SUSTAINABLE WATER SHARING MODEL FOR INTER BASIN WATER TRANSFER PROJECT

Submitted in fulfilment of the requirements
Of the degree of

Doctor of Philosophy

By

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BONAFIDE CERTIFICATE

Certified that this thesis titled **"SUSTAINABLE WATER SHARING MODEL FOR INTER BASIN WATER TRANSFER PROJECT",** is the bonafide work of Mr. SUDHEER P, who carried out the research under our supervision. Certified further that to the best of my knowledge the work reported herein does not form part of any other thesis or dissertation on the basis of which a degree or award was conferred on an earlier occasion of this or any other candidate.

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DECLARATION

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

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Sudheer Padikkal

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LIST OF ABBREVIATIONS

ANSWERS: Areal Nonpoint Source Watershed Environmental Simulation

AZEWNA: Arizona Environmental Water Needs Assessment

BCM: Billion Cubic Metre

CREAMS: Chemicals, Runoff and Erosion from Agricultural Management Systems

CWC: Central Water Commission

CWRDM: Centre for Water Resources Development and management

DRIFT: Downstream Response to Imposed Flow Alteration

E Flows: Environmental Flow

Eco flood: Ecological Benefits of Flood

ECO-DRR: Ecosystem based Disaster Risk Reduction

EFA: Environmental Flow Assessment

EIA: Environmental Impact Assessment

ELOHA: Ecologic Limits of Hydrologic Alteration

FER: Flow – Ecosystem Relationships

FFI: Flood Flow Interval

FH: Flow Health

FRL: Full Reservoir Level

GCD AMP: Glen Canyon Dam Adaptive Management Plan

GCM: Global Circulation Model

GDSQ: Gauge Discharge Silt Water Quality

GIS: Geographical Information System

HAV: Hydrologic Alteration Values

HEC-HMS: Hydrologic Engineering Centre – Hydrologic Modelling System

HF: High Flow Volume

HM: Highest Monthly Flow

HSPF: Hydrological Simulation Program Fortran

IBWT: Inter Basin Water Transfer

ICPDR: International Commission for Protection of Danube River

IFIM: In-stream Flow Incremental Method

IHA: Indicators of Hydrological Alteration

ISWD: Inter State Water Disputes

ISWDT: Inter State Water Disputes Tribunal

IWRM: Integrated Water Resources Management

JWRB: Joint Water Regulation Board

LCR MSCP: Lower Colorado Region Multi-Species Conservation Plan

LF: Low Flow Volume

LM: Lowest Monthly Flow

LN: Lower Nirar

MCFT: Million Cubic Feet

MCM: Million Cubic Metre

MDBA: Murray Darling Basin Authority

MoEF & CC: Ministry of Environment Forest & Climate Change

MONERIS: Modelling Nutrient Emissions in River Systems

MSL: Mean Sea Level

MW: Mega Watt

NDRO: Net Dependable Run Off

NRLP: National River Linking Project

NSE: Nash-Sutcliffe Efficiency

NWDA: National Water Development Agency

PAP: Parambikulam Aliyar Project

PET: Potential Evapo Transpiration

PH: Power House

PHABSIM: Physical Habitat Simulation

PKM: Parambikulam

PL: Persistently Low Flow

PPM: Peruvaripallam

PVL: Persistently Very Low Flow

RAP: River Analysis Package

RB: River Board

RCM: Regional Climate Model

RRL: Rainfall Runoff Library

RVA: Range of Variability Approach

SCL: Stochastic Climate Library

SFS: Seasonality Flow Shift

SG: Sustainability by Group

SI: Sustainability Index

SWAT: Soil and Water Assessment Tool

SWMPRO: South West Monsoon Period Run Off

TIME: The Invisible Modelling Environment

TKV: Thunacadavu

TMC: Thousand Million Cubic Feet

TN: Tamil Nadu

TNS: Tamil Nadu Sholayar

TSA: Time Series Analysis

UNFCC: United nations Framework for Climate Change

UNGA: United Nations General Assembly

USBR: United States Bureau of Reclamation

USGS: United States Geological Survey

WFRTK: West Flowing Rivers from Tadri to Kanyakumari

WMS: Watershed Modelling System

Abstract:

Existence of life on earth very much depends on the availability of freshwater. Per capita freshwater availability is decreasing all over the world. Therefore, sustainable sharing of available water is vital for the existence of humanity and all ecosystems. However, designing institutional arrangements for a sustainable water-sharing process in the case of a catchment spread across the geopolitical boundary is challenging. The uncertainties in climate and lack of enough runoff data make the water-sharing process more complex and complicated.

Inter Basin Water Transfer is an innovative technical solution for balancing the water availability across the surplus and deficit basins. Water transfer between basins or sharing across upstream and downstream stakeholders is a complex process. Water-sharing pacts were designed for this purpose. However, the sustainability perspective of these pacts were not considered while developing such pacts in the past. Sustainability of existing pacts needs to be evaluated for developing a sustainable water-sharing model. Eco-hydrology is being recognized as the new paradigm for sustainability. Even then, an eco-hydrological framework to contemplate water-sharing is yet to be evolved. Though quantitative aspects of sustainability are seen dealt in literature, the indicators of sustainability to be used in any water-sharing pact are not yet crystalized.

This study investigates all these challenges in trans-basin water-sharing and suggests a decision-making model that can be relied upon for sustainable water-sharing in an Inter-Basin Water Transfer (IBWT) network. The utility of the model is demonstrated by taking a case study of the Parambikulam-Aliyar Project (PAP), Asia’s largest IBWT network. This thesis builds on the identification of sustainability indicators of water-sharing pacts, the development of a conceptual eco-hydrological framework for water sharing, the critical examination of the PAP water-sharing pact in the backdrop of the eco-hydrological framework suggested above. The assessment of environmental flow (E Flows) of PAP sub-basin, the development of a decision-making tool for helping the water-sharing policy makers and its managers, and the assessment of its utility in the PAP sub-basin are also dealt with.

The study revealed that the current sharing pact of PAP is not at all sustainable. One of the significant outcomes of the study is the development of a decision-making tool which can be utilised in the Indian context where the availability of data is limited. The decision-making tool can facilitate sustainable water sharing and it can be adopted in other IBWT projects, interstate river water-sharing projects and by the interstate water dispute tribunals.

Chapter 1

1. INTRODUCTION

1.1 General

Almost all ancient civilisations evolved on the banks of rivers or water bodies. These civilisations existed for centuries without affecting the ecological and hydrological balance and were sustainable. In the recent past, over-exploitation of resources and pollution by the greedy human has affected the ecological and hydrological balance, which in turn, has led to the degradation of ecosystem services and water scarcity. The United Nations World Water Development report observes that nearly two billion people over forty countries are affected by water shortages. Water scarcity and its effects are multidimensional. The outcome of water scarcity is poorer food security, increase in disease, conflicts among users, and limitations on livelihood and income generating activities. Access to water is one of the Millennium Development Goals and is considered as a development indicator capable of designating the status of poverty, health etc.

The focus of new development paradigm is based on sustainable development which ensures the access to water by the larger ecosystem of which human is an integral part. This is clearly reflected in the global recognition of value of ecosystem services at an unprecedented scale. The Millennium Ecosystem Assessment disclosed that the ecosystem services have been declined by 60% in the last half century. Increased water demands proportionate to population growth, irrigation development, urbanization, etc. shoots up the pressure to develop and protect surface water resources, especially the rivers.

The importance of rivers and its ecosystems in delivering IWRM (Integrated Water Resources Management) solutions has been widely appreciated in the recent past. Sustainable management of rivers is an essential prerequisite for the conservation of its ecosystems. However, over abstraction of water from rivers is an increasing concern today. When water is abstracted for different purposes, enough water needs to remain in the rivers for the sustenance of its ecosystems. Unsustainable level of abstraction of water for different uses reduces the available quantum to maintain ecosystem integrity.

If the present trends of ecosystem degradation are to be reversed, actions to ensure the availability of water for the needs of the environment are considered critical and a central part of water management paradigm. Historically, river managers have focused on maximizing the short-term economic growth from the use of water. However, the IWRM paradigm now emphasizes the need to take care of aquatic ecosystems for long-term economic viability. Restoring the over abstracted rivers and their ecosystems to its pristine condition may not be possible in most of the situations. But they can be brought back closer to this condition by modifying the river flows scientifically. Ecohydrology the new paradigm for sustainability, must be significantly understood in this context.

In India, water has always been one of the natural resources under stress. The fact that only 4% of world water is available to 17% of the world population living in India adequately justifies its low per capita water availability of 1633 cubic metre. When compared to the water availability of developed countries like Australia or USA, this figure is less than even one-fifth of their per capita water availability. The total annual utilizable water resources in India including surface water and groundwater are estimated as 1123 billion cubic metres which is spread non-uniform across the nation. Rivers, the major source of surface water in India, are grouped into 20 sub-systems and their total average annual potential is estimated as 1869.35 billion cubic metres, of which utilisable water is much less than this value.

The satisfaction of basic human needs, protection of our environment, socio-economic development and poverty reduction are all heavily dependent on availability of water. Hence, sharing of available water resources in a sustainable manner is vital for existence of human and all ecosystems. However, the increase in demand on water resources worldwide has led to many conflicts over its sharing. Water as a shared resource poses many challenges in its conservation and development. Sustainable sharing of this resource is an essential prerequisite for IWRM practice. Sharing this resource among its different stakeholders certainly trigger different types of problems of which water conflicts are the most challenging ones. The institutional arrangement for water sharing therefore needs to be specific and sustainable.

Most popular institutional arrangements for sharing are water sharing compacts. Water sharing compacts on both surface and aquifer resources are very common. Whether these compacts are based on postulates of sustainability is an important question to be investigated. Normally, conflicts resurface when the sustainability of a compact is at stake. Transboundary rivers and aquifers are the typical examples of this resource being shared across the geographical boundaries. According to UN-Water, about 263 transboundary river basins covering almost half the world’s land surface are shared by 145 countries. About 2 billion people worldwide share 300 transboundary aquifer systems. The potential for conflict over increasingly stressed water resources throughout the world, is therefore evident.

Inter Basin Water Transfer (IBWT) is a technological innovation to address the water issues of deficit basins. The policy makers and practitioners of water resource development believe that the problem of spatial and temporal variation of water availability can be managed with IBWT networks. Government of India is planning IBWTs at national level as a massive water resource development project. But water conflicts are predominant in most of the IBWT networks already executed in India. Parambikulam Aliyar Project (PAP), Asia's largest IBWT network, is a classic example for this. It clearly shows that big gaps exist in the research on how a sustainable water sharing model could be fitted into the IBWT framework. The institutional arrangements for water sharing in transboundary, interstate or IBWT basins must be realistically designed considering the potential runoff from the participating catchments. But there are many uncertainties in the prediction of runoff like uncertainties in the measurement of rainfall and other meteorological characteristics, changes in slope and soil characteristics due to erosion, changes in land use and land cover pattern and changes in the development model of the region, especially in the backdrop of climate change. The development paradigm that would follow in the watershed is also critical in this regard. Downscaling climate change models to catchments and assessing the hydrological impacts is one way of addressing these uncertainties. Nevertheless, decision-making tools for sustainable water sharing, planning and management are to be robust enough to account for the many uncertainties about the future. Though it is very much essential to consider the yearly variability in runoff while designing a water sharing pact, limited efforts in this regard have been reported with reference to the existing pacts in India.

This limitation is reflected in three specific instances of (i) interstate water sharing agreements (ii) Inter Basin Water Transfer (IBWT) agreements and (iii) Inter State Water Disputes Tribunal (ISWDT) awards. All these are based on deterministic principles of water sharing without considering the stochastic nature of runoff. Limited historical data then available (e.g., in the case of Parambikulam sub catchment used in this project, the decision makers on water sharing agreement had to depend on just two years rainfall and runoff data) has been taken as the basis for decision making in all these three cases. The likely variations in runoff are not considered here and hence the water sharing models proposed here are deterministic. That is, the allocation to a party in the deterministic sharing model is fixed irrespective of the changes in total runoff in a year. Even if the total runoff is more than what was originally anticipated, or less than that, the allocation to a party remains to be the same. These deterministic water sharing agreements have the lowest stability compared to other water sharing rules. Water sharing models that incorporate the variation of yearly hydrological and ecological factors are increasingly used now in the other parts of the world. Colorado river basin agreement (USA) and Murray Darling Basin agreement (Australia) are the examples for this. The distress sharing model of Colorado basin (USBR, 2007, USBR, 2015, USBR, 2018) and its environmental needs assessment (Gaber et al., 2009) use hydrological and ecological metrics to develop the comprehensive sharing model for the basin. Murray Darling Basin Authority (Authority, 2010, Authority, 2015) incorporates the ecosystems response modelling into the basin plan of Murray Darling. However, such methodology cannot be adapted directly in the Indian context as the availability of enough hydrological and ecological data is limited in almost all river basins. Historical ecological data is not available for almost all the river basins of India. Hence, a sustainable water sharing compact model for the Indian context which can work with limited amount of hydrological data is inevitable to reduce the water conflicts among the stake holders. Therefore, the research gap in this area is evident. Present study is an attempt to bridge this gap. Following are the research gaps which form the basis for this study.

1. An ecohydrological framework to contemplate sustainable water sharing is not available
2. E Flows modelling approach purely based on hydrological metrics is essential in the Indian context as the historical ecological data is hardly available
3. In the context of limited data availability, a decision-making tool facilitating sustainable water sharing is very much appropriate

Ecohydrology is being recognized as the new paradigm for sustainability (Zalewski, 2014). Even then, an ecohydrological framework to contemplate water sharing is yet to be evolved. Though quantitative aspects of sustainability are seen thought of in the literature, the indicators of sustainability to be used in any water sharing pact are not yet crystalized. The first and second objectives of this study are formulated in this context.

Inter Basin Water Transfer is an innovative technical solution for balancing the water availability across the surplus and deficit basins. Water transfer between basins and sharing across upstream and downstream stakeholders is a complex procedure. Water sharing pacts are designed for this purpose. But the sustainability perspective of these pacts needs to be understood for developing a sustainable water sharing model. IBWT in PAP is used as a case study for this purpose. The third objective is evolved towards this end.

Though E Flows are recognized in the IWRM discourse, how this can be modelled with the available minimal data and incorporated into a water sharing pact is an important area to be researched further. For most of the river basins, at least in India, scientific data on ecosystems and how they respond to water availability are seriously missing. Using hydrological metrics as surrogates for ecosystem data is an innovative solution. Fourth objective of this study is focusing on it. Lack of enough hydrological data is a major challenge in designing water sharing models as the available limited data reflects, perhaps, only one climate scenario. These challenges warrant the development of an appropriate decision-making tool which can work even in case of limited data. This is the fifth objective of this study. The decision-making tool must be tested in real life situation which is the sixth objective of this study. This tool is applied to one of the sub catchments of PAP and different scenarios of water sharing are examined.

Based on the above discussion, the aim and objectives of this study are presented below.

1.2 Aim:

Modelling sustainable water sharing for inter basin water transfer project

1.3 Objectives

1. To examine the water sharing models across the globe from their sustainability perspective
2. To develop an ecohydrological framework for sustainable water sharing by identifying its key components
3. To evaluate the water sharing pattern of an IBWT project by taking a case study of PAP
4. To assess the environmental flow requirements of one of the PAP basins using appropriate models
5. To develop a decision-making tool that can facilitate sustainable water sharing
6. To model the water sharing of one of the sub catchments of PAP using the decision-making tool

Hence the present study investigates the challenges in trans basin water management and attempts to suggest a decision-making model that can be relied upon for sustainable water sharing by taking a case study of PAP's IBWT network. This thesis builds on the identification of sustainability indicators of water sharing pacts, the development of a conceptual eco-hydrological framework for water sharing, the critical examination of PAP's water-sharing pact in the backdrop of the eco-hydrological framework, the assessment of environmental flow (E Flows) of PAP sub-basin, the development of a decision-making tool for helping the water sharing policy makers and its managers, and the assessment of its utility in the PAP sub-basin.

1.4 Chapter Organization

Rest of the thesis is organized in five chapters. Chapter two reviews the literature and summarises the research gap. It also justifies the aim and objectives of this study formulated in the context of the identified research gap. The materials and methods of this study are presented in chapter three. The results and analysis are discussed in two parts in chapter four and chapter five. Summary of the study and conclusions drawn are presented in the final chapter six.

Chapter 2

2. LITERATURE REVIEW

2.1 Introduction*:*

This research project aims to develop a water sharing model for IBWT projects, specifically within a sustainability framework. Research in the area of water sharing model among different states in India is rather limited. Decision making on water sharing in the IBWT projects in India, both existing and the newly proposed ones, is currently impaired with this gap in the research field. Normally this gap is manifested as the conflicts among stakeholders. This lacuna justifies the need for the present study. Being a unique research project, the literature of exactly similar studies is not available. However, vast volume of literature on different aspects of this project is available. These aspects can be grouped under five subheads of (1) Sustainability Framework; (2) Institutional Arrangements for Water Sharing; (3) Environmental Flows Modelling; (4) IBWT; and (5) Hydrological Modelling. In this chapter, literature reviews of each of these aspects which are particularly relevant to the study are presented in the same order.

2.2 Sustainability Framework:

Sustainability is the buzzword commonly being used in the IWRM literature. Many investigators discussed the Qualitative assessment of sustainability (Brundtland et al., 1987, Dresner, 2008, Harrison, 2000, Robert et al., 2005, Seghezzo, 2009, Fenner et al., 2006). Loucks(2009) conceptualised a quantitative approach to sustainability, particularly in the water resources sector. Performance criteria based Sustainability Index (SI) is a further advancement of this concept (Sandoval-Solis et al., 2010). SI is very useful in comparing the sustainability of different policies and agreements on water sharing. It is defined as the geometric average of ‘M’ performance criteria c_m and is given by:

$$SI = \left[\prod_{m=1}^{M} c_m\right]^{1/M} \qquad (2.1)$$

The performance criteria may include Resilience, Reliability, Vulnerability, Standard Deviation, Maximum Deficit etc. These performance criteria for any water-sharing agreement can be computed if the data about water availability is existing. Equation 2.1 refers to the sustainability by the user. Sustainability by group (SG) is used to compare the groups of water users; for example, different states of an interstate water-sharing agreement. SG for a group *k* with i^{th} to j^{th} users is given by:

$$SG^k = \sum_{i=1\in k}^{i=j\in k} W^i * SI^i \qquad (2.2)$$

Where W^i is the relative weight for the i^{th} water user ranging from 0 to 1 and summing up all to 1. SI and SG can be used to compare the sustainability of different policies or water sharing models among individual users and groups of users.

The sustainability of any water-sharing agreement concerning individual uses like irrigation, municipal drinking water schemes, E Flows etc. can be compared using SI. SG would facilitate comparison across different groups like Kerala and Tamil Nadu of PAP agreement. The sustainability of different water sharing models can be compared using SI and SG to make a final choice of the best model for agreement.

It is possible to numerically compute the sustainability of water-sharing agreements in different basins using SI and SG. But a numerical comparison of sustainability in the basins of significantly different climatic and socio-economic conditions is illogical. In this case, it would be more logical to assess the sustainability by subjective assessment of the different parameters being used to benchmark. In this context, the idea of 'sustainable water sharing' finds an important place. This concept has a broader meaning than just sharing. Theoretically speaking, sustainable water sharing model shall facilitate the following:

1. Sharing without any conflict on environment and ecosystems
2. Sharing without any conflict on the resource availability constraints
3. Sharing without any conflict on the needs of the states

Each agreement on water sharing is unique. Even then, critical examination from its sustainability perspectives would provide many new insights aiding the modelling philosophy of water sharing.

2.3 Institutional Arrangements for Water Sharing

Water, as a shared resource, poses many challenges in its conservation and development. Sustainable sharing of this resource is an essential prerequisite for IWRM practice. Surface water and groundwater are the most commonly available resources. Sharing of this resource among its different stakeholders certainly triggers different types of problems. The institutional arrangement for water sharing, therefore, needs to be specific. Transboundary Rivers and transboundary aquifers are the typical examples of sharing this resource across the geopolitical boundaries. According to UN-Water (2008), 145 countries and 2 billion people worldwide share the water resources in both surface and groundwater systems. The chances for triggering conflicts over the increasingly stressed water resources are therefore evident throughout the world.

2.3.1 Water Conflicts:

Intensified competition worldwide over water resources has increased conflicts. Population growth, economic development and changing regional values are some of the reasons for this intensified competition. Water conflicts have many dimensions, and they can be grouped into many categories. Conflicts are predominant in trans-boundary waters. They all originate from the increasing concern about access, equity and the response to growing needs.

Some of the commonly identified types of water conflicts are:

- ✓ Between two or more nations as in the case of trans-boundary basins like the Nile
- ✓ Between different states within a nation like India, USA, Australia etc.
- ✓ Between rural and urban populations
- ✓ Between upstream and downstream interests
- ✓ Between agricultural, industrial and domestic sectors
- ✓ Between human and non-human needs
- ✓ Between human needs and the requirements of a healthy environment.

Sustainable development of water resources without leading to any of the above types of conflict is challenging. Majority of the water conflicts are development induced.

2.3.2 Legal instruments for water conflict resolution:

Internationally, many legal instruments including policies and strategies have been evolved specifically for preventing and controlling the water conflicts (CWC, 2015a, CWC, 2015b). Helsinki Rules (Salman, 2007) is perhaps the very first one legal instrument in the chronological aspect. International Law Association adopted a widely acclaimed set of principles at its session at Helsinki in 1966. Later, these principles have reformed from the concept of an international river to that of an international drainage basin. It also included groundwater, covering the areas of equitable utilisation, pollution, navigation, timber floating and dispute settlement procedures. Helsinki rules have been cited worldwide by the jurists and tribunals. However, Helsinki rules emanated from a nongovernmental organisation had its limitations in getting an international law status. In this context, the United Nations General Assembly (UNGA) asked the International Law Commission to take up the study of the law of international watercourses for its progressive development and its codification. Known as the Convention on the Law of the Non-Navigational Uses of International Water Courses, UNGA adopted this and remained open for signature till May 2000. The Convention adopted it by a recorded vote of 104-3-26. (Yes: 104, No: 3 and Abstain: 26) Though India agreed with most of the clauses of the Convention, it abstained from voting. The goal of the Convention is to utilise the resources optimally and sustainably, while paying special regard to vital human needs and the interests of the other watercourse states. (Flavia Loures et al., 2009)

The literature available on water conflicts reveals that research on managing water conflicts largely focuses on trans-boundary river basins. International efforts have been devoted towards establishing institutions for cooperation on the management of such trans-boundary water resources. Two or more nations are involved in these conflicts, and hence they always have an international dimension. Some examples are Nile basin, Mekong basin, Indus basin etc. But there are many conflicts at the local level which are not given adequate importance by researchers. Many factors including climate change attributes to increase in the number and intensity of local water conflicts (Gosling and Arnell, 2016, Iglesias et al., 2007, Qureshi et al., 2013, Raleigh and Urdal, 2007, Schewe et al., 2014). India has many such local level conflicts known as interstate water disputes.

The Interstate Water Disputes (ISWD) Act and the River Boards Act are the two legal instruments in India to tackle this issue. These two Acts create two legal institutions called Interstate Water Disputes Tribunal (ISWDT) and River Boards (RB) respectively (Iyer, 2003). The focus of these two institutions and their operational framework are significantly different. The RB Act is primarily concerned with the planning and management of interstate rivers and river valleys. Conflict resolution is not its primary objective though it does provide for the arbitration of disputes arising in the context of the functioning of the RB.

ISWDT specifically deals with ISWDs and enables the National Parliament to pass legislation for its adjudication. Because of resistance by the states, no RB has been set up under RB Act. The RB Act has been inoperative and is a dead letter now (VENOT et al., 2011). However, there are no policy guidelines in these two Acts for sharing or distribution of interstate river water resources. Recently, as originally envisaged in the National Water Policy and subsequently recommended by the National Water Resources Council, the Ministry of Water Resources of Government of India has proposed draft national policy guidelines for water sharing/distribution amongst states.

2.3.3Water Sharing Agreements:

Water sharing agreements can be broadly grouped into three. One group is the agreements on Transboundary Rivers. The second group is the agreements on the Transboundary Aquifers. The third group is the agreements on Interstate Rivers. The nomenclature of Transboundary Rivers, Transboundary aquifers and Interstate Rivers are given below (Figure 2.1):

Rivers and aquifers that cross an international border are Transboundary (UN-Water, 2008, Shaminder Puri and Aureli, 2009). Rivers that cross an interstate border within a nation are called Interstate Rivers.

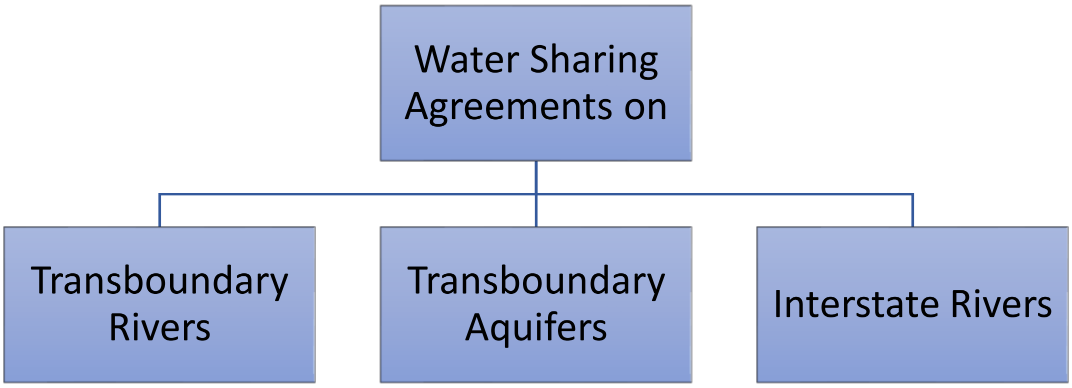


Figure 2-1: Types of Water Sharing Agreements

This classification of water sharing agreements is schematically represented in figure 2.1. Some examples of each category with its salient features are enumerated in Tables 2.1, 2.2 and 2.3.

