in dam construction. Among the works that have examined these developments are:

In Quebec, Canada, Lajoie et al. (2007) contrasted and studied the impact of reservoir-induced changes in regulated and natural rivers. According to the study's findings, the winter and spring flows were altered during the estimation of controlled flows. The estimation methods revealed that the flows had been underestimated. The frequency and time of occurrence of the flows downstream of the dam were the most influenced. According to Kummu and Sarkkula (2008), building a hydropower dam on the Mekong River will result in increased dry season water levels and lower flood peaks. Furthermore, negative effects on ecosystem production and permanent floods in vegetative regions were detected. FitzHugh and Vogel (2011) examined the effects of dams on flood flow in the United States using a multivariate regional model, and the results revealed that flood flows were altered in all parts of the country, with the western region of the Mississippi exhibiting the greatest changes. The median annual flow was found to have decreased by more than 25% in 55% of the large rivers, 25% of the medium size rivers, and 10% of the minor rivers. To assess the influence of the Three Gorges Dam and Water Transfer Project on Changjiang floods, Nakayama and Shankman (2013) created a process-based model. The study found that the Three Gorges Model (TGD) enhanced flood risk due to summer groundwater. Furthermore, the impact of flood peaks can be mitigated due to reservoir release. However, electricity generation from the dam during the rainy season is impacted.

The impact of a dam on the flood trend of the lower watershed of the Mayurakshi river basin, India, was studied by Ghosh and Pal (2015), who examined alterations in the regular sequence of high flows. Flow analysis utilizing various probability distributions and flood studies were performed in this study, and the results showed that the frequency of medium and low flows had increased due to the basin's moderation. Ghosh and Guchhait (2016) investigated the effects of dams on flood hydrology and frequency in the Damodar river basin, West Bengal, India. To investigate the river system changes caused by the dam, this study used flood frequency analysis and the Gumbel probability distribution. The work results revealed that the intensity of the floods and peak flows were lowered during post-dam construction. Mei et al. (2017) investigated the dam's impact on flood occurrence in rivers in the United States, and the findings of the trend and change point analysis revealed that in 37 rivers, the reduction in peak discharge ranged from 7.4% to 95.14%.
Furthermore, the frequency and intensity of the incidents were reduced once the dam was built. Flood inundation mapping of Surat in India by Patel et al. (2017) revealed that floods were detected in the city of Surat as a result of the release of peak discharges from the Tapi river. It was also discovered that the city's west was inundated, and an examination was conducted to see whether preventive measures could preserve the areas. Furthermore, despite preventative precautions, the city's west zone was inundated, according to the analysis. Zhao et al. (2020) examined many dams in the GRanD database in the United States to better understand how dams influence design discharge (2020). Several models, including Random Forest, MLR models, and LISTFLOOD-FP 2D models, were utilized in this study to understand the changes in river systems after dams were built. Figure 1-1 depicts all relevant studies and models employed.

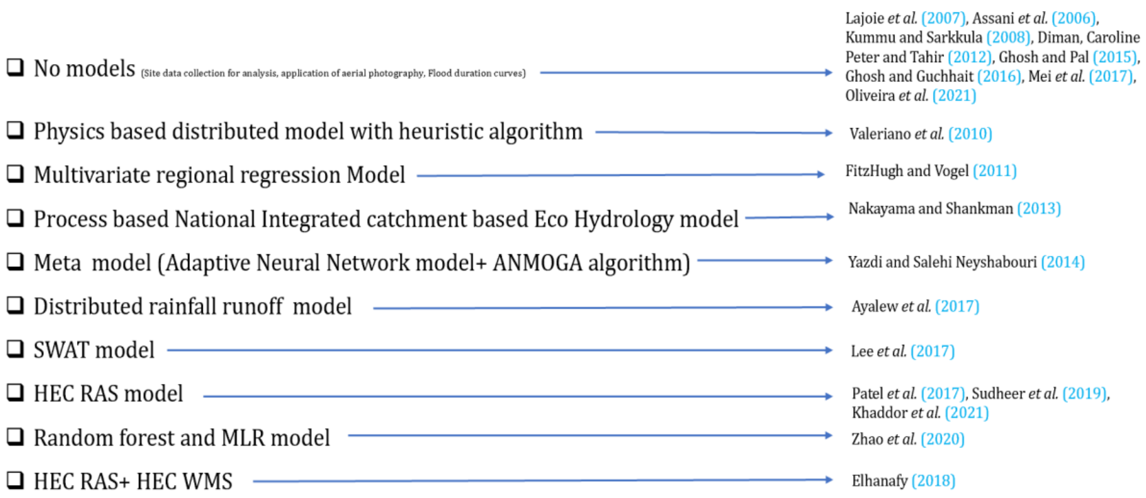


Figure 1-1: Methods adopted in previous studies

1.3.2 Reservoir operation

The primary aim of flood control is to determine appropriate reservoir operation patterns that minimize downstream damage while keeping the dam within its design limitations. Due to the task of decision-making in short and uncertain times, the challenges and implications of these decisions can either alleviate the downstream or render it prone to larger calamities. The time frame of these changes ranges from a few hours to a few days, and the information available to make these decisions is frequently restricted, as is the predictability of the influential parameters. The operating patterns of the gate are significant because of their direct impact on the downstream property, human life, and the dam's safety.

Several studies have been conducted over many decades to understand better reservoir operations, some of which are included below.

Marien (1984) developed multi reservoir control systems for flood management 1984. The conditions revealed no flooding at the downstream flood damage centre. Kelman et al. (1989) calculated the optimal flood control volume using the above results. Following the findings of 1989, Marien et al. (1994) established a methodology for developing flood control rule curves for multi-purpose reservoir systems. For dams with a gated spillway, Acanal et al. (2000) developed a six-stage operation method for routing floods with return times ranging from 1.01 years to the Probable Maximum Flood (PMF). They demonstrated that the proposed six-stage operating philosophy might be applied for flood routing regardless of the magnitude and timing of any incoming flood. Cheng and Chau (2001) created a fuzzy iteration methodology for swiftly developing some practical and effective solutions for flood control reservoir operation management. Cheng and Chau (2004) created a flood control program for real-time reservoir operation using fuzzy iteration methodology. Mediero et al., (2007) introduced a probabilistic model based on Bayesian networks calibrated with the results of a rainfall-runoff model linked with a reservoir operation. Hanasaki et al. (2006) developed a dam operation algorithm and implemented it in a global hydrological model. Pinthong et al. (2009) have mostly concentrated on optimizing reservoirs operating in Thailand's comparatively smaller-scale catchments and reservoirs. A reservoir operation model was developed using the global hydrodynamic model CaMa-Flood to simulate floods with high accuracy, and the result showed that the accuracy of the daily river discharge improved worldwide compared to the value with simulations without dams, and the estimated peaks from the model have reduced during floods compared to precious studies (Boulange et al., 2021).

2 STUDY AREA

2.1 Details of the Cauvery River basin

The Cauvery River is one of India's longest and the third-largest rivers. The river originates at Talakaveri, Western Ghats, in Karnataka's Kodagu district, at 12° 31' 42.9276" N latitude and 75° 59' 37.0644" E longitude (Figure 2-1).

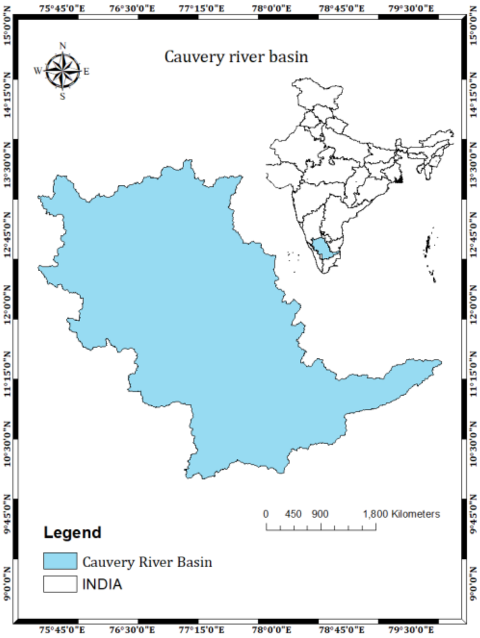
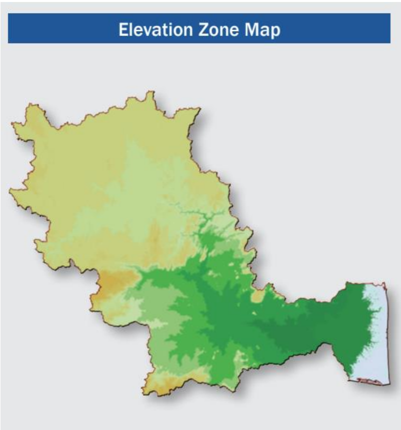


Figure 2-1: Location of Cauvery River Basin

The elevation of the origin is 1341 m above the seal level, and the lowest elevation in the basin is near the delta, with a value of less than 5 m. The highest elevation in the basin is to the west of the basin, with a value between 2000-3000 m (Figure 2-2).



Symbol	Elevation (m)	Area (Sq. km)	% of Total Area
	< 5	2058.03	2.54
	5-10	1444.14	1.78
	10-50	4120.77	5.08
	50-100	3297.20	4.06
	100-200	7202.59	8.88
	200-300	8903.69	10.97
	300-400	6957.78	8.57
	400-500	2837.79	3.50
	500-750	12718.66	15.67
	750-1000	25890.97	31.90
	1000-1500	3938.50	4.85
	1500-2000	975.24	1.20
	2000-3000	809.63	1.00

Figure 2-2: Elevation map of Cauvery River Basin
Source: WRIS India

The river continues for 800 kilometres downstream until it reaches its mouth in the Bay of Bengal, passing through four states: Karnataka, Tamil Nadu, Kerala, and Puducherry. The total catchment area of the Cauvery basin is 81.155 km^2, with 42% of the basin in Karnataka, 52% in Tamil Nadu and Puducherry and 4% in Kerala (Figure 2-3).

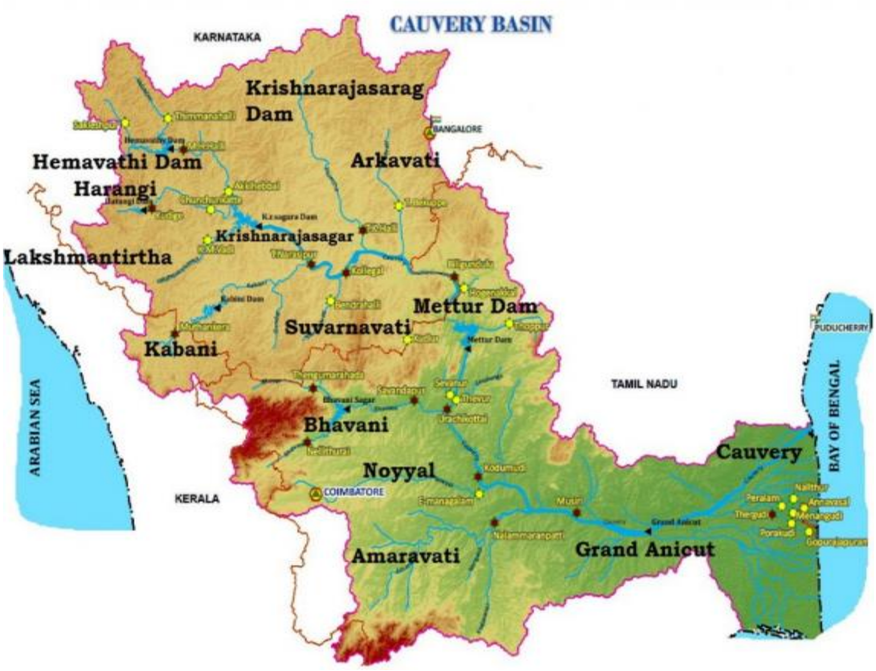


Figure 2-3:Various states covered by the Cauvery river basin along with tributaries and dams
Source: WRIS India

The river basin receives rainfall from both the South-West and North-East monsoon. The average annual rainfall of the basin is 1080.82 mm (Figure 2-4), and the river's average discharge is 677 m^3/s.

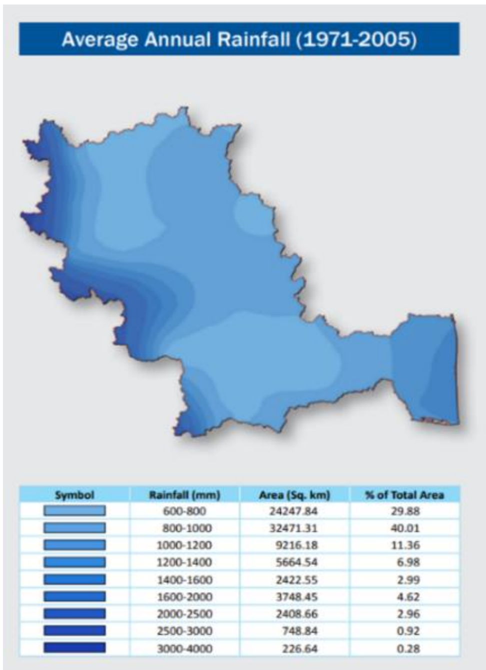


Figure 2-4: Rainfall distribution in the Cauvery river basin
Source: WRIS India

The Cauvery River basin is categorized as a Dry sub-humid climate by CWC. As per the Koppen climate classification (Figure 2-5), the basin has four distinct climate patterns varying from Tropical wet and dry climate covering most of the basin, Tropical monsoon climate in the North-west, Hot semi-arid climate in the north and lower-middle part of the basin and Subtropical highland climate in a small portion of the west of the basin.

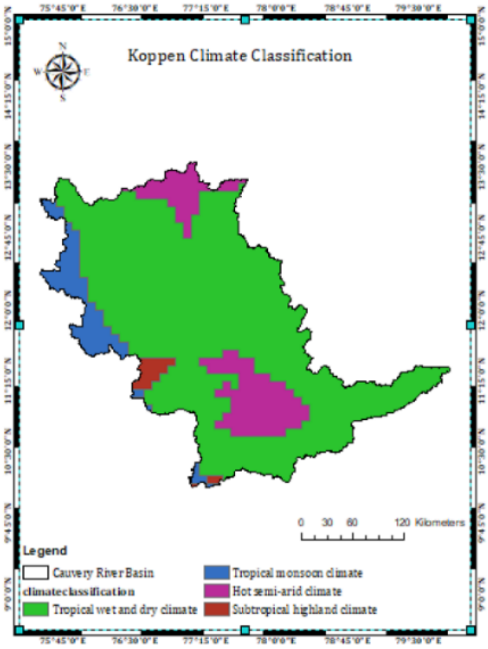


Figure 2-5: Koppen climate classification for Cauvery river basin

The catchment region is divided into different land uses and land covers, with agricultural land making up 66.21 % of the area, forests making up 20.50 percent, waterbodies making up 4.09 percent, and built-up land surrounding waterbodies making up 4.01 percent (Figure 2-6).

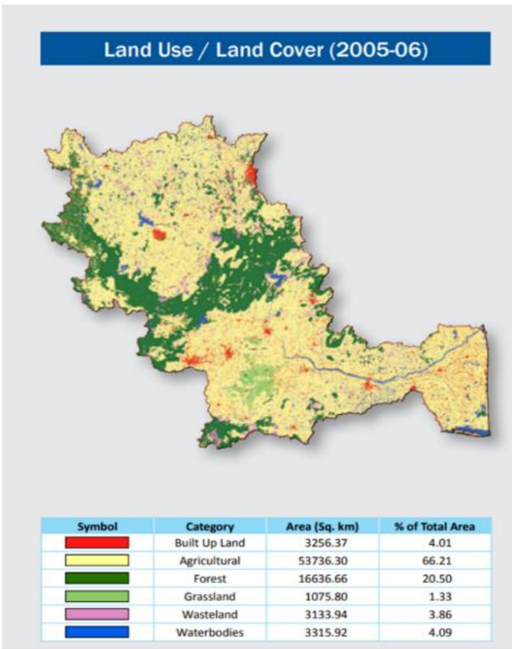


Figure 2-6: Land use and Land cover map of the Cauvery river basin
Source: WRIS India

The Cauvery River has 21 tributaries, out of which the major tributaries are Harangi, Hemavathi, Shimsha, Arkavathy, Lakshmanathirtha, Kabini, Suvarnavathi, Noyyal, Amaravati and Bhavani rivers.

2.2 Dams in the basin

Due to water availability and the fact that it is one of India's major rivers, the entire basin has been substantially dammed. The basin contains 102 dams (major and minor), the primary aim of which is to provide water for irrigation, water supply, or energy production. The river has been regarded as a vital source of irrigation and water supply for all regions through which it flows. The Krishna Raja Sagara dam (KRS) and the Mettur dam are the two major dams on the main river under consideration in this study. Both dams help to supply water to several major cities in the area.

Krishna Raja Sagara dam (KRS):

The KRS dam is a multipurpose hydraulic structure on the Cauvery River in Karnataka; it is situated at 12^o 25’30’’ N latitude and 76^{o}34’30’’ E longitude, and it is 19.3 km near Mysore city. Hemavathy and Lakshmanathirtha, two of the major tributaries of the Cauvery River, meet at the confluence where the dam is situated. The dam's catchment area is 10.619 km^2, and the river flow at the dam has a normal high flood of 2,832 m^3/s during the monsoon season and less than 3 m^3/s during the summer. The river saw its biggest flood, with a magnitude of 10,787 m^3/s, in 1924. The dam is 2.62 km long and has 152 sluice gates at different elevations in the dam body. The reservoir typically fills during the monsoon season (June to September), and the water stored is used from October to May. Table 2-1 lists the main characteristics of the KRS dam.

Table 2-1: Salient features of KRS dam

Parameter	Value
Full Reservoir Level (FRL)	RL 752.50 m
Crest level of Spillway	RL 737.45 m
Length of dam	2.62 Km
Height of the dam	39.867 m (above bed level of the river)
Bed level of the river	RL 714.45 m
Top of the dam	RL 754.32 m
Maximum release capacity	9,794 m^3/s through sluice gates
Gross storage capacity	1400 MCM
Live storage capacity	1232.17 MCM

Source: CWC

Mettur dam:

Mettur dam was built in 1934 and was the highest masonry dam in Asia and the largest in the world at the time. The dam is situated at 11^o 49’N latitude, 52 km from Salem. The Mettur dam is 270 km downstream of the KRS dam, and the reservoir has a catchment area of 42.217 km^2. The length of the dam is 85 m masonry section with a 1.615 km long earth section. The Mettur dam, like the KRS dam, fills during the monsoon and uses the stored water during summer. Table 2-2 summarizes the main characteristics of the Mettur dam.

Table 2-2: Salient features of Mettur dam

Parameter	Value
Full Reservoir Level (FRL)	RL 240.79 m
Crest level of Spillway	RL 234.69 m
Length of dam	1.70 Km
Height of the dam	37 m (above bed level of the river)
Bed level of the river	RL 190.50 m
Live storage capacity	2650 MCM

Source: CWC

2.3 Flood problems in the Cauvery River basin

The Cauvery River basin receives rainfall from both North-East and South-West monsoons. During the South-West monsoon, considerable rainfall is reported in the basin for a short time, causing floods in various regions. Flooding causes significant inundation owing to riverbank overtopping. According to many news articles and flood studies conducted by the Indian government, some localities near the dams are reported to be swamped following the release of water from the dams during the flood period. Although there are multiple dams in the basin, none are utilized for flood control; normally, the dam level is maintained at a certain level by releasing the incoming flow downstream. The flooding downstream of the basin is blamed for these actions. Figure 2-7 depicts the main regions of the Cauvery river basin that are subjected to floods during the monsoon during the specified investigation period.

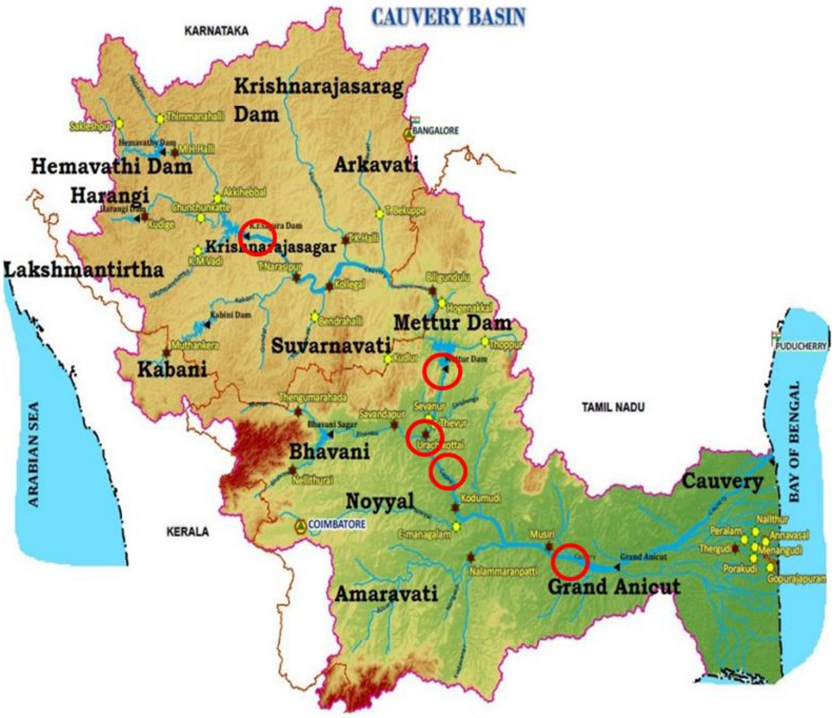


Figure 2-7: Flooded area in Cauvery river basin during Monsoon season

Source: WRIS India

2.4 Case study area and period of analysis

In the current effort, an investigation of the Cauvery River basin and the influence of dams on flood propagation along the river is being carried out. The study region is limited to a stretch of the river between two hydrological observation (HO) stations which measure the water level and flow in the river, namely the Kudige and Musuri stations, which include the Krishna Raja Sagara dam and Mettur dam, as well as various branches of the Cauvery River, as shown in Figure 2-8. The longitudinal profile of the research region and the locations of the observation stations and dams is depicted in Figure 2-9.
In the case of the analysis period, the most recent flood that occurred in the Cauvery river basin, namely in 2018, during the southwest monsoon (June to September), was chosen based on data availability and the impact it caused. The magnitudes of floods observed at several observation stations during the 2018 flood are depicted in section 3.3.2. As a result of the floods, all of the basin's major dams, KRS, Kabini, Mettur, Bhavani Sagar, and Amaravathi, reached their FRL and discharged all of their excess flow downstream. Due to the enormous volume of water released, numerous districts in Karnataka and Tamil Nadu were issued flood warnings, and low-lying settlements along the river were evacuated to safer places. Since the severe rains flooded the low-lying districts, thousands of people were forced to flee their homes. Figure 2-10 shows the specifics of the areas impacted by the 2018 flood. To better understand the dynamics of the floods that occurred, their causes, and alternative techniques to use the dams in the basin to prevent floods, the 2018 monsoon floods (June to October) were used as a case study in this work.

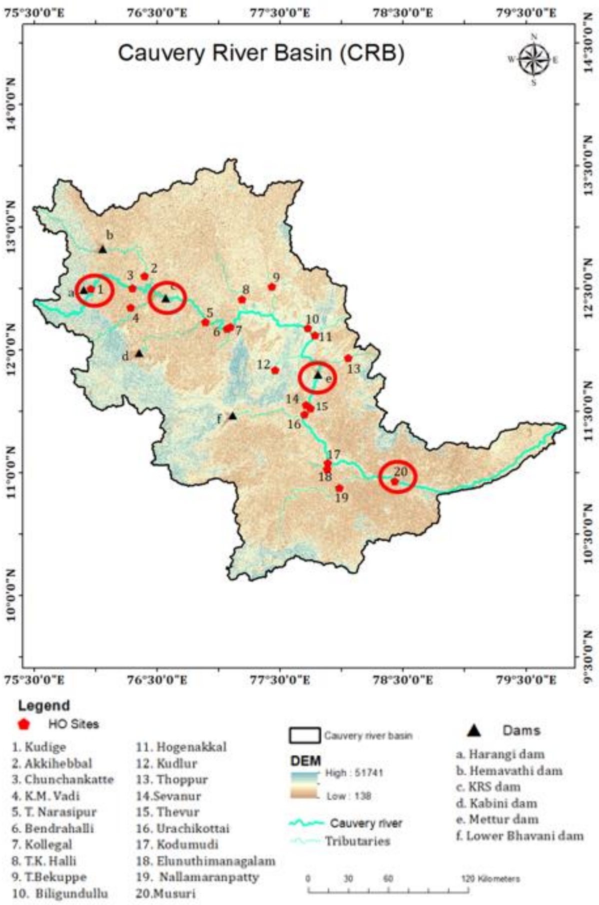


Figure 2-8: Details of the study area with observation stations and dams

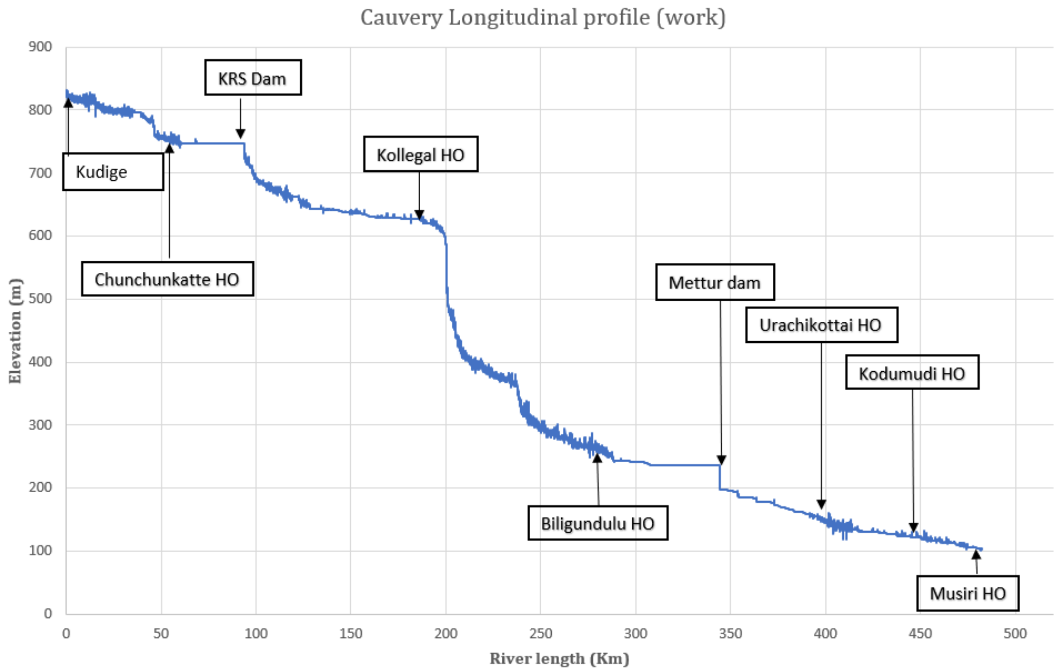


Figure 2-9: Longitudinal profile of the river in the study area

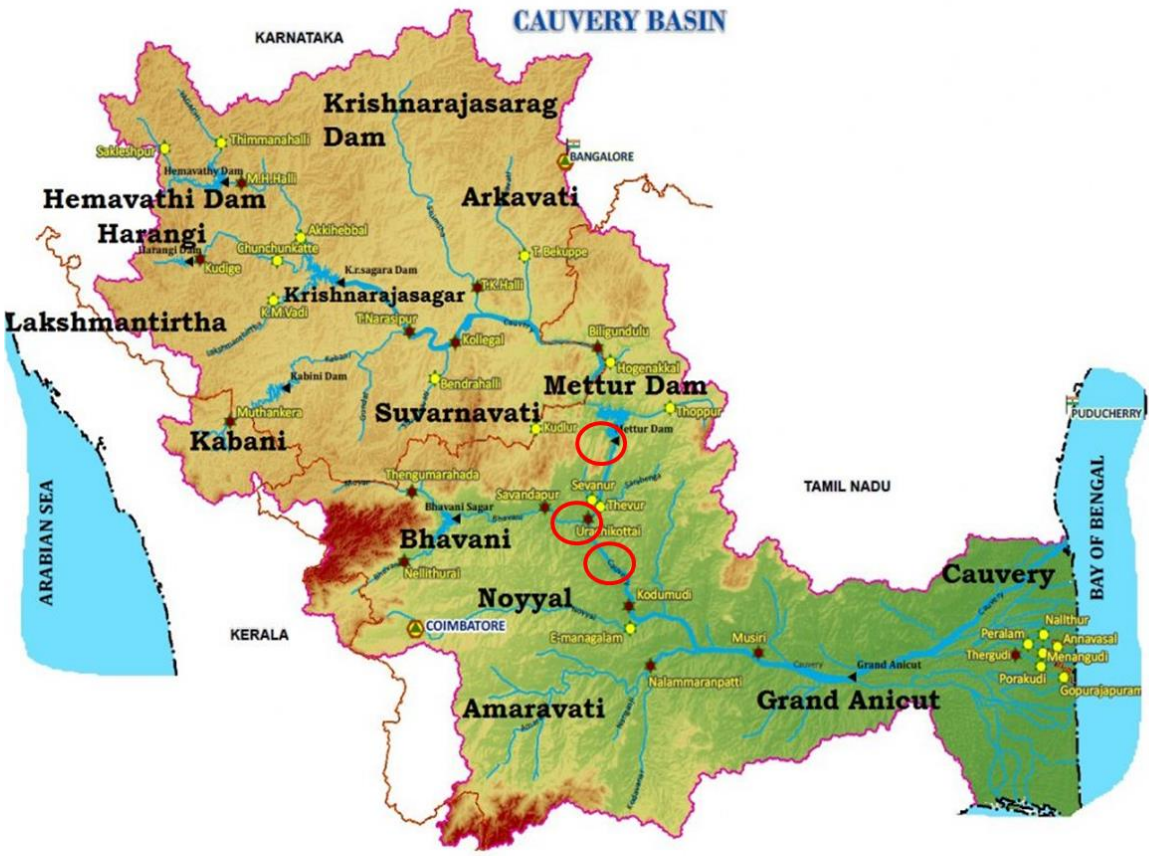


Figure 2-10: Flood-affected areas in the 2018 floods
Source: WRIS India

2.5 Previous studies in the Cauvery River basin

When looking at the works done in the study area, there is a wide range of work from the 1900s to the present. The research encompassed a wide range of fields, including sediment transport (dissolved, suspended, and erosion), with Subramanian (1988) finding that the yearly sediment transfer is 1.5 tons, with 95% of the movement occurring during the three months of the monsoon. Similarly, Panda et al. (2011) demonstrated that the trend in sediment movement in the basin has decreased in 80% of the gauging stations. Ramkumar et al. (2015) investigated the fluvial process of the basin. They discovered that there are deteriorations of the fluvial process of the basin due to the influence of dams, urbanization, sand mining, and other causes, and it requires prompt attention to prevent damage to the basin's delta. Maheshwari and Chavan (2021) investigated the effective discharge impacting the movement of sediments in the basin, and the findings can be used to improve dam planning and operation. Hao et al. 2021 created flood inundation mapping using the ensemble decision tree model for the Kabini River (a tributary of the Cauvery River) in the realm of floods. Sathya and Thampi (2021) have developed flood inundation maps for the Cauvery River basin using HEC RAS and GIS, where inundation areas were shown, and related measures for protection from floods were proposed in the results of the work.
Similarly, Thilagavathi et al. (2011) used GIS-based methods to map flood zones in the Papanasam taluk of the Cauvery river basin. Gosain et al. 2006 and Gowri et al. (2021) conducted climate parameter analyses (precipitation, climate change, and other meteorological parameters) linked to climate effect assessment and variability of water resources owing to future climate. Morphological analysis was performed by (Harsha et al., 2020; Ramkumar et al., 2019; Sunil et al., 2010), and the impact of dams on the basin was examined by (Agoramoorthy and Hsu, 2008; Ekka et al., 2022; Gholami and Srikantaswamy, 2009; Sharda and Ojasvi, 2016; Susheela et al., 2014; Vedula, 1985).