Table 2-1: Examples of Agreements on Transboundary Rivers (Source: (Mekong River Commission, 2003, NBI and Hilhorst, 2014, Muckleston, 2003, UNW-DPAC, 2015, Wolf and Food and Agriculture Organization of the United Nations., 2002)

Basin	Nodal Agency / Treaty	Nations Involved	Date
Indus	Indus Water Treaty	India, Pakistan	19 September 1960
Mekong	Mekong River Commission	Cambodia, Laos, Thailand, Vietnam	05 April 1995
Nile	Nile Basin Initiative	Burundi, DR Congo, Egypt, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania and Uganda	22 February 1999
Columbia	Columbia River Treaty	USA, Canada	17 January 1961
Danube	ICPDR (International Commission for the Protection of Danube River)	Austria, Bulgaria, Croatia, the Czech Republic, Germany, Hungary, Moldova, Romania, Slovakia, Slovenia and Ukraine – and the European Community	29 June 1994

Table 2-2: Examples of Agreements on Transboundary aquifers (Source: (Shaminder Puri and Aureli, 2009, UNW-DPAC, 2015, Lena He Inrich, 2012, Puri, 2001))

Aquifer	Nodal Agency / Treaty	Nations	Date
Guarani	Guarani Aquifer Agreement	Argentina, Brazil, Paraguay, Uruguay	02 August 2010
Genevese	Genevese Aquifer Management Commission	France, Switzerland	18 December 2007
Nubian Sandstone	Regional Strategic Action Plan	Libya, Egypt, Chad, Sudan	18 September 2013

Table 2-3: Examples of Agreements on Interstate Rivers (Source: (USBR, 2015, MDBA, 2015, India-WRIS, 2015))

Interstate River / Nation	Nodal Agency / Treaty	States / Parties	Year
Colorado / USA	Colorado River Compact	Colorado, New Mexico, Utah, Wyoming, Nevada, Arizona, California	1922
Murray Darling / Australia	Murray Darling Basin Authority	The Commonwealth of Australia, New South Wales, Victoria, South Australia, Queensland, Australian Capital Territory	2008
Parambikulam Aliyar Project (PAP) Basins / India	PAP Interstate agreement	Tamil Nadu, Kerala	1970

2.4 Environmental Flows Modelling:

The importance of rivers and its ecosystems in delivering IWRM solutions has been widely appreciated in the recent past. Sustainable management of rivers is an essential prerequisite for the conservation of its ecosystems. However, over-abstraction of water from rivers is an increasing concern today. Millennium Ecosystem Assessment (Millennium Assessment Board, 2005) has observed that 15 – 35 % of irrigation withdrawal exceeds supply rates and are therefore unsustainable. Historically, river managers have focused on maximising the short-term economic growth from the use of water. The IWRM paradigm now emphasises the need to take care of aquatic ecosystems for long-term economic viability (Dyson et al., 2003). Restoring the over abstracted rivers and their ecosystems to its pristine condition may not be possible in most of the situations. But they can be brought back closer to this condition by modifying the river flows scientifically. E-Flows modelling in the case of hydrologically altered rivers is the methodology for identifying the volume of river flows required to mimic the pristine condition over different periods of a year.

In general, E-flows refer to the hydrological regime required to sustain freshwater and estuarine ecosystems, and the human livelihoods and wellbeing that depend on them (Gippel et al., 2009, Webb et al., 2012, Banks and Docker, 2013, Hirji et al., 2009, Jain and Kumar, 2014, Overton et al., 2014, Saintilan et al., 2010, Gippel et al., 2012, Warner et al., 2014). It is the natural pattern of high and low flows that maintain ecosystems in a less than pristine condition. Critical factors that maintain river ecosystems are quantity, quality, timing and its duration of lean flow together with the flood flows. Therefore, E-flows are different from natural flows, minimum flows or the average flows. Nevertheless, river rejuvenation cannot be ensured just by providing adequate E-flows. The key idea is to recognise it as an integral part of modern river management and restoration processes.

In the literature, there are many definitions for E-Flows. Two prominently used definitions in the scientific discourse of E-flows are as follows:

1. *Environmental Flows is the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits (Dyson et al., 2003)*
2. *Environmental Flows describes the quantity, quality and timing of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (The Brisbane Declaration 2007).*

In a country like India where competition for water is increasing continuously, setting the objectives of environmental flows becomes a negotiated trade-off. How much water the society is ready to allocate for the ecosystems must be negotiated with how much it wants to consume for different purposes. It is also necessary to assess whether the resulting ecosystem with this allocation a desirable one or not. Any environmentally sustainable development proposal for river water resources management should not ignore the E-Flows. The cost of ignoring E-Flows would be the cost of ecosystem services offered by the river. While constructing a storage or diversion structure in the upstream reaches of a river basin, an Environmental Impact Assessment (EIA) is carried out normally. But in most of the cases, this assessment is localised to the upstream stretches of river, and the impact of the proposed structure on the entire ecosystems enveloping up to river mouth is often ignored. E-Flows aim to address this missing link. However, assessing the exact quantities of water with its distribution in time for the maintenance of its ecosystems is a challenging exercise.

Assessment of the E-flows for ecosystem sustainability is a very complex exercise. Ideally, Ecologists and Hydrologists must work together for a comprehensive assessment of E-flows. But for most of the E-flows studies, particularly in India, unavailability of historical ecological data is critical. However, as observed in the study ‘Assessment of environmental flows for the Upper Ganga Basin’ in India (O Keeffe et al., 2012)

"*Lack of information and resources should never be a barrier to the implementation of E-Flows. Some attempt to restore the natural flow variability is always better than none, and fine-tuning can be done as more knowledge and resources become available over time*."

This lack of sufficient ecosystem data is mostly addressed by using Hydrological metrics as surrogates of river ecosystem (Gippel et al., 2009, Gippel et al., 2012, Thompson et al., 2013). The changing role of ecohydrological sciences in modelling the ecosystem and prescribing E-flows regimes are increasingly recognized as a key basic concept in the literature on E-flows (Zalewski, 2014). Linking E-flows with current water management frameworks such as IWRM, EIA, Ecological benefits of flood (Eco flood), Ecosystem Approach (EA), Ecosystem based Disaster Risk Reduction (ECO-DRR) etc. is the thrust area of research in E-Flows.

More than 200 methods of estimation have been recorded in the available literature on E-Flows (Tharme, 2003). For generalization, these methods can be grouped into four, depending upon the approach adopted (Table 2.4). The table gives an indication of range and scope of different categories. The river basin planning may have to focus on certain issues like sustaining endangered species. In this connection, PHABSIM (Physical Habitat Simulation) developed by USGS is the most commonly used habitat simulation method (USGS 2001). A compilation of 93 cases of E Flow assessments of various streams in Arizona state in the USA was completed in 2011 (Megdal and Nadeau, 2011). Different methods have been adopted in this study, and the grouping of these methods was under three contexts namely, aquatic, riparian and holistic. As a result, experts have recommended the use of AZEWNA (Arizona Environmental Water Needs Assessment) and gave importance to the E-Flows in the future planning exercise of Arizona State's water resources (Gammage et al., 2011).

There are many open source and commercial software available today, aiding the E-flows modelling. These tools differ mainly in their approach to the design of flow regimes as discussed above. Some of them are purely based on the linkages of hydrological metrics with the ecosystem functions. Rather, some others have the capability of inputting and analysing site-specific species data. Table 2.5 illustrates a few examples of both types. The hydrological metrics-based methods are preferred over the other types owing to the requirement of detailed species data which are difficult to obtain (Gippel, 2012, Thompson et al., 2013).

Table 2-4: Groups of E Flows Assessment Methods and their Characteristics

Assessment Approach	Examples	Assessment Duration	Description
Hydraulic Rating	Wetted Perimeter Method	2 – 4 months	Can be used for preliminary assessments only
Hydrological Index	1. Tenant Method (USA) 2. Range of Variability Approach (RVA) [USA]	One month	Can be used if long term hydrological data is available
Habitat Simulation	PHABSIM (USGS)	6 – 18 months	Specific simulation models of habitat response to flow
Holistic	1. In-stream Flow Incremental Method (IFIM) [USA] 2. Downstream Response to Imposed Flow Alteration (DRIFT) [USA] 3. Ecologic Limits of Hydrologic Alteration (ELOHA) [USA]	Up to 3 Years	Very expensive and involves large scientific expertise. A holistic approach to ecosystems

Table 2-5: Types of E Flow Modelling Software

Hydrological Metrics Based		(Hydrological Metrics + Species Data) Based	
Software	Developed By	Software	Developed By
IHA (Indicators of Hydrologic Alteration)	The Nature Conservancy(2009)	PHABSIM (Physical Habitat Simulation)	USGS(2001)
Flow Health	International Water Centre, Brisbane(2012a)	SEFA (System for Environmental Flow Analysis)	Sefa.co.nz(2012)
eFlow Predictor	eWater Source, Australia (2012)		

In Australia, Murray Darling Basin Authority (MDBA) has supported extensive research on E Flows. Its assessment studies and the relevant findings are given a place in their draft basin plan deliberations. The ecosystem response modelling of Murray Darling basin was completed in 2010 which is a striking example of comprehensive E Flows Assessment

(Saintilan et al., 2010). ‘The Living Murray’ project of MDBA purchases water from other core demand sectors for E-Flows purpose. In California, ‘environmental water district’ purchases water from the Colorado river allocations for the purpose of E-Flows. These are the two specific examples of E-Flows management in the developed world (Authority, 2010; Hirji et al., 2009).

The ecohydrological approach in the assessment of E Flows has therefore gained momentum. In this approach, the quantities as well as the quality of water are equally important. Many hydrological water quality models are available now which connects the flows and the ecosystem functioning (Singh Vijay et al., 2006). CREAMS (A field scale model for Chemicals, Runoff and Erosion from Agricultural Management Systems) consists of three components; hydrology, Erosion/sedimentation, and Chemistry (Knisel, 1980). ANSWERS (Areal Nonpoint Source Watershed Environmental Simulation) simulate the impacts of watershed management practices on runoff, sediment, and nutrient losses (Migliaccio and Srivastava, 2007). HSPF (Hydrological Simulation Program Fortran) simulates hydrologic and water quality processes in natural and human-made water systems (Migliaccio and Srivastava, 2007).

MIKE SHE, another popular model, simulates the coupled hydrologic processes with emphasis on surface water - groundwater interactions, channel flow, unsaturated zone flow and groundwater flow (Graham and Butts, 2005). The MONERIS (Modelling Nutrient Emissions in River Systems) model, developed by ICPDR (International Commission for Protection of Danube River), can model the emissions of nitrogen and phosphorus to the surface water, by different pathways as well as the instream retention in the surface water network(ICPDR, 2007). BASINS is an extensible, open-source GIS-based Decision Support System that integrates watershed models with ready access to data (flow, meteorological, water quality, and various GIS layers) (Whittemore, 1998). Recently, SWAT (Soil and Water Assessment Tool) has become a much more popular hydrologic model in this category (Arnold et al., 1994).

In quality modelling, sediment load of flowing water is an important ecosystem services parameter as it can contain a lot of nutrient and can affect the ecosystem very much. SPNM (Sediment Phosphorous Nitrogen Model) can simulate the sediment, phosphorous and nitrogen yields from agricultural basins. It is designed to predict sediment, phosphorous and nitrogen yields for individual storms on small basins and to route these yields through streams and valleys of large basins (Williams J. R, 1980). Kourgialas and Karatzas (2014) developed a hydro-sedimentary modelling system for flash flood propagation and hazard estimation under different agricultural practices. Riparian vegetation's effect on flood propagation parameters such as inundation depth, discharge, flow velocity, and sediment load can be investigated using this model. Though sediment load is an important ecosystem services parameter, lack of detailed data on sediment loads is a common situation in many regions of the world. As the E Flows and sediment load are inextricably linked, special efforts should be made in the future to improve long term databases on sediment transport and develop a better knowledge of temporal and spatial patterns of sediment transport variability (Batalla and Sala, 1994)

Environmental Flows (E Flows) must be considered in any water sharing agreement to make it sustainable. A study in Rio Grande basin by Sandoval-Solis et al. (2010) proposes the following SI for E Flows.

$$SI^{Envi} = \left[Rel^{Envi} * Res^{Envi} * \left(1 - Vul^{Envi}\right) * (1 - Max\ def^{Envi}\right]^{1/4} \tag{2.3}$$

Reliability, Resilience, (1 – Vulnerability) and (1 – Maximum deficit) with respect to E Flows are the performance criteria being used in this SI. (The superscript *Envi* indicates the E Flows)

2.5 IBWT:

IBWT is a technological innovation. Spatial and temporal variation of the water resources availability is one of the prominent challenges in water management of any region. IBWT mainly aims at addressing this challenge through technical intervention. Essentially IBWT is the transfer of water from a surplus basin to a deficit basin and hence it involves massive construction of infrastructure as the water conductor system. A complicated network of tunnels, canals and aqueducts are found to be essential to facilitate IBWT. Significant amount of public investment will be required to complete any IBWT project.

Though IBWT is an innovative solution to meet the water requirements of deficit basins, its sustainability is a subject of debate. Two schools of thought which are diametrically opposite prevail in the IBWT literature. Thatte (2007) argues that IBWT is the comprehensive solution for India's water problems. Based on the Indian IBWT schemes, already in operation for more than 100 years, he argues further that no ecological imbalance has been caused by them. However, those who argue against the IBWT believe that the social and environmental costs of water transfer between basins are significantly high. World Wildlife Fund Global Fresh Water Program (2007) argues that many of the IBWTs in the past have caused a disproportionate amount of damage to the freshwater ecosystems in relation to those schemes' benefits.

2.5.1 Global Scenario of IBWT:

In the global scenario, IBWT has been an accepted practice of water management from the very inception of large-scale storage reservoirs for water conservation. Examples of IBWT can be cited in Asia, Europe, America, Africa and Oceania (Ballestero, 2004, Bhaduri and Barbier, 2011, Ghassemi and White, 2007). A brief list of completed IBWTs in the above continents is given in Table 2.6.

2.5.2 IBWT Scenario in India

Some of the major schemes of IBWT already executed in India are (National Water Development Agency, 2015):

1. Mullaperiyar Project
2. Parambikulam Aliyar Project
3. Kurnool – Cudappah canal
4. Telugu Ganga Project
5. Ravi – Beas – Sutlej – Indira Gandhi Nahar Project

Of these five schemes, Kerala state is a party in the first and second IBWT projects. Both are having water sharing agreements with Tamil Nadu state. The IBWT schemes in India, both executed and proposed, are grouped into two major heads as Himalayan Component and Peninsular Component. The new IBWT proposals in India are collectively known as River Linking Projects. India's National River Linking Project (NRLP) proposals grouped under Himalayan and Peninsular components are given in Table 2.7. Feasibility studies of these projects have been conducted by the NWDA.

Table 2-6: Global IBWT Scenario (Thatte, 2007)

Continent	Country	No of IBWT Schemes Completed	Annual Water Transfer in BCM
Asia	China	6	Not Available
	India	5	56
	Iraq	6	16
	Japan	1	Not Available
	Malaysia	1	Not Available

Continent	Country	No of IBWT Schemes Completed	Annual Water Transfer in BCM
	Pakistan	8	100
	Total	27	172
Europe	Czech Rep	4	15
	Finland	1	.09
	France	5	2.35
	Germany	2	0.47
	Portugal	1	0.01
	Romania	3	Not Available
	Russia	5	60
	Spain	3	1.3
	Total	24	79
America	Brazil	3	5
	Canada	38	262
	Chile	2	3.15
	USA	19	38
	Total	62	308
Africa	Morocco	1	1.51
	South Africa	24	2.51
	Sudan	1	7.3
	Total	26	11
Oceania	Australia	1	1.13
Grand Total		**140**	**571**

Table 2-7: India's Proposed River Linking Schemes (Source (NWDA, 2015))

No	Name	Involved States	Benefitted States	Irrigation Lakh Ha	Domestic & Industrial Supply (MCM)	Hydropower MW
Peninsular Component						
1	Mahanadi – Godavari	Orissa, Maharashtra, Andhra Pradesh, Karnataka &Chattisgarh	Andhra Pradesh & Orissa	4.43	802	445
2	Godavari - Krishna	do	Do	6.13	413	--
3	Godavari – Krishna	Orissa, Maharashtra, Madhya Pradesh, Andhra Pradesh, Karanataka&Chattisgarh	Do	2.87	237	975

No	Name	Involved States	Benefitted States	Irrigation Lakh Ha	Domestic & Industrial Supply (MCM)	Hydropower MW
4	Godavari - Krishna	Orissa, Maharashtra, Andhra Pradesh, Karnataka &Chattisgarh	Andhra Pradesh	5.82	162	--
5	Krishna - Pennar	do	Andhra Pradesh & Karnataka	2.58	56	--
6	Krishna - Pennar	do	do	--	--	17
7	Krishna - Pennar	Maharashtra, Andhra Pradesh & Karnataka	do	5.81	124	90
8	Pennar - Cauvery	Andhra Pradesh, Karnataka, Tamil Nadu, Kerala & Puducherry	Andhra Pradesh, Tamil Nadu & Puducherry	4.91	1105	--
9	Cauvery - Vaigai	Karnataka, Tamil Nadu, Kerala & Puducherry	Tamil Nadu	3.38	185	--
10	Ken - Betwa	Uttar Pradesh & Madhya Pradesh	Uttar Pradesh & Madhya Pradesh	7.34	55	78
11	Parbati – Kalisindh - Chambal	Madhya Pradesh, Rajasthan & Uttar Pradesh	Madhya Pradesh & Rajasthan	2.3 (I) 2.2 (II)	13.2	--
12	Par – Tapi - Narmada	Do	Gujarat	1.69	--	32.5
13	Damanganga - Pinjal	Maharashtra & Gujarat	Maharashtra	--	895	--
14	Bedti - Varda	Maharashtra, Andhra Pradesh & Karnataka	Karnataka	0.60	--	4
15	Netravati - Hemavati	Karnataka, Tamil Nadu & Kerala	Karnataka	0.34	--	--
16	Pamba – Achankovil - Vaippar	Kerala & Tamil Nadu	Tamil Nadu	0.91	--	508
Himalayan Component						
1	Manas – Sankosh – Tista - Ganga	Assam, West Bengal, Bihar & Bhutan	Assam, West	6.54	--	5287

No	Name	Involved States	Benefitted States	Irrigation Lakh Ha	Domestic & Industrial Supply (MCM)	Hydropower MW
			Bengal & Bihar			
2	Kosi - Ghagra	Bihar, Uttar Pradesh & Nepal	Bihar & Uttar Pradesh	10.58	48	--
3	Gandak - Ganga	Do	Uttar Pradesh	40.40	700	--
4	Gaghra - Yamuna	Do	Uttar Pradesh	26.65	1391	10884
5	Sarda - Yamuna	Bihar, Uttar Pradesh, Haryana, Rajasthan, Uttarakhand & Nepal	Uttar Pradesh & Uttarakhand	3.75	6250	3600
6	Yamuna - Rajasthan	Uttar Pradesh, Gujarat, Haryana & Rajasthan	Haryana & Rajasthan	2.877	57	--
7	Rajasthan - Sabarmati	Do	Rajasthan & Gujarat	7.39	282	--
8	Chunar – Sone Barrage	Bihar & Uttar Pradesh	Bihar & Uttar Pradesh	0.67	--	--
9	Sone Dam – Southern tributaries of Ganga	Bihar & Jharkhand	Bihar & Jharkhand	3.07	360	95
10	Ganga – Damodar-Subarnarekha	West Bengal, Orissa & Jharkhand	West Bengal, Orissa & Jharkhand	8.47	484	--
11	Subarnarekha - Mahanadi	West Bengal & Orissa	West Bengal & Orissa	0.545	--	9
12	Kosi - Mechi	Bihar, West Bengal & Nepal	Bihar	4.74	24	3180
13	Farakka - Sunderbans	West Bengal	West Bengal	1.5	184	--
14	Jogighopa – Tista – Farakka	Do	Assam, West Bengal & Bihar	--	216	1115

The proposed NRLP has evoked mixed reaction in India (Amarasinghe and Srinivasulu, 2008, Gupta, 2001, India-WRIS, 2012, Iyer, 2003, Upali A Amarasinghe and Sharma, 2008). In general, the NRLP triggered three types of responses. They are:

1. NRLP should be implemented as a solution for the spatial and temporal variation in the water resources availability across the nation.
2. NRLP should be abandoned considering its social and environmental costs
3. NRLP should be implemented only after ascertaining its social, economic and environmental sustainability.

The state of Kerala has concern in the following three links.

1. Pennar – Cauvery Link
2. Cauvery – Vaigai Link
3. Pamba – Achankovil – Vaippar Link

Kerala has strongly objected the Pamba - Achankovil – Vaippar Link citing the environmental degradation which this link would evoke. Unpublished internal research reports of the Irrigation Department of Government of Kerala State underlines that the ecosystem of Vembanad Lake to which both Pamba and Achankovil drain would be jeopardized if the link is executed. CWRDM (2014) also substantiate this viewpoint.

2.6 Hydrological Modelling

Hydrological modelling plays a vital role in water management. It facilitates resource assessment and informed decision making on water sharing rules. A model is a representation of reality in a simple form based on hypotheses and equations. A hydrologic simulation model has three essential elements, which are: (1) Equations that govern the hydrologic processes, (2) Maps that define the study area and (3) Database tables that numerically describe the study area and model parameters (Karmakar, 2012).

Hydrologic models are classified in many ways based on their structure, spatial representation, processes involved, time-scale, and space-scale etc. (Pechlivanidis et al., 2011). The strengths and weaknesses of hydrological modelling are presented in Table 2.8. There are many hydrologic models (commercial and open source) widely used by water resources researchers. A few popular acronyms in these categories are HEC-HMS (hydrologic Engineering Centre – Hydrologic Modelling System), SWAT (Soil and Water Assessment Tool), MIKE, WMS (Watershed Modelling System), eWater etc. In current scenario, guideline materials for best modelling practice are plenty (Bay Delta Modeling Forum, 2000, Gaber et al., 2009, Jakeman et al., 2006, Scholten et al., 2007, eWater, 2011). eWater is Australia's national hydrological modelling platform which integrates water resources management with water policy and governance. eWater defines the best practice modelling as a series of quality assurance principles and actions to ensure that model development, implementation and application are the best achievable, commensurate with the intended purpose. It recognises, peer review, stakeholder consultation, information communication and documentation as some of the critical quality assurance principles.

Table 2-8: Strengths and Weaknesses of Hydrological Modelling (Karmakar, 2012)

Strengths:	Weaknesses:
1. With the diversity and multitude of the current generation of models, one can easily find more than one model for addressing any practical problem. 2. With their Comprehensive Nature, many of the models can be applied to a large range of problems. 3. With the cognitive modelling of physical phenomena, most models mimic reasonably well the physics of the underlying hydrologic processes in space and time. 4. Many models are distributed in space and time. 5. Several of the models attempt to integrate with the many subsystems a) Ecosystems and ecology, b) Environmental components, c) Biosystems, d) Geochemistry, e) Atmospheric sciences and f) Coastal processes	1. Lack of user-friendliness, 2. Large data requirements, 3. Lack of quantitative measures of their reliability, 4. Lack of clear statement of their limitations, 5. Lack of clear guidance as to the conditions for their applicability. 6. Some of the models cannot be embedded in social, political, and environmental systems.

2.6.1 Model Selection:

From the multitude of hydrologic models, the right model to investigate a problem must be chosen meticulously. Many aspects need to be considered in this selection process. World

Meteorological Organization (2008) suggests the following factors and criteria as being relevant while selecting the model.

1. Model objective (hydrological forecasting, climate change impact assessment etc.)
2. Type of system to be modelled (small catchment, large catchment etc.)
3. The hydrological elements to be modelled (daily discharge, monthly discharge etc.)
4. The climatic characteristics of the system
5. Data availability
6. Model simplicity
7. Need to replicate results at larger scales
8. Updating capability of the model

Scientific literature on comparing the performance of different models are available. A general conclusion of these studies is the uniqueness of each model for the intended purpose. Studies on comparison of different models used for the same purpose have indicated that calibration strategy and model structure influence their performance (Caldwell et al., 2015). In the present study, eWater models are used more frequently. Hence this chapter is concluded in the next section with a brief review of eWater literature.

2.6.2 The eWater

The eWater products for hydrological modelling can be grouped under three subheads of:

1. The eWater Source,
2. The eWater Toolkit
3. The eWater MUSIC

The eWater Source is Australia's National Hydrological Modelling Platform. It is designed to simulate all aspects of water resource systems to support integrated planning, operations and governance from catchment to river basin scales including human and ecological influences. Source accommodates diverse climatic, geographic, water policy and governance settings. The free public version of Source is suitable for IWRM studies and development of customized Decision Support Systems. It is a fully-featured hydrological, water balance and water quality tool ideal for Transboundary IWRM studies and research(eWater Source, 2017). The public version of Source is available under eWater Toolkit.