2.6 Research gap

Following a successful evaluation of diverse literature utilized in various regions of the world and specific to the current study, it was found that there were many works which have used the concepts of Probable Maximum Flood, return period, and other methodologies like fuzzy iteration and probabilistic models and less emphasis was on the development of singular models integrated with real-time control groups for reservoir operation for flood management. Furthermore, it was noticed that it is very little to minimum work done in the domain of utilizing the irrigation dams in the basin for flood control in the study area. Hence in this work, a process-based model is developed for understanding the movement of floods and the aspects of reservoir operation for flood control in the chosen study area with real-time control groups.

2.7 Research Objectives

As stated below, three key objectives are defined based on the necessity of research in the chosen study region and to solve the research deficit in the Cauvery River basin.

i. Investigating the effect of dam operation in CRB utilizing a one-dimensional computational model created with D-Hydro Suite 1D2D to simulate the effects of dam operation on river floods.
ii. Determining the applicability of dams in CRB in capturing floods.

2.8 Research questions

The scope of this research is applied in the subject area to a real-world application. As a result, the study topics focus on the current state of the Cauvery River basin. The questions are designed to aid in achieving the study's objectives.

i. What are the main factors influencing the occurrence of floods in the basin?
ii. What are the dam's positive and negative impacts on the main river and some major tributaries?
iii. How do the existing dams and their operation in the Cauvery River (and some major tributaries) influence floods?
iv. Can the existing dams in the Cauvery river basin be used for flood control?

2.9 Innovation

In the study area, the following innovative approaches are proposed to apply the proposed methodology to a real-world application and address the problems to reach the objects. In this work, a new approach using multiple dams is used to understand the changes in the river in terms of flood movement. "Development of a process-based river system model with multiple dams and their operation to replicate the flood propagation " is proposed to accomplish this. Secondly, reservoir volume is mostly employed for irrigation and power generation in the chosen study area. As a result, in the study, analysis is carried out to check if optimal dam operation can reduce flood risk in the basin. "Application of the developed model to study and optimize the dam operation on river flood (to reduce the flood risk) " is carried out to achieve it. Furthermore, the use of a hydrodynamic model with reservoir operation was not adopted, particularly in the research area, and this model contributes to the novel approach.

2.10 Practical value

The primary goal of this research is to determine how existing dams affect floods in the Cauvery River basin. As previously stated, the importance of the basin in India and the impact of floods in the basin, this research seeks to comprehend the impact dams can play in rising floods. "Assist the decision-making processes connected to enhancing dam operation for proper flood" is the research's main contribution.

3 RESEARCH METHODOLOGY

3.1 Introduction

To accomplish the goals and respond to the research questions, the task is completed in five steps: literature review, data collecting, data analysis, model creation, and result analysis. Figure 3-1 depicts the precise structure of the research approach used in the paper, and the following explanations are given for each component.

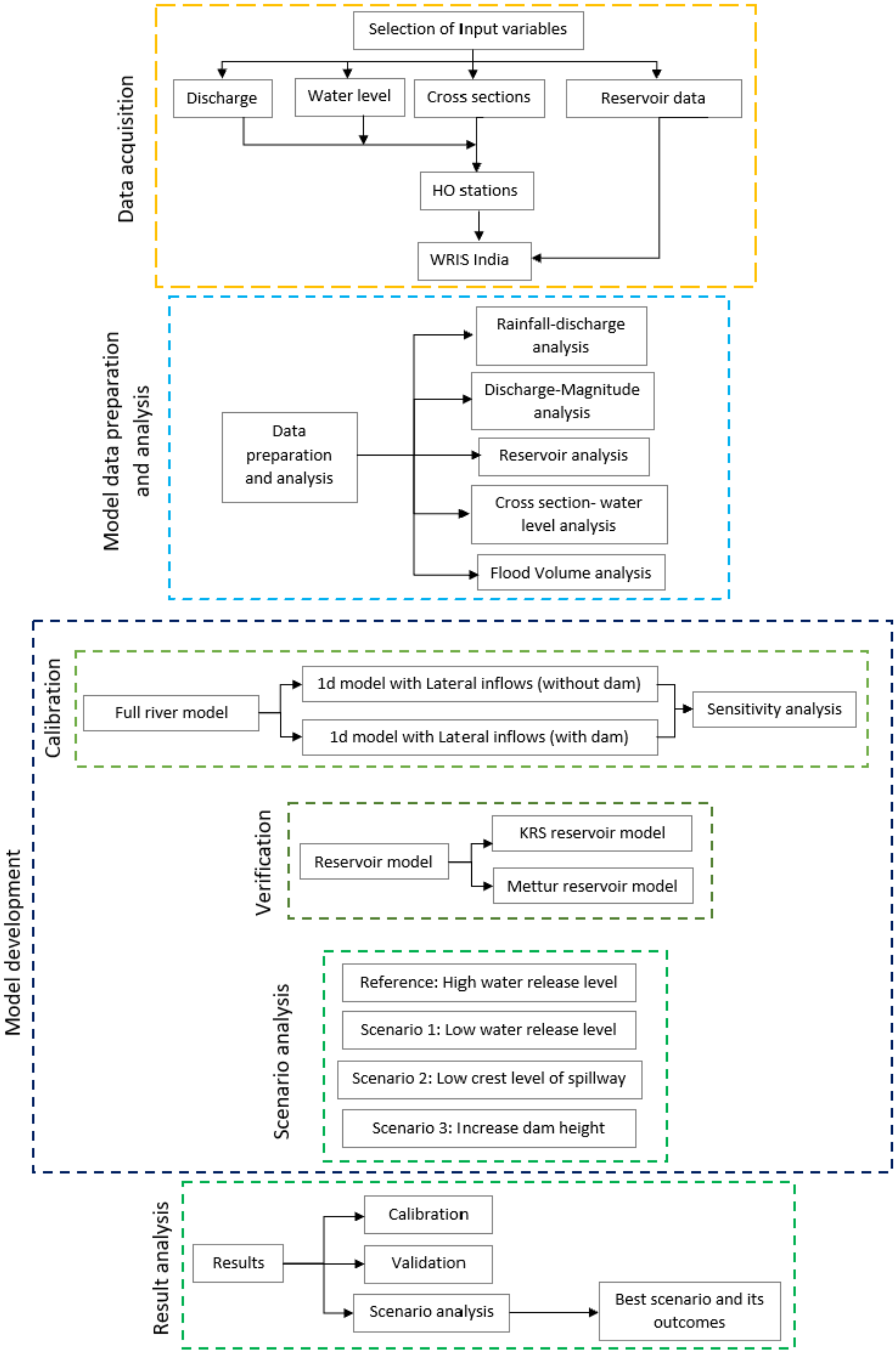


Figure 3-1: Frame work of Research methodology

3.2 Data acquisition

The primary goal of this step is to gather the data required to complete the research successfully; many forms of data are required to effectively build a model to comprehend how dams affect flood flow in a river basin. The Indian government's websites, including those of the Indian Meteorological Department (IMD), WRIS India, and the Central Water Commission (CWC), as well as additional information from the Deltares project on the Cauvery River basin, provided all the information required for the project's catchment area.

3.2.1 Precipitation data

Precipitation is the key component that controls other factors such as river discharge, overland flow, and many other parameters that aid in the development of floods in a region. Although precipitation data is not utilized to create the model in this work, it is used to understand the influence of precipitation on the floods that emerged in the Cauvery River basin (CRB). Precipitation data sets in India are created by the Indian Meteorological Department, Pune (IMD) and are accessible in gridded format. The data is accessible in 0.25º × 0.25 º (2.75 x 2.75 km) grids for the entire country, ranging from January 1901 to December 2021, as seen in Figure 3-2. The data can be downloaded from https://imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html. Understanding the occurrence of extreme events on an hourly scale is not possible due to the availability of data at a daily resolution.

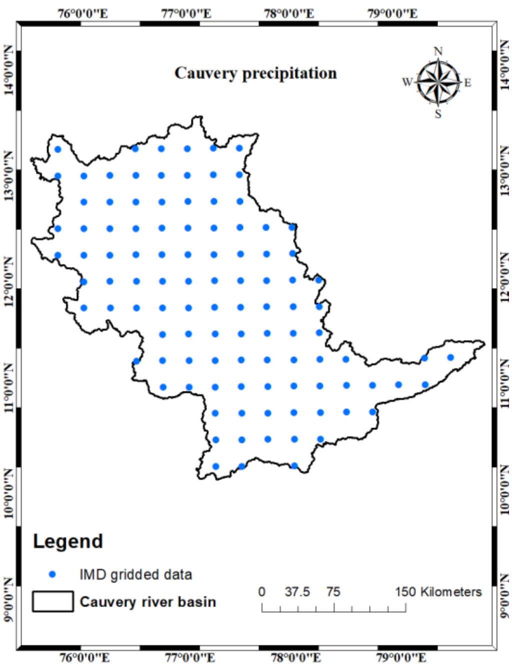


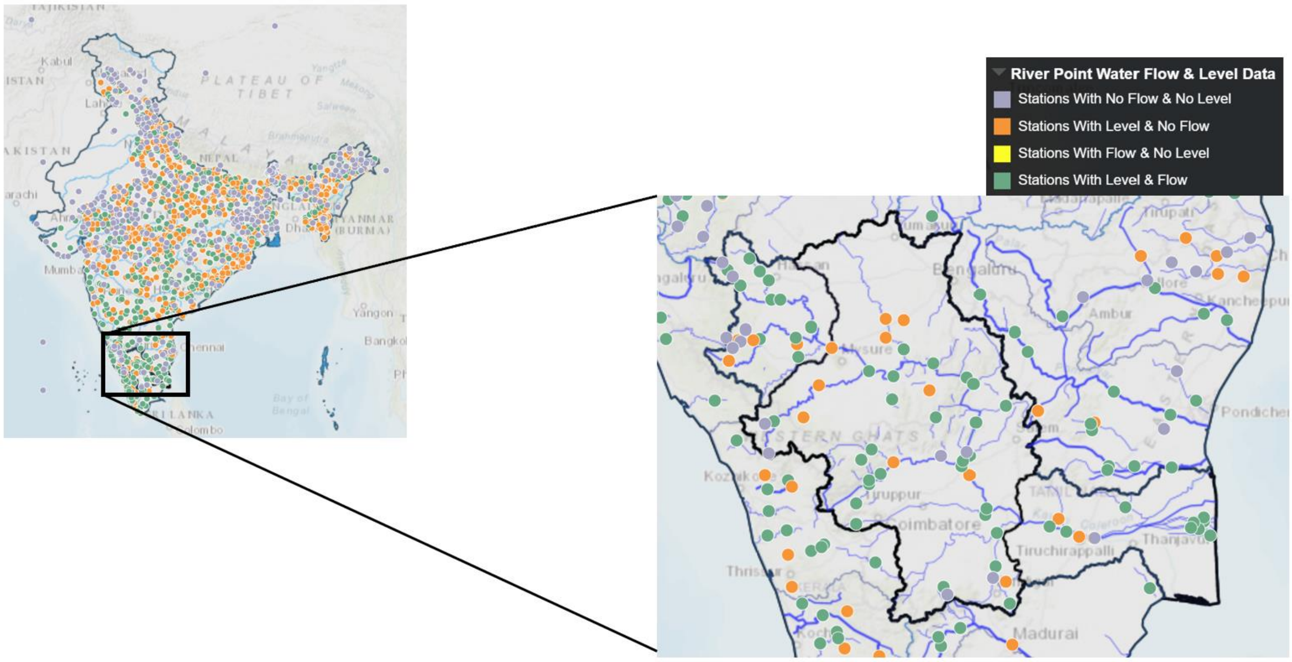
Figure 3-2: IMD gridded precipitation data locations

3.2.2 Discharge and water level

The essential data sets for this investigation are the discharge and water level data sets. To create a good flood model and comprehend its spread in a river system, the discharge and water level data sets require accurate and continuous information with no missing values. River gauging stations are used in India to measure discharge and water level data for all rivers. Both state and federal government departments collect these data types. The data sets used in this analysis are from the Central Water Commission

(CWC). Data availability and length are regulated by the location and working conditions of the stations. In the current study for the Cauvery River basin, both flow and water levels are recorded at the gauging station. Figure 3-3 shows the site where both measurements are made. These data sets can be downloaded from the WRIS India website at https://www.indiawris.gov.in/wris/#/RiverMonitoring.

CWC river points India



CWC river points Cauvery River basin

Figure 3-3: Discharge and water level gauging stations in the Cauvery river basin
Source: WRIS India

3.2.3 Cross section data

Along with discharge and water level, one of the crucial characteristics that aid in constructing a realistic flood model reproducing the original river system is the river studied cross-section information. Obtaining good and precise bed level information throughout the river is one of the most important parts of constructing a solid hydraulic model. Bathymetric information along rivers in India is measured at gauging stations, where both discharge and water level data are taken and at various locations along the river to understand the longitudinal profile of the river. However, bathymetry data is available but not openly accessible to the public. The information needed to create the model for the Cauvery River basin (CRB) is acquired at the gauging station with the help of Deltares.

Along with the cross-section information in the river sections, the cross-section information in the reservoirs for both the Krishna Raja Sagara and Mettur dams is collected. The data used was measured at the observation stations during May 2018. To replicate the original system in the model for this investigation, 64 cross sections throughout a 530 km stretch of the river were used. The average distance of the cross sections in the reservoirs is 1.50 km. However, the distance varies depending on the location of the observation station available in the remaining stretches of the river.

3.2.4 Reservoir data

Reservoirs are the principal structures created to control water flow in the river system. These reservoirs can be utilized for various functions, including irrigation, power generating, flood control, and multi-purpose applications. Each reservoir operation differs depending on its purpose. There are currently 5701 dams in India (according to the CWC), and a few notable dam locations are depicted in Figure 3-4.

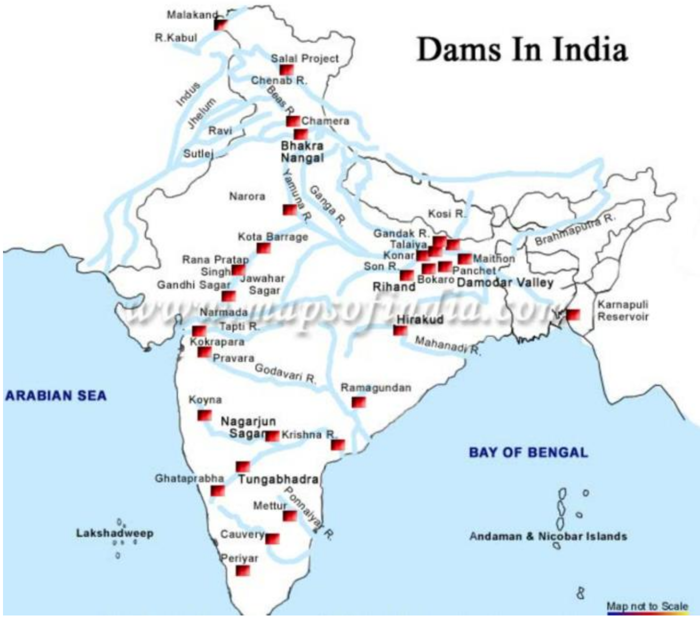


Figure 3-4: Location of Major dams in India
Source: WRIS India

The Cauvery river basin is one of the most highly dammed basins in India, with 102 dams, both major and minor. Some of the main dams in the river include the Krishna Raja Sagara dam, Kabini dam, Harangi dam, Hemavathi and Mettur dams. The yearly reports of CWC contain thorough information about each dam. Details about reservoir information can be found in Figure 3-5.

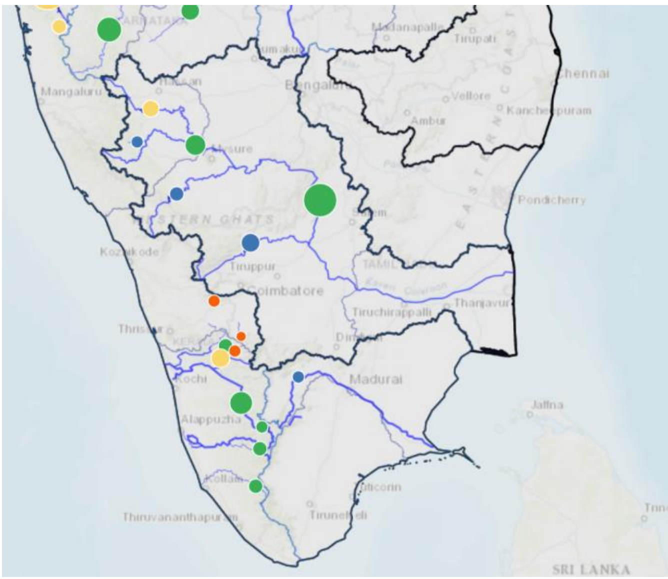


Figure 3-5: Reservoirs in the Cauvery river basin
Source: WRIS India

The Central Water Commission monitors the water level and discharges in reservoirs in the same way it monitors the discharge and water level at gauging stations (CWC). Details of the discharge from the reservoir, water level in the reservoir, and reservoir fill (%) are obtained from the WRIS India https://www.indiawris.gov.in/wris/#/Reservoirs.

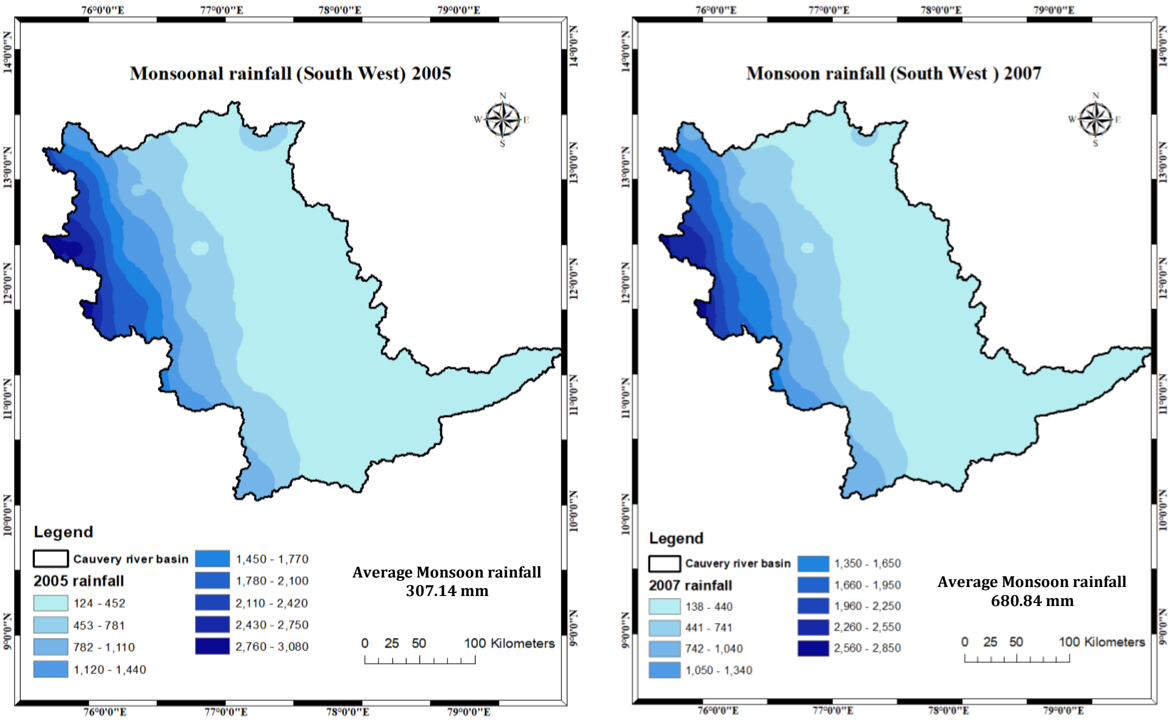
3.3 Model data preparation and analysis

Understanding the changes in the many variables used in the study is critical to establishing the cause and implementing an effective technique to prevent unforeseen events caused by these changes. To link complicated changes in the basin, all the variables are studied to find trends and the timing of these changes. The approaches utilized in this paper are depicted below.

3.3.1 Rainfall and Discharge analysis

This section analyzes rainfall data to understand how it fluctuates in the basin at different times. The Cauvery River is a seasonal river with high flows only during certain times. During the monsoon season, the Cauvery River basin receives heavy rainfall from both the South West and North East monsoons, allowing for increased river flows. Figure 2-4 shows the specifics of the rainfall patterns in the basin from 1995 to 2005. According to this data, higher altitude locations west of the basin have higher precipitation, whereas lower altitude areas have less precipitation.
These high-altitude precipitation episodes contribute to the basin's significant inflows. Discharge and precipitation patterns are examined across several years during the monsoon season to determine whether precipitation in the basin is the driving factor behind high flows. Figure 3-6 and Figure 3-7 depict the precipitation plots in the Cauvery river basin for the South-West monsoon (June to September) and the discharge at Kudige station (u/s location of the river) for the same time frame, respectively.

(a) (b)



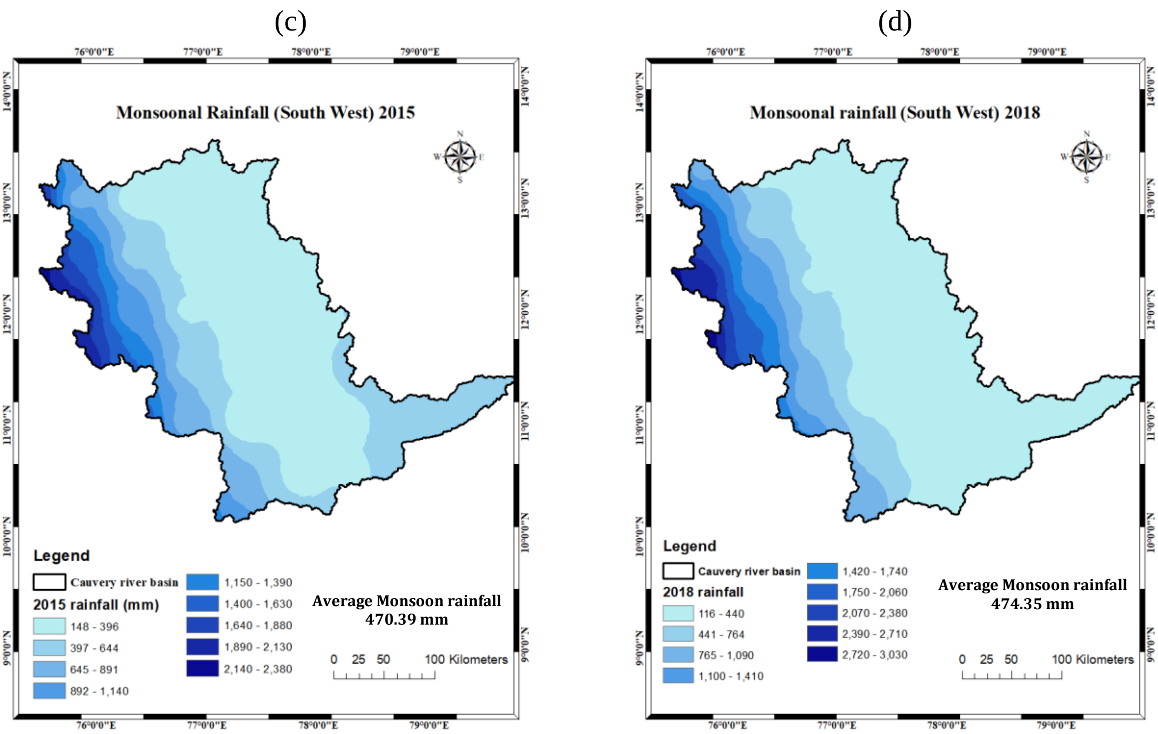


Figure 3-6: Monsoonal rainfall in the Cauvery river basin

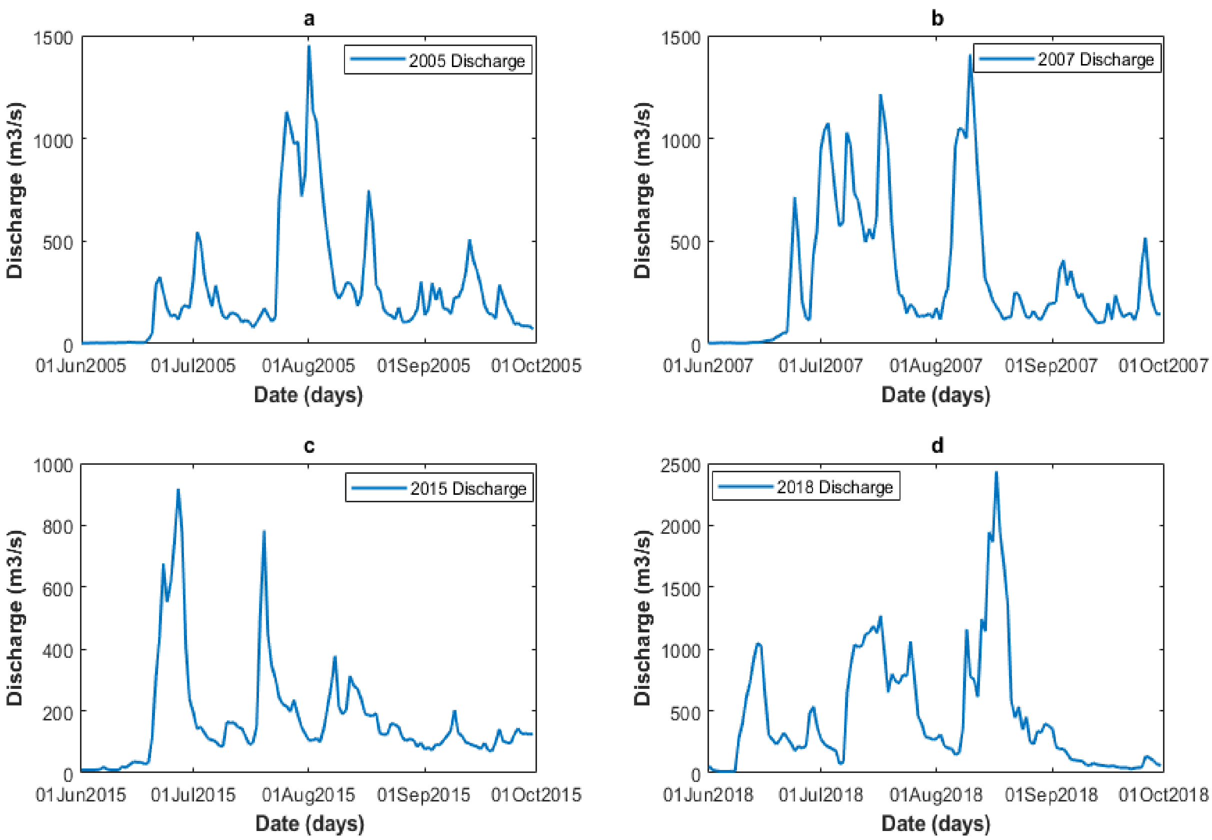


Figure 3-7: Discharge at Kudige station during monsoon period

Based on the observations of the rainfall patterns in Figure 3-6 and discharge in Figure 3-7, it is reasonable to conclude that when the average monsoon rainfall surpasses 450 mm, flood waves of greater magnitude and frequency are seen to enter the river basin, as shown in Figure 3-7(b-d). Following the reports of authorities and various surveys, it was discovered that floods occurred in the river basin during the inflow of high floods shown in Figure 3-7(b-d). Based on this information, it can be stated that when average rainfall of less than 450 mm is seen throughout the monsoon season, discharge with lesser magnitudes, as shown in Figure 3-7(a), occur. Whereas if the average rainfall reaches 450 mm (Figure 3-6 (b-d)), the discharge has larger magnitudes, as indicated in Figure 3-7(b-d). These statistics concluded that higher rainfall values equate to higher peaks in the river system's flow. This data supports the theory that precipitation is a major contributor to the high flows that cause flooding in the area.

3.3.2 Discharge analysis

This section examines the observed discharge magnitude at several sites (gauging stations) along the river to comprehend the flood hydrograph's movement. The goal of the analysis is to see if more water is entering the river besides the input from the river's origin, presence of offtake canal, or any other river joining the main river. This stage is important for the model calibration process. During the magnitude analysis procedure, discharge is manually computed based on observed river inputs to compare the computed discharge with observed discharges. The inflows of the branches into the main river are added together simultaneously to determine the discharge without considering the time difference between the two observation places. This phase is performed to find any additional water that has not been considered for modelling in this work. The observed and estimated data are also compared to find differences and further validate the generated model.

Figure 3-8 depicts the plots of observed discharge and calculated discharge. Figure 3-8(a) demonstrates that in mid-august, the gauging station Chunchunkatte has a larger peak discharge than the station measurement at Kudige. The calculated discharge at the Kollegal station is compared to the observed/measured discharge in Figure 3-8 (b). Plotting the data reveals that during the first peak in mid-June, the calculated discharge is higher than the observed, but during the second peak in mid-August, the measured data shows a higher peak value than the calculated discharge. Figure 3-8(c) depicts the observed and calculated discharge plots at the Biligundulu station, and their comparison demonstrates that the observed discharge is lower than the calculated discharge during both the initial peak in mid-June and the higher peak in mid-August. Although there is a minor discrepancy in the early peak discharge during the first week of August in Figure 3-8(d), the observed and estimated discharge peaks coincide in mid-August. The flood peak in mid-august for the gauging stations Kodumudi and Musuri in observed and calculated data matches correctly in Figure 3-8(e & f). According to Figure 3-8 (a-c) findings, there is higher/lower discharge in the river system at the Chunchunkatte, Kollegal, and Biligundulu stations compared to the calculated discharge. The higher value represents additional water entering the system whose source is unknown, whereas the lower value represents water leaving the system, either owing to diversion structures or overflowing from riverbanks.

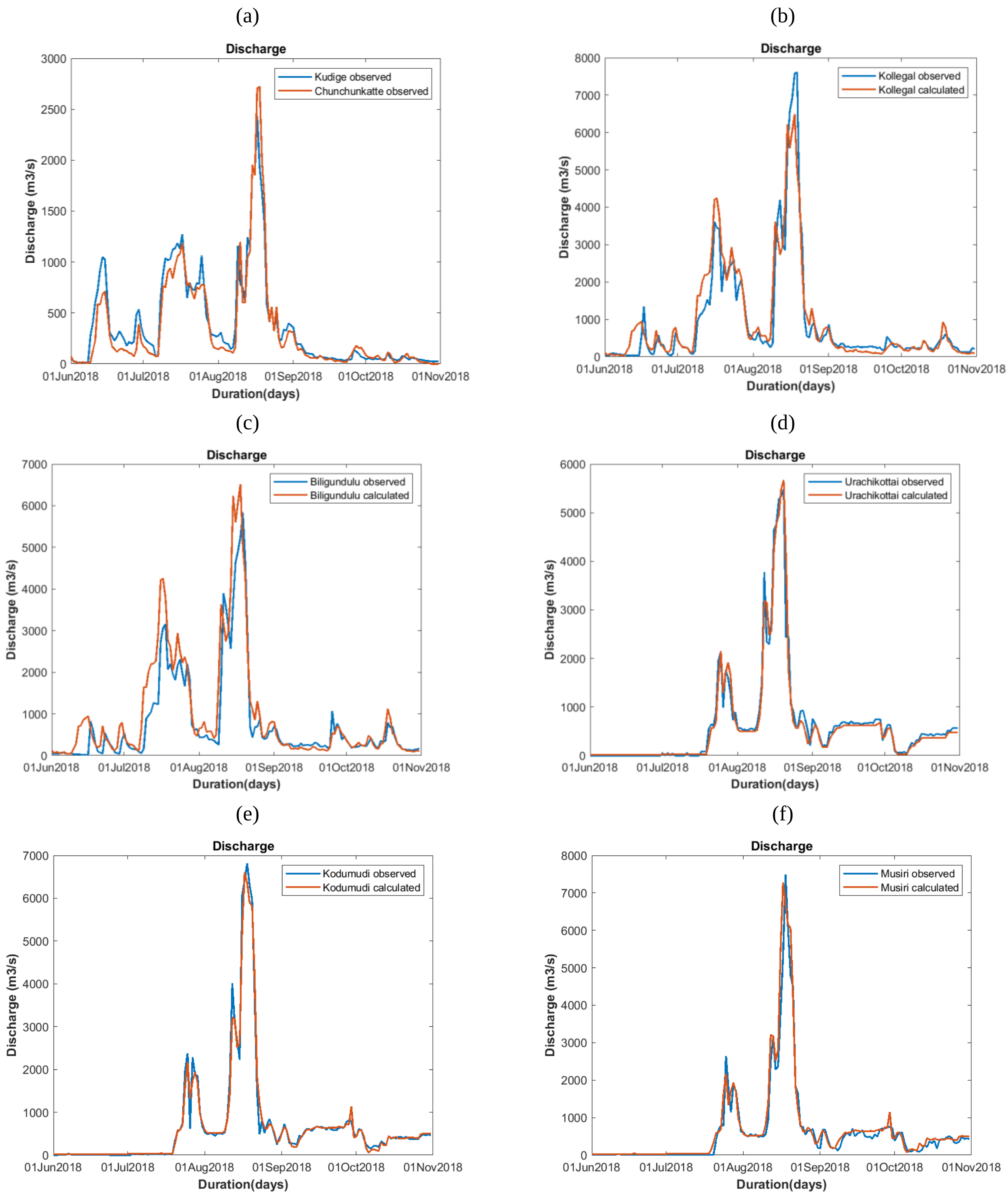


Figure 3-8: Comparison of discharge magnitude of gauging stations

3.3.3 Reservoir operation analysis

Figure 3-9 depicts the plot of the Krishna Raja Sagara dam's (KRS) water level, inflow, and outflow from June to October 2018. This graph shows that the dam inflow had two maxima from June to mid-August 2018. During the initial flood peak, the water level is seen to rise and reach the reservoir's FRL. As seen in Figure 3-9, the dam gates are closed until the water level reaches FRL (752.4 m above MSL). Once the water reaches the FRL, the dam gates are opened, and the dam's outflow reaches an initial peak of 2500 m^3/s; when the first peak decreases gradually, the dam's water level decreases, and during the first few days of August, the inflow decreases, which reduces the dam's outflow. During the peak flood season (17-18 August), practically all the inflow coming into the dam is directly released as outflow. Because of the massive release of water during the peak flood period, the reservoir water level is noted to remain low for a short duration in mid-August. Once the flood peak has passed, the water level is restored to the FRL and utilised for various purposes such as irrigation and water delivery. Due to this operation pattern, there is no prospect of storing the peak flood behind the dam since there is no water level reduction in the reservoir during the first flood peak so that the reservoir can accept the main flood peak.

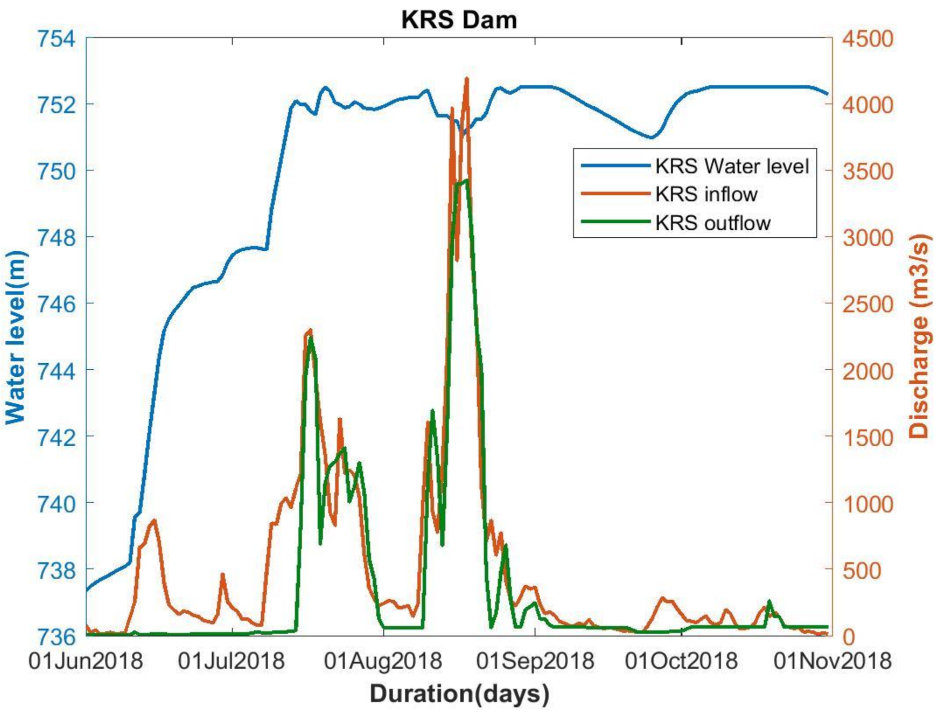


Figure 3-9: Plot of the KRS dam inflow, outflow and water level

The water level, intake, and outflow of the Mettur dam are depicted in Figure 3-10. The plot shows that the water level rises in early June and exceeds the reservoir's FRL by mid-July, just as the first flood peak approaches the dam. The dam gates are closed until the end of the first flood peak, and the discharge is zero until mid-July. When the water level exceeds FRL (240.79 m above sea level), the dam gates are opened to prevent the water level from rising above the FRL, and surplus water entering the dam is released as outflow. When the primary flood peak arrives at the reservoir, the water level is at FRL, and all of the water entering the reservoir is released as outflow, as shown in Figure 3-10 with a green line. The Mettur dam, like the KRS dam, is never operated to release excess water to satisfy the major flood peak; thus, the flood peak is released downstream of the reservoir. According to the observations in Figure 3-9 and Figure 3-10, the outflow from both dams (KRS and Mettur dam) is equal to or less than the intake into the dam. These inflow-outflow trends suggest that the flood peak discharged downstream is not more than the input, implying that dams have no role in creating additional outflow. As a result of these observations, dams do not contribute to floods in the areas downstream of the dam.

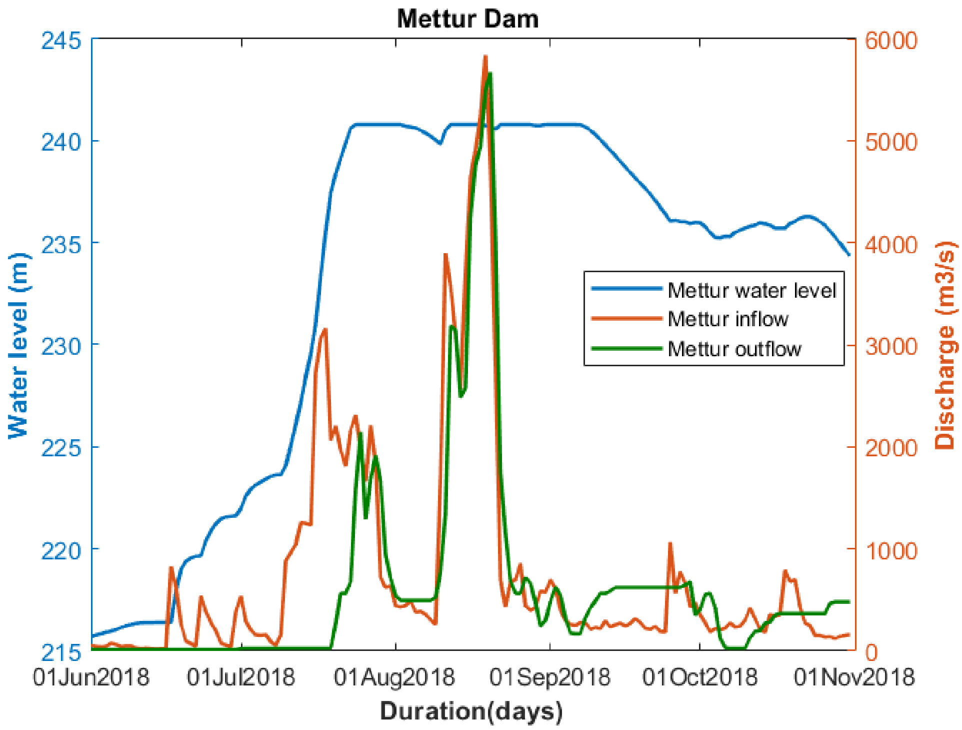


Figure 3-10: Plot of Mettur dam inflow, outflow and water level

3.3.4 Flood Volume analysis

The primary goal of this operation is to prevent floods in the CRB, i.e., floods in the river system downstream of the reservoir, by storing water during the flood peak in the reservoir. The reservoir volume should be large enough to hold the incoming volume without overflow to capture floods. As a result, flood volume analysis is performed to understand the intricacies of the oncoming flood and the reservoir's capacity to hold the influx. Table 3-1 and Figure 3-11 show the specifics of the analysis.

Based on the volume analysis results, the whole volume of the peak flood from 09-08-2018 to 23-08-2018 is 4.8 billion m^3. In addition, based on water level observations during the dry season, as shown in Table 3-1, the reservoir achieved FRL by 18-08-2018, as shown in Figure 3-11. This means that the reservoir has attained its carrying capacity of 2.6 billion m^3 based on calculated volume estimates. This suggests that the modelled volume is accurate compared to the observed volume of 2.6 billion m^3. Secondly, it can be observed that the Mettur reservoir cannot contain the incoming volume of 4.8 billion m^3, so the reservoir must release stored water before the peak flood arrives if the flood peak is to be captured. The outcomes of this analysis are crucial in creating the scenario analysis in section 3.8.

Table 3-1: Details of incoming flood volume during peak flood period in Mettur reservoir

Date	*Flood (m^3/s)*	*Volume (million m^3)*	*Cumulative volume (million m^3)*	*The water level in reservoir (m)*
09-08-2018	580.84	-	-	196.90
10-08-2018	1443.30	87.41	87.41	209.88
11-08-2018	3568.80	216.52	303.93	215.85
12-08-2018	3624.00	310.73	614.66	221.90
13-08-2018	3183.30	294.08	908.74	225.99
14-08-2018	3648.30	251.93	1160.66	228.88
15-08-2018	3524.40	266.66	1427.32	231.46
16-08-2018	4502.40	346.76	1774.08	234.58
17-08-2018	4861.10	404.50	2178.58	237.83
18-08-2018	5189.40	434.18	2612.76	240.74
19-08-2018	5485.40	461.15	3073.92	240.74
20-08-2018	4567.20	434.27	3508.19	240.64
21-08-2018	3101.40	31.28	3839.47	240.92

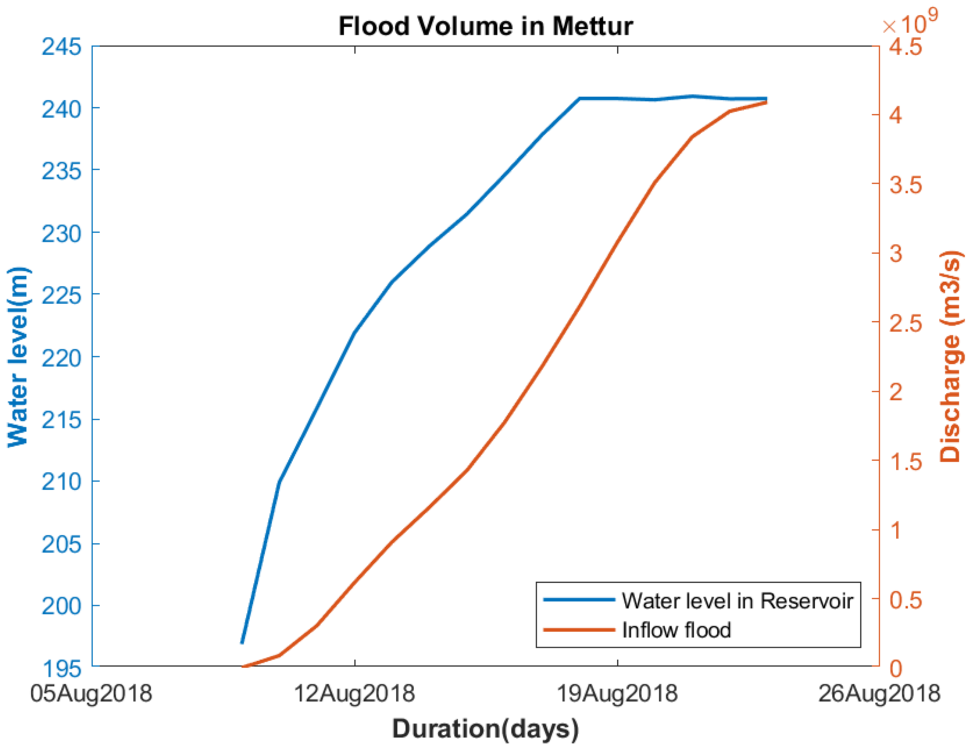


Figure 3-11: Plot of Inflow peak flood vs Water level in Mettur reservoir

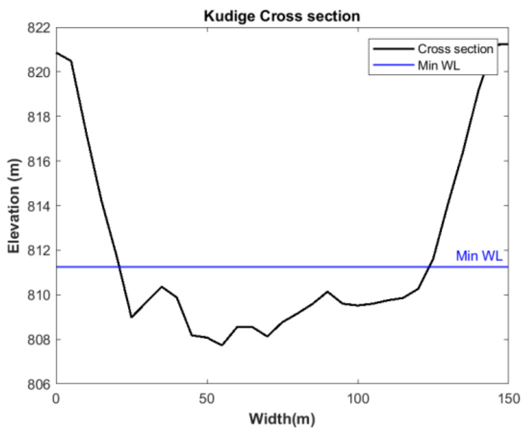
3.3.5 Cross section- Water level analysis

The cross-section information of the river is one of the most critical data sets required to create any good hydraulic model. This data aids in the development of a proper and accurate depiction of the flow in the river system, improving the accuracy of the model outputs. On the public websites of India's state and federal government portals, which were used in this study, the information regarding the cross sections of the rivers was not readily accessible. These data sets were collected with the assistance of Deltares at a variety of locations, including discharge measurement stations and reservoirs. Although the data is measured or observed, its origin and legitimacy remain uncertain. As a result, it must be carefully cross-checked. In this study, a basic check is performed to see if the cross-section elevation is lower/higher than the lowest/highest water level in that river segment by comparing cross-section and water level data at all places where both cross-section and water level data are available.

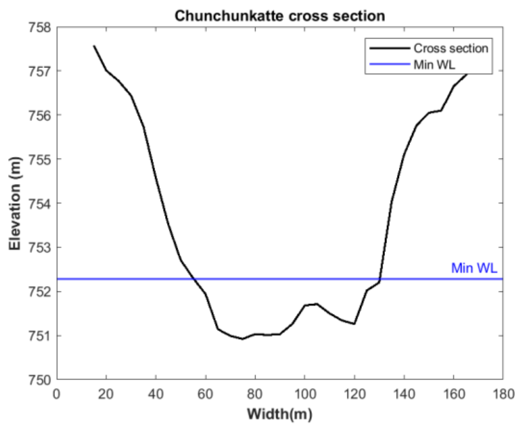
Figure 3-12 depicts the cross sections and accompanying water levels for the gauging station on the major Cauvery river. Figure 3-12 (a) depicts the cross-section details for the Kudige station (in black), which was chosen as the starting point for the model in this work. According to the figure, the lowest elevation of the cross-section is near 807.73 m (above MSL), and the highest elevation is on the river's banks, reaching 821.24 m. (above MSL). In addition, the blue line represents the minimum water level (811.25 m) in the cross-section for the whole chronology of this work's research. Similarly, Figure 3-12 (b) depicts the Chunchunkatte station's details, including cross-section details (in black) and the minimum water level (in blue). The cross-section's lowest and highest elevations are 750.92 m (riverbed) and 757.24 m (riverbanks), with a minimum water level of 752.28 m. The lowest and highest heights in the Kollegal cross-section (Figure 3-12 (c)) are 621.64 m and 626.85 m (above MSL), respectively, whereas the minimum water level in the section is 624.58 m. In the instance of Biligundulu station (Figure 3-12 (d), the lowest and highest elevations are 253.23 m and 266.13 m (above MSL), respectively, while the minimum water level is 257.79 m.

While the minimum water level in the Urachikottai cross-section (Figure 3-12 (e)) is 157.92 meters, the cross section's lowest and highest levels are 152.07 meters and 166.60 meters (above MSL), respectively. Similarly, at the Kodumudi station (Figure 3-12 (f)), the lowest and highest levels in the cross-section are 119.82 m and 127.21 m (above MSL), respectively, while the section's minimum water level is 121.33 m. Finally, at the Musuri station (Figure 3-12 (g)), the model's downstream control point/outlet, the minimum water level in the section is 80.63 m (above MSL), and the lowest and highest cross-section levels are 80.14 m and 85.43 m, respectively (above MSL). The initial tests for the water level in the cross-section being greater than the minimum cross-section elevation are satisfied based on observation of the cross-section plots and minimum water level for all gauging stations. If the lowest elevation of any of the cross-sections is more than the reservoir's minimum water level, it indicates an error in either the observed water level or the cross-section data. Because the lowest cross section elevation is more than the minimum water level, water cannot flow in that section. In our case, however, there is no problem since the lowest cross-section elevation is lower than the minimum water level in the cross-section.

(a)



(b)



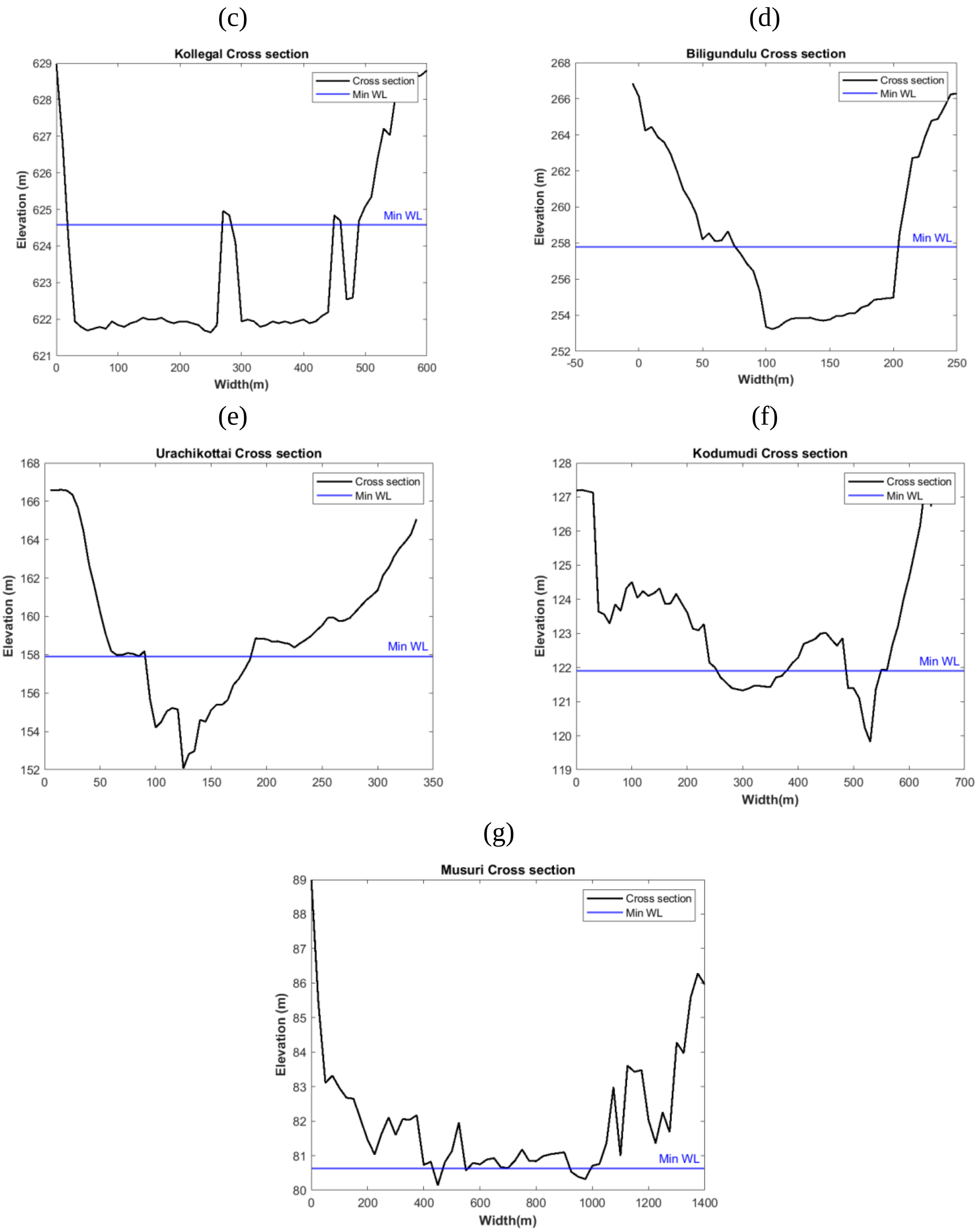


Figure 3-12: Cross section- minimum water level figures for gauging stations in CRB.