The eWater Toolkit is a conglomeration of hydrological, ecological and catchment management models and databases. Some of the most popular tools are RRL (Rainfall-

Runoff Library), Stochastic Climate Library (SCL), River Analysis Package (RAP), E Flow Predictor, Source Public Version etc. A classification of the eWater Toolkit model is presented in Table 2.9. It also contains information of TIME (The Invisible Modeling Environment), a code-base and algorithm library. Most of the tools are freely downloadable, and they are upgradable or replaceable as new versions are available. They are designed for the analysis of catchments, rivers, terrain, ecological responses, vegetation, urban water as well as water quality and quantity. These tools help to predict the impact of land and water management decisions across the catchment (eWater Toolkit, 2017).

Table 2-9: Models in the eWater Toolkit

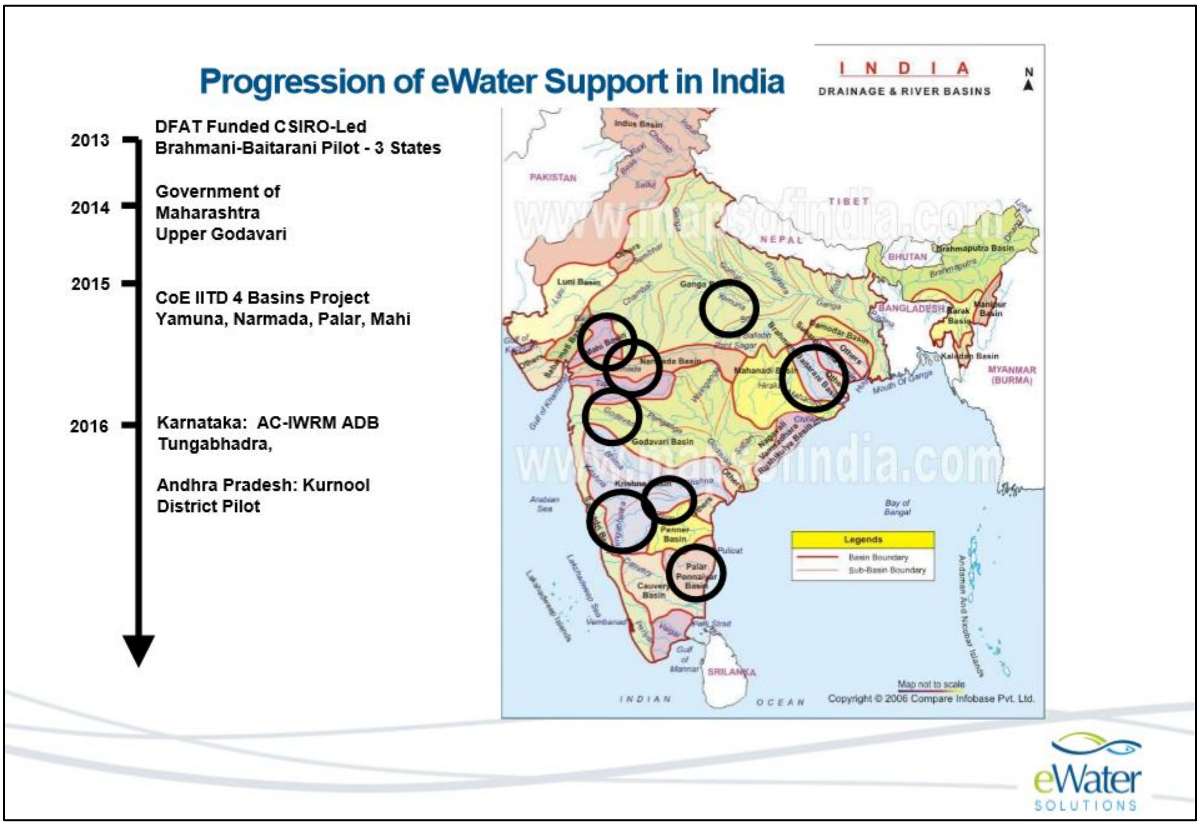
Model	**Description**
Catchment Tools	
BC2C	Biophysical Capacity to Change -Tool for estimating catchment scale water and salt export quantities
CatchmentSIM	3D-GIS topographic parameterization and hydrologic analysis model
CMSS	Catchment Management Support System - predicts average annual loads of pollutants
FCFC	Forest Cover Flow Change model- used to adjust daily time series, observed or simulated, flow records for significant changes in forest cover
RRL	Rainfall-Runoff Library – A library of Rainfall-Runoff simulation Models to Simulate catchment runoff from rainfall and evapotranspiration
SCL	Stochastic Climate Library – A library of models to generate climatic data
SedNet	Identifies sources and sinks of sediment and nutrients in river networks and predicts spatial patterns of erosion and sediment load
SHPA	Soil Hydrological Properties of Australia - a collection of maps and GIS data
NSFM	Non-parametric Seasonal Forecast Model - forecasts continuous Exceedance probabilities of streamflow (or any other hydroclimate variable)
IHACRES	Identification of unit Hydrographs and Component flows from Rainfall, Evaporation and Streamflow data
CLASS-U3M-1D	Unsaturated Moisture Movement Model - for estimating recharge, plant water use and soil evaporation across the soil profile at daily time steps using the Richards' equation
CLASS-CGM	Crop Growth Model - To simulate the growth of main crop types such as wheat, barley, canola, sunflowers. To simulate crop growth impacts on water balance from CLASS-U3M-1D.
CLASS-PGM	Pasture Growth Model- To simulate the growth of composite pasture types and to simulate pasture growth impacts on water balance from CLASS-U3M-1D.
CLASS-SA	Spatial Analyst -to generate climate zones, multi-resolution DEMs, wetness index, lateral multiple flow paths, accumulation and

Model	Description
	dispersion of water and solutes from hazard areas, estimation of soil depth, soil material distribution and soil moisture storage capacity in different parts of the landscape
River Tools	
RAP	River Analysis Package - a collection of 3 tools: Hydraulic Analysis - Time Series Analysis - Time Series Manager.
CHUTE	Spreadsheet program for the design and analysis of rock chutes
RIPRAP	Spreadsheet program for the design of rock lining (rip-rap) bank protection
WRAM	Water Re-Allocation Model -Simulates water allocation and trading between irrigation areas
Source Public Version	A special version of eWater Source – Australia's national hydrological modelling platform
Eco Tools	
Eco Modeler	A tool for building, storing and running quantitative models of ecological responses to physical and biological factors
E Flow Predictor	Uses environmental flow objectives to generate an altered flow regime and determine how much additional water would be required to achieve the new flow regime
Eco Evidence	Tool to review the literature on a specific topic of interest, particularly those seeking answers to cause-and-effect questions from existing research.
Urban Tools	
AQUACYCLE	A total urban water balance model that estimates water demand, stormwater yield, wastewater yield, evaporation, imported water use, stormwater use, and wastewater use for a site
MELS	Minimum Energy Loss Structures- a hydraulic design and analysis suite that enables designers to trial several alternative MEL culvert designs quickly
CONCEPT	Conceptual diagram drawing package that can be used to communicate dynamic relationships between multiple elements.

The eWater Music is the Model for Urban Storm Water Improvement Conceptualization. MUSIC is the software that helps the developers and planners to devise water sensitive urban designs (WSUD) and integrated water-cycle management capability (IWCM) for managing municipal stormwater. Thousands of professionals working on stormwater management across Australia use MUSIC. In some states, MUSIC is mandatory for designing new urban developments. It can predict the performance of stormwater quality management systems. It is intended to help local organisations to plan and develop appropriate urban stormwater management systems at a conceptual level for their catchments. (eWater Music, 2017).

A new Australia-India partnership includes the sharing of advanced Australian modelling work on river basin flows. The eWater solutions involved in this partnership is taking up many new projects in India as shown in Figure 2.2

The eWater products have been extensively used for water resources research in Australia. Abundant literature is available on this which can be accessed at eWater Toolkit site https://ewater.org.au/uploads/files/Papers%20and%20reports%202006-2009.pdf. In many research papers, SIMHYD, the rainfall-runoff model available within RRL has been successfully used to predict the runoff (Chiew and McMahon, 2002, Chiew and Siriwardena, 2005, Reichl et al., 2009, Zhang and Chiew, 2009). Chiew et al. (2009) used the same model for climate change impact studies on runoff across South East Australia.



Progression of eWater Support in India

2013 DFAT Funded CSIRO-Led Brahmani-Baitarani Pilot - 3 States

2014 Government of Maharashtra Upper Godavari

2015 CoE IITD 4 Basins Project Yamuna, Narmada, Palar, Mahi

2016 Karnataka: AC-IWRM ADB Tungabhadra,

Andhra Pradesh: Kurnool District Pilot

Figure 2-2: The eWater Projects Initiated in India (Source: (Carl Daamen et al., 2016))

2.7 Summary

In this chapter, the literature on different aspects of the research project are reviewed. Findings of this review can be summarised as follows:

1. Sustainability is a quantifiable aspect of water resources development but requires extensive data.

2. Inter-Basin Water Transfer is an innovative technical solution but to make its water sharing sustainable is a challenging exercise.
3. Informed decision making on sustainable water sharing must be supported with adequate further research.

The aim and objectives of this study have been formulated by considering the research gap identified in this review. Next chapter discusses the materials and methods that found use in this study.

Chapter 3

3. MATERIALS AND METHODS

3.1 Introduction

This chapter mainly discusses the materials and methods of the research project in six sections. The section3.2 describes the IBWT case study project, PAP, and its sub-catchment Parambikulam. The subsequent sections 3.3 and 3.4 cover two different water sharing models, one from USA (Colorado basin), and another one from Australia (Murray Darling basin). Observed field data form the database for modelling and analysing this project. Section 3.5 discusses the details of data assimilation for this project.

Different hydrologic models used in this study are (a) Flow Health and (b) eWater tools RRL (Rainfall-Runoff Library), SCL (Stochastic Climate Library) and RAP (River Analysis Package). Section 3.6 narrates all these models and their theoretical background. Though the impact of climate change is not directly modelled in this project, the results of the climate change impact assessment on Indian River basins carried out by the Ministry of Environment and Forests & Climate Change (MoEF&CC) are used for developing a decision-making tool to aid the process of sustainable water sharing. Gosain et al. (2011) explains the method used by MoEF&CC for assessing the impact of climate change.

3.2 PAP

In this study, ‘PAP’ is used as a case study because of certain important aspects. Firstly, this is Asia’s largest IBWT network. Secondly, it has an interstate aspect which will make this case study a unique one. Immediately after the commissioning of PAP, it was cited as a good example of interstate cooperation. However, many conflicts have evolved in due course of time and are largely focused on the water sharing pattern of this project. The sustainability of this water sharing project is also being questioned by its stakeholders. The government of India is planning to take up many projects like PAP’s IBWT. All these projects collectively are known as National River Linking Project (NRLP). The National Water Development Agency (NWDA), who are the planners of NRLP projects considered PAP as a thriving model of regional (interstate) collaboration for IBWT. But later PAP’s water sharing beheld many episodes of unsustainable water management practices. Moreover, the enduring drive in Kerala for the reconstruction of its tainted river systems argues that PAP’s diversion of water is detrimental to the river ecosystems. Rivers become dry for long stretches, and the consequent environmental impairment is vividly visible. The salinity intrusion to farther points from the river mouth is the direct indication of the degradation.

3.2.1 History of PAP

PAP was perceived to apportion the waters of three interstate rivers, Periyar, Chalakudipuzha and Bharathapuzha. Kerala and Tamil Nadu, two states in south India, share the waters of PAP. Thrust areas of this project are irrigation, hydropower generation and drinking water supply. Construction of this project was started in 1958. It is mentioned in the ancient documents of PAP that the discussion about this project was initiated in 1921. This project was mainly considered to bring water to the drought-hit areas of Tamil Nadu on the eastern side of the Western Ghats. Before reaching an agreement, Kerala and Tamil Nadu together had a long discussion for years about this project. Implementation of this project was a major challenge at that time. It is known as the sequel to intense work done by an orchestrated group of engineers who defied several natural disasters. The construction of this project was officially launched on 7th October 1961, by the first Prime Minister of independent India, Pandit Jawaharlal Nehru. The prime minister had reckoned PAP as the icon of regional collaboration for better management of national water resources. It took about ten years to complete the main network of PAP.

3.2.2 Hydrology

PAP interconnects three west flowing sub-basins namely, Periyar, Chalakudipuzha and Bharathapuzha. These three sub-basins begin from the Anamalai hills in the Western Ghats Ranges and are completely monsoon fed. The South-West monsoon and the North-East monsoon are the major contributors to their flows. Occasional summer showers make a less significant contribution to their lean flows. The spatial network of PAP ensembles the scenic milieus of the Western Ghats which are biodiversity hotspots. All the three sub-basins of PAP, flow towards west. To meet the irrigation demands of Tamil Nadu, PAP’s network of tunnels and canals divert a major share of flows in these west flowing sub-basins towards the east. With a formal agreement on water sharing, the paybacks of PAP’s intricate network are enjoyed by both Kerala and Tamil Nadu. The IBWT in PAP is accomplished by gravity alone. The intricate network of reservoirs, canals and tunnels are harmonised with the natural drainage channels of these sub-basins to avoid pumping anywhere in the system.

The embankment dams and gravity dams of varying heights built across different valleys of three sub-basins make the essential storage space in the PAP system. These storage dams are the primary source of water for the rain shadow region in Tamil Nadu, located on the eastern side of the Western Ghats. Having no other dependable source of water for this belt justifies the implementation of river linking and its IBWT in such a massive scale. Figure 3.1 shows the conceptual diagram of PAP which illustrates the network created over three river basins.

A cut off diagram of the system showing flow directions is shown in Figure 3.2, and the plan view of the project is shown in Figure 3.3. Mainly, there are four sub-catchments in this system. These sub-catchments and the structures built within each sub-catchment are shown in Table 3.1. Nirar is a sub-catchment of Periyar River, Sholayar and Parambikulam are the sub-catchments of Chalakudy River, and Aliyar is a sub-catchment of Bharathapuzha River.

Table 3-1: PAP Basins, Sub Catchments and Structures

Basin	Sub Catchment	Area of Sub Catchment in km^2	Dams / Weirs in the Sub Catchment
Periyar	Nirar	96.34	Upper Nirar Weir, Lower Nirar Dam
Chalakudy	Sholayar	186.48	Tamil Nadu Sholayar, Kerala Sholayar
	Parambikulam	331	Parambikulam, Thunacadavu, Peruvaripallam
Bharathapuzha	Aliyar	947.94	Aliyar, Upper Aliyar, Kadamparai, Thirumoorthy, Manacadavu Weir

Salient hydrologic features of the dams constructed under PAP are presented in Table 3.2. The capacities of powerhouses built under PAP are shown in Table 3.3. Total area irrigated using water from PAP in Kerala and Tamil Nadu together is more than 0.5 million acres. However, approximately 80 percent of this area lies in Tamil Nadu.

3.2.3 PAP River Pact

PAP River pact was signed in 1970. This pact is given a backdated effect from 1958. In addition to the terms of water sharing between Kerala and Tamil Nadu, the treaty clearly dictates the works that can be taken up under PAP and the conditions of project cost apportionment. The schedules and Annexure of the agreement are listed below.

Table 3-2: Hydrologic Features of Dams

Dam / Weir	Catchment area in Km^2	Full Reservoir Level (FRL) in m +MSL	Storage capacity at FRL in Mm^3
Upper Nirar Weir	75.11	1158.24	1.104
Lower Nirar	21.238	1021.08	7.759
TN Sholayar	121.73	1002.792	152.687
K Sholayar	64.75	811.682	153.480
Parambikulam	228.438	556.26	504.616
Thunacadavu	43.253	539.496	15.773
Peruvaripallam	15.799	539.496	17.557
Upper Aliyar	122.248	758.952	26.533
Aliyar	41.958	320.04	109.418
Thirumoorthy	121.73	407.518	54.794

Table 3-3: Powerhouses and Capacities

Powerhouse	Capacity in Mw
Sarkarpathy	1 X 30 = 30
Sholayar I	2 X 35 = 70
Sholayar II	1 X 25 = 25
K Sholayar	3 X 18 = 54
Aliyar	1 X 60 = 60
Kadamparai	4 X 100 = 400
TOTAL	639

Schedule I: Rivers and Works

Schedule II: Utilisation of Waters.

Schedule III: Financial Terms

Schedule IV: Miscellaneous Provisions

Schedule V: Constitution, Functions and Powers of JWR Board.

Annexure I: Statement of Fortnightly Water requirement in Million Cubic Feet for Chitturpuzha lands in Kerala.

Annexure II: Terms and Conditions on which Kerala lands are to be made available for the Parambikulam Aliyar Project of Tamil Nadu.

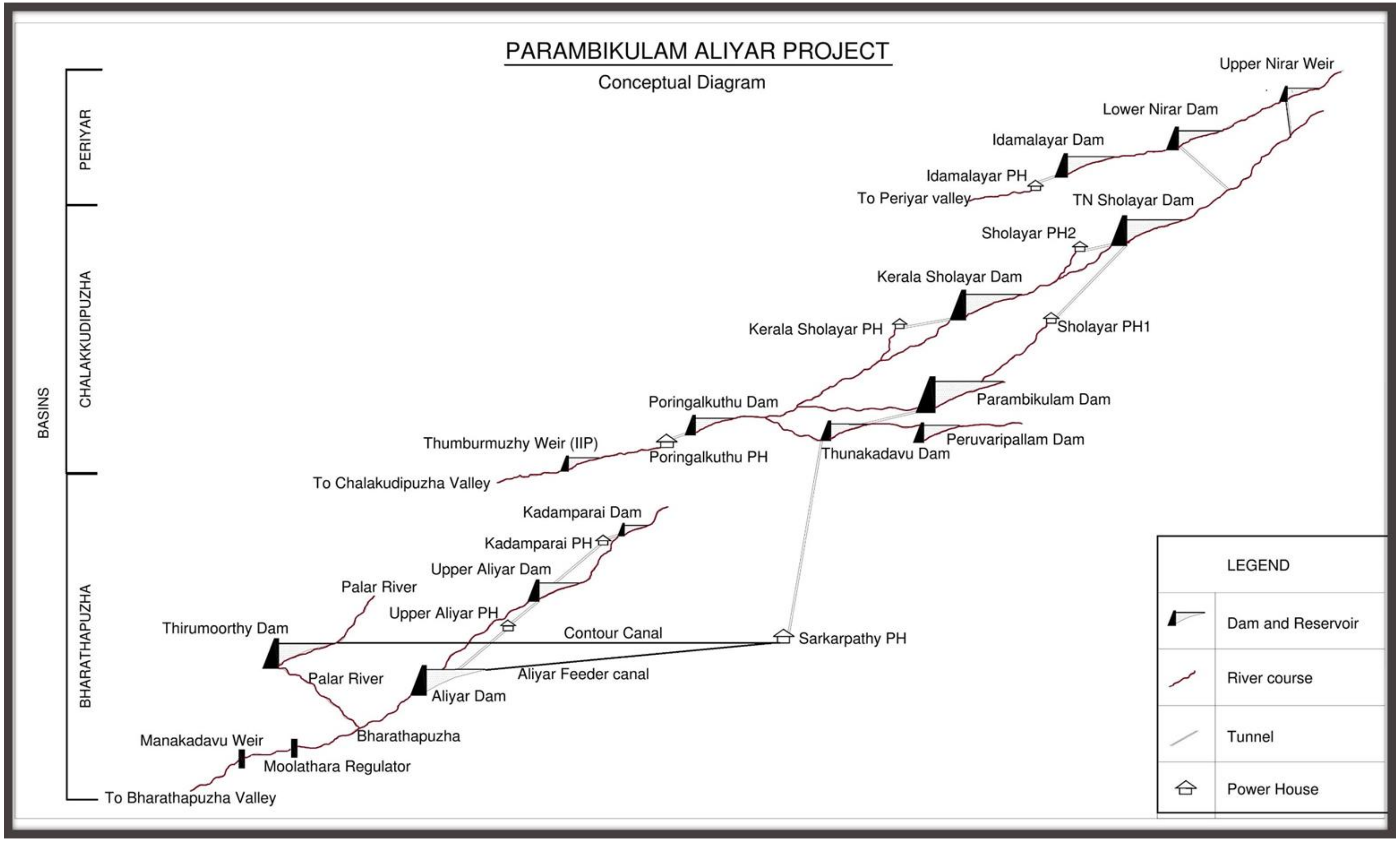
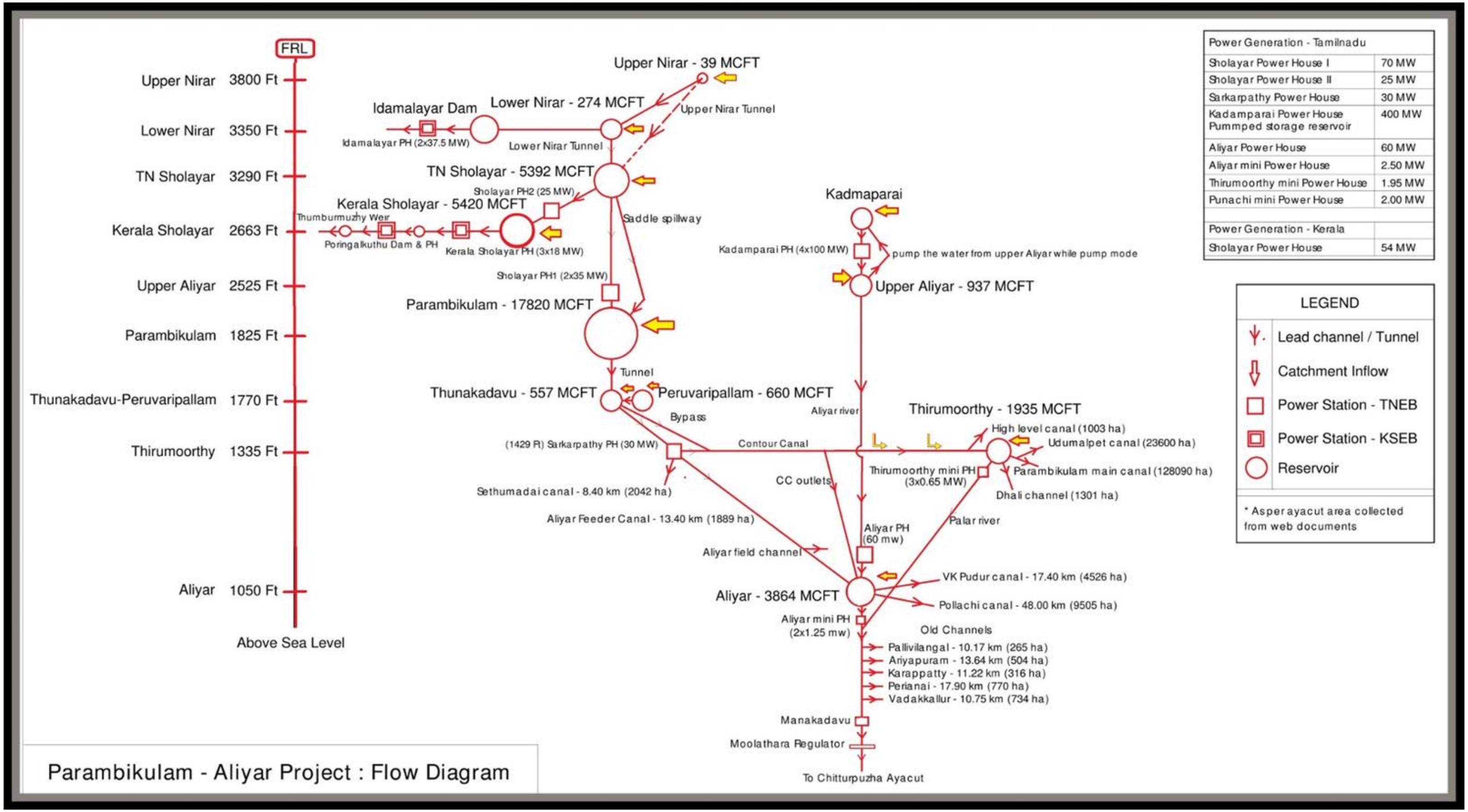


Figure 3-1: Conceptual Diagram of PAP



Power Generation - Tamilnadu	
Sholayar Power House I	70 MW
Sholayar Power House II	25 MW
Sarkarpathy Power House	30 MW
Kadamparai Power House Pummped storage reservoir	400 MW
Aliyar Power House	60 MW
Aliyar mini Power House	2.50 MW
Thirumoorthy mini Power House	1.95 MW
Punachi mini Power House	2.00 MW
Power Generation - Kerala	
Sholayar Power House	54 MW

Figure 3-2: PAP Cut off Diagram

Figure 3-3: Plan of PAP

The utilisation of waters and its sharing specified in Schedule II of the agreement are deterministic. The minimum entitlements of Kerala, the lower riparian state is only explicitly given in this agreement as in the case of a deterministic water sharing agreement. i.e., the understanding in principle is that the upper riparian state Tamil Nadu can divert waters after ensuring the supply of minimum entitlement to lower riparian state Kerala. The terms of sharing are summarised in Table 3.4

Table 3-4: Terms of Sharing in the PAP Agreement (CWC, 2015b, India-WRIS, 2015)

Sub Catchment	Entitlements	
	Kerala	Tamil Nadu
Nirar	1. Natural flow realised at the site of Upper Nirar Weir from 1st Oct to 31st Jan of every water year 2. A yield above 2.5 TMC of Lower Nirar dam	1. All flow at the site of Upper Nirar weir except for the four months from 1st Oct to 31st Jan 2. 2.5 TMC from the yield of Lower Nirar dam
Sholayar	1. 12.3 TMC to be measured at Kerala Sholayar powerhouse 2. FRL at Kerala Sholayar reservoir on 1st Sept and 1st Feb	All remaining waters after ensuring Kerala’s entitlement
Parambikulam	2.5 TMC when the total yield exceeds 14 TMC	14 TMC
Aliyar	7.25 TMC at Manacadavu weir exclusive of unutilisable flood waters	All remaining waters after ensuring Kerala’s entitlement

Though PAP agreement is perpetual, an explicit clause empowers both the states, to revise the terms of water sharing with their mutual consent. The thirty-year period is stipulated for considering this revision, and it must be based on the flow data set generated during this interval. As the pact is backdated from 1958, the first consideration of revision of its water sharing terms was due in 1988. Though Kerala and Tamil Nadu were engaged with a succession of discussion meetings since 1988 to revise the water sharing terms, the revision is not yet completed, mainly because of lacking consensus on a sustainable apportionment acceptable to both the parties. A Joint Water Regulation Board (JWRB) is constituted under this agreement. The enforcement of the conditions of PAP pact is the primary responsibility of JWRB. The Chief Engineers of Kerala and Tamil Nadu representing the Water and

Electricity departments respectively are the members of JWRB. Ultimately, JWRB is an engineering setup as epitomised in Figure 3.4.