3.4 Model development

Model selection and identification of the best model are critical activities for each research project. The modelling program chosen for this current endeavour to meet the main goal of the work is D-HYDRO Suite.1D2D. The following models are created using the software.

i. A 1D process-based model for analyzing flood
ii. Introduction of 1D dams and their operating scenario analysis employing real-time control (RTC)

3.4.1 D-Hydro suite 1D2D

SOBEK 2, developed by Deltares, is one of the Netherlands' most used tools for modelling water systems. SOBEK 2 assists the developer in creating and simulating hydrological processes by developing the Rainfall-Runoff module (RR) and Channel Flow modules (CF) for the hydraulic process. Deltares has been developing D-Hydro suite 1D2D for the past 10 years, with an initial concentration on 2D and 3D, but there has recently been a shift in producing a 1D2D model that can operate as a credible replacement to SOBEK 2. For hydrological processes, D-Hydro Suite 1D2D use the same Rainfall-Runoff module, and for channel flow and overland flow, it employs its hydrodynamic module D-Flow FM, which is also included in Delft3D FM. When comparing the capabilities of SOBEK 2 and D-Hydro Suite 1D2D models, the 1D model is nearly equivalent to SOBEK 2 and is based on Saint Venant equations (Lieverse, 2021).

1D Continuity equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad \text{Eq (1)}$$

Where Q is the discharge (m^3/s), A is the storage area (m^2)

1D momentum equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right) + gA_f\frac{\partial \zeta}{\partial x} + \frac{gQ|Q|}{C^2RA_f} - w_f\frac{\tau_{wind}}{\rho_w} + gA_f * \frac{\xi Q|Q|}{L_x} \qquad \text{Eq (2)}$$

Where Q is the discharge (m^3/s), t is the time (s), A_f is the Area of flow (m^2), g is the acceleration due to gravity (m/s^2), ζ represents the water level (m), C represents the Chezy's constant, R is the hydraulic radius (m), w_f represents the width of water surface (m), wind shear stress (N/m^2) is represented by τ_{wind}, ρ_w is the density of fresh water (kg/m^3), ξ is the coefficient of extra resistance (s^2/m^5), L_x is the length of branch segment, and x is the distance along the channel axis (m).

Although the 1D models in SOBEK 2 and D-Hydro Suite 1D2D are very similar, there are a few noticeable changes. For example, D-Hydro Suite 1D2D does not include cells with negative water depths when iteratively solving equations (at a computational time step). In the case of SOBEK 2, these cells are included, and the time step is reduced to half their original value. In addition to the previously mentioned background information, when D-Flow FM is used as the hydrodynamic module, various features such as fixed weirs and other hydraulic structures assist users in developing lower mesh resolutions and increasing the computational efficiency of the created models (Lieverse, 2021). Regarding the software's current status and usefulness, D-Hydro Suite 1D2D is still developing and thus a beta product. Several minor concerns developed while utilizing the Deltares D-Hydro Suite 1D2D model version 2022.03 for this investigation and have been added to the Deltares development list.

3.4.2 Model Parameters

These are the parameters that are fed into the model in order to construct, calibrate, and validate any developed model. This section outlines three major parameters.

3.4.2.1 Roughness

The coefficient of friction is the most important factor controlling the flood and water level spread in a river network. Several roughness coefficients can be used to create a river model. The Manning Roughness coefficient is employed in this work to create the model. The roughness values are assigned to the model based on the chainages since the bed material varies across the river. The river basin is divided into three parts, the western ghats, the plateau of Mysore and the delta. Because of this variation, the bathymetry of the basin varies along the river. The roughness of the bed increases as we go to higher altitudes in the basin due to the presence of materials like gravel, and it decreases while moving downstream of the basin, which has soils like black. Red and alluvial. In this work, the roughness values were obtained with the help of Deltares based on the ongoing project in the same basin, and the values of roughness values were the same for all of the models generated in this work. Figure 3-13 depicts the model's chainage and associated roughness values used in this work.

Show only map selection

Branch	Specification	Roughness type	Value	Unit	Function type
1	Branch Chainages	Manning		s*m^-1/3	Constant

Roughness (Manning, s*m^-1/3) for branch '1'

Chainage	Value
0	0,07
64809	0,05
1,9678E+05	0,05
2,941E+05	0,04
3,996E+05	0,04
4,5868E+05	0,04
5,3046E+05	0,04

Figure 3-13: Roughness values and their changes for CRB

3.4.2.2 Real-time Control (RTC)

Real-time control groups are a set of control parameters used to regulate the functioning of the variable of interest. There are numerous controllers available, including Proportional (P), Proportional Integral (PI), Proportional Integral Differential (PID), and many others. In D-Hydro Suite 1D2D, the D-RTC plug is used for modelling feedback control of the hydraulic structures. Some control parameters are crest level of the weirs, discharge of the pumps, gate openings at gated weirs and valve opening of culverts. Controllers are assigned to produce models in D-Hydro Suite 1D2D based on the model's objective and the control variable's characteristics. PID, Lookup table, and Conditional controllers are examples of common controllers. This work uses simple PID and Conditional PID controllers to build flood models. The accuracy of this PID controller is determined by the values of the gain factors K_P, K_i and K_d. Each type has a unique gain factor and gate speed based on its inline construction and inflow characteristics. A typical PID controller representation in D-Hydro Suite 1D2D is shown in Figure 3-14.

The equation governing the PID rule can be mathematically seen as

$$f(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt}$$

where $e(t)$ represents the error (deviation) from the set point, K_p indicates the current deviation from the set point, K_d denotes the previous deviations and K_i indicates all the previous deviations. These values of the parameters K_p, K_i and K_d are used for changing the response of the control group rule and either make the response fast or dampen it. Along with these parameters, the maximum speed of the control structures helps calibrate the output from the control structure.

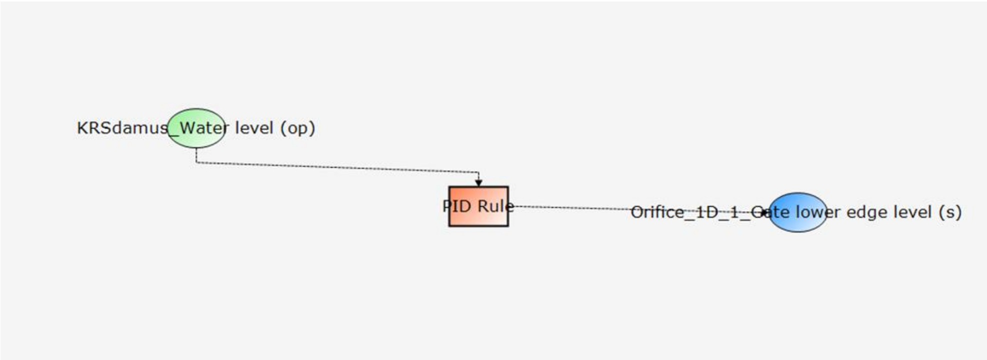


Figure 3-14: Typical representation of simple PID controller

3.5 Model inputs

3.5.1 Boundary conditions

The regulating factors for any model generated are the boundary conditions, and the values of these factors define the type of model intended and developed. The model allocates these conditions to the network's beginning and ending nodes. The node values might be either constant or time-dependent. Discharge, water level, and water depth are the several boundary conditions kinds that can be assigned. The boundary conditions employed in this work's created models to develop a flood model are discharged time series for the start node and water level time series for the end node. The boundary nodes for the entire river models are at Kudige in the u/s and Musuri in the d/s, as shown in Figure 3-15. Figure A-1 and Figure A-2 show the values allocated to these criteria. In the case of reservoir models, the boundary nodes for the KRS reservoir model are at the Kudige and Kollegal stations, as shown in Figure 3-16. Figure A-3 depicts the value allocated to the Kollegal station. The boundary nodes in the Mettur reservoir model are located at Biligundulu and Musuri (Figure 3-17), and Figure A-4 depicts the values attributed to these boundary conditions.

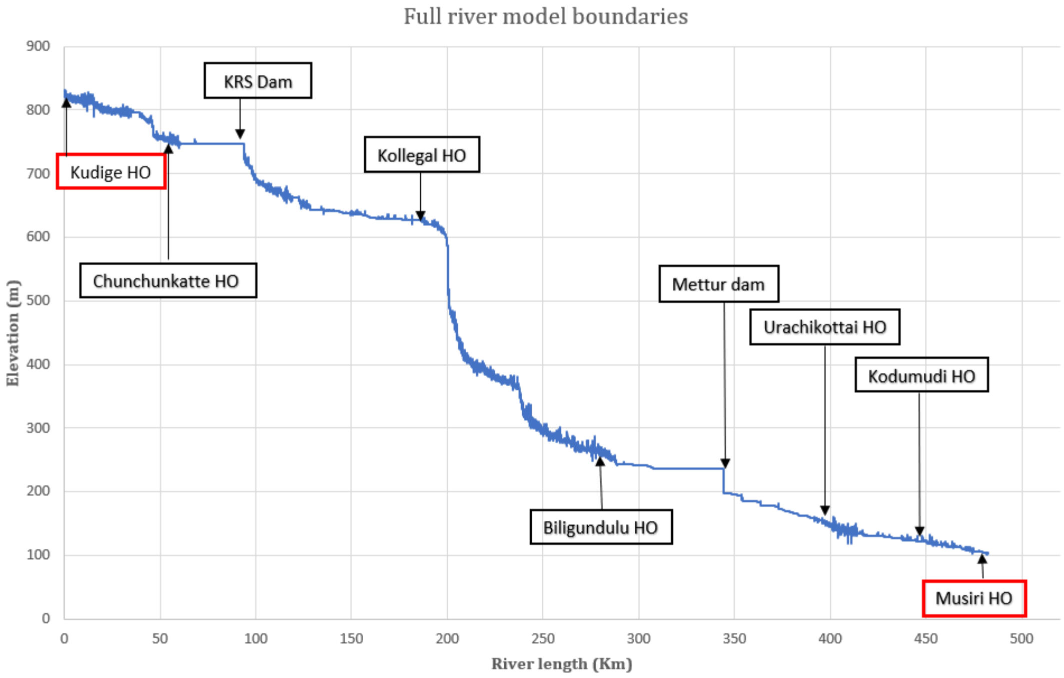


Figure 3-15: Boundary condition location for full reservoir models

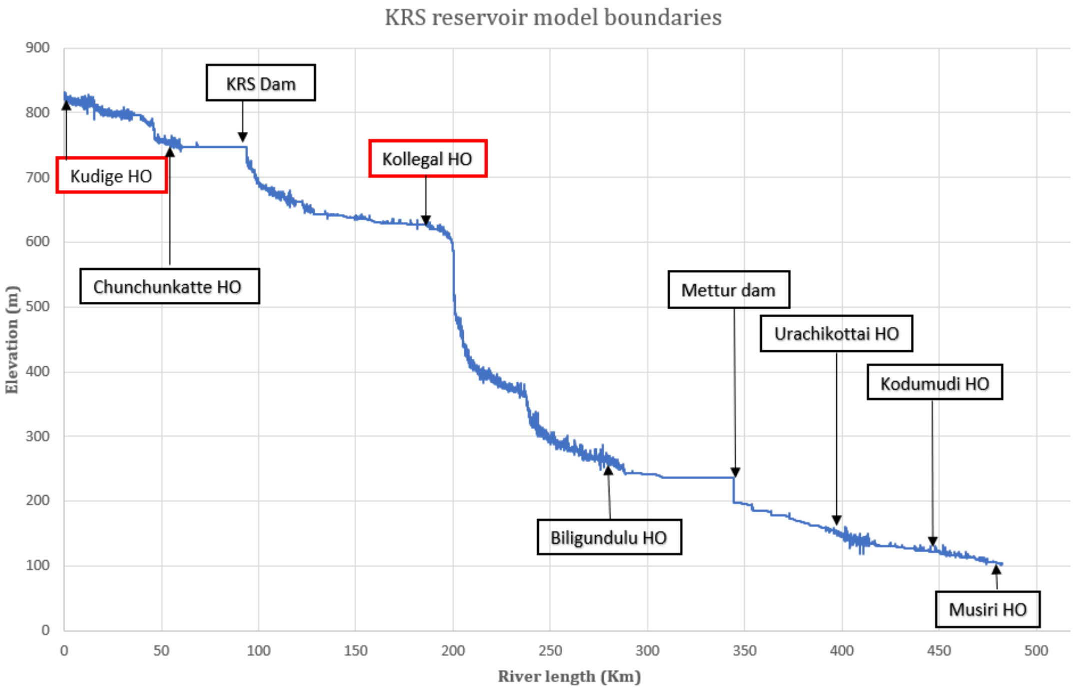


Figure 3-16: Boundary conditions for the KRS reservoir model

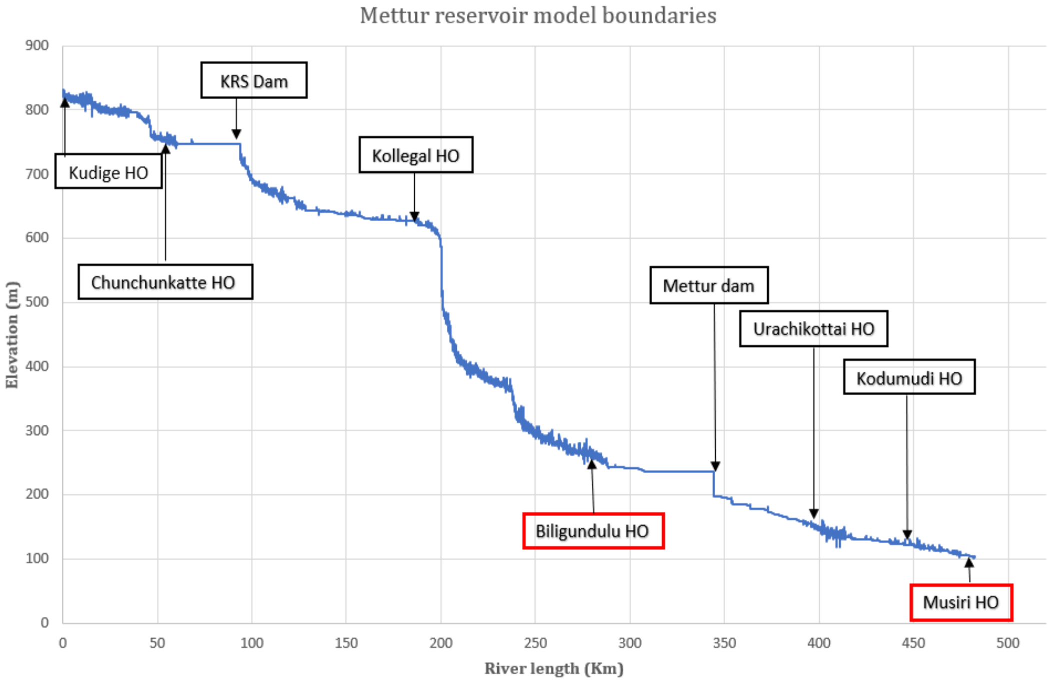


Figure 3-17: Boundary conditions for the Mettur reservoir model

3.5.2 Cross sections

Cross section information in the river system aids in accurately representing the original system in the model. The major elements that affect the water level and discharge at a specific stretch of the river are the width and depth of the cross-section. The cross-section in D-hydro suite 1D2D can be either YZ, WZ, or XYZ. A simple YZ cross section is used for flood modelling in this scenario. Figure 3-18 depicts a typical cross-section used in the construction of flood models.

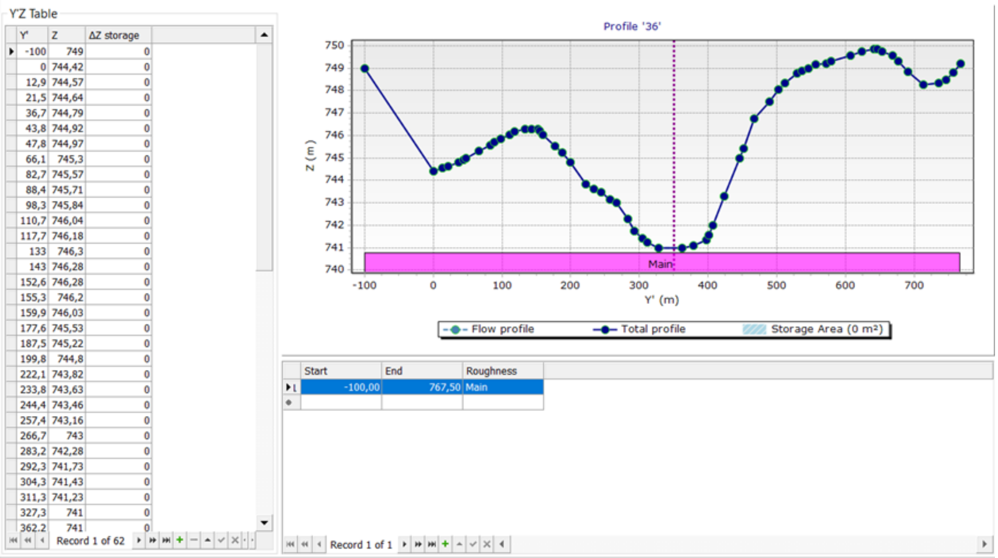


Figure 3-18: Typical representation of YZ cross section in D-Hydro Suite 1D2D

3.5.3 Inline structures

The structure assigned to the river network to manage the flow is the Inline structure. These structures are built in original systems to serve various functions such as water storage, power generating, diversion, and many more. Inline structures are utilized to depict the original flow patterns when creating a model effectively. Dams, weirs, and barrages are three of the most frequent inline structures. The research region in this paper has two dams represented in the model by a gated weir/dam in D-Hydro Suite 1D2D. Each inline structure created in the model requires information on the structure's crest level, the gate's crest level, the structure's width, and the gate's height. These parameters govern how closely the created inline structure resembles the original structure. Figure 3-19 depicts an inline structure utilized for flood modelling in this work.

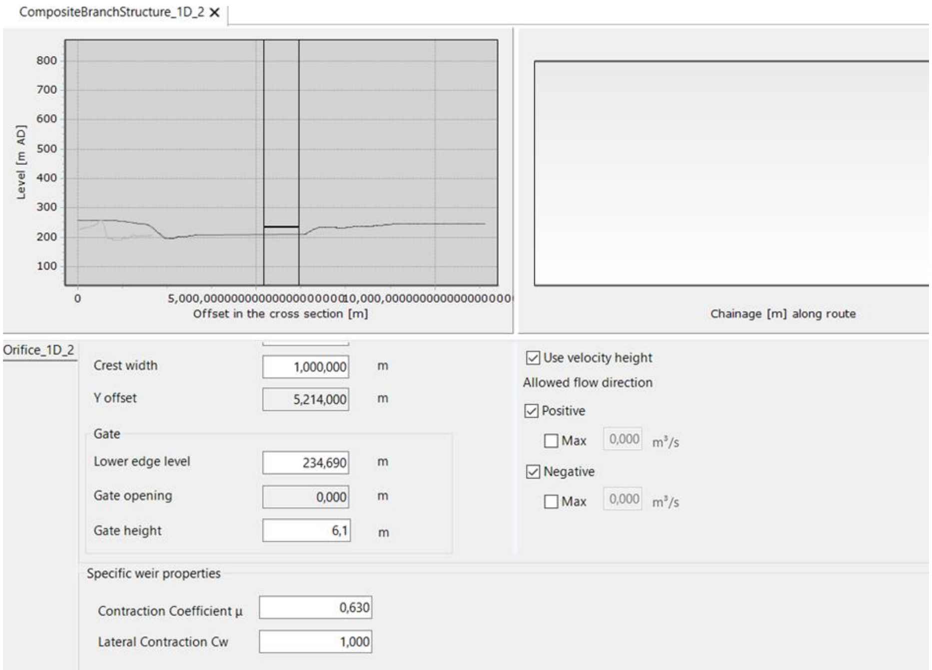


Figure 3-19: Inline structure and its components in D-Hydro Suite 1D2D

3.5.4 Model data processing

3.5.4.1 Kudige cross sections

Based on the results of the 1D model with Lateral inflow (no dams), it was found that the water level in the Kudige cross section is uniformly 2 m lower than the observed water level, as shown in Figure 3-20. This water level error was also recorded just at the Kudige station. Based on this information, it was established that the disparity in water level was caused by a datum error at the Kudige station. To address the problem, the datum of the Kudige cross section is raised by 2 m (Figure 3-21) to compare the observed water level variance to the observed value. The water level in Figure 3-22 shows that the 2 m elevation in the datum provided a water level substantially identical to the measured water level, with minor differences in the early phases.

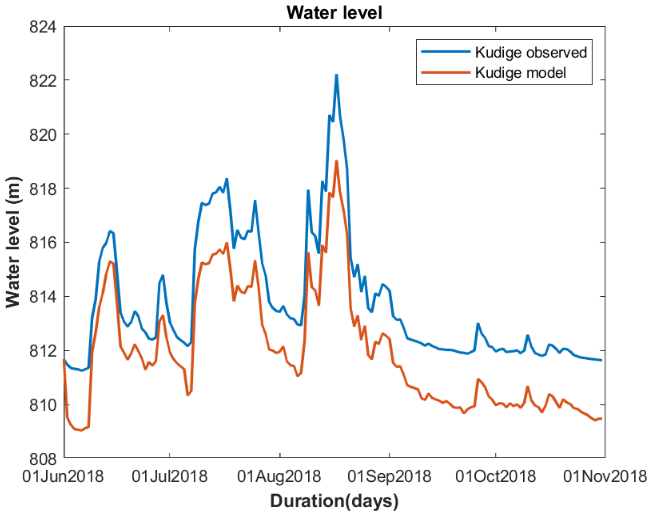


Figure 3-20: Water level at the Kudige station with original cross-sections

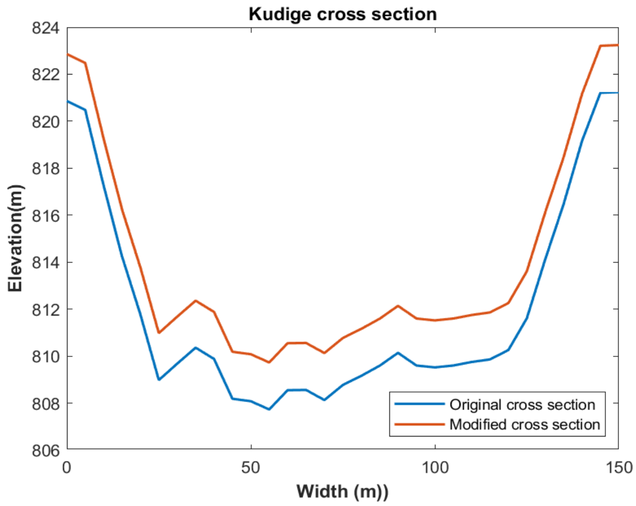


Figure 3-21: Modification of cross-section elevation at the Kudige station

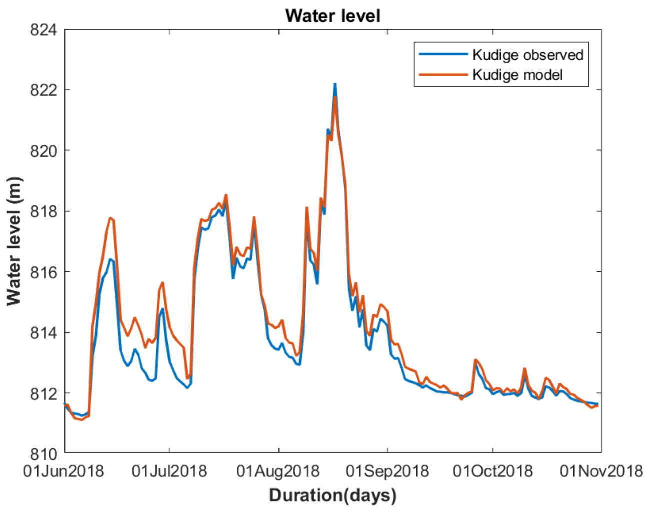


Figure 3-22: Water level at the Kudige station with modified cross-sections

3.5.4.2 Mettur reservoir corrections

Based on the results shown in Figure 3-23, the water level in the simulated Mettur reservoir rises quicker than the observed water level. A volume-elevation analysis is performed to learn more about the rapid rise in water level.

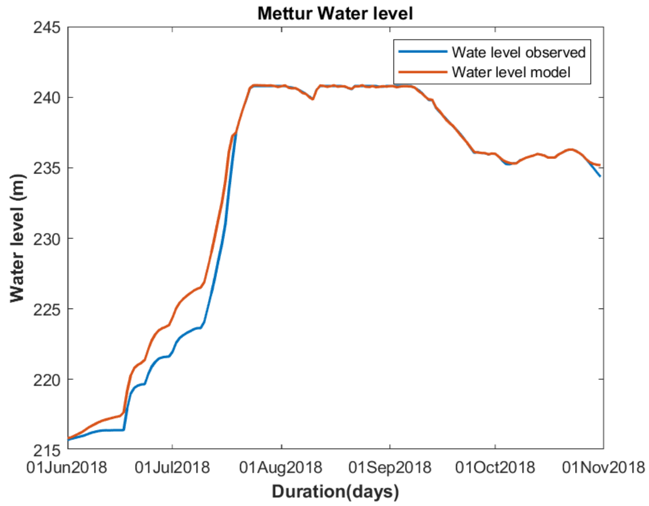


Figure 3-23: Observed and modelled water level in the Mettur reservoir

Figure 3-24 depicts the present volume elevation of the Mettur reservoir in comparison to the observed volume of the reservoir using the available data on water level and volume. Based on both model and observed levels, it is clear that the reservoir volume in the early stages, i.e., from elevation 215.00, is much lower than the reported volume values (seen in red). To address the issue of erroneous volume, three cross-sections in the Mettur reservoir were adjusted to enhance the volume in the model. Figure 3-25 (a-b) shows the features of the original cross-section and the modified cross-section for one cross-section in the Mettur reservoir, and the details of the remaining changed cross-sections are observed in Appendix A-5.