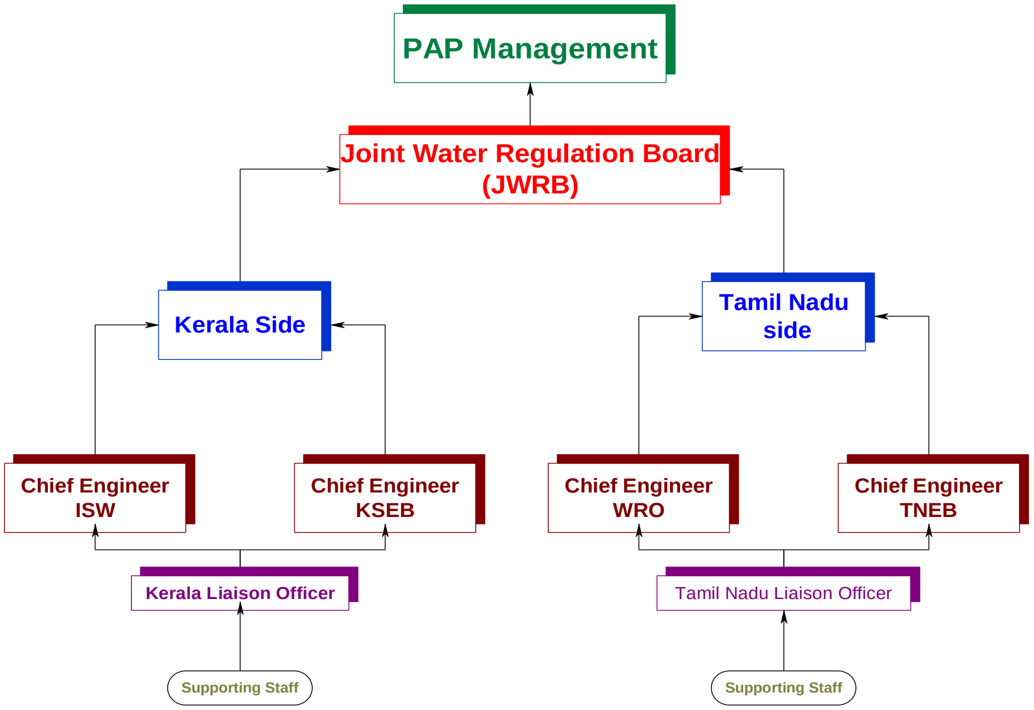


Figure 3-4: Organizational Hierarchy of JWRB for PAP Agreement Management

3.2.4 Parambikulam Sub Catchment

Parambikulam sub-catchment of PAP is a part of Chalakudy River. Both this sub-catchment and River are more detailed here as they have been explicitly used in this research project to model the sustainable water sharing and environmental flows.

Parambikulam sub-catchment lies between east longitudes $76^0$43’18.08” & $77^0$0’6.25” and north latitudes $10^0$20’5.34” & $10^0$28’57”. This sub-catchment consists of three watersheds Parambikulam, Thunacadavu and Peruvaripallam. It is a sub-catchment of Chalakudy River which is a part of West Flowing Rivers from Tadri to Kanyakumari (WFRTK) basin, in Southern Peninsular India. Mean annual rainfall of WFRTK basin is 2186.31 mm with an average maximum and minimum temperatures of 30.27^{o}C and 20.76^{0}C respectively. Parambikulam sub-catchment is spread across Kerala – Tamil Nadu Interstate Border. Figure

3.5 shows the sub-catchment and its location in the Chalakudy basin. It has an area of 331 square kilometres.

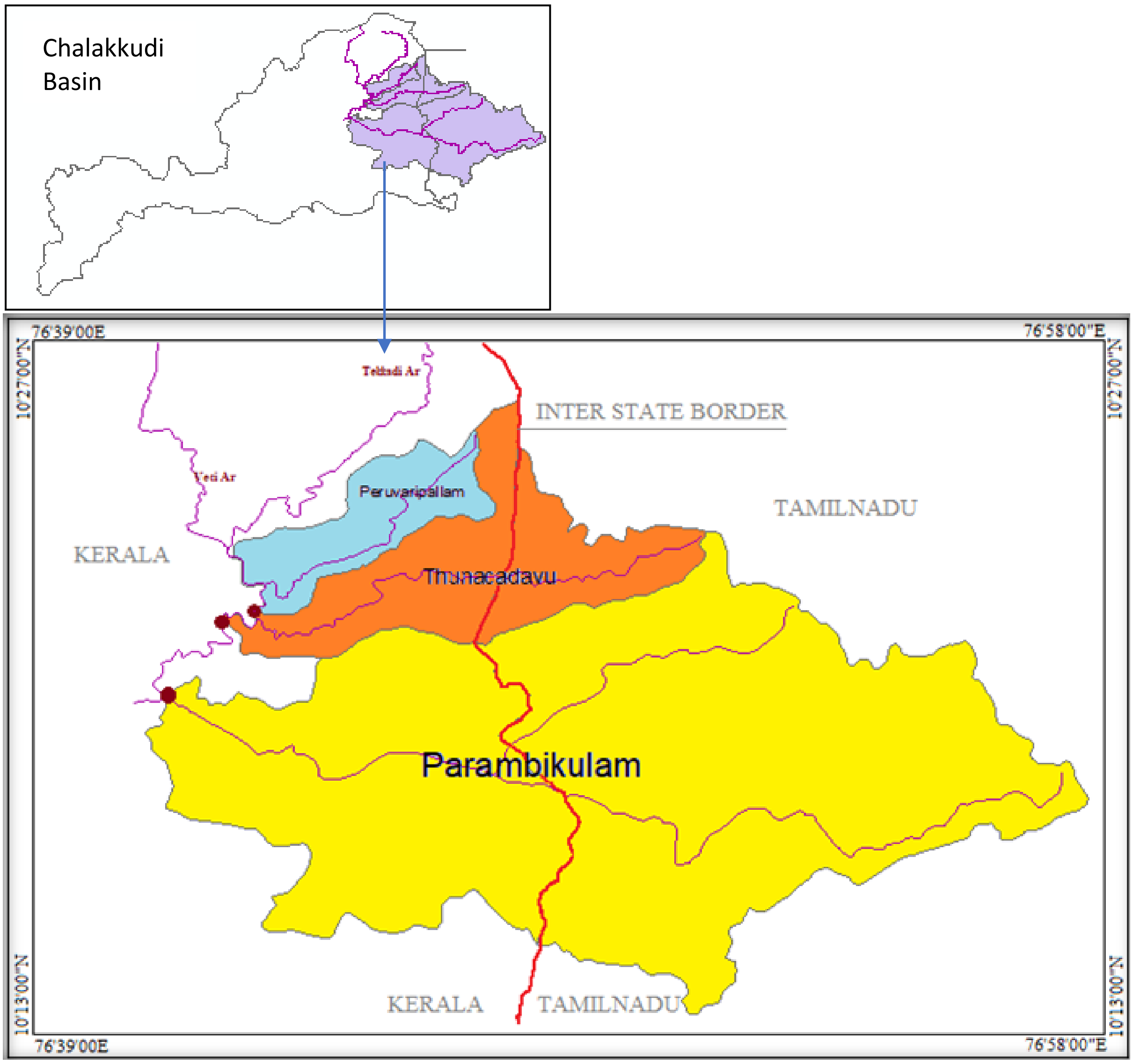


Figure 3-5: Parambikulam Catchment and its Location

3.2.4.1 Chalakudy River

This river originates at Anamalai Hills in the Western Ghats at an elevation of 1250 m. It has a length of 145 km with a basin area approximately, 1700 km^2. This river and neighborhood have very rich biodiversity and is identified as a hotspot of Western Ghats. This river is very popular for its rich variety of fish species. More than 104 species found in Chalakudy River makes it one of the top ranking in India. But the abundance of fish affluence has been reduced notably over the past few decades. The disconnectivity of the river course due to structural interventions, degradation of riparian forest ecosystems, sand mining, etc., have contributed to this. A primary recommendation of the National Bureau of Fish Genetic

Resources is to notify the upper reaches of this river system as the fish sanctuary (Latha et al., 2012). About sixteen species of the fish fauna of this river are endangered, and four are critically endangered. It has been reported that three of the critically endangered are strictly endemic to Chalakudy Sub Basin system (Raghavan et al., 2008). The riparian vegetation also includes endemic species of flowering plants of Western Ghats.

Six major storage reservoirs have been constructed across various tributaries of this river as shown in Figure 3.6. Table 3.5 gives the salient features of these reservoirs. All these storage reservoirs except Poringalkuthu are a part of PAP. Three sub-catchments on the upstream side contribute the flows in the main stretch of river. Table 3.6 presents the details of these sub-catchments.

Table 3-5: Reservoirs in Chalakudy Basin

Serial No	Reservoir	Tributary	Storage Capacity Mm^3	Year of Completion
1	Poringalkuthu	Poringalkuthu	32	1957
2	Kerala Sholayar	Sholayar	153.5	1966
3	Tamil Nadu Sholayar	Sholayar	152.7	1971
4	Parambikulam	Parambikulam Ar	504.6	1967
5	Thunacadavu	Thunacadavu Ar	15.8	1965
6	Peruvaripallam	Peruvaripallam Ar	17.6	1971
	Total		876.2	

Table 3-6: Sub Catchments of Chalakudy Basin

Sub Catchment	Area in Km^2
Poringalkuthu	512
Sholayar	314.4
Parambikulam	331
Total	1157.4

In this research project, environmental flow modelling of the Chalakudy River requires the cross section of the river. For this purpose, Arangali is selected as an icon site (marked as Arangali E Flow Modelling Icon Site in Figure 3.6). Figure 3.7 presents the cross sections of the river at this site during pre-monsoon and post-monsoon.

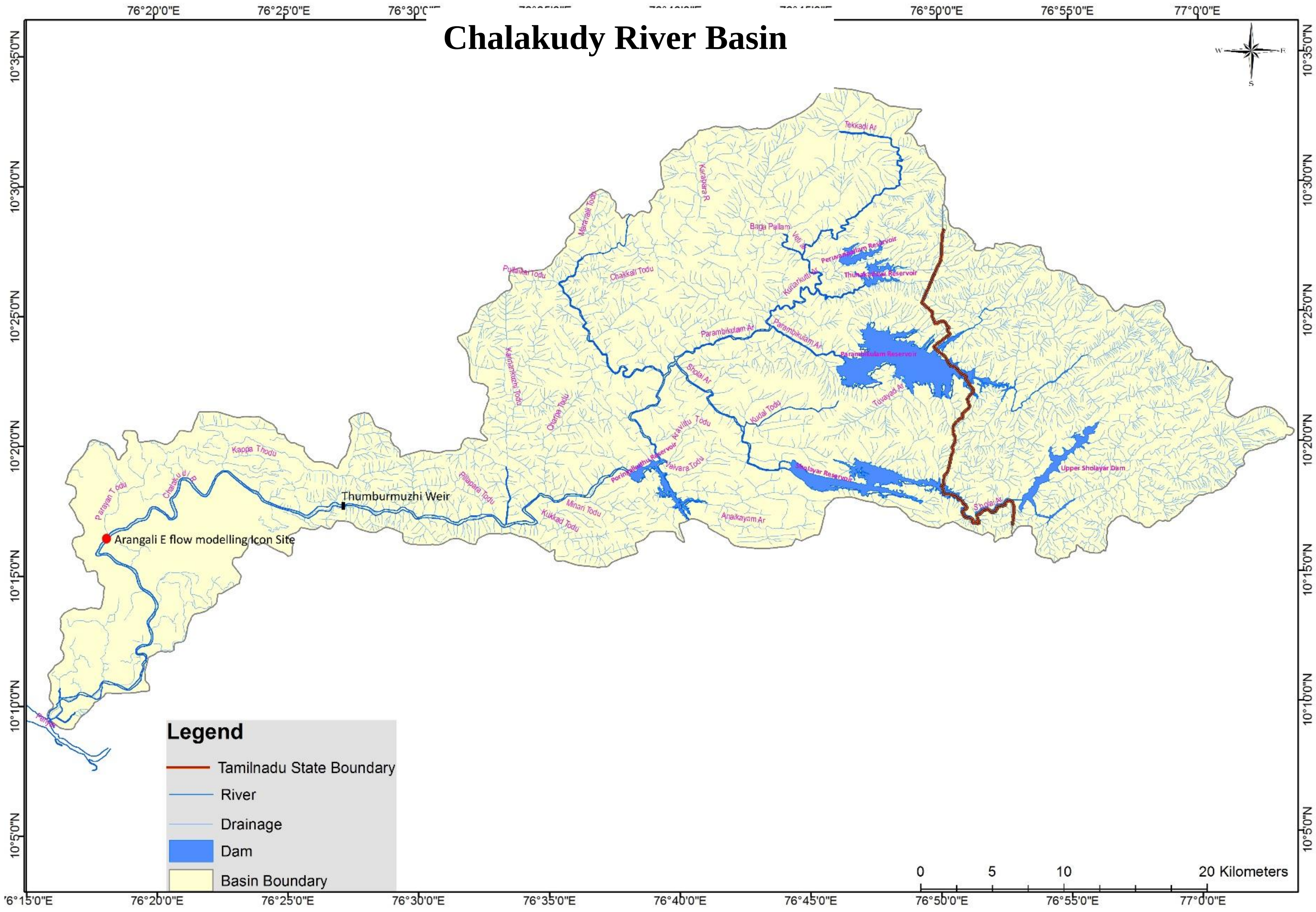


Figure 3-6: Chalakudy River Basin and the Reservoirs

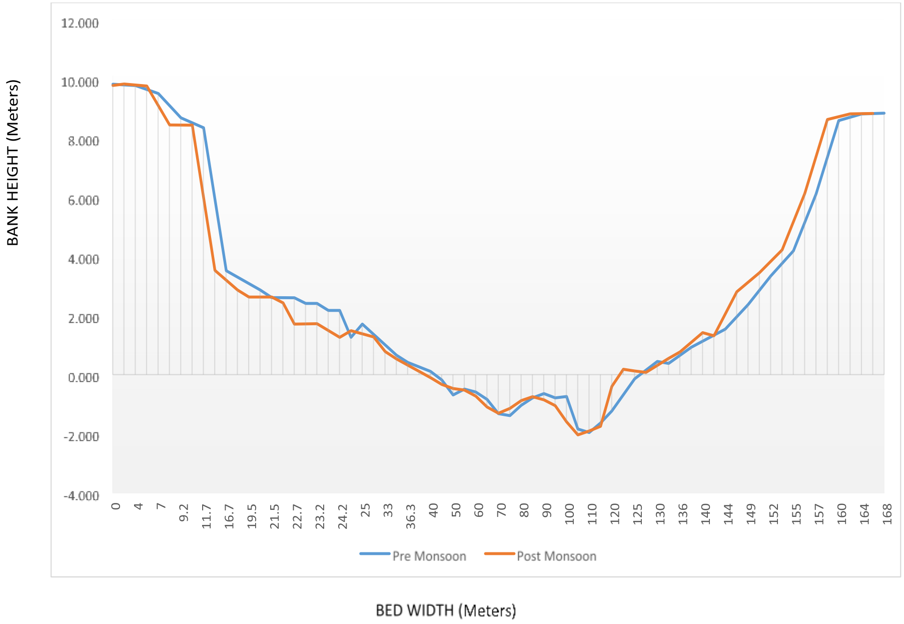


Figure 3-7: Chalakudy River Cross Section at Arangali

3.3 Colorado Basin Water Sharing Agreement

Colorado River Basin (Figure 3.8) is transboundary as well as interstate. USA and Mexico are the two riparian countries of this basin. Within USA, Colorado, New Mexico, Utah, Wyoming, Nevada, California and Arizona are the seven riparian states (USBR, 2016). Green River, Gila River, Little Colorado River, San Juan River etc. are some of its major tributaries. Approximately 420 m^3/s is the average discharge of Colorado at its half-length (USGS, 2016). The preliminary water sharing agreement on Colorado basin between the riparian states of USA is very old. It came into existence in 1922.

For the purpose of water sharing, this compact divide the basin into two as, Upper Basin and Lower Basin. Colorado, New Mexico, Utah and Wyoming are the Upper Basin states whereas Nevada, Arizona and California are the Lower Basin states. As per the agreement, both Upper and Lower Basins would get 9.3 BCM (Billion Cubic Meter) each (USBR, 2015). The percentagewise distribution of this quantity among the states is given in Table 3.7.

In 2007, a set of interim guidelines supplementing the above sharing pattern was evolved. They suggest sharing mechanisms in the event of water shortages due to climate change and increased hydrologic variability (USBR, 2007). The water level recorded at Mead reservoir is the basis for assessment of this deficit. Three types of shortages and corresponding entitlements for Lower Basin states are specified (Table 3.8). These guidelines helped to reduce the chances of triggering conflicts in the event of water shortages. It has also considered the environmental demands by due consideration of LCR MSCP (Lower Colorado

Region Multi-Species Conservation Plan), GCD AMP (Glen Canyon Dam Adaptive Management Plan), ESA (Endangered Species Act) etc.

Figure 3-8: Colorado Basin (USBR, 2016)

Table 3-7: Basin wise and State wise Distribution of Colorado Compact (USBR, 2015)

Upper Basin		
Total Quantity	State	Percentage
9.3 BCM	Colorado	51.75
	Utah	23
	Wyoming	14
	New Mexico	11.25
Lower Basin		
Total Quantity	State	Percentage
9.3 BCM	California	58.7
	Arizona	37.3
	Nevada	4

Table 3-8: Colorado Basin Guidelines for Shortage Sharing (USBR, 2007)

Shortage	Mead Level on 1st Jan	Lower Basin Entitlement in BCM	Break up of Lower Basin states' entitlement in BCM	
Light	>320 m <328 m	8.84	California	5.43
			Arizona	3.06
			Nevada	0.354
Heavy	>312 <320	8.74	California	5.4
			Arizona	3.0
			Nevada	0.349
Extreme	<312	8.63	California	5.43
			Arizona	2.86
			Nevada	0.345

3.4 Murray Darling Basin Agreement

Murray Darling (Figure 3.9) is an interstate basin in Australia shared by four states Queensland (Qld), New South Wales (NSW), Victoria (Vic), South Australia (SA) and Australian Capital Territory (ACT). Murray and Darling are the two main tributaries of this basin. It has an average discharge of 1030 m^3/s in the main stream (Authority, 2015). The parties of the interstate water sharing agreement include the Commonwealth of Australia (the

Central Government) in addition to the above four states and Australian Capital Territory. Primary water sharing is among the states, New South Wales , Victoria and South Australia.

Figure 3-9: Murray Darling Basin Map (Source: MDBA)

This agreement has specified the monthly entitlements only for SA as that is the lowermost riparian state. SA is entitled to 1.154 BCM annually with specific monthly quantities. In addition to this, every month SA is entitled to receive 0.058 BCM for dilution and losses. For NSW and Vic, the amounts are not specified as for SA. The entitlements proportional to the natural flows recorded at different points in the basin are prescribed for these two states. Intergovernmental Agreement on Murray Darling Basin Reform and the Murray Darling Basin Plan are the two subsequent legal instruments aimed to address water shortages and environmental demands.

3.5 Data Assimilation for Research

Mainly four types of data are assimilated for this project which is schematically shown in Figure 3.10. From this database the input data for running different models used in this study are prepared. All these input data are presented digitally in a compact disc and attached to this thesis as Annexure. In addition to this, the cross-section at Arangali of the Chalakudy River is also received. A brief description of different types of data and their observation procedure is given below.

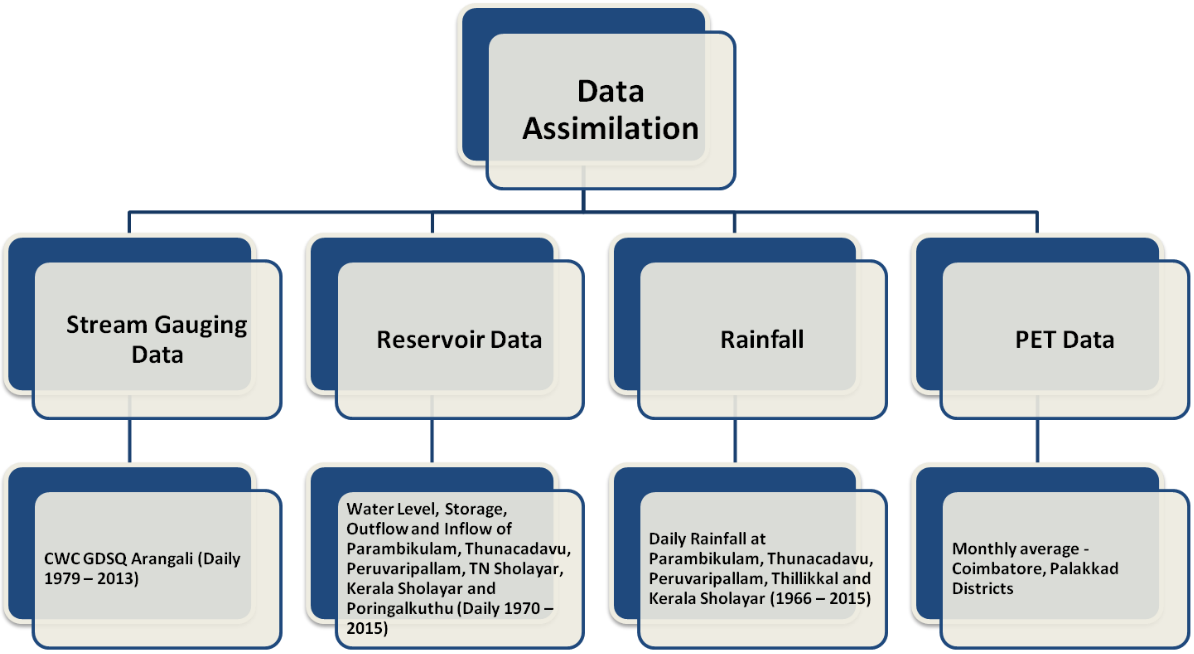


Figure 3-10: Data Assimilation for Research

3.5.1 Stream Gauging Data

Arangali GDSQ (Gauge Discharge Silt Water Quality) is the hydrological observation station of Central Water Commission (CWC). Discharge is measured using water current meter for which the wading/boat with cableway arrangements are permanently set up at site. The Latitude and Longitude of this station are 10°16’53” and 76°18’55” respectively. Daily gauge discharge data from 1978 is available in the public domain. The elevation data pertaining to river cross section is also taken from CWC database.

3.5.2 Rainfall Data

Daily rainfall data of 5 rain gauge stations in Chalakudy River basin are collected. This data is collected from the Water Resources Department of Government of Kerala and the Kerala State Electricity Board. The data availability of different stations is presented in Table 3-9.

Table 3-9: Rain Gauge Stations and Data Availability

Sl no	Rain Gauge Station	Period of Daily Rainfall Data Availability
1	Parambikulam	1966 – 2015
2	Thunacadavu	1966 – 2015
3	Peruvaripallam	1974 – 2015
4	Thillikkal	1995 – 2014
5	Kerala Sholayar	1986 – 2013

3.5.3 Reservoir data

Daily observation data from the year 1970 to 2015 of the reservoirs in Chalakudy basin except Poringalkuthu are collected. It includes the following.

1. Daily reservoir level and corresponding storage
2. Outflows
3. Inflows through IBWT or from Upper Reservoir

These data were used to compute the inflow from own catchment of each reservoir. Storage capacity chart of each reservoir is used to compute the storage corresponding to the observed water level. All the outlets of reservoirs are calibrated to measure the outflows. Inflows through IBWT or from Upper reservoirs are measured separately. Typical data acquisition tabulation for Kerala Sholayar reservoir is presented in Table 3.10.