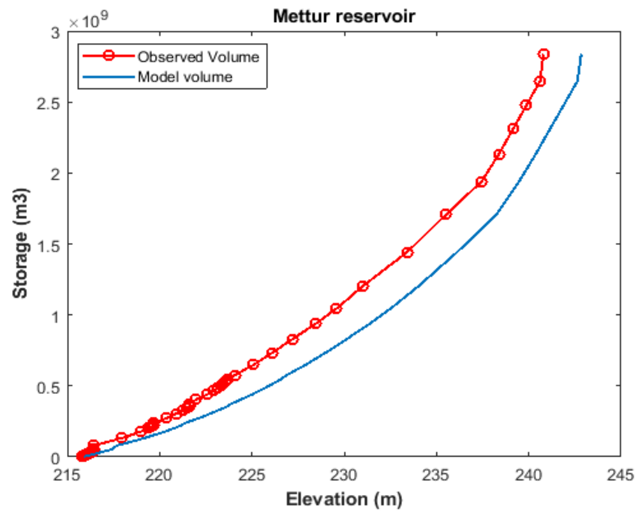


Figure 3-24: Volume-Elevation curve of the Mettur reservoir (original cross-sections)

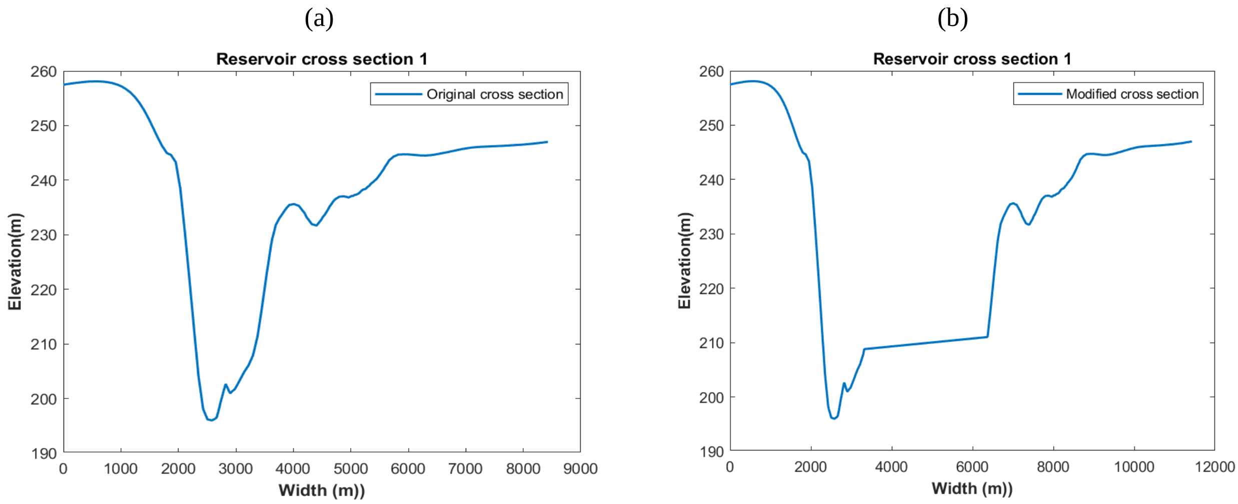


Figure 3-25: Details of original and modified cross sections in the Mettur reservoir

The changes are made at 210.00 m based on the difference between the observed and modelled volumes of the reservoir, as shown in Figure 3-25. The updated volume of the reservoir is then compared to the original volume to determine its proximity to the real volume of the reservoir. Figure 3-26 depicts the updated volume-elevation curve results. According to Figure 3-26, the new reservoir's volume is close to the actual reservoir's volume. These modified cross sections from the Kudige and Mettur reservoirs are utilized to construct calibration and verification models.

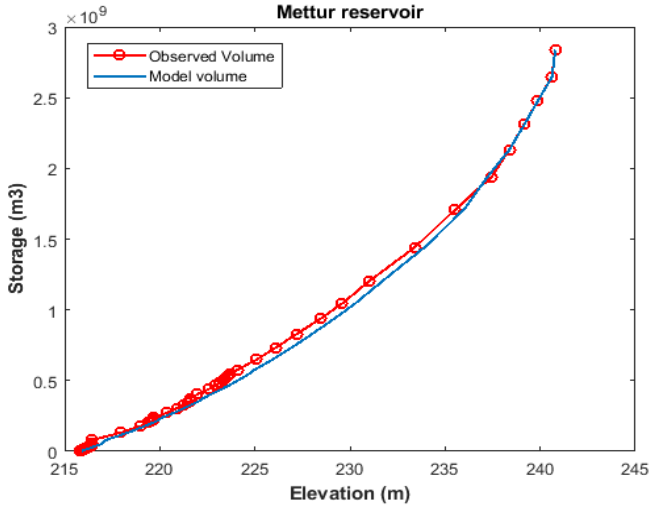


Figure 3-26: Volume-Elevation curve of the Mettur reservoir (modified cross sections)

3.5.5 Simulation parameters

3.5.5.1 Model time step

The time step governs the accuracy of the model in producing sub-daily processes. Lowering the time step increases accuracy, but it also increases run time. A 15-minute time step was best for this study's objectives. All of the models generated in this work use the same model time step.

3.5.5.2 Model time frame

The model time frame represents the overall run-time parameters of the generated model. All of the scenario analysis models, except the flood peak model, have the same time period for model runs. The model period runs from 01-06-2018 to 31-10-2018, and in the case of peak flood models in scenario analysis, the model time frame is from 09-08-2018 to 23-08-2018.

3.5.5.3 Restart files

Restart files save the model's input and output data at predefined time intervals. Based on the data in these files, they can be utilized as initial conditions for boosting the accuracy of the models during the calibration and verification stages. These files are saved in NetCDF files, and each model requires its restart file containing the model's data.

3.6 Model Calibration

3.6.1 Full river model

3.6.1.1 1D model with lateral inflows (without dams)

To comprehend flood propagation in the specified study area, a basic 1D model with lateral inflow is created. As stated in sections 3.4.2-3.5, all model inputs and parameters are introduced into the model, which is then run with the original cross-section to discover changes in flood propagation throughout the river basin. The supplementary flows to the main river are induced as lateral inflows (pint inputs) to the main river in this model. Figure 3-27 depicts a typical 1D model with lateral inputs (without dams). Because the model contains no dams, the discharge values at the observation stations are compared to the calculated discharge values indicated in section 3.3.2.

Figure 3-27: 1D model with lateral inflows (without dams)

3.6.1.2 1D model with lateral inflow (with a dam)

Dams are introduced to the 1D model to comprehend and analyze the flow of the flood in the model, similar to its behaviour in the real system, and the outline of the model can be seen in Figure 3-28. The KRS dam and the Mettur dam are induced into this model and Figure A-6 depicts the specifics of the

KRS and Mettur dam in the appendix. Real-time control groups are added to each dam together with the introduction of the dams. To recreate the dams' original discharge and water level, a simple PID control, as detailed in section 3.6.1.1, is built in this model with a controlled water level. Each dam has a different control point based on the measured water level in the reservoir. Using these control points, the water is kept in the observed patterns, and the model's outflow is calibrated by adjusting the sensitive RTC parameters. Sensitivity analysis is performed to determine the gain factors (K_p, K_i and K_d) and gate speed, as shown in section 3.6.1.3. Based on these data, the model is calibrated to generate the same output as the existing system. Figure 3-29 depicts the details of the RTC control groups and their parameters. To maintain the starting water levels in the reservoirs to their observed levels when constructing these models, a constant flow is employed to set the initial levels, and then the original flood wave is brought into the system. To avoid model instability, restart files are prepared and used as the initial conditions for the models' smooth and successful development.

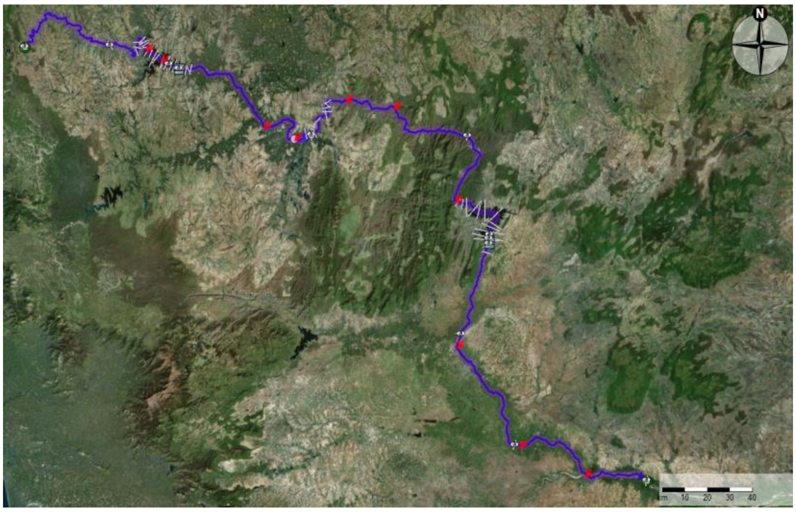


Figure 3-28: Outline of a 1D model with lateral inflows (with dams)

(a) (b)

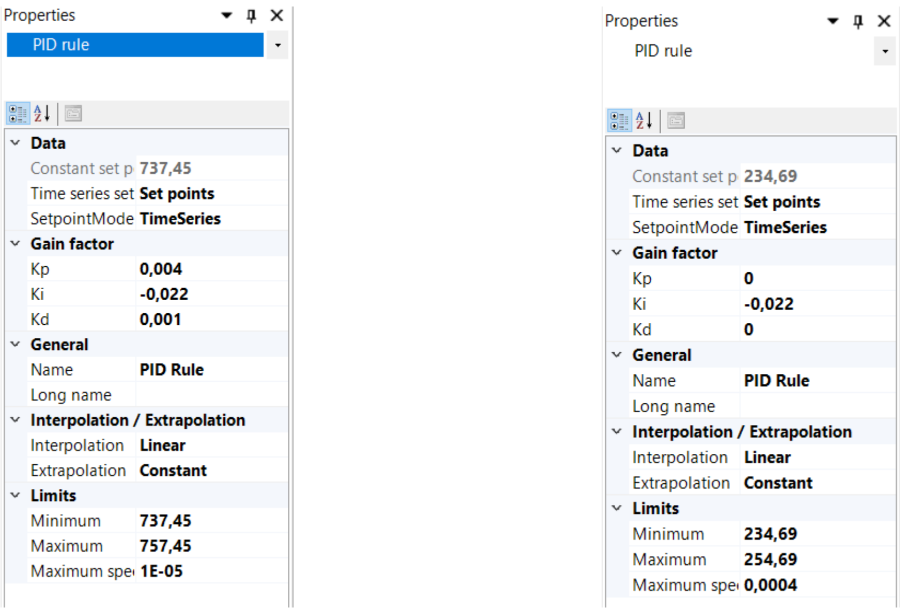


Figure 3-29: PID control paramters for the KRS dam (a) and the Mettur dam (b)

Reservoir models for the KRS and Mettur dams are built based on the models developed with lateral inflows to verify the developed models. Section 3.7 contains information on the model parameters and their governing aspects, while Section 3.6.1.3 has information on the PID control parameters.

3.6.1.3 Sensitivity analysis of the PID control parameters

As demonstrated in section 3.4.2.2, a PID controller is employed in the model to build Real-time control activities. The gain factors K_P, K_i, K_d, and gate speed are the primary parameters that govern the PID controller and its operations on the applied variable, are shown in Table 3-2. During the calibration stage, sensitivity analysis is performed to identify the gain factor and gate speed settings that produce the best results. Several parameter combinations are developed separately for both the KRS dam and the Mettur dam to explore the influence of variation on model outcomes. This section discusses the specifics of the combinations created for the KRS dam.

Table 3-2: Parameter combinations for PID control of KRS dam

Combination	K_p	K_i	K_d
1	0	-0.01	0
2	0	-0.02	0
3	0	-0.03	0
4	0	-0.04	0
5	0	-0.05	0
6	0	-0.10	0
7	0	-0.20	0
8	0	-0.30	0
9	0	-0.40	0
10	0	-0.022	0
11	0	-0.022	0.01
12	0	-0.022	0.02
13	0	-0.022	0.001
14	0.01	-0.022	0.001
15	0.02	-0.022	0.001
16	0.03	-0.022	0.001
17	0.04	-0.022	0.001

Based on an understanding of the parameters from the D-Hydro Suite 1D2D documentation, it was evident that the sign convention of K_i should be negative since the value of K_i reflects the error of the value assigned to the controller relative to the observed value, and so the K_i values are marked with a negative sign to correct the model. In the instance of K_p and K_d sign conventions, the manual states that the general practice is to have a positive denotation for both variables. As a result, in this study, while calibrating the parameters of the PID controller, the K_i is assigned a negative value, while the others are allocated a positive value, as shown in Table 3-2. A trial-and-error method with a steady increase in parameter values is used to establish the ideal parameter values, as shown in Table 3-2, and the model results are compared to the observed values to determine the best possible combination. Based on the results shown in Figure 4-2 (c), the combination of 17 with values of 0.04, -0.022, and 0.001 for K_i, K_p, and K_d, respectively, created the optimal outflow from the KRS dam in the gate speed. A similar study was performed, and the optimal value of the gate speed was found to be 0.00001 m/s. As a result, this combination was employed during the calibration and verification steps. Similarly, the same approach was used to generate a set of values for the Mettur dam. During the parameter calibration, it was discovered that minor alterations in the gate factors had a significant impact on the dam's outflow.

3.7 Model verification

3.7.1 Reservoir Models

3.7.1.1 The KRS reservoir model

The KRS reservoir model follows the same development approach as the model presented in Section 3.6. The main difference between the lateral flow model and the reservoir model is the introduction of branch inflows in place of lateral flows and the model's boundary conditions. Section 3.5.1 discusses the specifics of the boundary conditions utilized for the KRS model. Simultaneously, the details of the real-time control and its parameters are the same as in section 3.6.1.2, and the model's outline can be seen in Figure 3-30. Constant inflow is utilized for the reservoir's initial condition to maintain the water level in the reservoir, similar to the construction of a 1D later flow model with the dam.

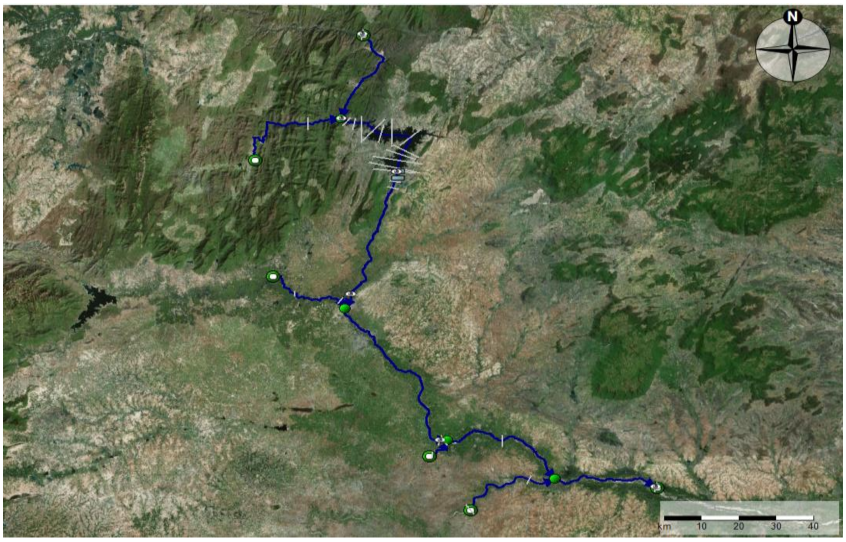


Figure 3-30: Outline of the KRS reservoir model with branches

3.7.1.2 The Mettur Reservoir model

Similar to the KRS reservoir model, branch inflows were devised for multiple branches joining the river system rather than lateral inflows. The settings utilized for RTC and other regulating parameters are the same as in the model constructed in section 3.6.1.2. In addition, the model's specifics of the boundary conditions and nodes of the boundary conditions differ from section 3.6.1.2, and their details can be found in section 3.5.1. Figure 3-31 depicts an outline of the Mettur reservoir model.

Figure 3-31: Outline of the Mettur reservoir model with branches

3.8 Scenario development

The primary goal of this part of the study is to prevent floods in the CRB, i.e., to prevent floods in the river system downstream of the reservoir by trapping the flood peak in the dam. To accomplish this goal, the essential aspect is to create scenarios of gate operations for the dams in the basin. The flooded locations described in numerous articles are all downstream of the Mettur reservoir, based on the observation of the flooded areas in Figure 2-10. As a result, scenario operations for the Mettur reservoir model are carried out in this part. Understanding the dam's capabilities and constructing scenarios based on its limits is critical to developing a successful scenario. Volume study is performed to understand the limitations of the Mettur reservoir and the volume of incoming floods during flood peaks. Section 3.3.4 has more information on the volume analysis.

The following assertions about the reservoir, operation, and capacity are kept in mind as the scenarios are being built.

i. During the analysis period, the Mettur reservoir is not lowered in preparation for any impending flood.
ii. Until the FRL is achieved, there is no water outflow (the dam retains the water until the FRL is reached).
iii. The reservoir fills up completely before the flood peak appears.
iv. The water level in the reservoir must be decreased in time to store the flood peak.

With these assertions in mind, three scenarios are created to capture the reservoir's flood peak. Along with preparing scenarios, numerous case evaluations were performed for each scenario to establish the dam's performance under varying water level situations. Table 3-3 provides a summary of the scenarios and cases developed, and sections 3.8.1-3.8.3 discuss each scenario and its associated gate operation conditions.

Table 3-3: Details of Scenario development

<table>
<tr><th>Scenario number</th><th>Description</th><th>case</th><th>Initial water level in reservoir (m)</th><th>Spillway crest level (m)</th><th>Water release level (m)</th><th>FRL (m)</th><th>Gate operation rule</th><th>Remarks (case details)</th></tr>
<tr><td>0</td><td>High water release level</td><td>Reference</td><td>215.45</td><td>234.69</td><td>240.79</td><td rowspan="11">240.79</td><td>0</td><td>ORL</td></tr>
<tr><td rowspan="5">1</td><td rowspan="5">Lower water release level</td><td>1.1</td><td>215.45</td><td rowspan="5">234.69</td><td rowspan="5">234.69</td><td>1</td><td>ORL</td></tr>
<tr><td>1.2 (a)</td><td rowspan="2">196.90</td><td rowspan="2">2</td><td rowspan="2">DRL</td></tr>
<tr><td>1.2 (b)</td></tr>
<tr><td>1.3 (a)</td><td rowspan="2">208.45</td><td rowspan="2">3</td><td rowspan="2">LRL</td></tr>
<tr><td>1.3 (b)</td></tr>
<tr><td rowspan="5">2</td><td rowspan="5">Lower crest level of spillway</td><td>2.1</td><td>215.45</td><td rowspan="5">215.00</td><td rowspan="5">220.00</td><td>1</td><td>ORL</td></tr>
<tr><td>2.2 (a)</td><td rowspan="2">196.90</td><td rowspan="2">2</td><td rowspan="2">DRL</td></tr>
<tr><td>2.2 (b)</td></tr>
<tr><td>2.3 (a)</td><td rowspan="2">208.45</td><td rowspan="2">3</td><td rowspan="2">LRL</td></tr>
<tr><td>2.3 (b)</td></tr>
<tr><td>3</td><td>Increase dam height</td><td>3.1</td><td>215.45</td><td>234.69</td><td>234.69</td><td>250.79</td><td>1</td><td>ORL</td></tr>
</table>

*ORL- Original initial reservoir level, DRL- Dry reservoir level, LRL- Lowest reservoir level

*a- Peak flood period, b- Full period of analysis

3.8.1 Scenario 1: Lower water release level (234.69 m)

Based on our understanding of the dam's operation in the reference case (section 3.7.1.2), we understood that no water is permitted to flow downstream unless the FRL of the dam is reached. Based on this concept and the observation of the original outflow in Figure 4-4 (d), a minor adjustment to the original system is recommended in this scenario to see if the reservoir can capture the peak. The alteration proposed in this scenario is to change the condition of the water release to 234.69 m, i.e., to the spillway's crest level rather than the FRL.

Case 1.1: Initial water level in reservoir (215.45 m)

The time-dependent water level release is translated in D-Hydro Suite 1D2D using a conditional PID controller, as seen in Figure 3-32. To understand how the reservoir works when scenario 1 is applied to the original system, the details of the rules are presented in Table 3-4.

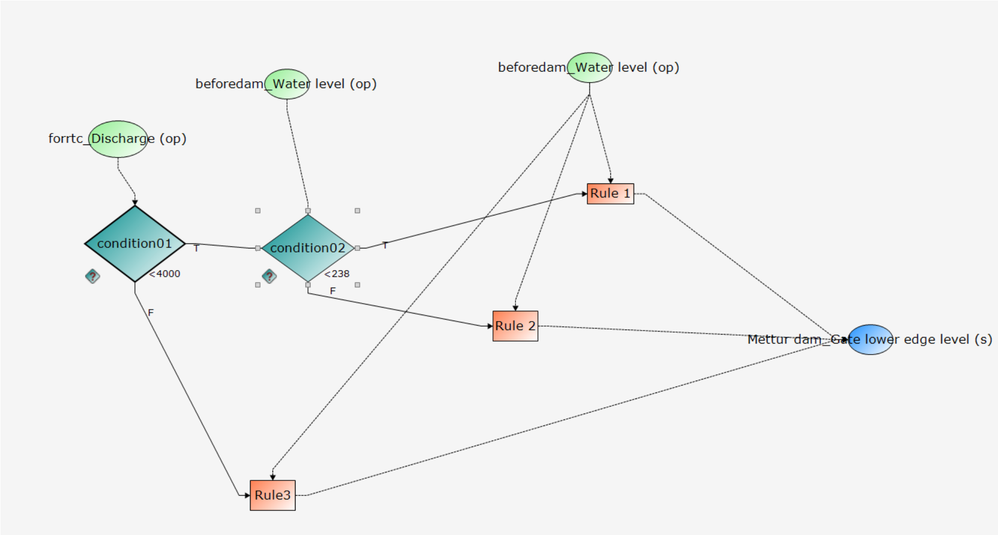


Figure 3-32: Conditonal PID controller for Scenario 1

Table 3-4: Rules of gate operation for Scenario 1

Scenario: 1				
Rule	Condition			Maintain water level
	Q	WL	Q/WL	
1	<4000	<238	True/True	234.69
2			True/False	240.50
3			False/False	240.40

A water level and discharge-based PID controller successfully maintain the target water level and avoid excess outflow from the dam during peak flood from the reservoir. The controller is programmed so that until the discharge lies below 4000 m^3/s and the water level falls below 238.00 m, the controller attempts to keep the water level at 234.69 m (unlike the reference model with FRL). When the water level or the discharge does not meet the stated requirement, the controller closes the gates and maintains the dam's FRL. In this manner, the water level is dropped in the early days to capture the flood peak.

Case 1.2: Initial water level in the reservoir (196.50 m)

a) Peak flood period analysis

In the original water level condition, the observed initial water level in the reservoir is utilized to test the model's applicability. In this case, the reservoir is considered dry during the analysis, and the proposed scenario is tested to see if the flood peak can be caught. The reservoir's water level was 196.9 m during the analysis period. Except for the time frame of analysis, all of the RTC settings and conditions are the same as in the prior scenario. This model's analysis period runs from 09-08-2018 to 23-08-2018.

b) Full period of analysis

The only change in the model between full period analysis and flood peak analysis is the time frame of the analysis. In this scenario, the model is developed over the entire period, from 01-06-2018 to 31-10-2018, with all parameters remaining constant.

Case 1.3: Initial water level in the reservoir (208.45 m)

a) Peak flood period analysis

The water level in the reservoir at the start of the analysis is maintained at 208.45 m in the condition of the lowest water level (the lowest water level in the last 40 years). This condition was added to comprehend better how the suggested scenario will handle a flood wave if the initial water level is the same as the lowest observed water level in the reservoir. Similar to the creation of the model in Case 1.2, all of the model's parameters stay the same as the model with the original water level, except the initial level in the reservoir and the model's time frame.

b) Full period of analysis

Similarly, the changes made to the full period model compared to the flood peak model are the change in the model's time frame to the entire analysis period built for the full period with the lowest water level.

3.8.2 Scenario 2: Lower crest level of spillway (215.00 m)

Following the successful development and observation of scenario 1, the aspect of having numerous gates in the Mettur dam is considered, and the spillway's crest is reduced to match the gate level available at approximately 215.00 m. When the spillway's crest level is at 215.00 m, there is an opportunity to release more water in the days preceding the arrival of the flood peak than when the crest level is at 234.69 m. Similar to the model cases produced in Scenario 1, three cases of varied water levels are modelled to test the proposed modification's capabilities in capturing the flood peak.

Case 2.1: Initial water level in reservoir (215.45 m)

To understand how the reservoir behaves when the spillway's crest level is reduced to 215.00 m, a Conditional PID controller is created in D-Hydro Suite 1D2D, as shown in Figure 3-33, and the gate operation rules can be examined in Table 3-5.

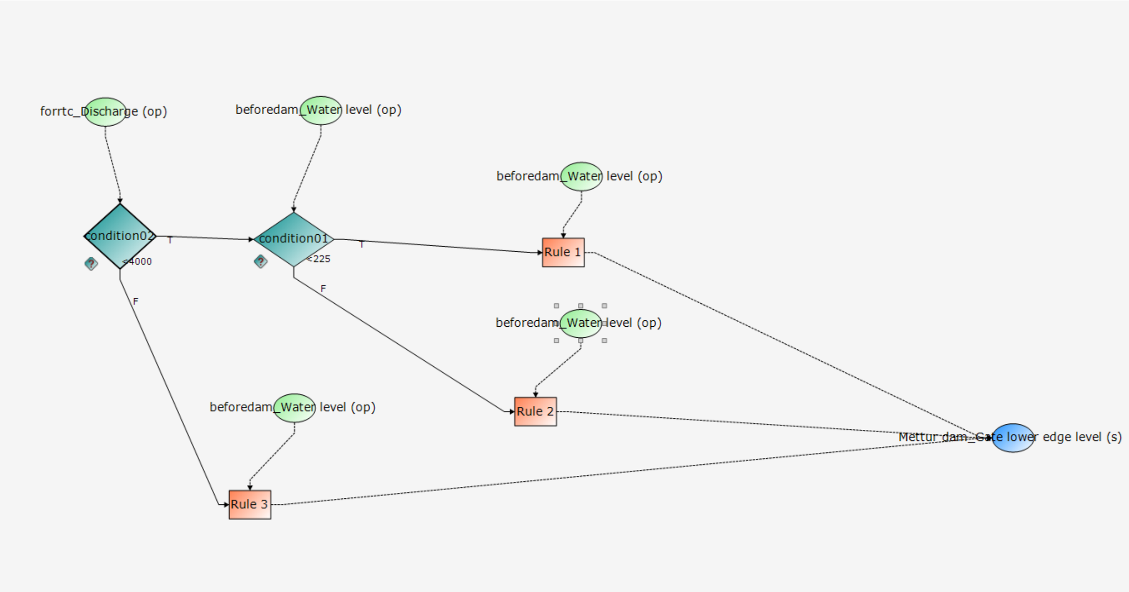


Figure 3-33: Conditional PID controller for Scenario 2

Table 3-5: Rules of gate operation for Scenario 2

Scenario: 2				
Rule	Condition			Maintain water level
	Q	WL	Q/WL	
1	<4000	<225	True/True	200.00
2			True/False	240.50
3			False/False	240.40

A water level and discharge-based PID controller are used to successfully maintain the required water level and avoid excess outflow from the reservoir. The controller is programmed so that until the discharge lies below 4000 m^3/s and the water level falls below 225.00 m, the controller attempts to keep the water level at 220.00 m. When the water level or discharge does not meet the set requirement, the controller closes the gates and maintains the dam's FRL. In this manner, the water level is dropped in the early days to capture the flood peak. In model development parameters, all parameters except the spillway crest level remain constant in the basic model configuration. The crest level has been reduced to 215.00 meters (instead of 234.69 m in the reference model).

Case 2.2: Initial water level in the reservoir (196.50 m)

a) Peak flood period analysis

In this case, the reservoir is considered dry during the analysis, and the proposed scenario is tested to see if the flood peak can be caught. Except for the time frame of analysis, the water level in the reservoir at the start of the analysis is 196.9 m, and all of the parameters and circumstances of RTC are the same as in the prior case. This model's period of the analysis is from 09-08-2018 to 23-08-2018.

b) Full period of analysis

The only change in the model between full period analysis and flood peak analysis is the time frame of the analysis. In this scenario, the model is developed over the entire period, from 01-06-2018 to 31-10-2018, with all parameters remaining constant.