3.5.4: Potential Evapo-Transpiration (ET_0)

The monthly average values of ET_0 data are collected for Coimbatore and Palakkad districts. PAP and its Parambikulam sub catchment modelled in this project are mainly spread over these two districts in Tamil Nadu and Kerala state respectively. ET_0 values for Coimbatore are computed using the 'ET_0 Calc' of Food and Agricultural Organization (FAO)(Raes, 2009).

Table 3-10: Sample Data Acquisition for Kerala Sholayar Reservoir

Date	Water level in feet above MSL	Storage in MCFT.	Difference in storage in MCFT	Outflows in MCFT			Total outflow in MCFT	Total inflow in MCFT	Power Generation in Units	Tailrace water level in feet above MSL	Rain fall in mm		Inflow from TN Sholayar (from Gauge station 3 to 11)				Net inflow
				Spill way	River sluice	Power house					PH	Dam	Masonry Spillway	River sluice	Bye-pass II	Power house II	
01/01/2011	2659.40	5063.40	19.20	0.00	0.00	41.74	41.74	60.94	795500	1552.19	0.00	0.00	0.00	0.00	0.00	57.20	3.74
02/01/2011	2659.60	5082.60	19.20	0.00	0.00	44.00	44.00	63.20	838600	1552.28	0.00	0.00	0.00	0.00	0.00	57.57	5.63
03/01/2011	2659.80	5101.80	19.20	0.00	0.00	42.09	42.09	61.29	802400	1552.20	6.00	0.00	0.00	0.00	0.00	57.47	3.82
04/01/2011	2660.00	5121.00	19.80	0.00	0.00	43.68	43.68	63.48	832900	1552.27	0.00	0.00	0.00	0.00	0.00	58.34	5.14
05/01/2011	2660.20	5140.80	29.70	0.00	0.00	40.33	40.33	70.03	769200	1552.14	0.00	0.00	0.00	0.00	0.00	58.37	11.66
06/01/2011	2660.50	5170.50	19.80	0.00	0.00	43.81	43.81	63.61	835600	1552.28	0.00	0.00	0.00	0.00	0.00	58.20	5.41
07/01/2011	2660.70	5190.30	19.80	0.00	0.00	40.60	40.60	60.40	774700	1552.15	0.00	0.00	0.00	0.00	0.00	58.73	1.67
08/01/2011	2660.90	5210.10	29.90	0.00	0.00	43.37	43.37	73.27	827600	1552.26	0.00	0.00	0.00	0.00	0.00	59.87	13.40
09/01/2011	2661.20	5240.00	30.00	0.00	0.00	38.88	38.88	68.88	742200	1552.09	0.00	0.00	0.00	0.00	0.00	60.05	8.83
10/01/2011	2661.50	5270.00	20.00	0.00	0.00	40.46	40.46	60.46	772600	1552.15	0.00	0.00	0.00	0.00	0.00	59.93	0.53
11/01/2011	2661.70	5290.00	10.00	0.00	0.00	44.43	44.43	54.43	848400	1552.30	0.00	0.00	0.00	0.00	0.00	51.38	3.05
12/01/2011	2661.80	5300.00	30.00	0.00	0.00	44.42	44.42	74.42	848400	1552.30	0.00	0.00	0.00	0.00	0.00	60.61	13.81
13/01/2011	2662.10	5330.00	20.00	0.00	0.00	47.61	47.61	67.61	909400	1552.40	0.00	0.00	0.00	0.00	0.00	61.26	6.35
14/01/2011	2662.30	5350.00	30.00	0.00	0.00	39.88	39.88	69.88	762000	1552.12	0.00	0.00	0.00	0.00	0.00	61.31	8.57
15/01/2011	2662.60	5380.00	0.00	0.00	0.00	51.04	51.04	51.04	975200	1552.56	0.00	0.00	0.00	0.00	0.00	42.02	9.02
16/01/2011	2662.60	5380.00															
17/01/2011																	0.00
	Total		316.60	0.00	0.00	646.34	646.34	962.94	12334700		6.00	0.00	0.00	0.00	0.00	862.31	100.63

'CLIMWAT 2.0' local station distribution of FAO (Smith, 1993, CLIMWAT, 2006)is used to import the climate data for ET_0 Calc. ET_0 for Palakkad is taken from the ET_0 database for different districts in Kerala (Joseph, 2011).

3.6 Hydrologic Models

The hydrologic models used in this research project are all open source based. Flow Health, used for environmental flow modelling is developed by the International Water Centre, Australia. RRL (Rainfall Runoff Library), RAP (River Analysis Package) and SCL (Stochastic Climate Library) (eWater toolkit components) are developed by the eWater Source, Australia.

3.6.1 Flow Health

Flow Health is based on those components of flow that are ecologically most relevant. Only hydrologic data is required to run this model. This is the main rationale for selecting this model. The main advantage of these hydrologic data is its acceptability by the stakeholders of Chalakudy Sub Basin. These data are jointly gauged by the riparian States of Chalakudy Sub Basin, Kerala and Tamil Nadu, and hence its validity is not contested.

Though a few studies on ecosystem of Chalakudy Sub Basin are available, there are two issues with respect to its adoption in E Flows Assessment (EFA). They are given as follows

i. These studies are mainly conducted by the scientists from lower riparian State, Kerala alone, and hence they do not have acceptability by all the stakeholders.
ii. Moreover, these studies highlight only the rich biodiversity of the basin and there are no standard peer reviewed articles relating the flows to ecosystem functionalities of the basin.

When PAP's water sharing pact is revisited, it is difficult to negotiate the environmental flows, if the EFA is conducted based on ecosystem data observed by one party alone. The water conflicts in this basin (and other proposed IBWT basins) are intense. It is difficult for the upper and lower riparian States to have consensus on any data that are not jointly gauged or observed. Therefore, Flow Health is an ideal choice for modelling E-flows in the basin and has direct linkage to the real-life management decisions that is underway with respect to the PAP revision (and any other IBWT proposals).

Flow Health is an E-flows modelling software which uses a suite of 9 hydrological indicators of flow that are ecologically relevant. These indicators are given below(Gippel et al., 2012).

1. High Flow Volume (HF): HF is the sum of the monthly flows in the natural high flow period
2. Low Flow Volume (LF): LF is the sum of the monthly flows in the natural low flow period
3. Highest Monthly Flow (HM): HM is the highest monthly flow in the year
4. Lowest Monthly Flow (LM): LM is the lowest monthly flow in the year
5. Persistently Higher Flow (PH): PH is a measure of how many sequential months in the natural low flow season in which higher flows than expected flows were observed
6. Persistently Lower Flow (PL): PL is a measure of how many sequential months in the natural low flow season in which lower flows than expected flows were observed
7. Persistently Very Low Flow (PVL): PVL is a measure of how many sequential months in the natural low flow season in which much lower flows than expected flows were observed
8. Seasonality Flow Shift (SFS): SFS if a measure of the degree to which the seasonality of the monthly flows has been altered
9. Flood Flow Interval (FFI): FFI is a measure of the time interval between the last significant floods in months.

These nine indicators are then combined to give an overall Flow Health (FH) score. Comparison of the distributions of the values of these indicators under reference period with that of the test period is the primary logic applied for deriving the flow health score. It uses a 0-1 scale; with score 0 for substantial deviation and score 1 for minimal deviations from the reference conditions. Reference period is the benchmark, and its flow data are unimpaired through regulation. FH components are assessed as dimensionless parameters which can be globally applied to any river system. They have no specificity attached with Australian scenario, where this model has been developed. Table 3.11 summarises the concept and ecological relevance of Flow Health indicators (Clausen and Biggs, 1997, Gippel et al., 2009, Richter et al., 1996, Richter and Thomas, 2007).

Table 3-11: Concept and Ecological Relevance of Flow Health Indicators

Indicator	Concept / Calculation Method	Ecological Relevance
HF	Assign the value of the percentile of high flow total in reference distribution $(Percentile\ in\ IndicatorReference\ Distribution)$, Apply Equations 3.1 to 3.4	Relates to Gross Habitat Area Availability
LF	Assign the value of the percentile of low flow total in reference distribution $(Percentile\ in\ Indicator\ Reference\ Distribution)$, Apply Equations 3.1 to 3.4	
HM	Assign the value of the percentile of highest monthly flow in reference distribution $(Percentile\ in\ Indicator\ Reference\ Distribution)$, Apply Equations 3.1 to 3.4	Relates to Magnitude of flood flows critical for inundating wetlands, cuing fish spawning behavior, facilitating fish migration and mobilizing sediment for creation of physical habitat
LM	Assign the value of the percentile of lowest monthly flow total in reference distribution $(Percentile\ in\ Indicator\ Reference\ Distribution)$, Apply Equations 3.1 to 3.4	Minimum flows required for survival
PH	Counts the number of consecutive months in the low flow period having a flow that lies outside the upper range of the flow for each month in the reference $(Annual\ maximum\ cumulative\ total)$, Apply equations 3.5 to 3.7	Primary production of benthic algae
PL	Counts the number of consecutive months having a flow that lies below the 25th percentile flow for each month in the reference period$(Annual\ minimum\ cumulative\ total)$, Apply equations 3.8 to 3.10	Colonization of the stream bed by invasive vegetation or accumulation of the fine sediments
PVL	Counts the number of consecutive months having a flow that lies outside the 1st percentile flow in the reference period $(Annual\ maximum\ cumulative\ total)$, Apply equations 3.11 to 3.13	Loss of riffle habitats, crowding of organisms in pools, temperature extremes, increased risk of hypoxia and high salinity
SFS	Based on the rank of median flow of each month in the reference period and the mean of the deviations in position for test year $(Percentile\ in\ reference\ distribution)$, Apply equations 3.14 to 3.15	A barrier to stimulate the behaviour of aquatic organisms
FFI	Based on a comparison of the interval between floods in the reference and test periods, default flood frequency of 48 months (N), Apply equations 3.16 to	Seed dispersal and propagation, plants overgrowth on channels

Indicator	Concept / Calculation Method	Ecological Relevance
	3.18	
Flow Health (FH)	**Averages the scores of above nine indicators with a modified LF which is the product of LF and PH**	**Overall ecosystem health**

Default thresholds and its scoring pattern for HF, LF, HM and LM are illustrated in Figure 3.11. The general equations for calculating their scores with default thresholds are also given as equations from 1 to 4 under the 3 cases.

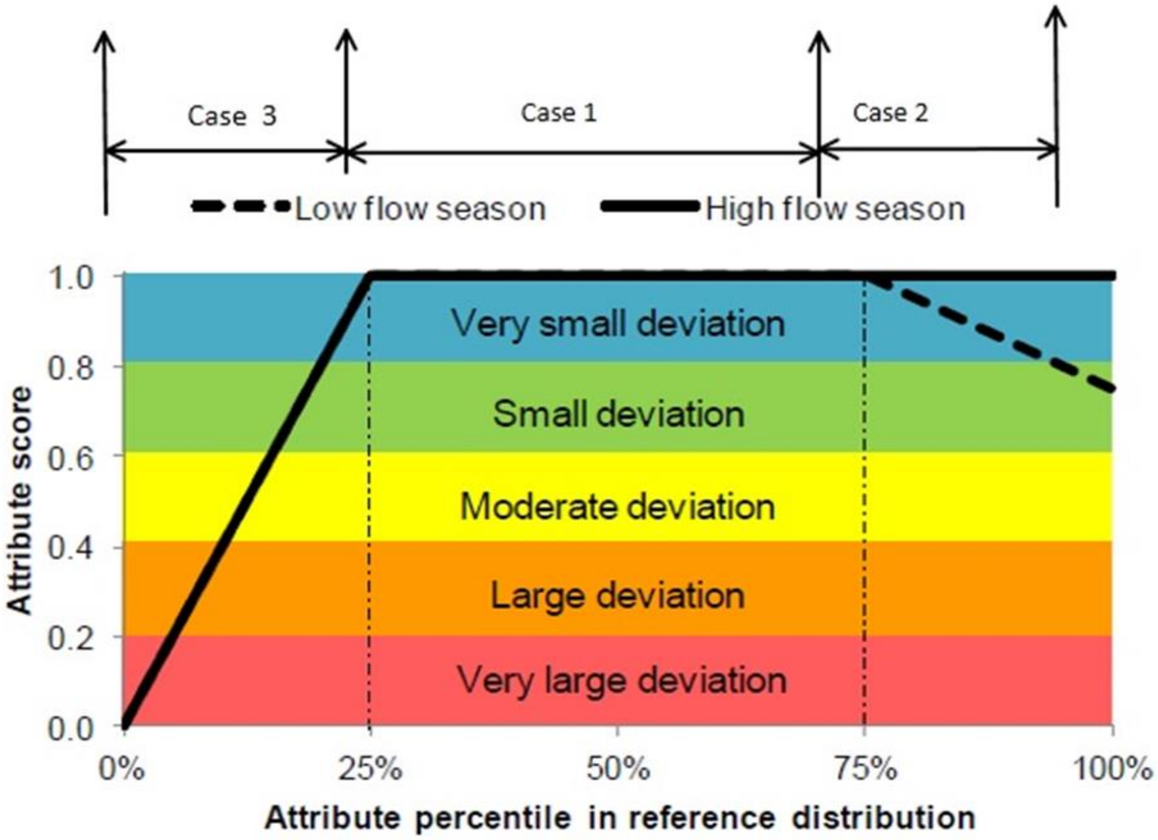


Figure 3-11: Scoring Pattern for Default Thresholds (Source: Flow Health Technical Manual and User Guide)

Case 1: $25 < Percentile\ in\ Indicator\ Reference\ Distribution < 75$

$$score = 1 \tag{3.1}$$

Case 2: $Percentile\ in\ Indicator\ Reference\ Distribution\ > 75$

$$high\ flow\ season\ score\ = 1 \tag{3.2}$$

$$low\ flow\ season\ score = 1.75 - \frac{percentile\ in\ Indicator\ Reference\ Distribution}{100} \tag{3.3}$$

Case 3: $Percentile\ in\ Indicator\ Reference\ Distribution < 25$

$$Score = 4 \times \frac{Percentile\ in\ Indicator\ Reference\ Distribution}{100} \tag{3.4}$$

The equations 5 to 18 are used for calculating PH, PL, PVL, SFS and FFI for default thresholds.

PH case 1: $Annual\ maximum\ cumulative\ total\ = 6$

$$Score\ = 0 \tag{3.5}$$

PH case 2: $Annual\ maximum\ cumulative\ total \leq 1$

$$Score = 1 \tag{3.6}$$

PH case 3: $6 > Annual\ maximum\ cumulative\ total > 1 Score\ = 1.2 - 0.2 \times Maximum\ cumulative\ total$ (3.7)

Annual maximum cumulative total counts the number of consecutive months in the low flow period having a flow that lies outside the upper range of the flow for each month in the reference

PL case 1: $Annual\ minimum\ cumulative\ total \leq -12$

$$Score = 0 \tag{3.8}$$

PL case 2: $Annual\ minimum\ cumulative\ total \geq -1$

$$Score = 1 \tag{3.9}$$

PL case 3: $-12 < Annual\ minimum\ cumulative\ total < -1$

$$Score = 1.0909 + 0.0909 \times Minimum\ Cumulative\ Total \tag{3.10}$$

Annual minimum cumulative total counts the number of consecutive months having a flow that lies below the 25th percentile flow for each month in the reference period

PVL case 1: $Annual\ maximum\ cumulative\ total \geq 6$

$$Score = 0 \tag{3.11}$$

PVL case 2: $Annual\ maximum\ cumulative\ total = 0$

$$Score = 1 \tag{3.12}$$

PVL case 3: $Annual\ maximum\ cumulative\ total > 0$

$$Score = 1 - \frac{Cumulative\ total}{6} \tag{3.13}$$

Here the Annual maximum cumulative total counts the number of consecutive months having a flow that lies outside the 1st percentile flow in the reference period

SFS case1: $Percentile\ in\ reference\ distribution < 75$

$$Score = 1 \quad (3.14)$$

SFS case 2: $Percentile\ in\ reference\ distribution > 75$

$$Score = 4 - 4 \times \frac{Percentile\ in\ parameter\ reference\ distribution}{100} \quad (3.15)$$

FFI case 1: $If\ N < 48$

$$Score = 1 \quad (3.16)$$

FFI case 2: $If\ N > 96$

$$Score = 0 \quad (3.17)$$

FFI case 3: $If\ 48 < N < 96$

$$Score = 2 - \frac{N}{48} \quad (3.18)$$

N is the flood frequency in months, and by default, it is 48 months

3.6.1.1 E-flow Modelling Using Flow Health:

Flow Health provides two methods of designing E-flow regime. These are the **Minimum Monthly Flow** method and the **Design Flow** method. The Minimum Monthly Flow method derives the E-flow regime based on achieving specific target scores for the nine indicators or overall FH score. The highest target is a flow regime that scores one on every index. This would represent a very low-risk E-flow regime. However, such schemes are difficult to follow. But the model can also be used to design E-flow regimes with lower FH scores which certainly carry higher environmental risk.

Design Flow method: In this method, E-flow regime based on achieving a certain percentage of the mean reference flow for each month is designed. This method also offers the facility of inputting the E-flow requirement value, estimated using a different approach, for example, Wetted Perimeter Method.

3.6.1.2 Wetted Perimeter Method:

This method is commonly used to make a preliminary estimate of the E-flows requirement(Davie, 2008, Padikkal and Rema, 2013, Gippel and Stewardson, 1998, Gene W. Parker and Armstrong, 2001). The basic theory behind this method is based on the direct relationship between the wetted perimeter of the stream and the habitat it supports. The wetted perimeter of a stream is defined as the width of stream bed and stream banks in contact with the water. This is used as a measure of the availability of aquatic habitat over a range of discharges. This method involves the following steps.

1. Survey the crosssection of the river and plot it to compute the wetted perimeter for different depths of flow.
2. Establish a stage-discharge relationship for this cross section by appropriate methods
3. Plot the relationship between discharge and wetted perimeter
4. Observe the discharge corresponding to the point of maximum curvature of the above plot as minimum E-flow requirement (See Figure 3.12)

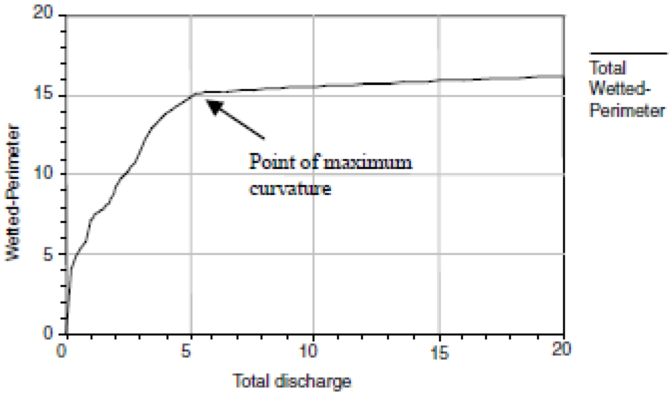


Figure 3-12: Wetted Perimeter Method (Source:(Gene W. Parker and Armstrong, 2001))

In this study, the wetted perimeter method is used only to demonstrate the quick estimation of E Flows and to compare it with the results of a detailed E Flows modelling exercise using Flow Health. This comparison would help the stakeholders of the river basin in appreciating the difference in E-Flows regimes designed by applying different methods.

3.6.1.3 Input Data Assimilation

The daily flows at Arangali site are simulated to its pristine values by using the following water balance method

$$\begin{aligned} &Pristine\ Flow\ at\ Arangali \\ &\qquad = Current\ flow\ at\ Arangali \\ &\qquad + Cumulative\ Inflow\ stopped\ at\ 6\ reservoirs \\ &\qquad + Flow\ diverted\ at\ Thumburmuzhi\ Weir \\ &\qquad - (transmission + \ percolation + evaporation) losses \end{aligned}$$

To run the model, pristine flows from 1979 to 2005 at Arangali are taken as reference period flows for calibration and current flows from 2006 to 2013 (as directly measured at the site) are considered as the test period flows.

3.6.2 Rainfall-Runoff Library (RRL)

The RRL uses daily time series rainfall and evapotranspiration data to generate daily catchment runoff. This library provides several commonly used lumped rainfall-runoff models, calibration optimisers and display tools to facilitate model calibration. RRL version 1.0.5 that is used in this study is freely downloadable. It has five rainfall-runoff models, eight calibration optimisers, a choice of 11 objective functions and three types of data transformation for comparison against observed data (Podger, 2004). There is a graphical user interface that comprises menus, dialogues and graph display tools. Table 3.12 lists the models, calibration methods, parameter optimisation tools and the objective functions available in the RRL.

Table 3-12: RRL Models and Calibration

Sl. No.	**Type**	**Description**
Models		
1	AWBM	catchment water balance model that can relate runoff to rainfall with daily or hourly data
2	Sacramento	uses soil moisture accounting to simulate the water balance within the catchment.
3	Simhyd	A simplified version of the daily conceptual rainfall-runoff model, HYDROLOG (1972)
4	SMAR	provides daily estimates of surface run-off, groundwater discharge, evapotranspiration and leakage from the soil profile for the catchment
5	TANK	Elementary model conceptualised as four tanks laid vertically in series
Calibration Methods		
1	Generic	Automatic calibration
2	Custom	Only for AWBM
3	Manual	Manually adjusting model parameters
Parameter Optimization Tools		
1	Uniform random sampling	parameter space for each parameter is divided up into a specified number of intervals between the minimum and maximum bound
2	Pattern search	quick but can suffer from finding local optimums rather than global optimums

Sl. No.	Type	Description
3	Multi-start pattern search	locating the global optimum without being biased by pre-specified starting points
4	Rosenbrock search	Like pattern search but better use of the local information and an adaptive step size
5	Rosenbrock multi-start search	works by dividing the parameter values into a specified number of increments and carrying out Rosenbrock search
6	Genetic algorithm	Based on the principle of "survival of the fittest" with genetic operators abstracted from nature
7	Shuffled Complex Evolution (SCE-UA)	based on a synthesis of many concepts including competitive evolution, complex shuffling and deterministic and stochastic approaches
8	AWBM custom optimizer	specifically coded for AWBM model
Objective Functions		
1	Nash-Sutcliffe criterion (Coefficient of efficiency) NSE	
2	Sum of square errors	
3	Root mean square error (RMSE)	
4	Root mean square difference about bias	
5	The absolute value of the bias	
6	Sum of square roots	
7	Sum of the square of the difference of square root	
8	Sum of absolute difference of the log	
9	Runoff difference in %	
10	Flow duration curve	
11	Base flow method 2	

Though NSE alone should not be a deciding factor on the appropriateness of hydrologic models (Jain and Sudheer, 2008), the objective functions currently implemented within the eWater Source calibration tool are mainly focused on NSE and hence its values are of particular interest for any modeler using this platform. Moreover, it gives a better picture of the performance of the models compared to other objective functions. Hence, the current study utilizes NSE as the objective function. Out of the five models available in RRL, Sacramento is used in this study because the best performance was obtained for this model in terms of NSE compared to that from other available models in RRL. (These results of NSE are presented in the forthcoming section on Results and Discussion). The guidelines for best practice model application (Vaze et al., 2011) also justify the selection of Sacramento. Studies comparing different rainfall-runoff models have also reported that Sacramento outperformed other models (Zhang et al., 2013, Post et al., 2005). It is a continuous rainfall-runoff model used to generate daily streamflow from rainfall and evaporation records.

The Sacramento Model uses soil moisture accounting to simulate the water balance within the catchment. Sixteen parameters are used to simulate the water balance. Out of these, five parameters define the size of soil moisture stores, three calculate the rate of lateral outflows, three calculate the percolation water from the upper to the lower soil moisture stores, two calculate direct runoff, and three calculate losses in the system. These parameters are listed and described in Table 3.13. Their default values and the lower and upper bounds within which they can be optimized are also presented in this table.

Table 3-13: Sacramento Model Parameters and Default Values (Podger, 2004)

Parameter	**Description**	**Default Value**	**Lower Bound**	**Upper Bound**
UZTWM	Upper Zone Tension Water Maximum. The maximum volume of water held by the upper zone between field capacity and the wilting point which can be lost by direct evaporation and evapotranspiration from the soil surface. This storage is filled with before any water in the upper zone is transferred to other storages.	50	0	100
UZFWM	Upper Zone Free Water Maximum, this storage is the source of water for interflow and the driving force for transferring water to deeper depths.	40	0	80
LZTWM	Lower Zone Tension Water Maximum, the maximum capacity of lower zone tension water. Water from this store can only be removed through evapotranspiration	130	0	400
LZFSM	Lower Zone Free Water Supplemental Maximum, the maximum volume from which supplemental baseflow can be drawn.	23	0	50
LZFPM	Lower Zone Free Water Primary Maximum, the maximum capacity from which primary base flow can be drawn.	40	0	50
UZK	The ratio of water in UZFWM, which drains as interflow each day.	0.245	0	1
LZSK	The ratio of water in LZFSM which drains as baseflow each day.	0.043	0	1
LZPK	The ratio of water in LZFPM, which drains as baseflow each day	0.009	0	1
PFREE	The minimum proportion of percolation from the upper zone to the lower zone directly available for recharging the lower zone free	0.063	0	1

Parameter	Description	Default Value	Lower Bound	Upper Bound
	water stores.			
REXP	An exponent determining the rate of change of the percolation rate with changing lower zone water storage	1	0	3
ZPERC	The factor applied to PBASE to define maximum percolation rate.	40	0	80
SIDE	The decimal fraction of observed base flow, which leaves the basin, as groundwater flow.	0	0	1
SSOUT	The volume of the flow which can be conveyed by porous material in the bed of stream.	0.001	0	1
PCTIM	The impervious fraction of the basin, and contributes to direct runoff	0.01	0	1
ADIMP	The additional fraction of porous area, which develops impervious characteristics under soil saturation, conditions	0.01	0	1
SARVA	A decimal fraction representing that portion of the basin generally covered by streams, lakes and vegetation that can deplete stream flow by evapotranspiration.	0.01	0	1

3.6.3 RAP

RAP is a collection of utilities to assist river managers who undertake condition assessments, environmental flow planning and river restoration design. Time Series Analysis (TSA) is one module of RAP that is used for viewing time series data and generating its summary statistics (Marsh N, 2003). In this study, TSA is used for analysing the time series of RRL output. TSA can be used to compare different time series data in a meaningful manner. For example; the seasonal variations in the mean monthly flow of different daily time series data of 25 to 30 years can be easily depicted using TSA. TSA capabilities include the following techniques.

1. Generation of Flow Duration Curve
2. High/Low Flow Spells Analysis
3. Rates of Rise and Fall
4. Base Flow Separation
5. Flood Frequency analysis
6. Monte Carlo Simulation

Monte Carlo simulation of the existing climatic data is a requirement in this study to depict various possible climatic conditions within a year. Monte Carlo simulation of the period of 365 days for which water sharing must be done is accomplished in this study using TSA.

3.6.4 SCL

This is a library of stochastic models for generating climate data from the available historical data. Each stochastic replicate (sequence) is different and has different characteristics compared to the historical data, but the average of each characteristic from the collection of all the stochastic replicates (population or universal set) is the same as the historical data. Using historical climate data as inputs into rainfall-runoff models provides results that are based on only one realisation of the past climate. Stochastic climate data provide alternative realisations that are equally likely to occur, and can, therefore be used as inputs into models to quantify the uncertainty associated with climate variability (Sri Srikanthan et al., 2007).

SCL is used in this study to generate stochastic rainfall in the catchment at daily timescales. Transition Probability Matrix (TPM) method is used by SCL to generate daily rainfall. In the TPM model, the seasonality in occurrence and magnitude of daily rainfall are considered by taking each month separately. This is done by dividing the daily rainfalls into several states, up to a maximum of seven. State 1 is dry (no rainfall) and the other states are wet. The rainfall amounts for the last state are modelled using the shifted Gamma distribution. For all other intermediate states, a linear distribution is used. The latter is chosen because daily rainfall usually exhibits a J shape distribution.

3.7 Conclusion

In this chapter, the details of the case study project PAP and the database are discussed. The theoretical background of all the hydrologic models used is also explained. The results of this study and its discussion are presented in the next two chapters.

Chapter 4

4. RESULTS AND DISCUSSIONS – PART 1

4.1 Introduction

As indicated in the earlier sections, the institutional arrangements for water-sharing in transboundary, interstate or IBWT basins must be designed by considering the availability of the resource and its sustainable utilisation. But the assessment of available resource becomes a difficult task, especially in the backdrop of climate change, limited data, and its associated uncertainties. Decision-making tools for sustainable water-sharing, planning and management shall be capable of handling these uncertainties and be able to incorporate the yearly variability in runoff into the water-sharing pact. As indicated earlier, limited efforts in this regard have been reported concerning the existing compacts in India.

Existing pacts, though in different forms -like interstate water-sharing agreements, Inter-Basin Water Transfer (IBWT) agreements and Inter-State Water Disputes Tribunal (ISWDT) awards- are based on limited available historicalal data and in general, deterministic and static. Though water-sharing models that incorporate the variation in ecological and hydrological factors are increasingly used in other parts of the world, their utilisation for the water-sharing in Indian River basins becomes almost impossible, owing to the lack of enough hydrological and ecological data. Hence, for the Indian scenario, a sustainable water-sharing compact model which can work with a limited amount of hydrological data shall be developed to reduce the water conflicts among the stakeholders. In this context, the current research is taken up.

PAP, the case study project used here has many unique features which were already discussed in chapter 3, i.e., Materials and Methods. Before presenting the results of the evaluation of existing water-sharing pattern in PAP, PAP pact is compared with the other water-sharing agreements to investigate its sustainability. The evolution of an Ecohydrological framework for sustainable water-sharing is then discussed. The E Flow modelling of PAP basin and the development of a decision-making tool for sustainable water-sharing are subsequently taken up before suggesting a sustainable water-sharing model. In this chapter, out of the six objectives of the study, the results of the first three objectives are discussed, and the remaining are presented in the next chapter.

The analysis of three water-sharing pacts; Colorado, Murray Darling and PAP from its sustainability perspective is discussed in section 4.2. It also presents a critical review of the proposed policy guidelines for sustainable water-sharing in India. The Ecohydrological framework and its evolution are discussed in Section 4.3. The evaluations of the water-sharing pattern of the Parambikulam sub-catchment, its status along with its dependability analysis are discussed in section 4.4.

4.2 Analysis of Water-sharing Pacts

Before presenting the results of a study of the water-sharing pacts, this section critically analyses the examination of the policy guidelines on water-sharing prevalent in India. The draft policy guidelines on water-sharing, which contained six chapters, was circulated for public consultation of the implementing agencies like the Government of Kerala State. A critical review of these policy guidelines was presented in the International Symposium ‘IWRM-2014’ held at Kozhikode during 19-21 Feb 2014 (Padikkal et al., 2014) and its important findings are discussed in the subsequent subsections.

4.2.1 Review of Proposed Policy Guidelines on Water-sharing

The extent of this draft policy is restricted to interstate basins only, and in general, it is specified that trans-boundary basins do not come under the scope of it. Now, it is essential to clarify whether the policy is applicable only for surface water or both surface water and groundwater. Extraction of groundwater also leads to conflicts among the states, but the occurrence of groundwater in the aquifers may not reflect the surface flows in interstate basin concerned. Therefore, the scope of this policy concerning surface water/groundwater may be explicitly specified to avoid future conflicts.

The broad objective of the policy guidelines is silent about the ecosystem services offered by the interstate basin. Available water can be shared only after setting apart the required environmental flows for the up keeping of ecosystem services. This allocation of e-flow is more important for the lower riparian states of any interstate basin. Therefore, the broad objective may be redrafted as “Developing the waters of interstate rivers for the betterment of the population of the co-basin states/ Union Territories such that the developments are not detrimental to the interests of one another and the ecosystem services of the basin in totality and are guided by the national perspective”.

Return Flow: An outflow from a powerhouse is included in the definition of return flow. This inclusion is true only when there is 100 percent dependability for these outflows to use it for irrigation or any other demands like drinking. Most often, for the southern states like Tamil Nadu where power shortage is acute, this 100 percent dependability is not guaranteed for the lower riparian uses and hence practically speaking it becomes a consumptive use. Therefore, the definition of return flow must explicitly state this.

In the case of pumped storage power generation schemes, the recycled quantum of water shall be treated as consumptive use in every year, and that shall not be available for sharing. Conflicts due to this condition is already prevailing between Kerala and Tamil Nadu in Aliyar sub-basin of PAP. Therefore, the policy guidelines on return flow should take care of the above two conditions to avoid conflicts.

Equitable Apportionment: The principle of equity applied to an interstate basin for sustainable water-sharing should have the components that fit within the sustainability framework. Incorporation of these components in the policy guidelines can only facilitate sustainable water-sharing. For any interstate basin shared by the co-basin states, the sharing of waters in a sustainable manner can be ensured only if the resource limit is identified and the needs are defined collectively. At least in the case of a pristine basin, the policy guidelines should suggest all these steps vividly.

Sharing/Distribution Amongst States vis-à-vis sharing/distribution amongst uses: The policy guidelines suggest here that the actual sharing/distribution need not be qualified for a particular use. But this will lead to conflicts at a later stage. If there is no consensus among the co-basin states regarding the priorities to be applied beforehand, it will undoubtedly lead to conflicts at a later stage. The sharing of waters under PAP agreement between Kerala and Tamil Nadu faces this problem in acute drought years. Withholding of water by Tamil Nadu in the upstream reservoirs for power generation when the lower riparian stakeholders face severe drinking water shortage is a common problem here, and this is due to non-prioritization of the uses collectively. Therefore, the sharing/distribution need to be qualified for particular application in the background of this prioritisation. Tamil Nadu side was not ready to follow the priorities in National Water Policy, and Kerala side had to bear with it. To avoid this in future, the prioritization of the uses should be carried out.

Existing Interstate Agreements: The integration of the existing water-sharing pacts into the domain of these policy guidelines must have a vision statement focused on the prevention of the water conflicts, getting triggered. This guideline shall be corrected as follows:

Where an existing interstate agreement has the approval of all the co-basin States, this agreement shall be accommodated in the evolving water sharing scheme unless it is conflicting with the current interest of any of the States or the interest of the nation.

The requirement of water in each of the co-basin States: The provision of water to meet the environmental flows is not mentioned in the policy guidelines. This is an important aspect to be considered and must be incorporated within the policy domain.

Review of Sharing/distribution guidelines: In the policy guidelines it is suggested to consider the requirement for the next forty years. From the experience of water-sharing under PAP agreement between Kerala and Tamil Nadu, it is learned that more than ten years is required in any case to complete the review process. Hence, the review period may be fixed as 30 years.

Monitoring: If the observation of groundwater levels is a part of follow-up, the policy guidelines should suggest how the groundwater-sharing can be conceptualised. Otherwise, the policy guidelines should have some compulsion on conjunctive water management by the co-basin states, and it shall be added to the benefit of that state. The raising/lowering of the groundwater table throughout sharing should be reflected in the review process.

These are some of the critical areas that are found to be missing or not taken care by the proposed policy guidelines on water-sharing. Now, the results of critical analysis of three water-sharing compacts from their sustainability perspective are presented.

4.2.2 Review of existing water-sharing pacts

The water-sharing pacts on Colorado, Murray Darling and PAP are analysed in this section to assess their sustainability levels. Ideally speaking, a water-sharing pact must be reliable, resilient and must not be vulnerable to the extreme climatic events, to reckon it as sustainable. The reliability of a treaty depends very much on the resource availability and hence this must be assessed scientifically. Resilience and vulnerability, on the other hand, depends a lot on the stochasticity, being contemplated too. The water-sharing under a pact shall facilitate the following principles (Padikkal et al., 2018):

1. Sharing without any conflict on environment and ecosystems
2. Sharing without any dispute on the resource availability constraints
3. Sharing without any disagreement on the needs of the states

Based on this hypothesis, five parameters are identified to qualitatively examine how the sustainability being portrayed in these pacts. These are :

1. The dependable flow must be assessed scientifically
2. Need assessment of parties must be done for the agreement period and if necessary, must be redefined, subject to the first postulate.
3. E Flow requirements must be assessed separately, and it should be reckoned as a collective need of all parties
4. Stochastic sharing models must supersede the deterministic sharing models
5. Dynamism with finite agreement periods must overrule the perpetual ones

How these parameters are linked with the performance criteria in a numerical computation of sustainability are presented in Table 4.1. However, the performance criteria to be used in the assessment of sustainability are subjective. There can be many cases where specific criteria can be used in this assessment. However, some of the most commonly used performance criteria in any water-sharing pact are Reliability (Rel), Resilience (Res), Vulnerability (Vul), Maximum deficit (Max def), and Standard deviation (Std Dev)(Sandoval-Solis et al., 2010)

Reliability is the probability that the 'available water supply' under a pact meets the 'water demand'. In this definition, the term 'available water supply' is directly related to the parameter dependable flows and the term 'water demand' is directly related to the parameter needs assessment. Table 4.1 shows these direct linkages. As the water available for consumptive needs are also significantly affected by the E Flow needs, this parameter is also directly linked with reliability. Reliability is also reflected in the stochastic parameter because it accounts for the reduced water supply in the case of an extreme climatic event like drought.

The parameter 'dependable flow' is directly linked with all the performance criteria. The reliability of a water-sharing pact, whether it is deterministic or stochastic, largely depends on the precise estimation of dependable flows. This fact can be illustrated with an example of water-sharing in Parambikulam sub-catchment of PAP, as indicated in the later part of the thesis. At the time of framing PAP's water-sharing pact, the dependable flows from this sub-catchment was not assessed realistically and it has affected the reliability of this pact. Details of this are discussed in the section 4.4.

In the following subsections, the three water-sharing agreements on Colorado, Murray Darling and PAP are analyzed with respect to the above postulates. In this analysis, the values for the different dimensions (for the three case studies) are assigned based on objective data that is implicit in the respective water-sharing agreements. Each multidimensional indicator is examined for its different dimensions within the agreement to assign the value. For example, in the case of E Flows, scientific assessment of E Flows is its first dimension. The value of this dimension depends on whether this scientific assessment is being done or not.

Table 4-1: Sustainability Parameters of a Water Sharing Pact and their Linkages with Common Performance Criteria

	Rel	Res	1-Vul	1-Max def	Std dev
Dependable Flow	✓	✓	✓	✓	✓
Needs Assessment	✓		✓		
E Flow	✓	✓	✓	✓	✓
Stochastic	✓	✓	✓	✓	✓
Dynamism		✓			

E Flow: Environmental Flows. Rel: Reliability. Res: Resilience. Vul: Vulnerability. Max def: Maximum deficit. Std dev: Standard deviation

It is true that the dimensions chosen are relevant but not necessarily exhaustive. Mainly these dimensions are chosen from the vast experience of the author in managing PAP basin. It was finally evolved in a series of informal stakeholder consultation processes being held in PAP. The most relevant dimensions suggested by the stakeholders are taken here. Many different dimensions may come up if the same exercise is being carried out in other basins. But these are the most relevant dimensions for any basin and hence they are chosen. In any case, the qualitative approach (being used here) is very essential when designing a water-sharing compact. The numerical approach can be useful especially in a post project evaluation.

4.2.2.1 Dependable Flows

Most of the performance criteria have direct linkages with the dependable flow. Three indicators of this parameter considered in the analysis are:

1. Direct reference in the agreement about the dependable flows
2. A scientific assessment of dependable flows
3. Suggestions on its reassessment over a period

This comparison of the level of dependable flow parameter is shown in the Table 4.2.

Table 4-2: Comparison of the level of Dependable Flows Indicators across the Water Sharing Pacts

Parameter indicator	Colorado	Murray Darling	PAP
Direct Reference	No	No	No
Scientific Assessment	No	Yes	No
Suggested Reassessment	Yes, After 40 years	Yes, from Time to Time	Yes, after 30 years

A time to time assessment of dependable flows is ensured only in the Murray Darling Basin agreement. In the case of Colorado, the data used for the assessment of dependableflows was of the period 1905 – 1922. Now, there is a significant variation in the dependable flows of Colorado (Woodhouse et al., 2006). But this variation is not incorporated into the agreement. The case of PAP is also not different. Though realistic dependable flows based on short duration historical data have been established through joint gauging by the parties of the agreement, it is not incorporated into the agreement.

4.2.2.2 Needs Assessment

A sustainable water-sharing model must have clearly defined the needs of the participating states. These needs must then be revised subject to the dependable flows. It should also have a finite cap on the development proposals with respect to the needs of the participating states. These three criteria of need assessment are compared in Table 4.3.

Table 4-3: Comparison of Needs Assessment Indicators across the Three Water Sharing Pacts

Parameter indicator	Colorado	Murray Darling	PAP
Defining Needs	No	Partly Yes	Partly Yes
Revision Subject to Dependable Flow	No	Yes	No
Finite Cap	No	No	No

Clearly defining the needs of the involved states have been partly fulfilled in the case of Murray Darling and PAP whereas no such definition of needs is provided in the Colorado agreement. Revising the needs subject to dependable flows and assigning a finite cap on development are not complied in any of the agreements.

4.2.2.3E Flows

A sustainable water-sharing pact must have all the three elements of E Flow management. They are assessment, allocation and implementation of E Flows. Murray Darling agreement has made substantial progress with respect to assessment of E Flows as evident from Table 4.4

Table 4-4: Comparison of E Flows Indicators across Three Water Sharing Pacts

Parameter	Colorado	Murray Darling	PAP
Assessment	Partly Yes	Yes	No
Allocation	No	Yes	No
Implementation	No	Yes	No

Practically, no effort has been put in the case of Colorado and PAP agreements for the incorporation of E Flows in a holistic manner into the agreements. Nevertheless, there are fragmented efforts in Colorado basin for successful incorporation of environmental flows. The South Platte River compact between Colorado and Nebraska has specified the minimum flows to be maintained for native fish species (Blomquist et al., 2004). The guidelines for addressing water shortage in Colorado basin includes a Lower Colorado Region Multi Species Conservation Plan (LCR MSCP) and is another example.

4.2.2.4 Stochastism

The essence of a stochastic water-sharing agreement is its property of sharing the surplus and distress. An agreement becomes more sustainable when it is stochastic. But, one of the essential prerequisites for a stochastic water-sharing agreement to be operational is the carryover storage facility. Three parameters that can be directly related to the stochastic nature of water-sharing agreements are:

1. Distress – surplus sharing formula
2. Stochastic threshold
3. Explicit operation plan.

Colorado and Murray Darling agreements have partially fulfilled this condition. In 2007, Colorado agreement has incorporated the guidelines for coordinated operation of storage reservoirs under low reservoir and resource shortage conditions. Stochastic nature of water-sharing agreement is a powerful tool that controls the triggering of water conflicts. This has been proved in Colorado basin (USBR, 2018). Even in the extreme drought situation in the post 2000 period, stochastic nature of the guidelines significantly helped in the sustainable water management of this basin. Stochastic nature of the agreement is also particularly important when one consider the climate change and the associated uncertainties in water resources management. But PAP is continuing strictly deterministic sharing pattern based on unrealistic dependable flow computation from the data for a small period. Table 4.5 summarizes the comparison of stochastic parameters across the three water sharing pacts.

Table 4-5: Comparison of Stochastic Indicators across Three Water Sharing Pacts

Parameter	Colorado	Murray Darling	PAP
Distress – Surplus Sharing Formula	Yes	Yes	No
Stochastic Threshold	Yes	Yes	No
Explicit Operation Plan	Yes	Yes	No

4.2.2.5 Dynamism

Dynamic water-sharing agreements are sustainable compared to the static ones made in perpetuity. But most of the agreements by some unknown reasons are made in perpetuity. Colorado and PAP are perpetual in nature which is a major stumbling block in their pathways to sustainability. In perpetuity status, Review Provisions and Actual Review are the three parameters being used to compare the dynamism of agreements. Murray Darling is the most dynamic agreement with respect to these parameters. The main reason for this prime status is that the agreement is not perpetual. Review provisions in this agreement are adequate and the actual review has already been taken place. This comparison is presented in Table 4.6.

Table 4-6: Comparison of Dynamism Indicators across the Three Water Sharing Pacts

Parameter	Colorado	Murray Darling	PAP
In perpetuity	Yes	No	Yes
Review Provisions	Yes, 40 years	Yes, Time to Time	Yes, 30 Years
Actual Review	No	Yes	No

4.2.3 Summary of analysis of Existing Water-sharing Pacts

In this analysis, three water-sharing agreements are compared from its sustainability perspective by selecting certain basic parameters and their indicators. How these parameters can be related to the performance criteria used in quantitative analysis of sustainability, has also been explored. The subjective assessment of sustainability considered only the basic parameters that are commonly being surfaced in the negotiations of a water-sharing agreement. Many other parameters of specificity could be added to this. The multi dimensional indicators suggested here as evolved from the hypothetical postulates, is applicable globally and hence, the results can be extended to other regions.

This analytical review however, helped the investigators in comparing Colorado, Murray Darling and PAP agreements from sustainability angle. The Murray Darling agreement appears to be better in its overall considerations of sustainability. Compared to Colorado and Murray Darling, PAP's water-sharing needs major revisions for improving the sustainability of the pact. E Flows and stochastic modelling of water-sharing are the most important thrust areas for consideration for improving the sustainability of PAP.

4.3 Ecohydrological Framework (Eco-Frame)

Ecohydrology is the new paradigm for sustainability(Zalewski, 2014). Analysis of water-sharing compacts in the previous section has identified the multi-dimensional indicators useful in comprehending the sustainability of these compacts. How these indicators can be fitted within the processes of water-sharing, to develop an Eco- Frame, is the second objective of this study. This analysis is carried out with the basic assumption that the proposed Eco-Frame agrees to continue with development as far as the level of resources permit.

4.3.1 Evolution of Eco-Frame

In order to work out the components of Eco-Frame, it is assumed that an interstate river B is shared by two states A and C.

Task 1

The first task is quantification of available resources. This is a two-step process to identify the resource limit.

Step 1: Quantification of total available flows in B (say X)

Step 2: Quantification of permissible abstraction out of X.

Quantification of X shall be done by gauging the flows in B for a considerable number of years. If this is not available or the data available is only for a shorter duration, appropriate methods to ascertain the total available flows need to be developed. Based on this data, the dependable flows must be worked out. Step 2 is the appropriation of flows for the conservation of river ecosystems and development purposes. Appropriating the flows for conservation of river ecosystems (E Flows) is very important from inter and intra generational equity perspective. The net dependable flows available for sharing and development would be the difference of dependable flows and E Flows.

Task 2

The second task is to define the needs of states A and C. Both the states shall collectively define the requirements. The needs may have to be redefined if it is more than the resource limit identified in step 2.

Task 3

The final task is to allocate the flows to A and C according to their mutually agreed needs defined under Task 2. The Eco-Frame for sustainable water-sharing must be clearly characterized by these three tasks. These are schematically represented in Figure 4.1. Stakeholder participation in each task is imperative to ensure sustainability.

4.4 Evaluation of Water-sharing Pattern of Parambikulam Sub-catchment

Water-sharing pattern of Parambikulam sub-catchment in the existing PAP agreement is deterministic. It provides a total quantity of 396.4 Mm^3 to Tamil Nadu. If the total yield from this sub-catchment in any year exceeds this threshold value of 396.4 Mm^3, balance quantity in that year will be given to Kerala. From this, up to 70.8 Mm^3will be transferred to Bharathapuzha basin for irrigating Kerala lands in Chitturpuzha valley and the rest will be released to Chalakudy basin. Results of the analysis of historicalal data are presented in Table 4.7. Parambikulam sub-catchment has three reservoirs namely Parambikulam, Thunacadavu and Peruvaripallam. In this sub-catchment, total yield in a year is computed from the daily reservoir statistics which include daily storage in reservoirs, all outflows and the artificial inflow from the neighbouring catchment through IBWT.

Analysis of the historical data clearly shows that, the lower riparian (Kerala) got its share only during very few years, as shown in figure 4.2. Tamil Nadu’s share was also substantially below the threshold of 396.4 Mm^3 during majority of the years. This analysis shows that the total dependable flows from the sub-catchment were originally over estimated. Importance of the first component of the Eco-Frame discussed in the previous section is evident from this analysis. Water-sharing became unsustainable as resource limit identification component was missing in this pact. The impact of this water-sharing pattern based on the historical data alone is now analysed hypothetically as four cases below.

4.4.1 Case 1: Sharing based on historical average

In this case, the historical average of runoff (instead of 394.6Mm^3) is used for sharing the resource between Kerala and Tamil Nadu in the originally fixed ratio of 14: 2.5. Figure 4.3 shows the sharing and the benefits each state would have been enjoyed if such a pattern was adopted. In this case, Kerala’s benefits appear to have large variation over the years. Irrigation scheduling would be difficult in such a case. Tamil Nadu’s benefits are also varying, but not as severely as Kerala’s.