Case 2.3 Initial water level in the reservoir (208.45 m)

a) Peak flood period analysis

The water level in the reservoir at the start of the analysis is maintained at 208.45 m in the condition of the lowest water level (the lowest water level in the last 40 years). This condition was introduced to understand how the proposed scenario will handle the flood wave if the initial water level is the same as the lowest observed water level in the reservoir. Except for the reservoir's starting level and the model's period, all of the model's parameters remain the same as in case 2.2.

b) Full period of analysis

Similarly, the adjustments made to the entire period model compared to the flood peak model are changes in the model's time frame in the model generated for the full period with the lowest water level.

3.8.3 Scenario 3: Increase dam height (+10 m)

Instead of adjusting the specifications of the water level condition or the crest level of the spillway in this scenario, an effort was made to comprehend if the dam height should be extended to a certain level to store the approaching flood peak. As a result, to determine the applicability of this scenario, a basic trial and error modelling is performed to estimate the dam height sufficient to contain the flood peak without generating concerns upstream of the dam. This research showed that a 10 m increase in dam height is sufficient to capture the flood peak while lowering the release during the smaller peaks. Figure 3-34 details the conditions and dam characteristics, while Table 3-6 shows the gate operating regulations.

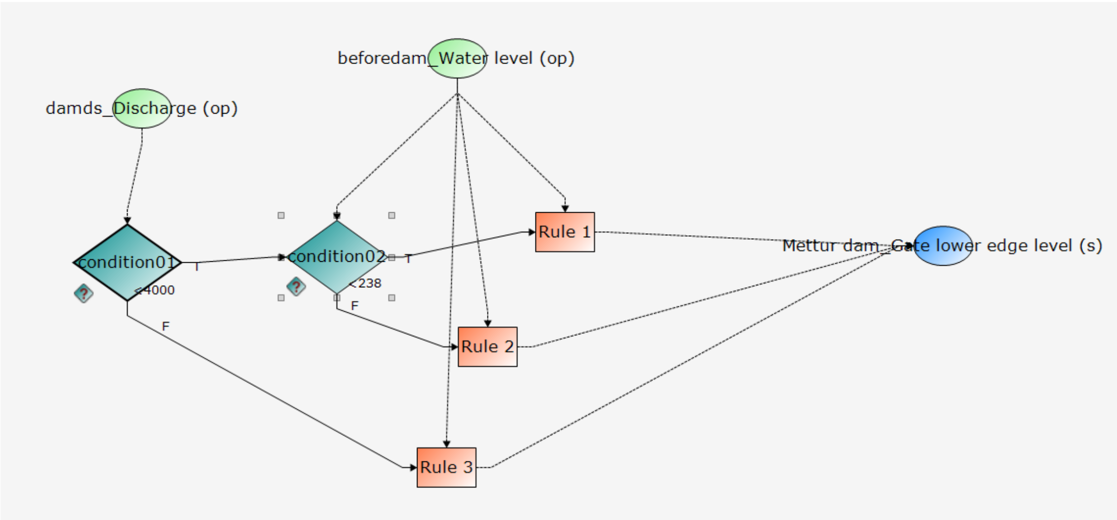


Figure 3-34: Conditional PID controller for Scenario 3

Table 3-6: Rules of gate operation for Scenario 3

Scenario: 3				
Rule	Condition			Maintain water level
	Q	WL	Q/WL	
1	<4000	<238	True/True	234.69
2			True/False	250.50
3			False/False	250.40

The conditional RTC parameters are set to maintain a level lower than the FRL until the peak flood enters the reservoir to prevent water from flowing out of the dam during the peak inflow period. A discharge of 4000 m^3/s is set as a restriction for opening and closing the dam gate, similar to prior models' initial conditional water level. If the discharge is less than 4000 m3/s and the water level is less than 238.00 m, the RTC attempts to keep it at 234.69 m (crest level of spillway). Models are constructed utilizing the three model scenarios and cases listed above to determine which model scenarios can successfully capture the flood peak during the analysis period.

4 RESULTS AND DISCUSSION

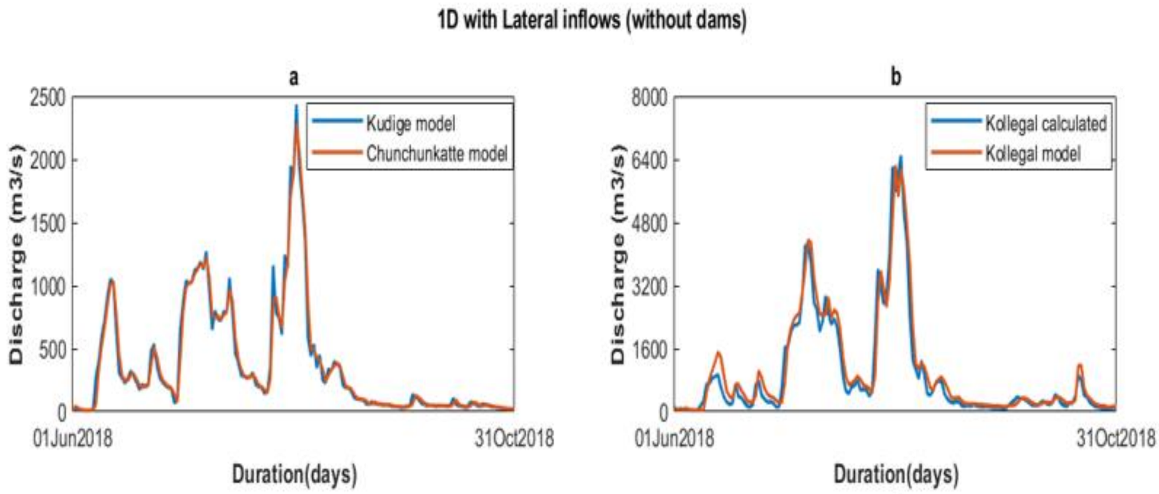
The results of the numerous model approach discussed in sections 3.6-3.8 were generated for calibration, verification, and further testing of various model situations. This section displays the output from each model created, along with a thorough analysis of the output.

4.1 Model Calibration

4.1.1 Full river model

4.1.1.1 1D model with lateral inflows (without dams)

Figure 4-1 (a) depicts the model's discharge output at the Kudige and Chunchunkatte stations. Observations show that both discharge hydrographs had values with nearly identical peaks during the entire period of analysis. It can be noticed that the peak in the first week of August and mid-August has changed slightly. The presence of three intake structures between the stations of Kudige and Chunchunkatte, which are not incorporated in the established model, could explain the drop in peaks. At the Kollegal station, Figure 4-1 (b) compares the calculated and predicted discharge results. The peak flow levels have a one-day lag between mid-July and mid-August. Similar to the values in Kollegal, there is a 1-day lag in discharge values derived by the model compared to calculated discharge at Biligundulu and Urachikottai stations, as seen in Figure 4-1 (c) & Figure 4-1 (d). Figure 4-1 (e-f) shows a lag of two days in modelled discharge compared to estimated discharge for discharge computed at the Kodumudi and Musuri stations. The entrance of the flows of the branches into the system in the form of lateral flow, which removes the travel time of the flows from the location of measurement to the point where it joins the main river, could explain the reported lags. Although there is a lag in the peak flows recorded in virtually all cross sections, the peak flows are close to the observed values in all cross sections. This validates that their assigned roughness values are meaningfully corrected for cross-section characteristics at the gauging sites. The Krishna Raja Sagara (KRS) and Mettur dams are added to the 1D model in the following phase to depict the existing river system. Section 3.6.1.2 describes the approach used for model development in detail. These sections detailed the dam's details and the real-time control groups utilized to operate the dam gates and retrieve the model's observed outflow. Figure 4-2 depicts the model's outcomes.



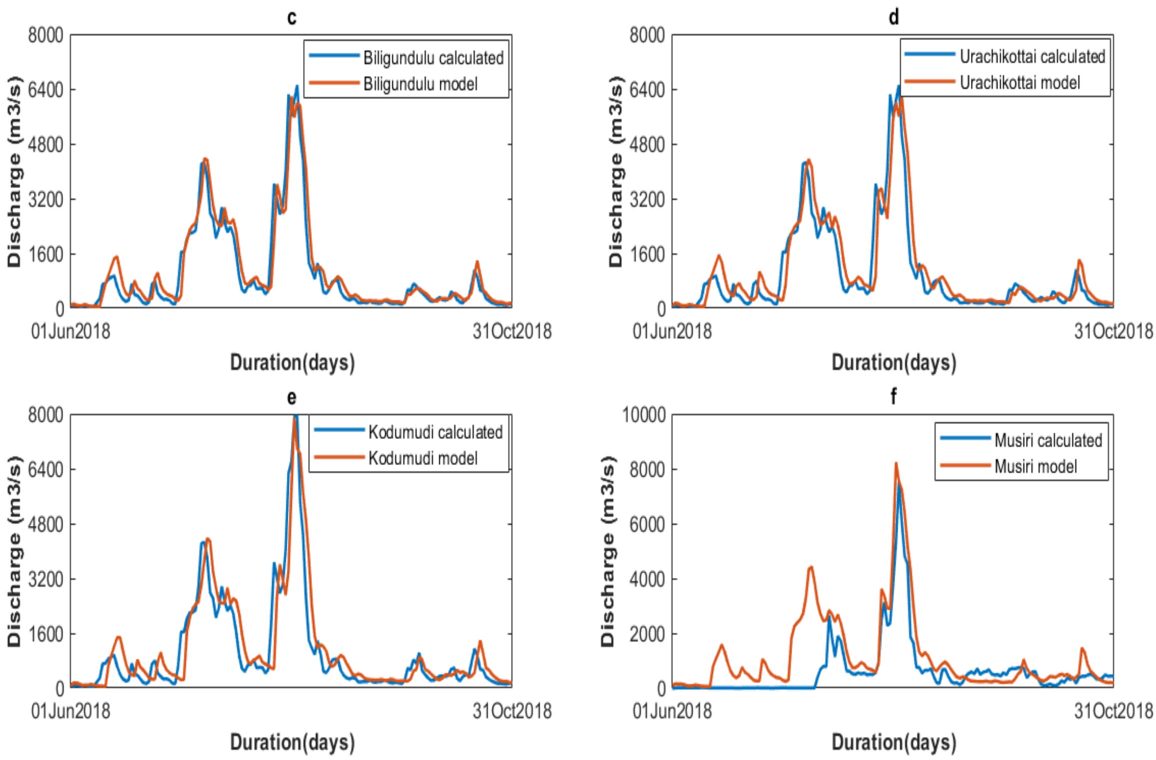


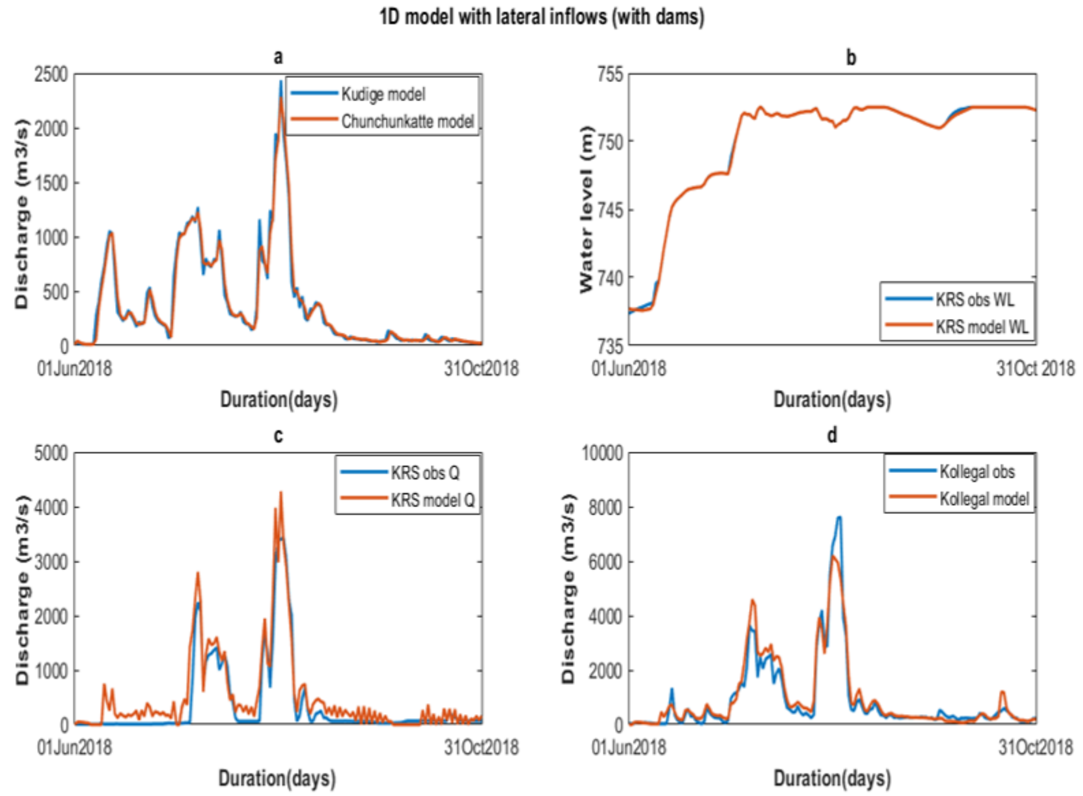
Figure 4-1: Comparision of the calculated and modelled discharge outputs

4.1.1.2 1D model with Lateral inflow with dams

Figure 4-2 (a-j) depicts the results of the 1D model with the lateral flow and the operation of both the KRS and Mettur dams. The flow data in the Kudige and Chunchunkatte stations are similar to the observations of the flows in the preceding case. According to the values in Figure 4-2 (a), the flow in the model is not deviating from the original values, and there are no flood/water losses in the system.

Following confirmation of the Chunchunkatte station results, the next major measurement after the Chunchunkatte station is the water level in the reservoir of the KRS dam, as shown in Figure 4-2 (b). Figure 4-2 (b) compares the model's water level to the observed water level in the reservoir during the flood. The details of the cross-section and volume for the KRS reservoir in the model are the same as the real-world values, based on a comparison of the modelled water level to the observed values. Because the KRS dam volume values are the same as the reservoir's original volume, the dam's outflow should follow the same pattern as the observed outflow. Figure 4-2 (c) depicts the outflow results from the KRS dam. When the observed dam outflow is compared to the model outflow, the model outflow follows the observed data pattern, with greater peak values during all flood maxima during the analysis period. The values of the gain factors employed in the RTC control groups, as described in section 3.6.1.3, can be linked to these greater peaks. As a result, the flood wave can be better matched to the observed value by adjusting the gain factors and gate parameters. Although further factor refining may or may not minimize the peak values, the higher peaks do not indicate erroneous model results. In addition, there are variations in the dam's output at low flows. These variations in the low flows are due to the model's forcing to maintain the reservoir's water level to the original water level, and thereby the outflow from the dam slightly increases compared to the observed values. The low values can be adjusted along with the peak flood by changing the fate parameters. While deciding whether to release the dam's outflow, the choice to open the gate remains the same when the outflow from the model is somewhat higher than the observed value. As a result, in this scenario, the influence of the model's larger peak value than observed has no effect on the dam's regular operation during the flooded state. The downstream discharge values at the Kollegal and Biligundulu stations differ from the observed values due to outflow from the KRS dam (Figure 4-2 (d-e)). The main influence of the KRS dam outflow is visible at Kollegal station compared to Biligundulu, as Kollegal station is closer to the KRS dam than Biligundulu. The next main detail of the water level and discharge are of the Mettur dam.

The results of the water level of the Mettur dam can be seen in Figure 4-2 (f). From observation, the modelled water level rises far quicker than the observed increase in water level. This quick increase in the reservoir's water level before it reaches the crest level of the spillway (234.69 m) shows that the reservoir's volume is less than the observed volume. This lower reservoir volume is causing the model's water level to reach the FRL faster. Due to the quick increase in the water level, there is a major change in the outflow of the dam, as seen in Figure 4-2 (g). A significant release of outflow is seen earlier in the earlier period when the observed outflow of the dam is zero. The model's output exceeds the dam's reported outflow in two peak floods. Figure 4-2 (g-j) shows that the new flood peak in model outflow is carried forward to the next observation sites. Despite the addition of a new peak element to the outflow, the values of the previous peaks in all of the stations downstream of the reservoir are close to the observed discharge. This is because if the dam's outflow can be modified by modifying the reservoir's capacity, the problem associated with the early opening of the gate resulting in a new peak can be resolved. The results of both models in sections 4.1.1.1 and 4.1.1.2 show a lag in the flood peaks in the model in part 4.1.1.1 and a problem with the reservoir volume (Mettur) in the model in section 4.1.1.2. A new model is created to address both difficulties and further validate the model by incorporating the branches and their flows into the river. After successfully adding the branches and correcting the capacity of the Mettur reservoir, as shown in section 3.5.4.2, the models are checked for accuracy, as shown in section 4.2.



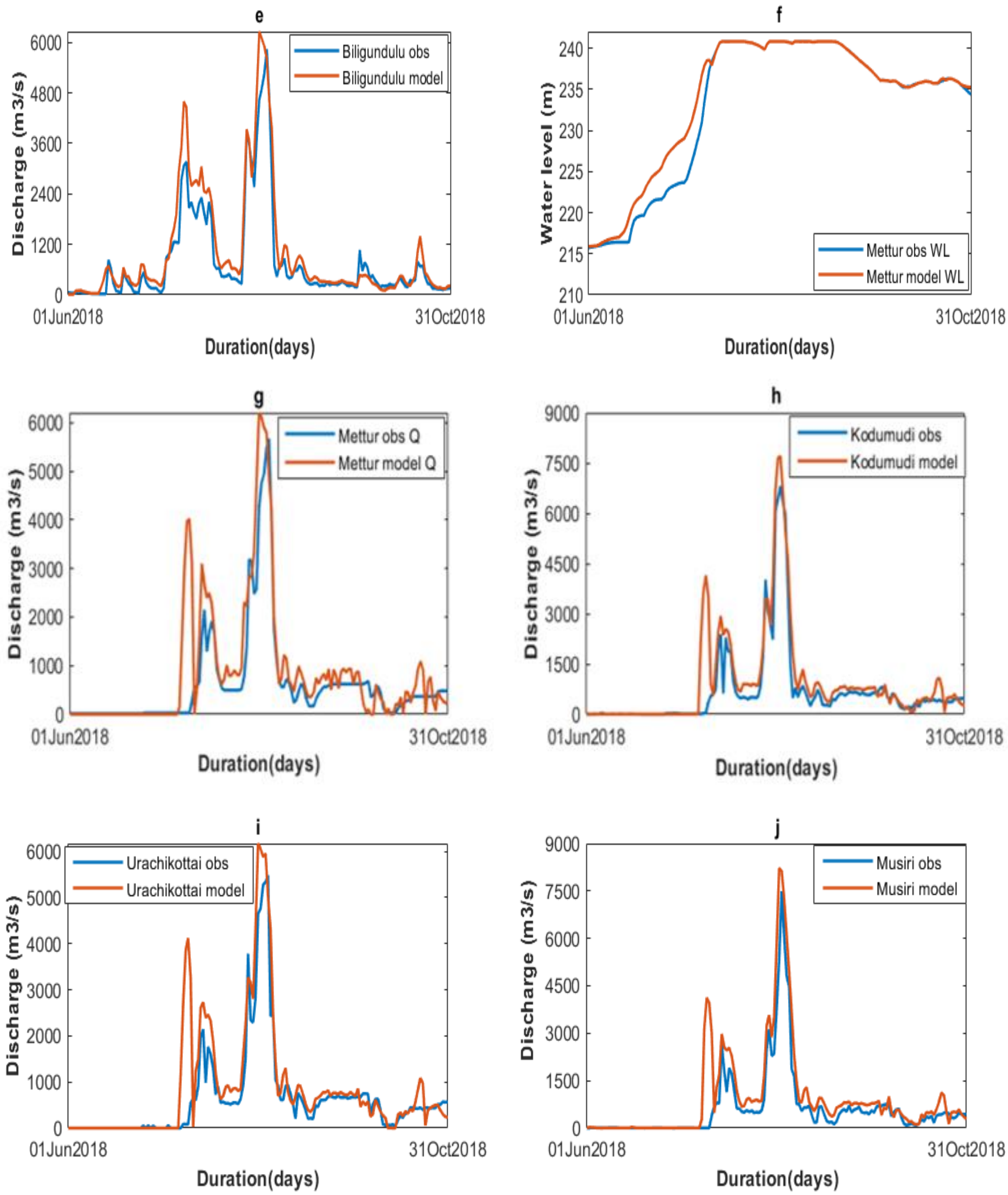


Figure 4-2: Results of lateral flow model with gate operations

4.2 Model verification

4.2.1 Reservoir models

4.2.1.1 The KRS dam model

The KRS dam and its dependent systems did not show any variations from the patterns of the original system and their observations based on the results of the calibration stage using the model with lateral inflow. As a result, except the amended cross sections at the Kudige station, the KRS model is built using original data. Figure 4-3 displays the KRS model's outcomes.

Figure 4-3 depicts the verification stage findings for the KRS model. The discharge values at the Kudige and Chunchunkatte stations are shown in Figure 4-3 (a). As noted in the calibration findings, there is no change in the discharge readings at the Kudige and Chunchunkatte stations, indicating no extra flow or loss of water from the system. This demonstrates that the model established is correct. Figure 4-3 (b) depicts the observed and predicted water levels in the KRS dam. As shown in Figure 4-3 (b), the values of both observed and modelled water levels are the same as in the calibration stages. When it comes to the dam's outflow, there is a noticeable variation in the peaks of the hydrograph. The gate operation and its governing elements have an impact on these modifications. Several gate mechanism scenarios were devised and tested in a trial-and-error method. Section 3.7.1.1 shows the parameter values used in developing the current mode. Despite a small change in the reservoir's outflow, the decision-making process for the dam's gate operation has not been affected by this change in the outflow. If the peak outflow is 3500 m^3/s or greater, the decision to release water from the dam remains the same because maintaining the reservoir level at FRL is the key concern.

Additionally, the slight uptick in peak values downstream from the reservoir has no appreciable impact. Figure 4-3 (d), which depicts the discharge at the Kollegal station, shows the presence of no impact. With only little variations in low flows, the computed and observed values both revealed the same peak values. The estimated discharge rather than the observed discharge is due to additional flow at the Kollegal station and the actual incoming flow. Section 3.3.2 provided a thorough explanation of this flow deviation.

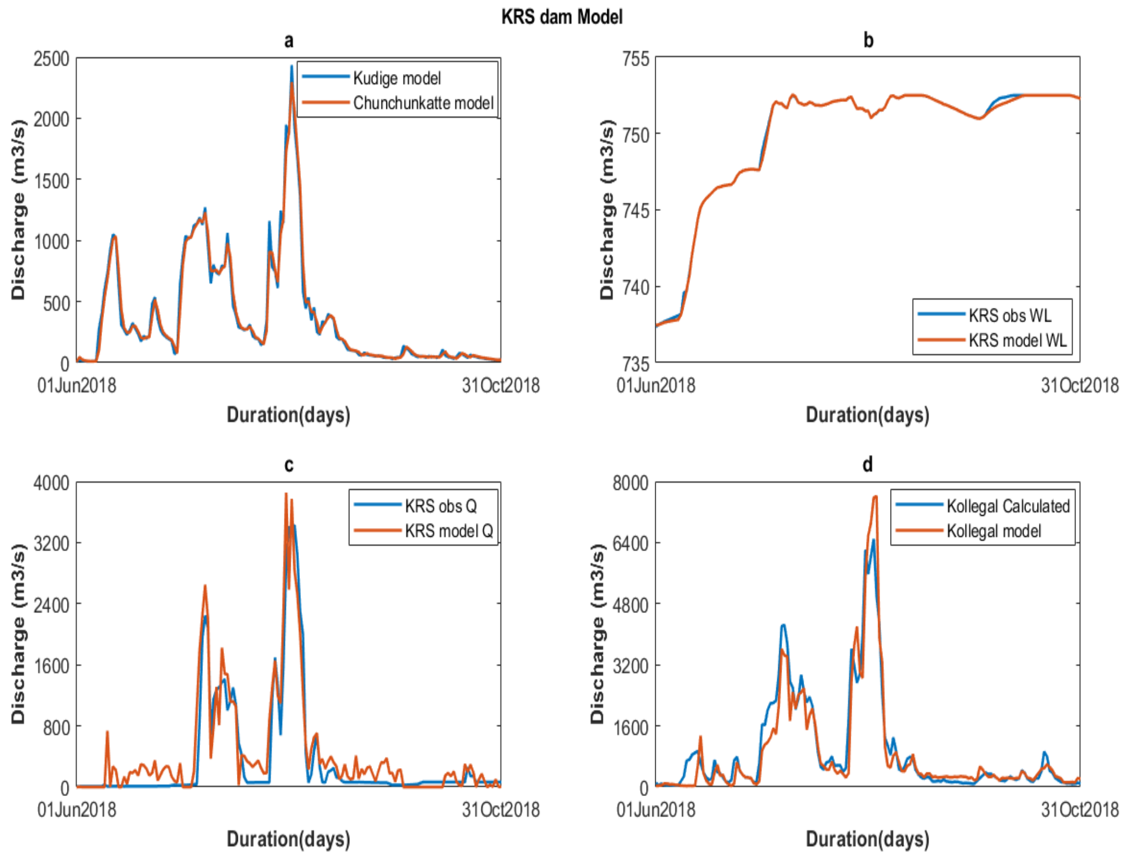


Figure 4-3: Verification results of the model with the KRS dam

4.2.1.2 The Mettur model

Figure 4-4 depicts the verification results for the Mettur dam. At Biligundulu, the observed and modelled discharges are identical. These results indicate that the model's initial assumptions are correct, as the values are correctly represented. Regarding the water level at the Mettur dam, Figure 4-4 (b) indicates that the trend of the modelled water level matches the actual water level, with little overprediction in the early stages. These difficulties are judged negligible in the early stages because the discharge outflow from the dam was determined to follow the same pattern as the observed outflow, with no substantial deviations. Figure 4-4 (c) displays actual and predicted discharge values from the Mettur dam. Based on keen observation, the model has higher peaks than the observed data during the peak flows. The model shows a higher peak with more than 800 m^3/s during the peak in mid-August. Similar to observations in the KRS dam, although in simpler terms, there is an over-prediction of the outflow by the model while decision making regarding the release of water from the reservoir, it does not affect the change in the decision as the gate remains open even when the outflow is 6000 m^3/s or greater than that. Although these higher peaks might not cause any reasonable changes in the decision-making, further fine-tuning of the RTC parameters mentioned in section 3.6.1.3 was carried out. In addition, there are variations in the dam's output at low flows. These variations in the low flows are due to the model's forcing to maintain the reservoir's water level to the original water level, and there by the outflow from the dam has slightly increased compared to the observed values. The low values can be adjusted along with the peak flood by changing the fate parameters.

Nonetheless, the concerns of low flows are not prioritized in this work because the primary goal of this research is to understand the reservoir's behaviour at flood peaks and build scenarios for effective reservoir maintenance without causing downstream floods. Because of an improvement in the accuracy of the Mettur dam's outflow compared to section 3.6.1.2 in the calibration stage, the water level at downstream sections at the Urachikottai, Kodumudi, and Musuri stations is determined to follow the same pattern as the observed data, as shown in Figure 4-4 (d-f). The KRS dam and the Mettur dam findings show that the model is accurately calibrated, and based on the verification results, these models can be utilized to generate additional models for scenario creation.