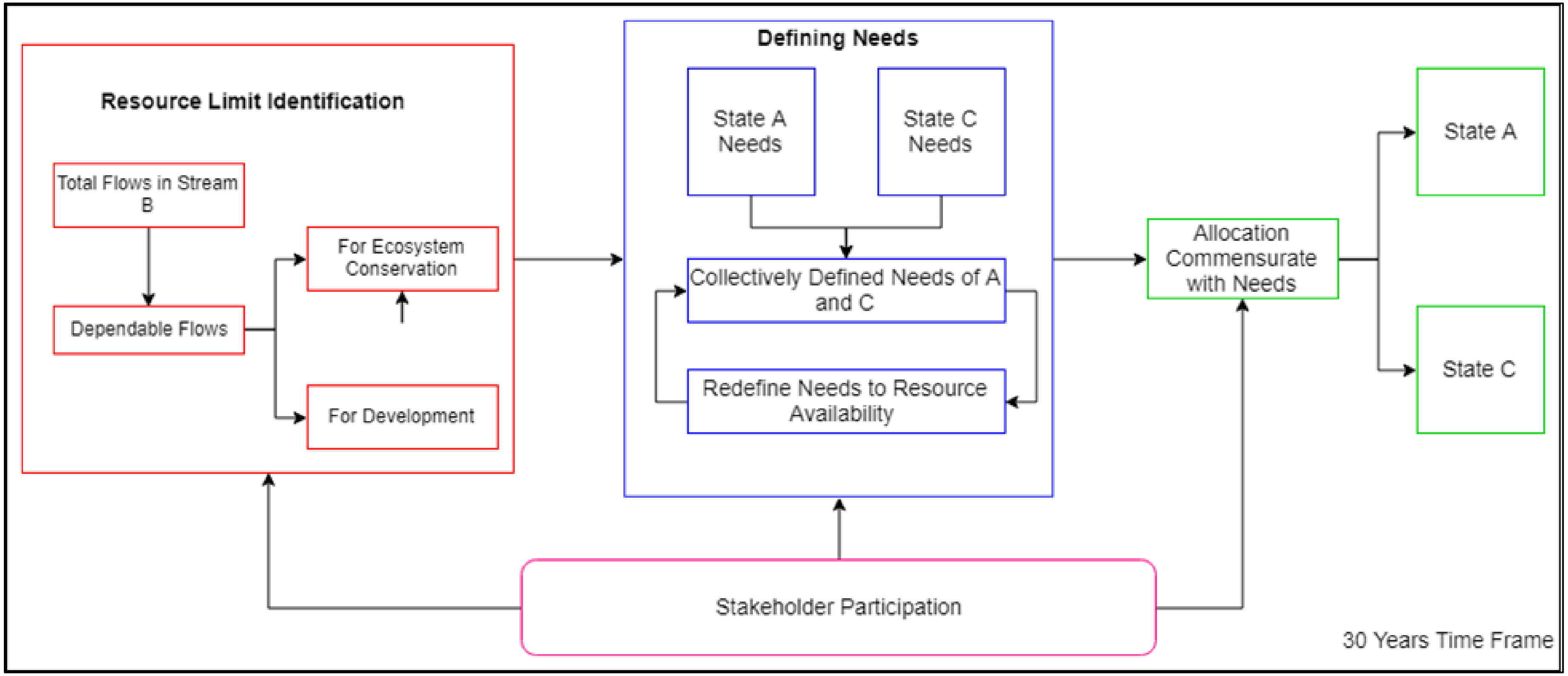


Figure 4-1: Ecohydrological Framework for Sustainable Water Sharing

Table 4-7: Analysis of Historical Data of Parambikulam Sub Catchment Yield

Water year	**Total Yield Mm^3**	**Tamil Nadu Mm^3**	**Kerala Mm^3**
1970-71	330.1	330.1	0
1971-72	356.69	356.69	0
1972-73	233.56	233.56	0
1973-74	242.37	242.37	0
1974-75	261.57	261.57	0
1975-76	327.69	327.69	0
1976-77	203.55	203.55	0
1977-78	281.53	281.53	0
1978-79	284.65	284.65	0
1979-80	456.19	396.44	59.75
1980-81	483.77	396.44	87.33
1981-82	392.25	392.25	0
1982-83	150.59	150.59	0
1983-84	263.61	263.61	0
1984-85	296.14	296.14	0
1985-86	231.81	231.81	0
1986-87	130.12	130.12	0
1987-88	195.98	195.98	0
1988-89	314.8	314.8	0
1989-90	153.79	153.79	0
1990-91	134.11	134.11	0
1991-92	297.9	297.9	0
1992-93	357.45	357.45	0
1993-94	305.29	305.29	0
1994-95	416.92	396.44	20.48
1995-96	291.33	291.33	0
1996-97	232.32	232.32	0
1997-98	358.41	358.41	0
1998-99	365.63	365.63	0
1999-00	310.16	310.16	0
2000-01	295.63	295.63	0
2001-02	227.92	227.92	0
2002-03	159.91	159.91	0
2003-04	186.96	186.96	0
2004-05	165.95	165.95	0
2005-06	361.86	361.86	0
2006-07	236.03	236.03	0
2007-08	451.27	396.44	54.83
2008-09	203.95	203.95	0
2009-10	289.31	289.31	0

Water year	**Total Yield Mm^3**	**Tamil Nadu Mm^3**	**Kerala Mm^3**
2010-11	320.99	320.99	0
2011-12	277.17	277.17	0
2012-13	135.02	135.02	0
2013-14	247.38	247.38	0
2014-15	268.14	268.14	0
Originally anticipated yield in Mm3			467.24
Historical Average in Mm3			277.51
90 % Dependable in Mm3			153.76
75% Dependable in Mm3			227.95
50 % Dependable in Mm3			281.47

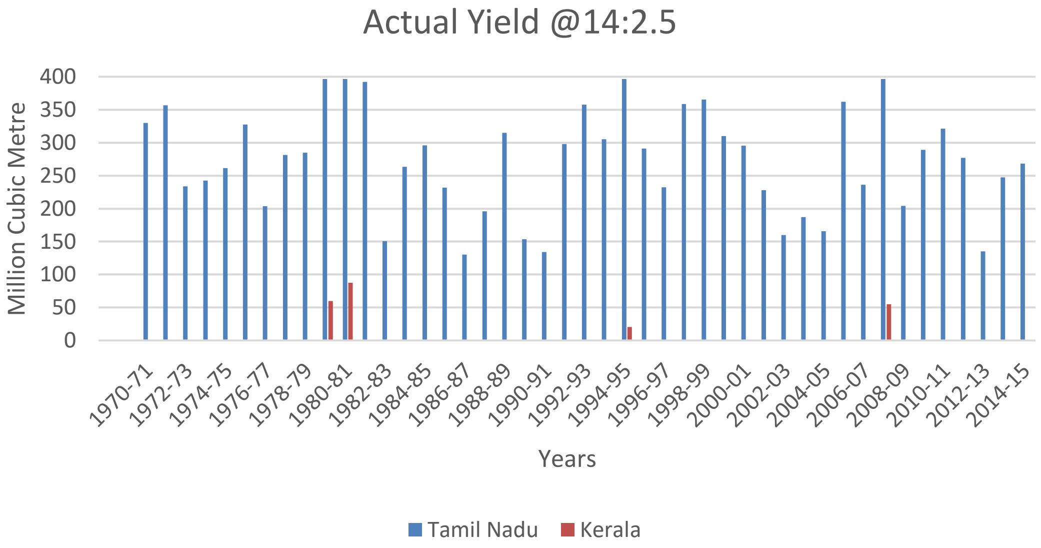


Figure 4-2: Sharing Pattern when the Historical Yield of Parambikulam Sub Catchment Shared in the Ratio14:2.5

4.4.2 Case 2: Sharing based on 90 % dependable flows

In this case, Initially the 90 % dependable flow of the historical data is estimated and used as the threshold value. Applying a sharing ratio of 14:2.5, the benefits of each state are investigated. Figure 4.4 shows the pattern of sharing. In this case, Tamil Nadu is getting a fixed volume of water throughout the historical data period, but Kerala's share is significantly varying, making the irrigation planning more complicated. Also, during many years, Kerala's share exceeds Tamil Nadu's share, which is basically contrary to the original ratio of sharing. It shows that sharing based on 90 % dependable flows would lead to a less equitable setup as far as the needs of each state is concerned.

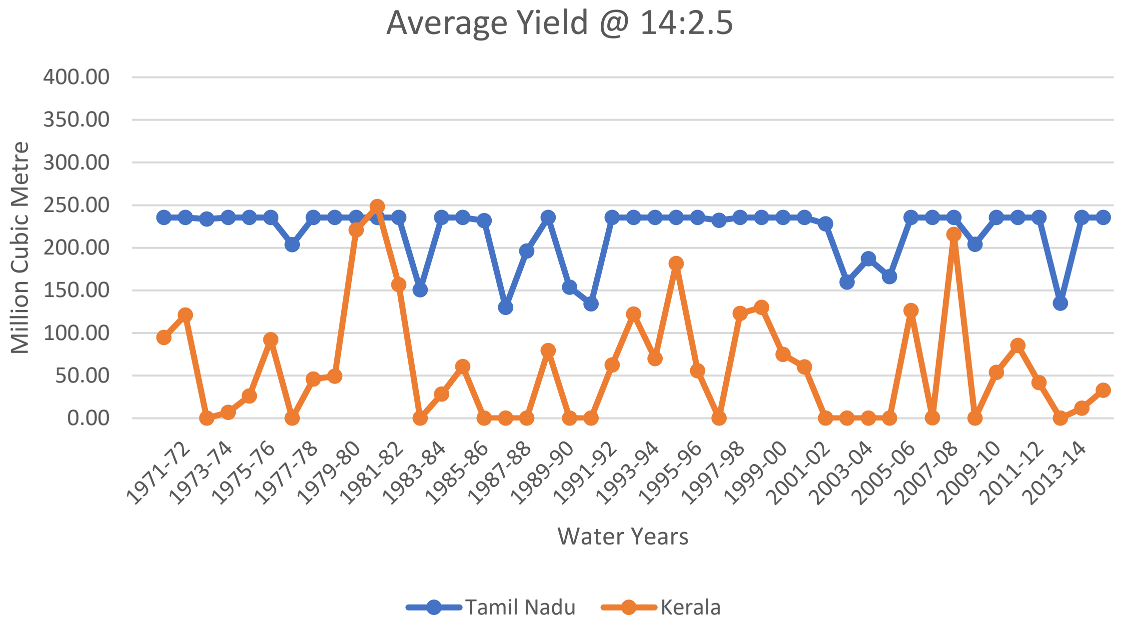


Figure 4-3: Sharing Pattern when the Average Historical Yield is Used as Threshold for Sharing the Runoff of Parambikulam Sub Catchment in the Ratio 14:2.5

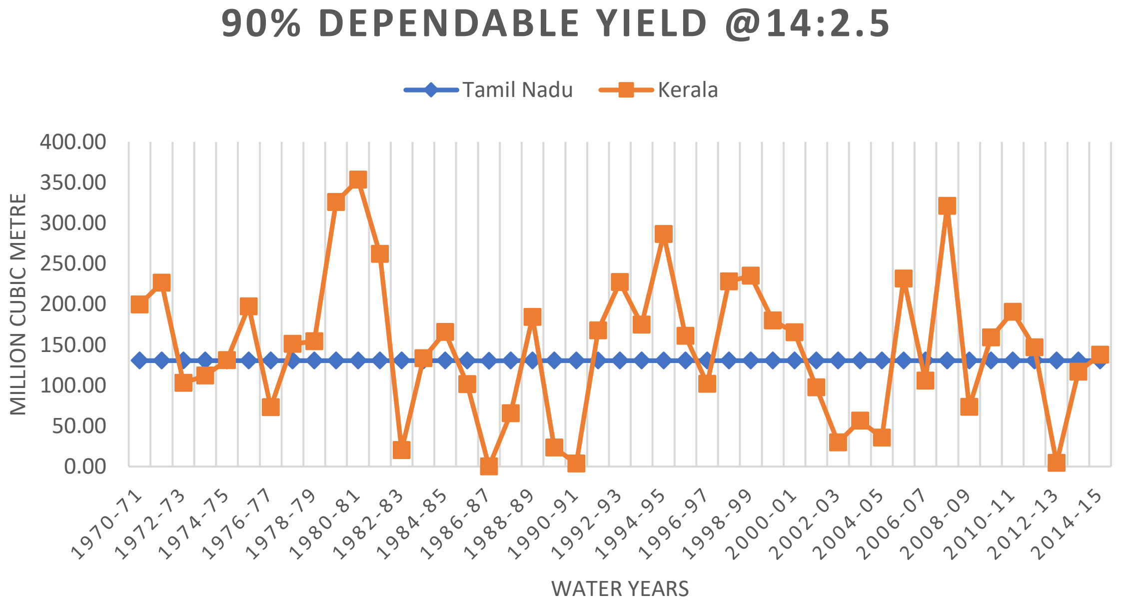


Figure 4-4: Sharing Pattern when 90% dependable Flow of Historical Yield is used as Threshold for Sharing the Runoff of Parambikulam Sub Catchment in the Ratio 14:2.5

4.4.3 Case 3: Sharing based on 75% dependable flows

In this case, 75% dependable flows of historical data are taken as the basis for sharing. Figure 4.5 shows the pattern of sharing over the historical data period. This case provides consistent allocation to Tamil Nadu. The duration in which the share of Kerala exceeding that of Tamil

Nadu, thus contradicting the original ratio, are also limited. When Kerala gets no allocation during the drought years, Tamil Nadu's allocation is also considerably reduced by 50 Mm$^{3.}$, Hence a comparatively equitable distribution of the resource is achieved.

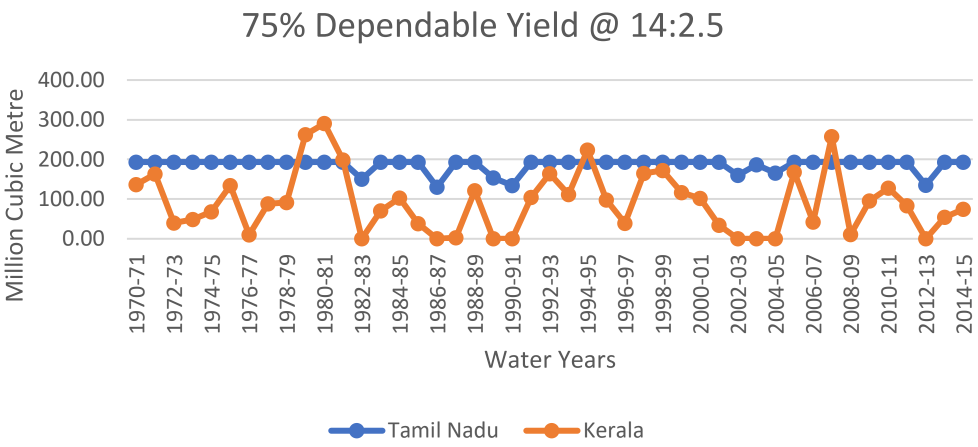


Figure 4-5: Sharing Pattern when 75% Dependable Flow of Historical Yield is Used as Threshold for Sharing the Runoff of Parambikulam Sub Catchment in the Ratio 14:2.5

4.4.4 Case 4: Sharing based on 50 % dependable flows

In this case, 50 % dependable flows of historical data are taken as the basis for sharing. Figure 4.6 shows the pattern of sharing. More inconsistency in Tamil Nadu's share is the problem associated with this pattern of sharing. But Kerala's share very rarely crosses Tamil Nadu's share. At the same time, Kerala is getting no allocation in many consecutive years, which is a crucial factor, compared to case 3.

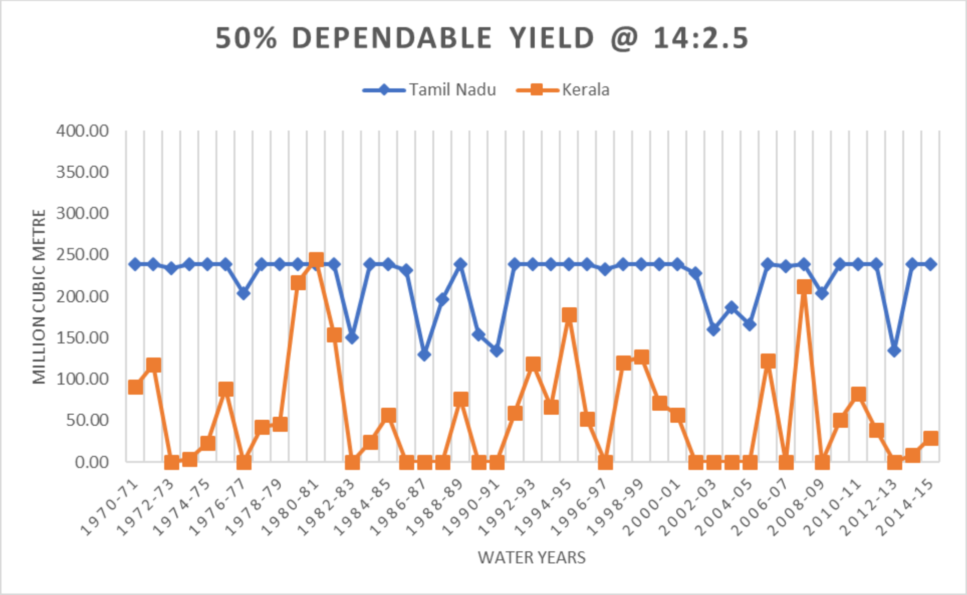


Figure 4-6: Sharing Pattern when 50 % Dependable Flows of Historical Yield is Used as Threshold for Sharing the Runoff of Parambikulam Sub Catchment in the Ratio 14:2.5

4.4.5 Summary and conclusion of evaluation of sharing pattern

The deterministic sharing pattern fixed for this sub-catchment has many problems which challenges its sustainability. The first one is the lack of realistic dependable flow estimation on which the sharing must rely. From the historicalal records of this water-sharing pact, it is understood that the dependable flow was estimated using very limited hydrological data, available at that time. Rainfall data of 4 gauging stations in this sub-catchment for 2 – 5 years together with the stream gauging data for 2 years were the basis of estimation. Estimation of the dependable flows based on the historicalal data, now available for a reasonably larger period, has indicated that the originally fixed value is exorbitantly biased to the higher side. This has resulted in making both the parties of the pact unhappy about its performance. Therefore, dependable flows need to be reestimated using a reasonably longer period data to design a sustainable water-sharing pattern.

The analysis of dependable flow and sharing pattern based on this value have also shown that the sharing based on 75% dependable flows is more equitable compared to the sharing based on other statistics like average flows, 90 % dependable flows and 50 % dependable flows. However, for the sharing to be more sustainable, the threshold value used for sharing shall be computed after earmarking the environmental flow requirement for the sub catchment. Results of the E Flows modelling of Chalakudy basin, which forms the basis for fixing E Flows contribution of the sub-catchment, are discussed in the first section of next chapter.

Chapter 5

5. RESULTS AND DISCUSSION – PART 2

5.1 Introduction

As indicated in the previous chapter, the current sharing pattern of PAP is unsustainable due to various reasons. No consideration for E-Flows, the resource limit identification not being carried out scientifically and deterministic nature of the compact are some of these reasons. In this chapter, the results addressing the above issues are discussed. In the first section of this chapter, the results of the E-Flows modelling of Chalakudy basin are presented. The decision-making tool developed in this study to facilitate sustainable water sharing is discussed in the next section. The last part of this chapter gives the results of sustainable water sharing patterns derived using the decision-making tool.

5.2 Environmental Flow Modelling of Chalakudy Basin

E-Flows modelling using Flow Health requires the flow data sets pertaining to pristine condition and the present condition. Flow data corresponding to the pristine condition of Chalakudy basin is not available as it is already altered. The streamflow data before the hydrologic alteration of this river system were not collected. Therefore, the flows in pristine condition are reconstructed using the method described in section 3.6.1.3. The natural flows at Arangali gauging site are computed by adding the flows, being intercepted at the respective dam sites to the present flows. From the field measurements, it is observed that the contribution from secondary flows is approximately equal to the losses. Therefore, while working out the daily natural flows, the loss component of equation 19 under section 3.6.1.3 is not considered. Hydrologic alteration of the basin due to PAP's IBWT is thus investigated. Its results are presented in Table 5.1

Fig 5.1 shows that the current mean flows are significantly below the natural flows except for a short span. The large difference between the computed pristine flow and the current flow is resulting from the hydrologic alteration of the basin due to construction of PAP. The flood flows are also reduced considerably. 90th percentile of current mean flows is appreciably lower than the 90th percentile of natural flows as can be seen from Figure 5.1. Hence it can be concluded that the hydrologic behaviour of the river is altered very much. In this analysis, only the mean monthly flows are taken. But many other hydrologic parameters also indicate the health of a river system. IHA (Indicators of Hydrologic Alteration) uses 33 parameters to investigate the health of a river system (The Nature Conservancy, 2009). A detailed analysis using IHA is carried out in the next section to comprehend the intensity of hydrologic alteration.

5.2.1 IHA Analysis Results

IHA uses the discharge data of pre-impact period and the post-impact period for analysing the hydrologic alteration. The pre-impact period is before the construction of PAP-IBWT. It is represented by the natural flows in Table 5.1. For the sake of IHA analysis, the pristine flows are taken for the period 1979-2005, though it is not originally so. This assumption against the actual situation may induce some amount of uncertainty in the analysis. However, it is assumed that the method indicated in the section 3.6.1.3 can take care of this uncertainty as the flow period considered in the current investigation is a month. The discharge data from 2006 to 2013 are taken to indicate the post-impact period.

Results of the IHA analysis is presented in Figure 5.2. IHA uses Range of Variability Approach (RVA) to categorise the flow alteration parameters. Hydrologic Alteration Values (HAV) is positive or negative indicating the increase or decrease in the respective category. The general conclusion from these results is that only the Low RVA category of flow alteration indicators have increased in the current situation. Most of the flow alteration indicators in High and Middle classes of RVA are showing negative values. It indicates the significant alteration of the basin.

IHA can be used to analyse the impact of hydrologic alteration on specific parameters of high ecological significance. The Extreme low flow is one of those parameters. Its analysis in the pre-impact and post-impact period is shown in Figure 5.3. The 75th percentile, Median and the 25th percentile of pre-impact and post-impact period's extreme low flows are appreciably different as shown in this Figure. The 75th percentile line in the post-impact period falls well below the 20th percentile line of the pre-impact period. The extreme low flows timing in the post-impact period is also significantly different from the pre-impact period as can be seen from Figure 5.4. A few other parameters like 90 days minimum and 90 days maximum flows are also compared in Figures 5.5 and 5.6. From the analysis of all these parameters, it can be concluded that the hydrologic alteration of Chalakudy river is significant.

Table 5-1: Pristine Flows and Current Flows at Arangali Site

Month	Reconstructed pristine Mean Monthly Flow in Cumecs	Current Mean Monthly Flow in Cumecs
Jan	17.928	3.112
Feb	17.959	0
Mar	17.708	0
Apr	17.607	0
May	17.718	4.931
Jun	131.533	88.916
Jul	260.828	181.966
Aug	193.11	150.645
Sep	126.922	135.108
Oct	94.33	82.06
Nov	63.788	61.683
Dec	33.279	12.58

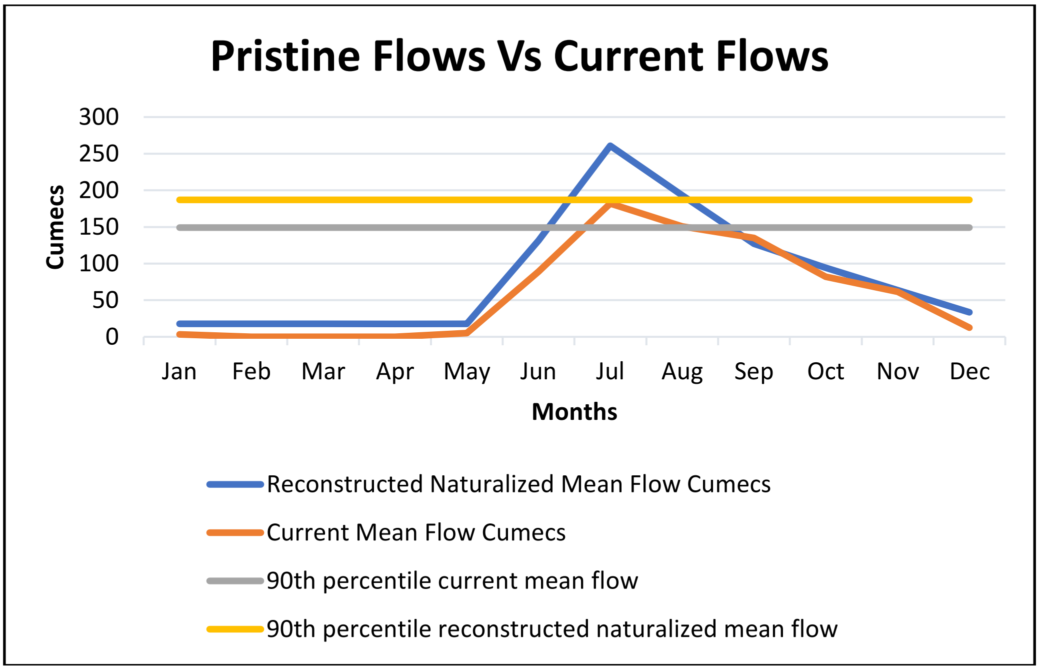


Figure 5-1: Hydrologic Alteration of Chalakudy Basin

In this study, IHA is used only to analyse the hydrologic alteration of Chalakudy basin. Though it can be used to model the E Flows regime, there are certain limitations in applying it to Chalakudy basin. To model E Flow regimes using IHA, the flow rules are to be formulated based on the results of studies conducted on Flow – Ecosystem Relationships (FER). As no such studies have been undertaken in the past, Flow Health is used here to design the E Flow regime. The specific advantages of using Flow Health and how it addresses the issue of FER data gap is already discussed in section 3.6.1.

5.2.2 Flow Health Analysis Results

Flow Health works with the components of flow that are ecologically most relevant and requires only hydrologic data to run this model. Hence it is suited to the current scenario where the historicalal ecological data is almost nil. The main advantage of these hydrologic data is its acceptability by the stakeholders of Chalakudy Sub Basin. These data are jointly gauged by the riparian States of Chalakudy Sub Basin, Kerala and Tamil Nadu, and hence its validity is not contested. As indicated earlier, the Flow Health uses nine parameters, viz., High Flow Volume (HF), Low Flow Volume (LF), Highest Monthly Flow (HM), Lowest Monthly Flow (LM), Persistently Higher Flow (PH), Persistently Lower Flow (PL), Persistently Very Low Flow (PVL), Seasonality Flow Shift (SFS), and Flood Flow Interval (FFI) to compute E-Flows

The running of Flow Health requires the setting up of threshold values of these parameters. The values of parameterss can be set to the user-defined or default values. In this study, default thresholds as well as custom selected thresholds are used to analyse the current status of Chalakudy River. These threshold values are presented in Table 5.2.