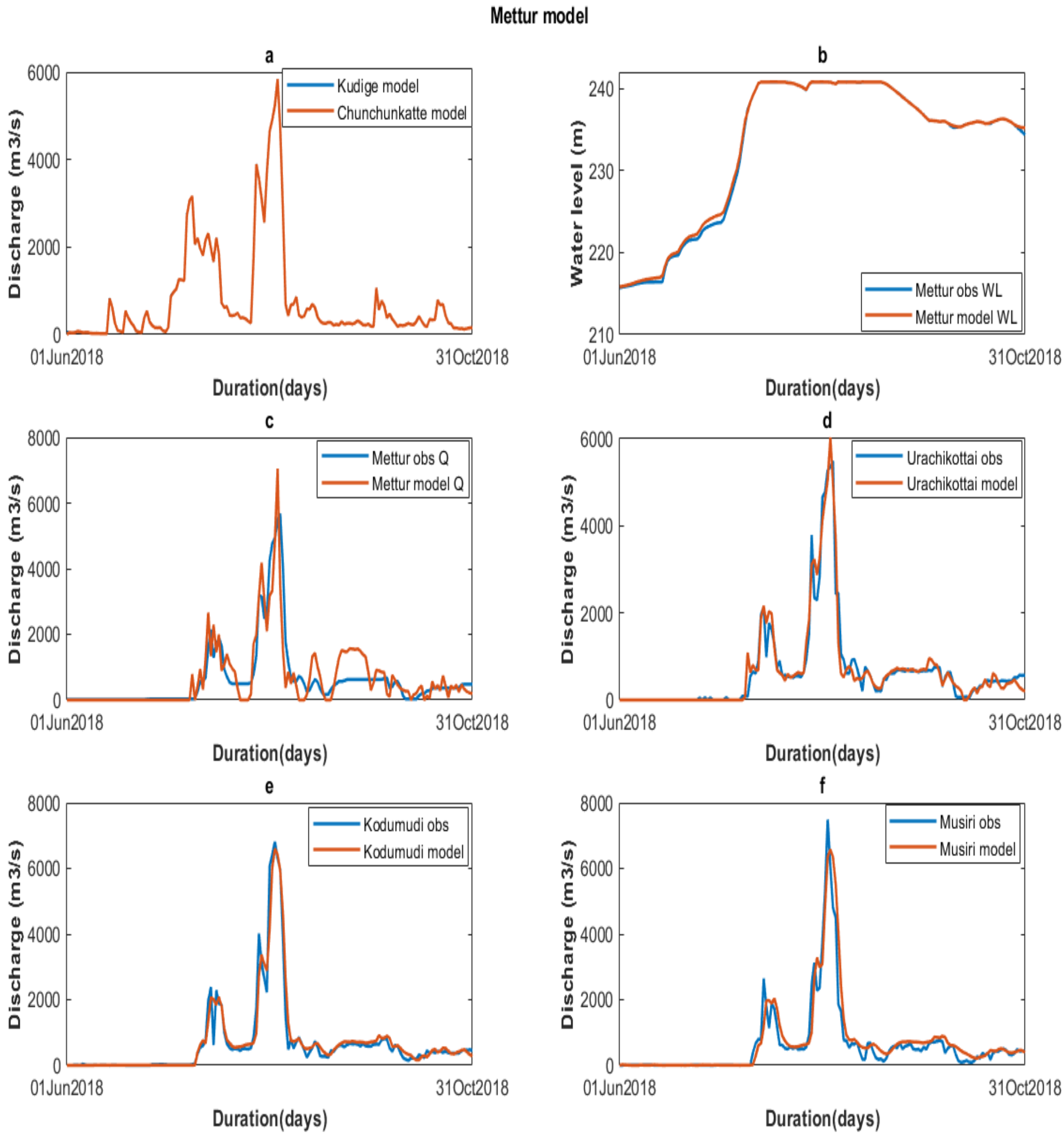


Figure 4-4: Verification results of the model with the Mettur dam

4.3 Scenario development

Following the validation of the models and an understanding of the current difficulties in the Cauvery River basin (Section 3.7), different model scenarios are built to regulate reservoir operation and prevent flood peaks from moving downstream. According to flooding reports during the monsoon season, the most impacted locations are downstream of the Mettur dam, as shown in section 2.4 and Figure 2-10. As a result, model scenarios for the Mettur dam are built to detect reservoir difficulties by analyzing inflow peaks and reservoir operation characteristics.

4.3.1 Scenario 1

4.3.1.1 Case 1.1

Figure 4-5 depicts the model's findings for Scenario 1 with the original water level. The reservoir's water level is shown in blue, the reservoir's inflow is in green, and the reservoir's outflow is in red. Based on the results, it can be seen that during the initial stages, while there is inflow to the reservoir, there is no outflow from the reservoir, and the water level is rising. This means that the incoming flow is filling the reservoir and that none of the conditions specified in section 3.8.1 currently influence the dam outflow. Significant outflow from the reservoir is observed beginning on July 18, and the water level in the reservoir is maintained at 234.69 m, following the conditional regulation in section 3.8.1 until the end of July. When the beginning of the peak flood period is noticed in the second week of August, the water level in the reservoir rises quickly and exceeds FRL within 3 days, and once the FRL is reached, all extra water is released as outflow, as shown in Figure 4-5 from 17 to 20 August. Observations of input and outflow during the peak flood period are virtually identical, indicating that all the flood water entering during that time is released downstream. As a result, the produced scenario with the original water level as the condition cannot represent the reservoir's flood peak.

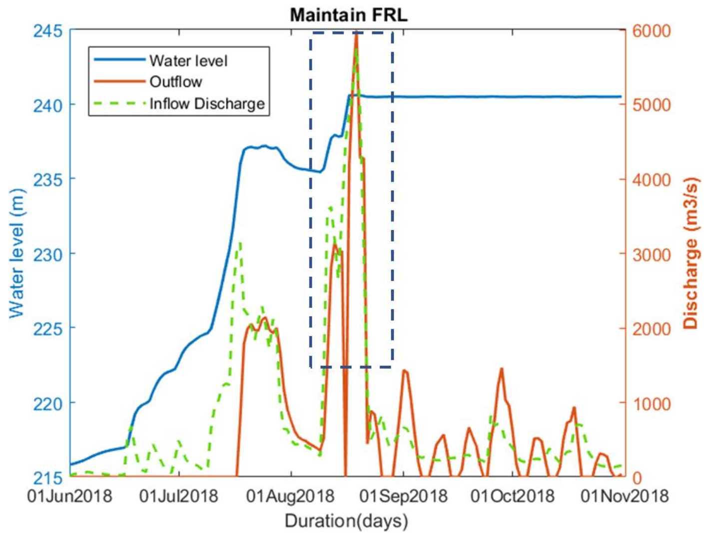


Figure 4-5: Maintaining FRL in the Mettur reservoir with the original water level

4.3.1.2 Case 1.2

a) Peak flood period analysis

Figure 4-6 depicts the Mettur dam's water level, inflow, and outflow when the gate level/crest of the spillway is 234.69 m, and the reservoir is dry. Based on the results, it can be seen that the outflow from the dam in the model is nil until August 17th. The reservoir has an outflow after August 17, equal to its intake between August 17 and August 18. These results reveal that the flood peak is not caught, which is consistent with the findings for the entire analysis period for original water level conditions. Case 1.2 (b) is created with an entire analysis period to test the model's ability to catch the flood peak with a longer model period.

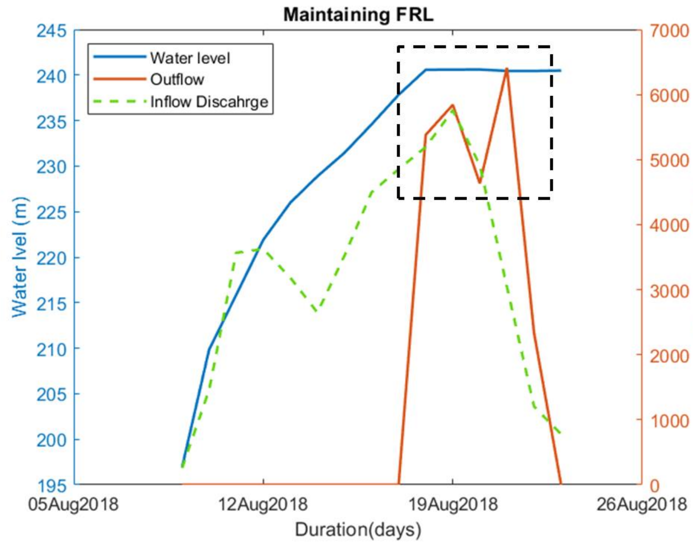


Figure 4-6: Water level and discharge of the Mettur dam during dry reservoir conditions

b) Full period of analysis

The pattern of reservoir water level during the initial stages, i.e., no outflow from the reservoir until 17 July, is similar to the results seen in Figure 4-5 with the original water level. However, the outflow hydrograph shows continual outflow from the dam during the initial and final peak floods in August, indicating that the flood peak is not captured in the reservoir. This could be due to insufficient water level reduction before the flood peak reaches the reservoir. To understand how the reservoir responds, instead of the reservoir is dry, case 1.3 is developed if there is water comparable to the lowest recorded water level in the reservoir.

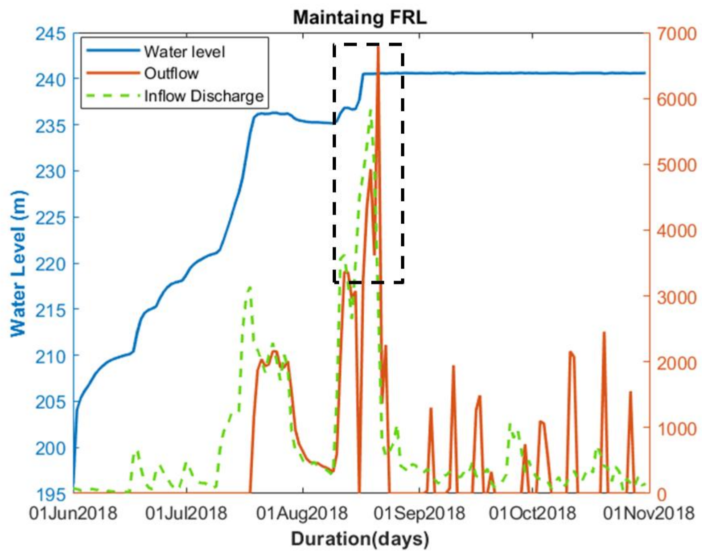


Figure 4-7: The Mettur reservoir model with the lowest water level

4.3.1.3 Case 1.3

a) Peak flood period analysis

Figure 4-8 depicts the water level, inflow, and outflow of Mettur dam when the gate level/crest of the spillway is at 234.69 m, and the reservoir's beginning water level is the lowest recorded in 40 years. Based on the results, it is clear that the outflow from the dam in the model is nil until August 17th. The reservoir's water level reaches the FRL during this period. When the water level exceeds the FRL, all extra volume is released as outflow, and the model attempts to maintain the FRL in the reservoir. Based on the water level in Figure 4-8, outflow release equals inflow as long as the water level remains at FRL. The reservoir's volume reaches its full capacity on the 10th day of the flood, as indicated in volume analysis in Table 3-1 and Figure 3-11; thus, all extra inflow is discharged as outflow.

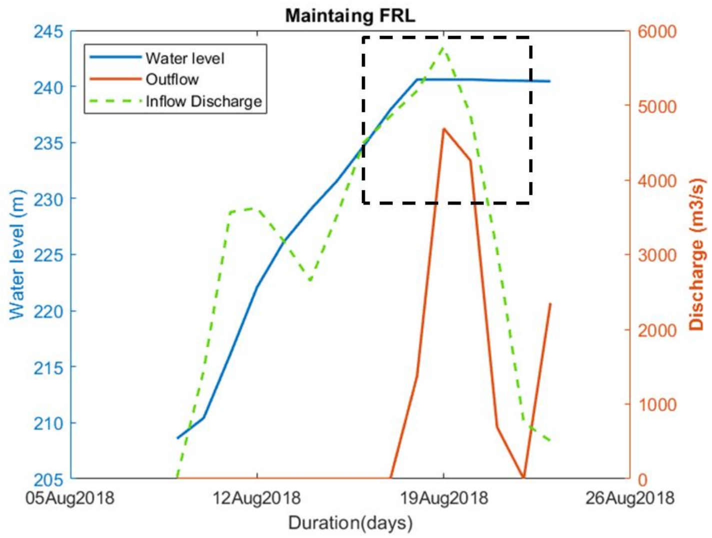


Figure 4-8: Water level and discharge of the Mettur dam with lowest water level (peak flood)

b) Full period of analysis

Figure 4-9 shows the model's findings with low water level as the water level condition for the entire analysis period. The results are identical to the observations in Figure 4-5 with the original flow and Figure 4-7 with a dry reservoir. During the peak flood period (17-20 August), an outflow equals the inflow. This suggests that the reservoir did not capture the maximum flood.

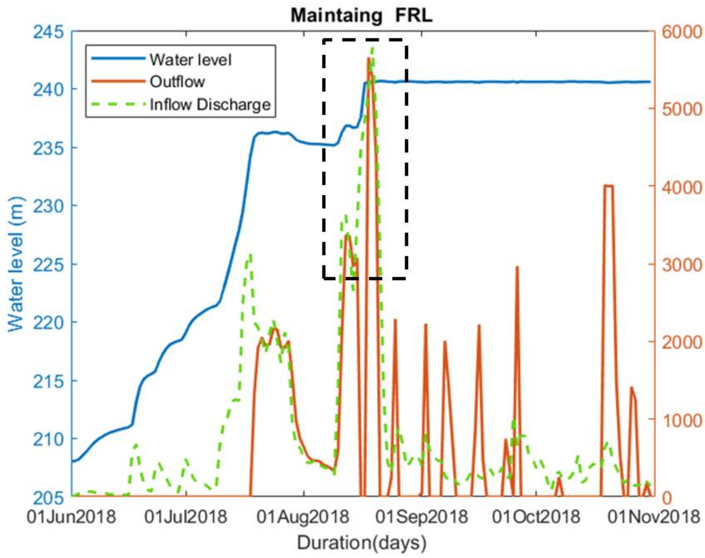


Figure 4-9: Water level and discharge of the Mettur dam with the lowest water level

4.3.2 Scenario 2

In this scenario, the reservoir's water level is decreased early to maintain a lower water level so that the reservoir can capture the incoming flood during the peak flood. To do this, the spillway's gate level is reduced to 215.00 m instead of 234.69 m. Section 3.8.2 shows the details of the approach employed, as well as the parameters and conditions used.

4.3.2.1 Case 2.1

Figure 4-10 depicts the Mettur dam's water level, inflow, and outflow features during the original water level with the spillway's lowered gate level. Figure 4-10 shows that the water level is maintained at 220.00 m during the initial periods (mid-June to mid-August), and the outflow from the dam is observed to be the same as the intake. This inflow trend equaling outflow (all input released as outflow) is observed until August 15th. The outflow of the dam is seen to be zero during the days of peak flood in the reservoir (17 August -20 August), and the water level increases swiftly and reaches the FRL.

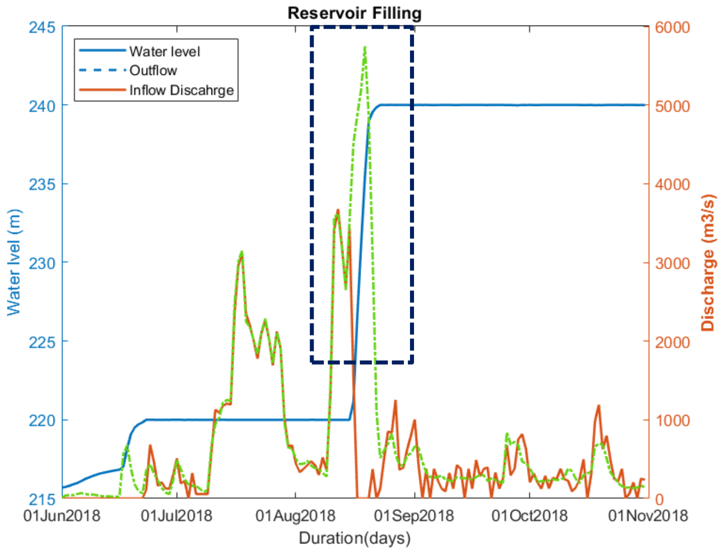


Figure 4-10: Water level and discharge of the Mettur dam for full flood period

4.3.2.2 Case 2.2

a) Peak flood period analysis

The water level in the reservoir (blue), outflow from the reservoir (red), and dam inflow (green-dashed line) during the flood peak inflow into the Mettur dam in 2018. In the early stages of the model, the dam attempted to maintain a level of 220.00 m, as shown in Figure 4-11, until the condition of incoming discharge >4000 m^3/s was achieved. When the condition is met, the water level remains at FRL. According to the outflow discharge graph in Figure 4-11, the initial flood peak is released as an outflow in the model, leaving enough empty volume in the reservoir to store the impending major flood peak. Based on these results, it can be stated that the flood peak can be caught during the reservoir's dry period by employing the criteria described in section 3.8.2 and retaining the same model parameters.

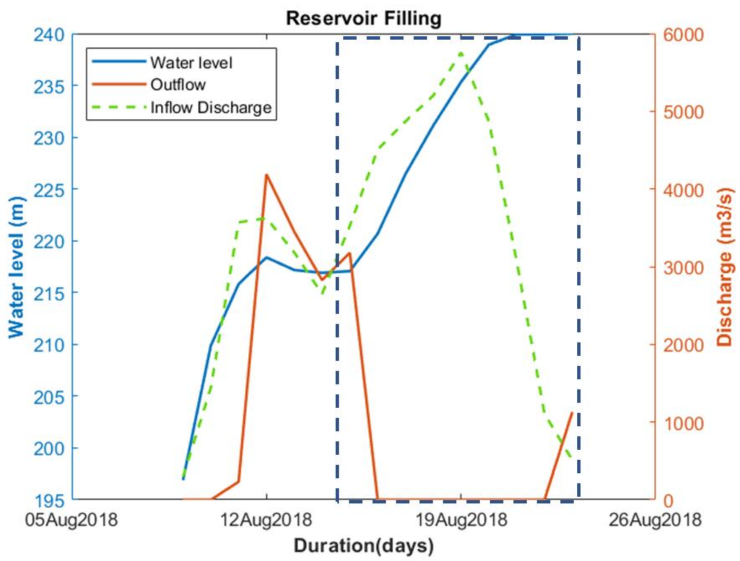


Figure 4-11: Water level and discharge of the Mettur dam during peak flood

b) Full period of analysis

The plot of the outflow hydrograph in Figure 4-12 follows the same inflow pattern as the results in Figure 4-10 with the original water level until the flood peak in the reservoir. During peak flood input, the reservoir's water level rises to the FRL, and the dam's outflow is zero (the gate is closed), as shown in Figure 4-12. The occurrence of zero discharges during the incoming flood peak suggests that the reservoir can capture the oncoming flood peak.

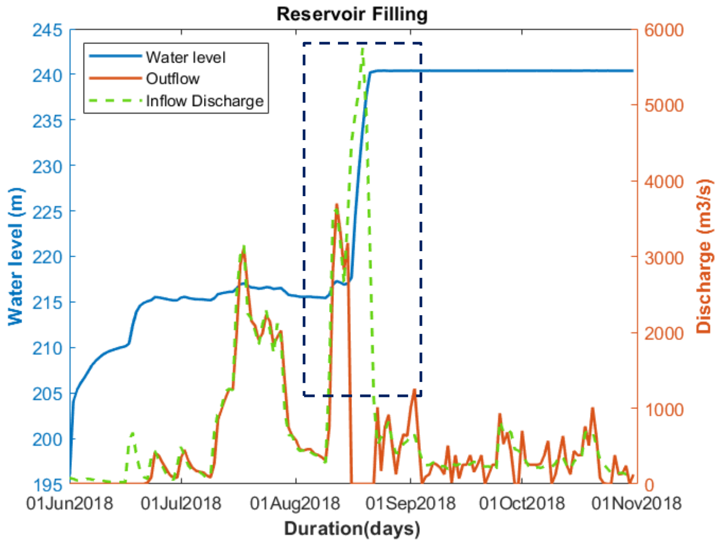


Figure 4-12: Water level and discharge of the Mettur dam for the full period

4.3.2.3 Case 2.3

a) Peak flood period analysis

Figure 4-13 depicts the reservoir water level (blue), reservoir outflow (red), and dam inflow (red-dashed line) during the flood peak inflow into the Mettur dam in the year 2018. In the beginning stages, the outflow of the model is zero until it reaches the prescribed crest level of the spillway, as shown in Figure 4-11 for the dry reservoir state. When the incoming discharge and water level conditions are met, the reservoir runs to maintain the set water levels while releasing excess water. Based on observations of the dam's outflow, it can be stated that it can capture the incoming flood peak even when the water level is at 208.51 m (the lowest water level in the reservoir). As a result of the observations in Figure 4-13, it is possible to record the flood peak if the water level is maintained using the condition (gate level at 215.00 m). The model is now applied for the entire analysis time to check its performance, using the same approaches used to capture the flood peak. The parameters and conditions are the same as those used for the small-scale model, discussed in section 3.8.2.

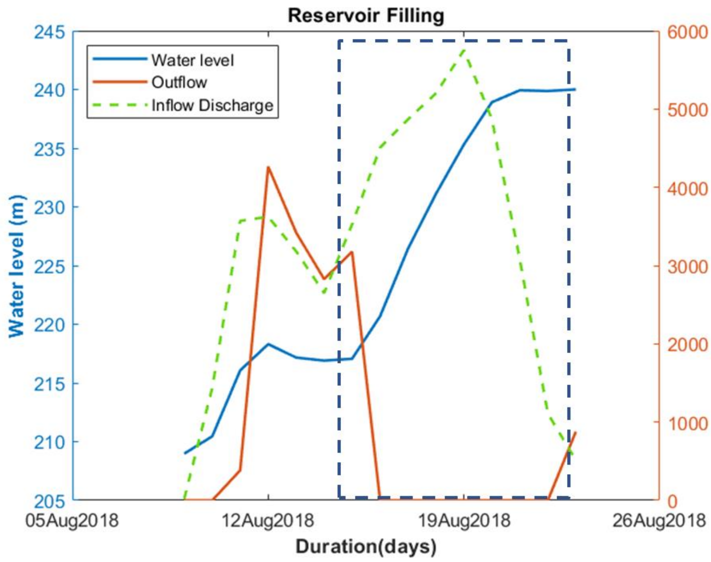


Figure 4-13: Water level and discharge of the Metturdam with peak flood

b) Full period of analysis

Figure 4-14 depicts the Mettur's water level, input, and outflow plot throughout the analysis. According to the findings in Figure 4-14, the dam discharged water until the flood peak arrived in the reservoir, and when the flood peak came in the reservoir, the peak was captured in the dam without any outflow. The same happened in mid-August when the outflow fell to zero from August 17 to 18. Towards the end of the flow time, a constant water level is maintained, and excess water is discharged as outflow. Also, based on observations, it can be stated that during the initial stages of water release, the outflow never exceeded peak values, indicating that the river system downstream can enable the water to create flooding because the main cause of the flooding is the presence of peak discharge greater than 5000 m^3/s.

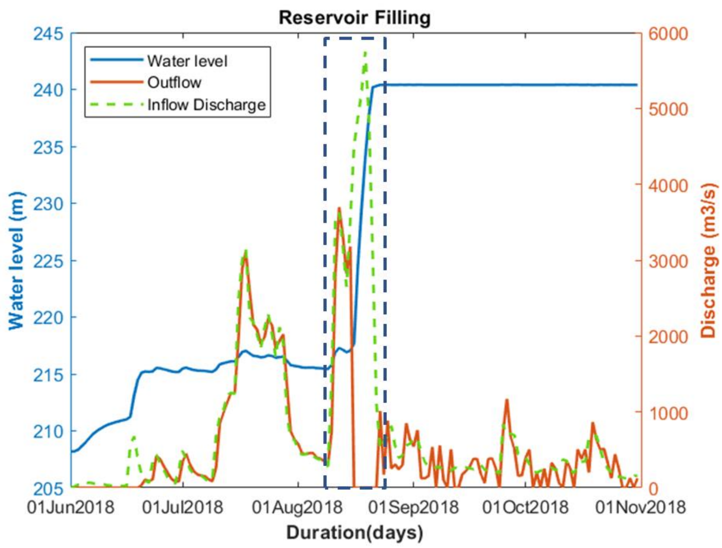


Figure 4-14: Water level and discharge of the Mettur dam for flood period

4.3.3 Scenario 3

4.3.3.1 Case 3.1

Increasing the dam's height is the third alternative for capturing the flood peak in the reservoir. Section 3.8.3 contains information about the conditions and height adjustments. As stated in section 3.8.3, the decision to raise the dam's height was made to identify the optimal height required to capture the peak flood. The optimal value of the dam height is displayed below based on the investigation's conclusions. Figure 4-15 depicts the water level, discharge intake, and outflow of the Mettur dam after increasing the dam height by 10 m. Based on observations of the dam's outflow and the reservoir's water level, it can be seen that there is an outflow from the dam in the early phases when the reservoir's water level is less than 237.00 m, and the discharge inflow is less than 4000 m^3/s, which is the beginning of the reservoir's flood peak. When the criterion in section 3.8.3 is met, the dam gates are closed, the reservoir water level rises, and the outflow is nil, as observed on the 17th and 18th of August. Based on these findings, we may conclude that the reservoir captured the peak flood for the whole analysis period, as shown by the increase in water level (blue line) in Figure 4-15.

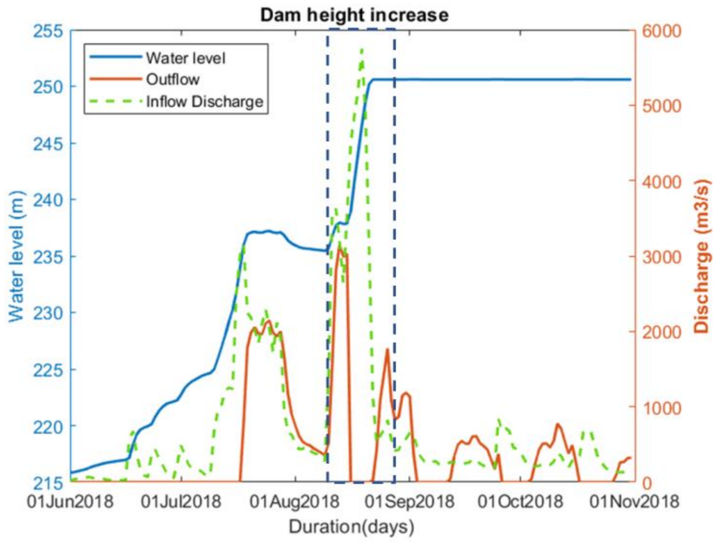


Figure 4-15: Water level and discharge of the Mettur dam with an increased dam height of 10 m

4.4 Summary of hydraulic results

Various models in D-Hydro Suite 1D2D were created in this work to analyze the flow dynamics in the Cauvery River basin and manage the dams' output utilizing real-time control. During the model calibration, it was found that the water level at the Kudige station is 2 m lower than the measured water level, as shown in Figure 3-20. This variance in water level is attributed to a datum difference at the station. This disparity occurs when the water level and cross-section elevations are not measured at the same spot. As a result, changes to the datum at the Kudige station were made, increasing the model estimate of the water level at Kudige. In the instance of issues in the Mettur reservoir's cross-section, which caused a rapid rise in water level, as shown in Figure 3-23, the discrepancies in water level from the observed water level are attributable to the reservoir's lower capacity relative to the original volume. Figure 3-24 shows the same results, and the reservoir volume is altered by adjusting three cross sections depending on the volume elevation curve. All verification and scenario creation models are constructed using these modified cross sections of the Kudige and Mettur reservoirs. According to the verification results of the models, the KRS dam produces similar results to actual flows with the original cross sections. After modifying the reservoir cross sections, the verification results for the Mettur dam were promising.

Scenarios were constructed only for Mettur dam reservoir models using the verification stage models because the flooded regions described were downstream of the reservoir. Based on this knowledge, three scenarios for capturing the flood peak were designed. In scenario 1, the findings for all models with varying water level circumstances showed that, while the water is initially released to maintain the crest level of the spillway (234.69 m), the reservoir's live storage throughout August is insufficient to capture the flood peak. In scenario 2, where the spillway's crest level is reduced to 215.00 m and a water level of 220.00 m is maintained, the results demonstrate that the initial release of water from the reservoir helped have a bigger empty volume during peak flood. As a result of the higher volume available, the reservoir captures the flood peak until the end of the flood peak period.

Similarly, in Scenario 3, where the dam height is suggested to be increased by 10 m, the reservoir water level is kept at 234.69 m, allowing the reservoir to release input during no-flood months and capture the flood peak when it arrives. Based on this knowledge, scenarios 2 and 3 are determined to capture the flood peak effectively. Scenario 2, an anticipatory flood control method, is highly based on the assumption that a peak flood of magnitude greater than a fixed number will occur. As a result, to find the best option, more research must be done to see if the reservoir is lowered in anticipation of a flood and if it can meet its obligations to the dependent areas. In the case of scenario 3, additional investigations and assessments will be conducted to assess the likelihood of a dam height increase and its potential economic, social, and environmental consequences.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The work's conclusions will be addressed in this section in the form of answers to the formulated research questions.

1) What are the main factors influencing the occurrence of floods in the basin?

The Cauvery River is one of India's largest rivers; as a non-perennial river, it receives significant precipitation during the North-East and South-West monsoons. During these seasons, the river discharge increases multifold, leading to flooding in several regions in the basin. Based on the observation of precipitation statistics in section 3.3.1, it is possible to see that the system has higher flows during periods of higher intensity of rainfall. These high flows have been identified as the primary cause of flooding in the basins.

2) What are the dam's positive and negative impacts on the main river and some major tributaries?

With over 102 dams, the Cauvery River is one of India's most dammed rivers. Most dams in the river basin are built for agriculture, water supply, and power generation. Major dams such as KRS and Mettur are primarily used to give water to numerous districts in Karnataka and Tamil Nadu. Although these dams are the primary source of drinking water for both states, they also have several detrimental consequences on the surrounding areas. Due to heavy rainfall, the dams reach their full capacity during the monsoon season, and the surplus water must be released downstream. The reservoirs are never lowered to capture the flood because these dams are never used for flood control. As a result, the inflow flood peak is discharged directly into the river system. In addition to insufficient flood control, poor reservoir water management has resulted in drought in the Tamil Nadu regions throughout the summer. Due to poor dam resource management, the Cauvery River has heavy inflows during the monsoon season and droughts throughout the summer.

3) How do the dams and their operation in the Cauvery River (and some major tributaries) influence floods?

The main objective of the dams in the Cauvery River basin, as described in sections 2.2 and 2), is irrigation, water supply, and power generation. As a result, the dams are operated so that there is enough water to serve agricultural and drinking water. These initiatives meet the demands of many communities relying on the dam as their primary water source. According to various reports and community opinions, dams are the primary cause of flooding in downstream areas. However, according to the study performed in this work and section 3.3.3, the outflow from the dams is not larger than the inflow; thus, the dams are not the primary source of floods in the regions. The existence of high inflow may be the primary cause, rather than dam effects.

4) Can the dams in the Cauvery River basin be used for flood control?

An analysis was carried out to understand the current reservoir operation circumstances and afterwards propose acceptable flood control conditions to understand the capabilities of the dams in the Cauvery River basin to be used for flood control. Under current operating conditions, dam outflow is only seen when it reaches its FRL, and all extra water is released. This condition makes flood management difficult since the available reservoir volume is insufficient to capture the flood peak because the reservoir's water level is never lowered to meet the impending flood.

As a result, scenario development with various gate operations was conducted to test the likely circumstances in which dams can be used for flood control. The results of the scenario operation revealed that if the dam's water is released in advance of floods (raising the available volume of the reservoir) or if the dam height (reservoir capacity) is increased, the incoming flood peak can be captured in the reservoir. The same results can be seen in section 4.3, which includes a case study of the 2018 flood, indicating the possibility of storing flood peaks.

5.2 Limitations

Even though the developed models have shown their capability in representing the river system and dam operations, there are few limitations to the kind of models developed in this work. Due to changes in the bathymetry data of the cross sections in the river basin each year, the developed model is limited to application for 2018 data. Being a 1D model, the model cannot fully replicate the dam's gate operation scenarios, which have multiple gates at different levels. The model is developed for 2018 floods; hence, their applicability to other floods is yet to be established. Implications or the effects of the developed scenarios on other dam purposes like (water supply and irrigation) were not considered in this work.

5.3 Recommendations

Based on the findings and conclusions of this study, various new options for future studies to improve reservoirs' ability to catch floods in the Cauvery River utilizing dams can be proposed. This study's major flood control approach was to reduce the spillway's crest level and raise the dam's height. Although both situations demonstrated the ability to capture floods, their relevance and viability have yet to be evaluated. As a result, for future research, the recommendations are divided as follows.

i. Recommendation for model development.
ii. Recommendation for capturing floods

i. Recommendation for flood management

A 1D process-based model is utilized in this work to investigate the dynamics of the Cauvery River basin during floods and to develop scenarios for collecting floods in reservoirs. In addition, this work used RTC control groups to control dam operations. Although the results of the constructed 1D models were adequate, there is always the potential for development in the type of models used to understand the river system. One of the biggest challenges while modelling the dam in 1D is limited to the spillway's crest level. In the original structure, many sluice gates at various elevations in a dam structure govern the outflow and water level in the reservoir. As a result, a 2D model with an improved likeness to the multifold river system is being developed to be successfully recreated in the reservoir and to design better scenarios for the gate operation. As a result, future work may include creating a 2D model of the same to better model the river system.

ii. Recommendation for flood management

While attempting to manage floods in the reservoir, the main emphasis in this endeavour is on lowering the reservoir's crest level or increasing reservoir capacity by raising the dam height. Both scenarios give good results and demonstrate their ability to capture the flood peak. As stated in section 4.4, additional research will be done to determine their application. As a result, instead of modifying dam construction, a natural-based technique might be used to capture the flood. A retention basin can be viewed as either decreasing the crest level of the spillway or increasing the dam height to capture the oncoming flood peak in the reservoir. During a flood, a retention basin can keep the water until the flood peak is reduced, and then that water can be used for other reasons instead of releasing it downstream as it does now. A study must be performed to determine the applicability of the retention basin based on the area's availability, the terrain, and the magnitude of the flood that can be captured. Similarly, studies can be done for basin-scale dams to improve flood management.

6 REFERENCES

Acanal, N., Yurtal, R., Haktanir, T., 2000. Multi-stage flood routing for gated reservoirs and conjunctive optimization of hydroelectricity income with flood losses. Hydrol. Sci. J. 45, 675–688. https://doi.org/10.1080/02626660009492370

Agoramoorthy, G., Hsu, M.J., 2008. Small size, big potential: Check dams for sustainable development. Environment 50, 22–35. https://doi.org/10.3200/ENVT.50.4.22-35

Boulange, J., Hanasaki, N., Yamazaki, D., Pokhrel, Y., 2021. Role of dams in reducing global flood exposure under climate change. Nat. Commun. 12, 1–7. https://doi.org/10.1038/s41467-020-20704-0

Cheng, C., Chau, K.W., 2001. Fuzzy iteration methodology for reservoir flood control operation. J. Am. Water Resour. Assoc. 37, 1381–1388. https://doi.org/10.1111/j.1752-1688.2001.tb03646.x

Cheng, C.T., Chau, K.W., 2004. Flood control management system for reservoirs. Environ. Model. Softw. 19, 1141–1150. https://doi.org/10.1016/j.envsoft.2003.12.004

Ekka, A., Kesav, S., Pande, S., Zaag, P. Van Der, Jiang, Y., 2022. Integrating reservoirs in a landscape-based hydrological model to understand the impact of the reservoir on flow regime in the Cauvery river basin , India.

FitzHugh, T.W., Vogel, R.M., 2011. The impact of dams on flood flows in the United States. River Res. Appl. 27, 1192–1215. https://doi.org/10.1002/rra.1417

Gholami, S., Srikantaswamy, S., 2009. Analysis of Agricultural Impact on the Cauvery River Water Around KRS Dam. Appl. Sci. 6, 1157–1169.

Ghosh, K.G., Pal, S., 2015. Impact of dam and barrage on flood trend of lower catchment of Mayurakshi river basin, eastern India. Eur. Water 50, 3–23.

Ghosh, S., Guchhait, S.K., 2016. Dam-induced changes in flood hydrology and flood frequency of tropical river: a study in Damodar River of West Bengal, India. Arab. J. Geosci. 9, 1–26. https://doi.org/10.1007/s12517-015-2046-6

Gosain, A.K., Rao, S., Basuray, D., 2006. Climate change impact assessment on hydrology of Indian river basins. Curr. Sci. 90, 346–353.

Gowri, R., Dey, P., Mujumdar, P.P., 2021. A hydro-climatological outlook on the long-term availability of water resources in Cauvery river basin. Water Secur. 14, 100102. https://doi.org/10.1016/j.wasec.2021.100102

Hanasaki, N., Kanae, S., Oki, T., 2006. A reservoir operation scheme for global river routing models. J. Hydrol. 327, 22–41. https://doi.org/10.1016/j.jhydrol.2005.11.011

Harsha, J., Ravikumar, A.S., Shivakumar, B.L., 2020. Evaluation of morphometric parameters and hypsometric curve of Arkavathy river basin using RS and GIS techniques. Appl. Water Sci. 10, 1–15. https://doi.org/10.1007/s13201-020-1164-9

Kelman, J., Damazio, J.M., Mariën, J.L., Da Costa, J.P., 1989. The determination of flood control volumes in a multireservoir system. Water Resour. Res. 25, 337–344. https://doi.org/10.1029/WR025i003p00337

Kummu, M., Sarkkula, J., 2008. Impact of the Mekong River flow alteration on the Tonle Sap flood pulse. Ambio 37, 185–192. https://doi.org/10.1579/0044-7447(2008)37[185:IOTMRF]2.0.CO;2

Lempérière, F., 2017. Dams and Floods. Engineering 3, 144–149. https://doi.org/10.1016/J.ENG.2017.01.018

Lieverse, T., 2021. Comparitive assessment of SOBEK2 and D-HYDRO SUITE 1D2D for regional inundation modelling.

Magilligan, F.J., Nislow, K.H., 2005. Changes in hydrologic regime by dams. Geomorphology 71, 61–78. https://doi.org/10.1016/j.geomorph.2004.08.017

Maheshwari, S., Chavan, S.R., 2021. Magnitude–frequency analysis to assess effective discharge at daily and monthly timescales in South Indian River basins. ISH J. Hydraul. Eng. 27, 496–505. https://doi.org/10.1080/09715010.2019.1603088

Mariën, J.L., 1984. Controllability conditions for reservoir flood control systems with applications. Water Resour. Res. 20, 1477–1488. https://doi.org/10.1029/WR020i011p01477

Marien, J.L., Damázio, J.M., Costa, F.S., 1994. Building flood control rule curves for multipurpose multireservoir systems using controllability conditions. Water Resour. Res. 30, 1135–1144. https://doi.org/10.1029/93WR03100

Mediero, L., Garrote, L., Martín-Carrasco, F., 2007. A probabilistic model to support reservoir operation decisions during flash floods. Hydrol. Sci. J. 52, 523–537. https://doi.org/10.1623/hysj.52.3.523

Mei, X., Van Gelder, P.H.A.J.M., Dai, Z., Tang, Z., 2017. Impact of dams on flood occurrence of selected rivers in the United States. Front. Earth Sci. 11, 268–282. https://doi.org/10.1007/s11707-016-0592-1

Nakayama, T., Shankman, D., 2013. Impact of the Three-Gorges Dam and water transfer project on Changjiang floods. Glob. Planet. Change 100, 38–50. https://doi.org/10.1016/j.gloplacha.2012.10.004

Panda, D.K., Kumar, A., Mohanty, S., 2011. Recent trends in sediment load of the tropical (Peninsular) river basins of India. Glob. Planet. Change 75, 108–118. https://doi.org/10.1016/j.gloplacha.2010.10.012

Patel, D.P., Ramirez, J.A., Srivastava, P.K., Bray, M., Han, D., 2017. Assessment of flood inundation mapping of Surat city by coupled 1D/2D hydrodynamic modeling: a case application of the new HEC-RAS 5. Nat. Hazards 89, 93–130. https://doi.org/10.1007/s11069-017-2956-6

Petkovsek, G., Roca, M., 2014. Impact of Reservoir Operation on Sediment Deposition. Proc. Inst. Civ. Eng. Water Manag. 167, 577–584. https://doi.org/10.1680/wama.13.00028

Pinthong, P., Gupta, A. Das, Babel, M.S., Weesakul, S., 2009. Improved reservoir operation using hybrid genetic algorithm and neurofuzzy computing. Water Resour. Manag. 23, 697–720. https://doi.org/10.1007/s11269-008-9295-z

Ramkumar, M., Kumaraswamy, K., James, R.A., Suresh, M., Sugantha, T., Jayaraj, L., Mathiyalagan, A., Saraswathi, M., Shyamala, J., 2015. Sand Mining, Channel Bar Dynamics and Sediment Textural Properties of the Kaveri River, South India: Implications on Flooding Hazard and Sustainability of the Natural Fluvial System. https://doi.org/10.1007/978-3-319-13425-3_14

Ramkumar, M., Santosh, M., Rahaman, S.M.A., Balasundareshwaran, A., Balasubramani, K., Mathew, M.J., Sautter, B., Siddiqui, N., Usha, K.P., Sreerhishya, K., Prithiviraj, G., Nagarajan, R., Thirukumaran, V., Menier, D., Kumaraswamy, K., 2019. Tectono-morphological evolution of the Cauvery, Vaigai, and Thamirabarani River basins: Implications on timing, stratigraphic markers, relative roles of intrinsic and extrinsic factors, and transience of Southern Indian landscape. Geol. J. 54, 2870–2911. https://doi.org/10.1002/gj.3520

Richter, B.D., Thomas, G.A., 2007. Restoring environmental flows by modifying dam operations. Ecol. Soc. 12. https://doi.org/10.5751/ES-02014-120112

Sathya, A., Thampi, S.G., 2021. Flood Inundation Mapping of Cauvery River Using HEC-RAS and GIS. pp. 15–23. https://doi.org/10.1007/978-981-15-5644-9_2

Sharda, V.N., Ojasvi, P.R., 2016. A revised soil erosion budget for India: role of reservoir sedimentation and land-use protection measures. Earth Surf. Process. Landforms 41, 2007–2023. https://doi.org/10.1002/esp.3965

Subramanian, V., 1988. Erosion, transport and deposition of sediments by the tropical rivers of India

Sunil, C., Somashekar, R.K., Nagaraja, B.C., 2010. Riparian vegetation assessment of Cauvery River Basin of South India. Environ. Monit. Assess. 170, 545–553. https://doi.org/10.1007/s10661-009-1256-3

Susheela, S., Srikantaswamy, S., Kumar, D.S., Gowda, A., Jagadish, K., 2014. Study of Cauvery River water pollution and its impact on socio-economic status around KRS Dam, Karnataka, India. J. Earth Sci. Geotech. Eng. 4, 91–109.

Thilagavathi, G, Tamilenthi, S, Ramu, C, Baskaran, R., 2011. Application of GIS in Flood Hazard Zonation Studies in Papanasam Taluk , Application of Gis in Flood Hazard Zonation Studies in Papanasam Taluk , Thanjavur District , Tamilnadu. Adv. Appl. Sci. Res. 2, 574–585.

Vedula, S., 1985. Optimal irrigation planning in river basin development: The case of the Upper Cauvery river basin. Sadhana 8, 223–252. https://doi.org/10.1007/BF02811895

Zhao, G., Bates, P., Neal, J., 2020. The Impact of Dams on Design Floods in the Conterminous US. Water Resour. Res. 56, 0–2. https://doi.org/10.1029/2019WR025380

APPENDIX

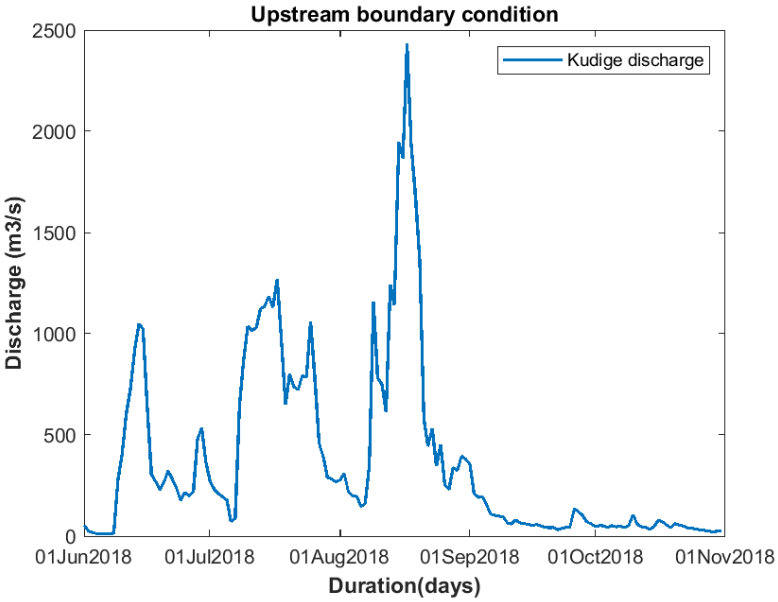


Figure A-1: Discharge timeseries at Kudige station

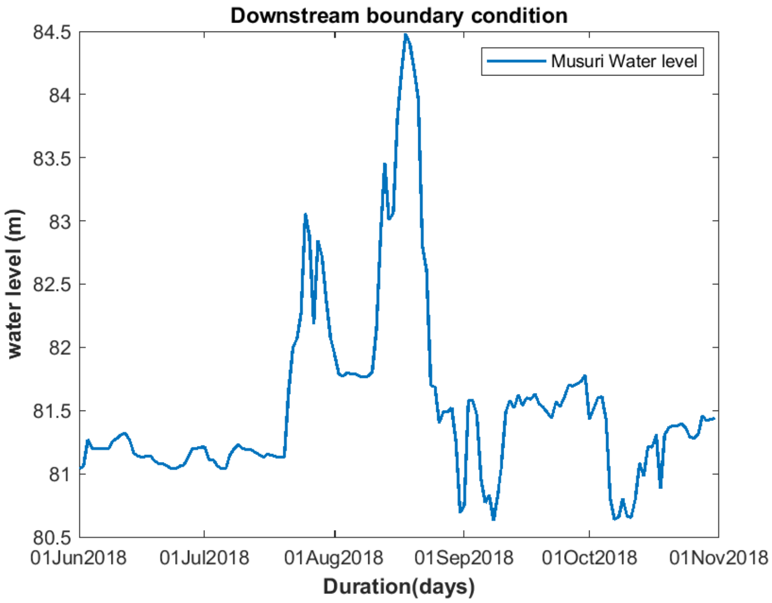


Figure A-2: Water level time series at Musuri station

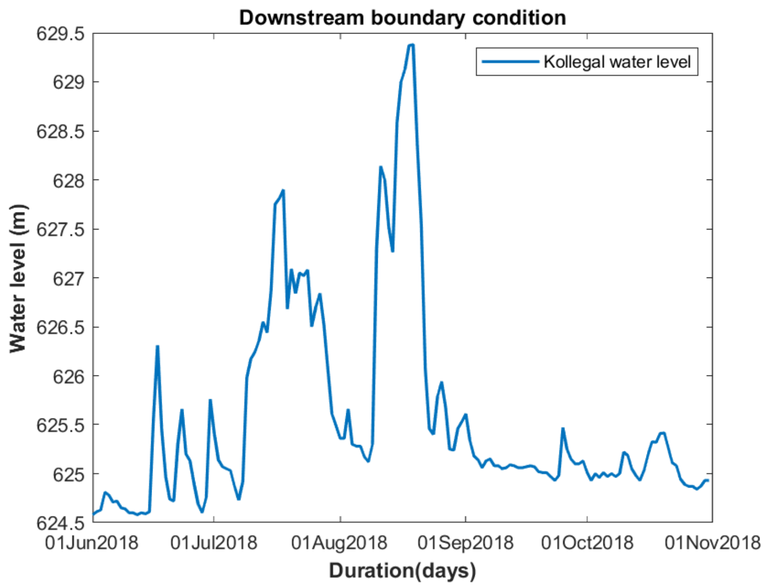


Figure A-3: Water level time series at Kollegal station

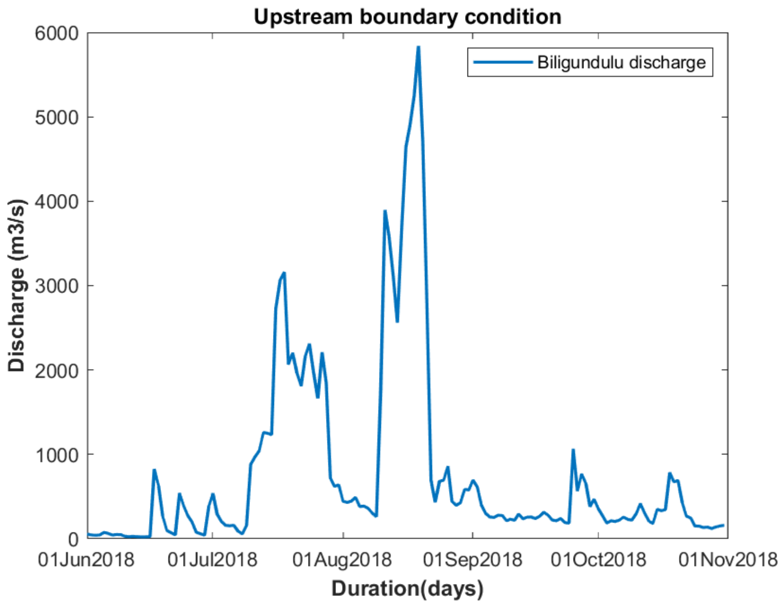


Figure A-4: Discharge time series at Biligundulu station

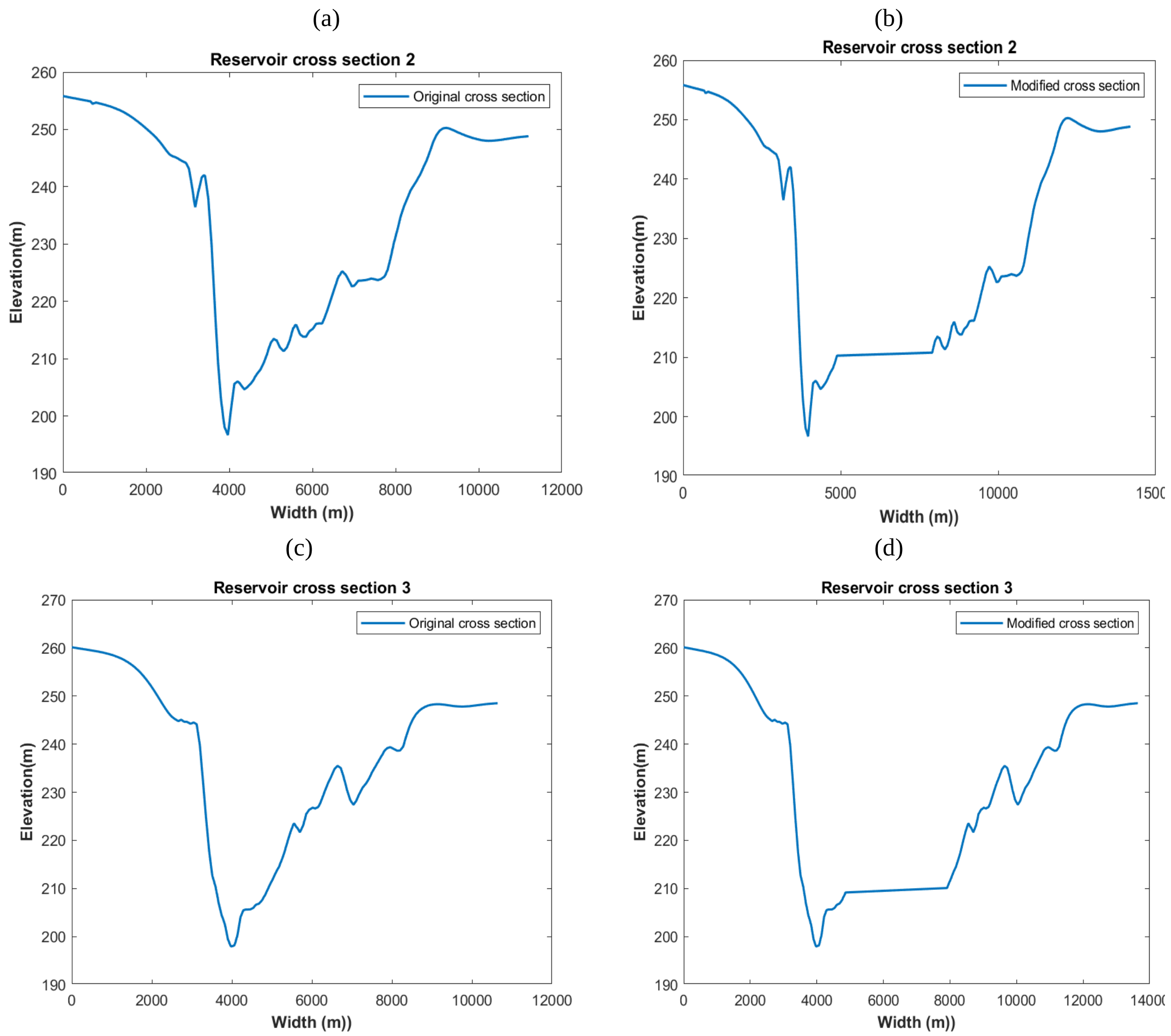


Figure A-5: Details of original and modified cross sections in the Mettur reservoir

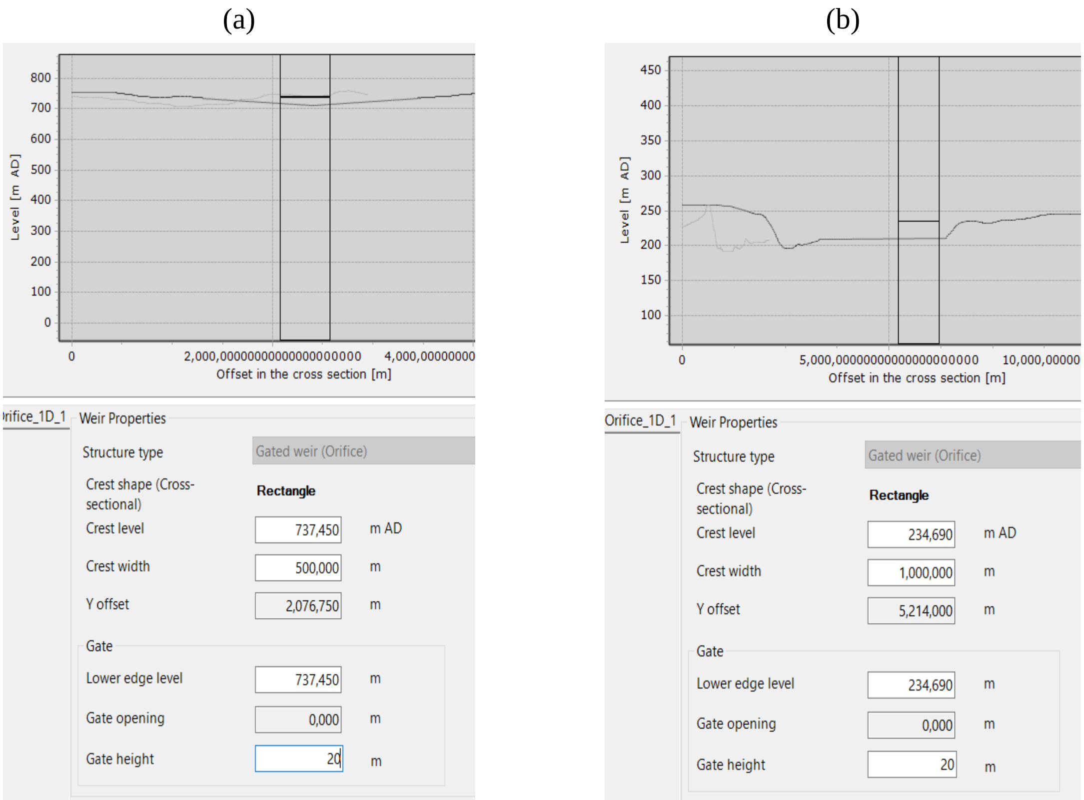


Figure A-6: Dam parameters for the KRS (a) and Mettur dam (b) respectively