Table 5-2: Default and Custom Selected Thresholds

Threshold	Default	Custom Selected
Upper range threshold (percentile):	75	75
Lower range threshold (percentile):	25	40
Persistently very low flow (percentile) threshold	1	10
Persistently higher flow (percentile) threshold	75	75
Flood frequency (years):	4	3
Length of the interval after which the score declines from 1 (years):	4	3
Length of the interval after which the score is zero (years):	8	6

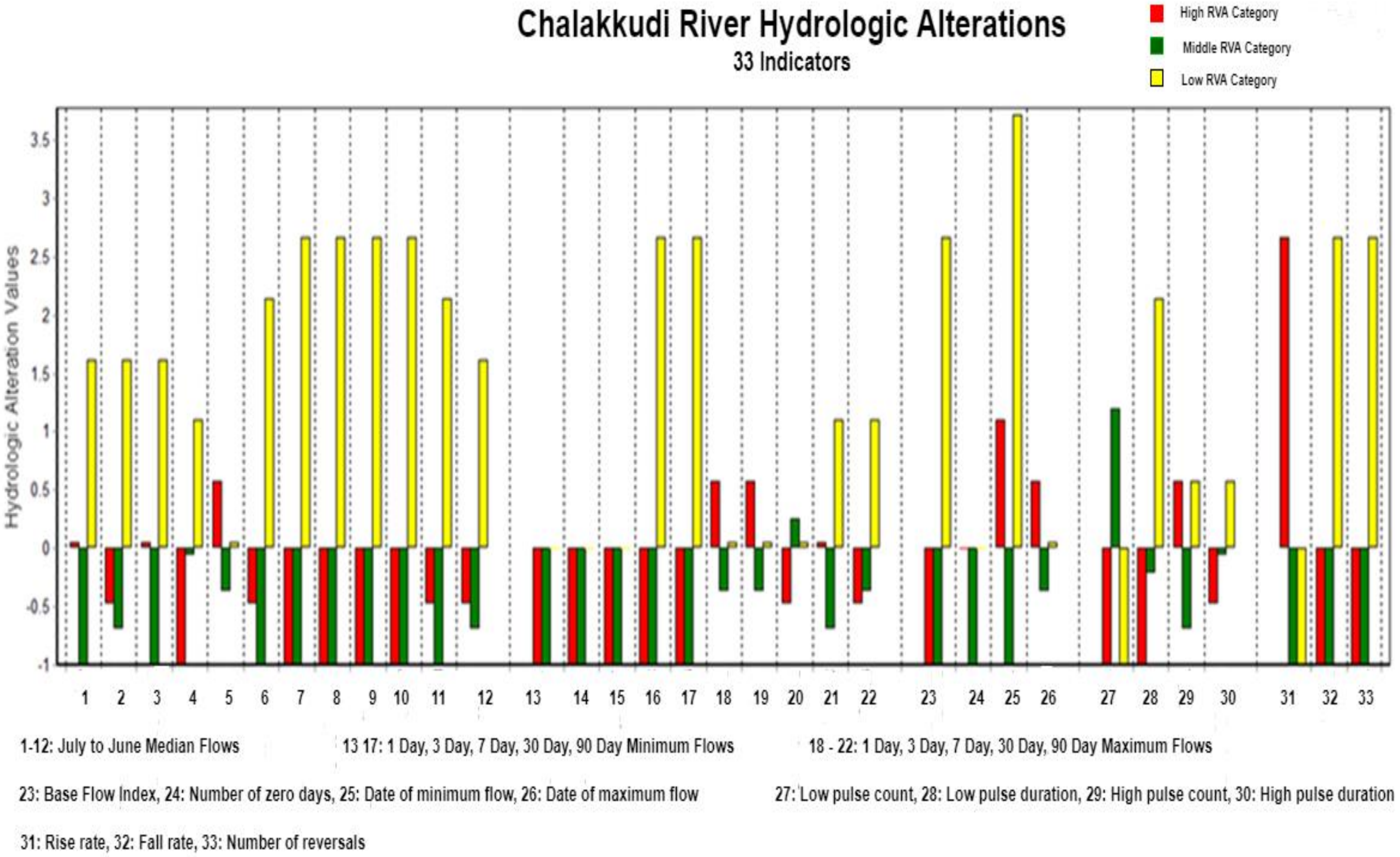


Figure 5-2: IHA General Analysis Results

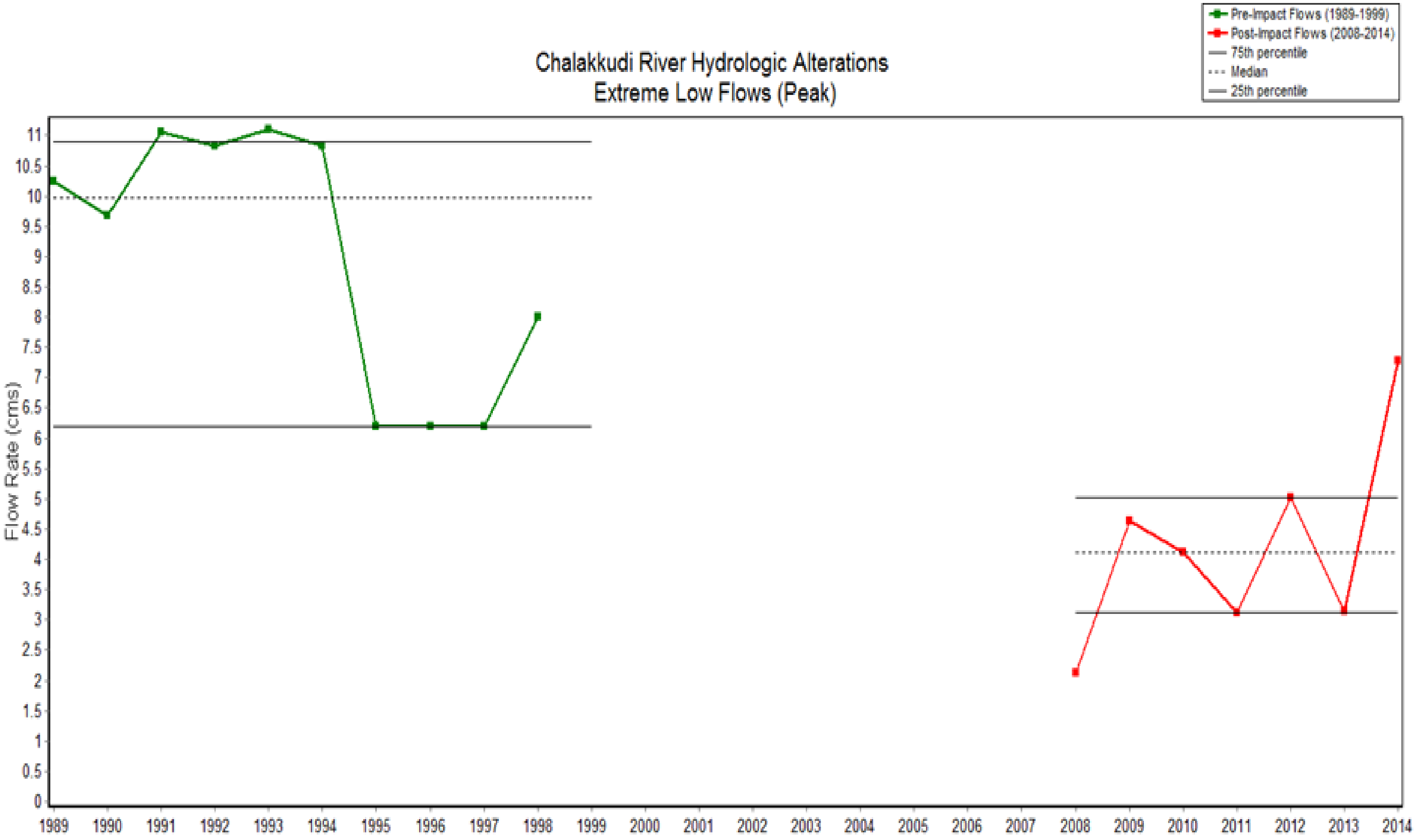


Figure 5-3: Comparison of Pristine and Current Extreme Low Flows

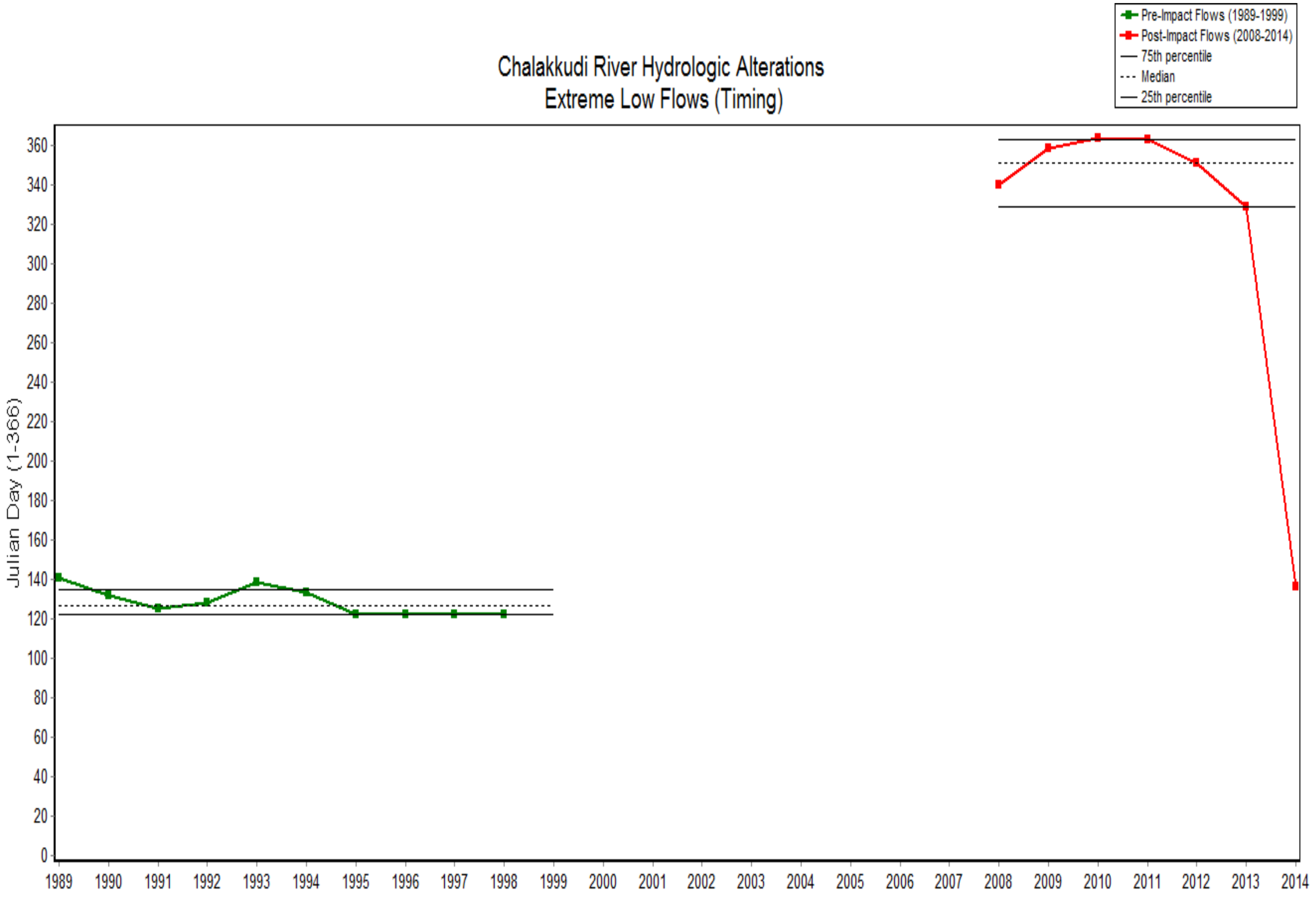


Figure 5-4: Comparison of Pre-impact and Post-impact Extreme Low Flows Timing

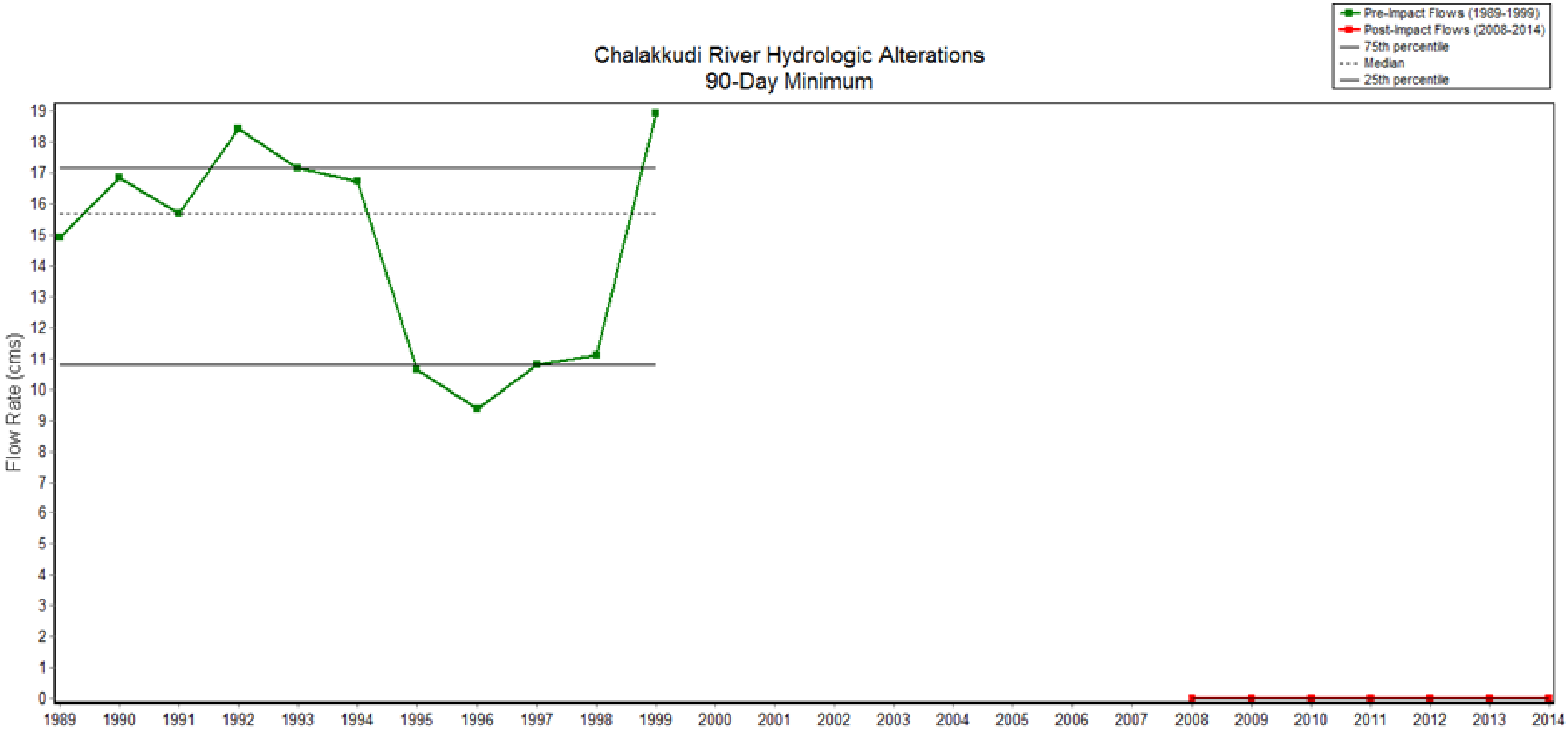


Figure 5-5: Comparison of 90 days Minimum Flows in the Pre-impact and Post-impact Period

(Note: The post impact flows are much less as indicated by the straight-line portion of graph on right bottom corner)

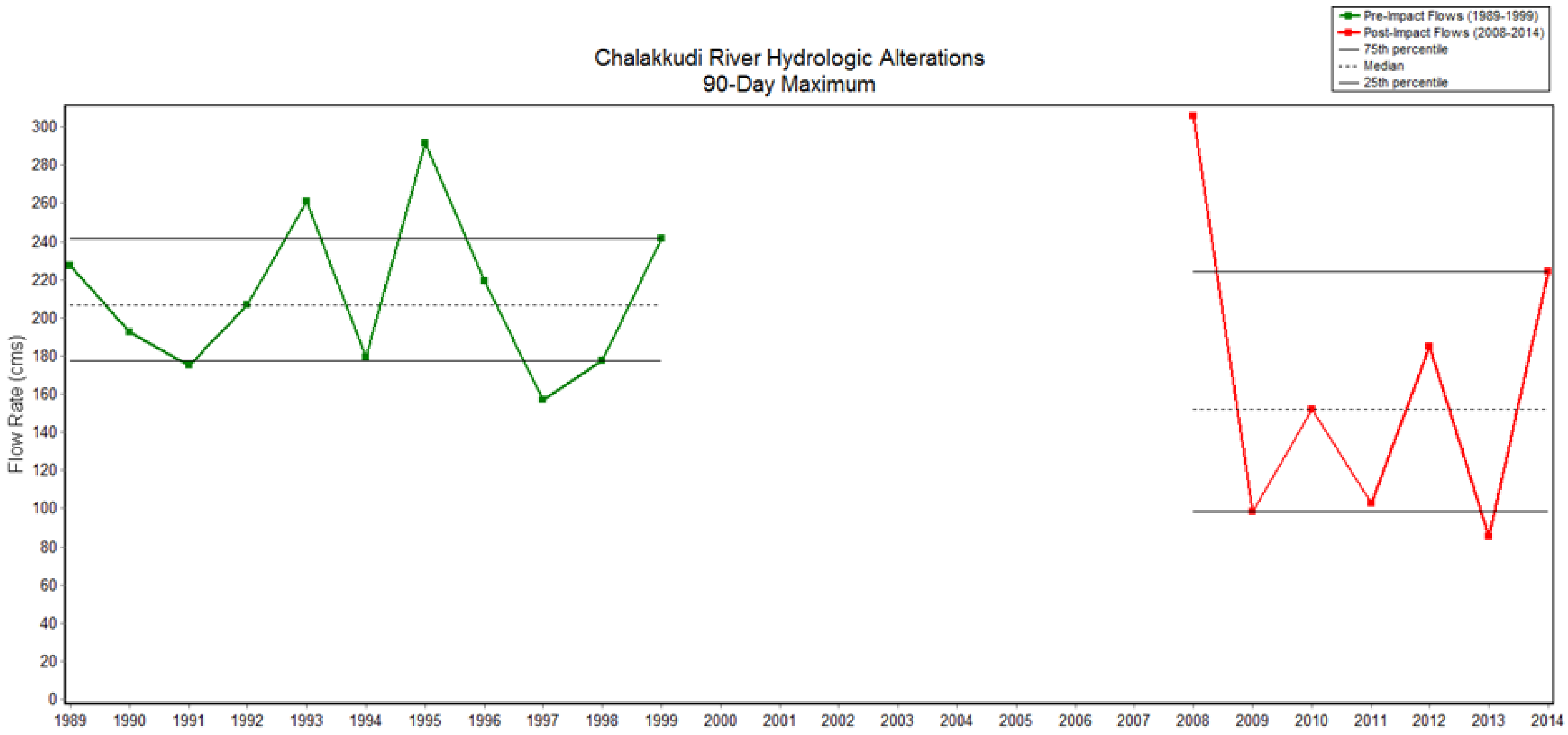


Figure 5-6: Comparison of 90 Days Maximum in the Pre-impact and Post-impact period

The “Length of the interval after which the score is zero” is the interval (from the last flood) where the environmental benefits from that flood, no longer provide any further benefit. For example, expecting that benefits from a flood may continue at a high level, say, for four years after a flood, and then decline to an FFI score of zero after a further four years. In this case, the length of the interval after which the score is zero would be eight years.

Flow Health allows setting the lower range thresholds from 5 to 40 percentiles, and the PVL threshold from 1 to 10 percentiles and thereby the users can select threshold different from default values. These customized thresholds are sort of extreme values such that one can understand the degree of change happening to the system compared to situations with default thresholds. Such information is very much essential and critical as it provides a slider to the stakeholder while deciding on the quantum of E Flows. It also illustrates the range of thresholds within which the stakeholders can have decision making on E Flows. This exercise would also help in understanding the cost of water to meet E Flows in each case.

5.2.2.1 Case 1: Default Thresholds Analysis

The Flow Health model was run with the data from Parambikulam sub-catchment. The used data include the reconstructed pristine flows and the actual flows. The period from 1979 to 2005 is taken as the reference period for which the pristine flows are reconstructed and the period from 2006 to 2013 is considered as test/impact period.

The output from the Flow Health analysis for the test period 2006 to 2013 in the form of flow health scores are given in Table 5.3. These are graphically represented in Figure 5.7. The overall FH scores during this period are significantly low, indicating moderate to significant deviation from that of reference. HF and HM scores show a considerable variation from the reference values in every alternate test year. The deviation is not uniform, and it is only an accidental occurrence. The lowest value of HM in the reference period occurred in 1987. In every alternate test year, HM was less than this lowest and hence, it scored as zero. It indicates that the flood inundations for several years were not enough for the sustenance of ecosystems. LF and LM are the indicators of gross habitat area availability and required minimum flows for the survival of the ecosystem respectively. They have consistently substantial deviation from the reference, indicating the ecosystem unsustainability.

PH scored one throughout the test period, indicating its very small or insignificant deviation from the reference values. It also shows the absence of an unusually dry low flow season probably due to heavy summer showers in the catchment. Out of the eight test years, only

2006, 2007, 2010 and 2011have PL scores above 0.5. It implies that the flows in the remaining test years were notably lower than the expected range for two or more consecutive months. PVL scores also indicate considerable variation from the reference values. In the year 2013, PVL scored zero which is indicative of the cessation of flow in the river.

Table 5-3: FH Scores for the Test Period while Using Default Thresholds

Year	HF	HM	LF	LM	PH	PL	PVL	SFS	FFI	**FH**
2006	0	0	0	0	1	0.73	0.33	0.54	1	**0.32**
2007	1	1	0	0	1	0.55	0.33	0.54	1	**0.55**
2008	0	0	0	0	1	0.18	0.17	0.15	1	**0.19**
2009	0.59	1	0	0	1	0.45	0.17	0	1	**0.4**
2010	0	0	0	0	1	0.64	0.33	0	1	**0.25**
2011	1	1	0	0	1	0.64	0.17	1	0.9	**0.59**
2012	0	0	0	0	1	0.09	0.17	0.62	0.65	**0.19**
2013	1	1	1	0	1	0.36	0	1	0.4	**0.59**

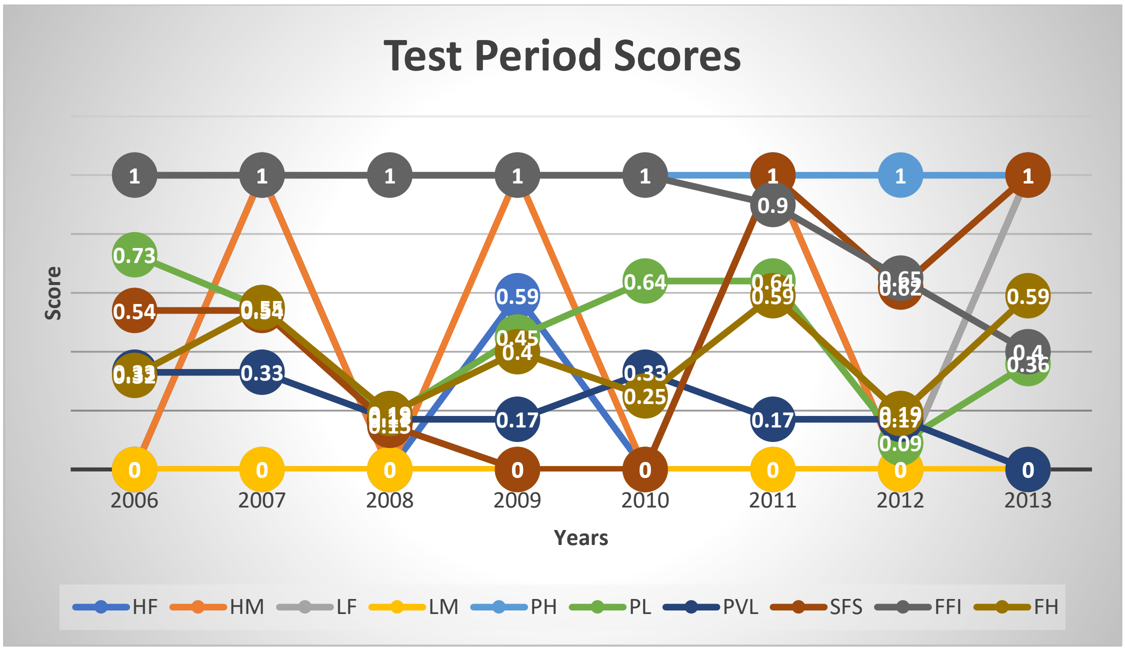


Figure 5-7: Test Period Scores of FH and its Components

HF: High Flow LF: Low Flow HM: Highest Monthly Flow LM: Lowest Monthly Flow PH: Persistently High Flow PL: Persistently Low Flow PVL: Persistently Very Low Flow SFS: Seasonality Flow Shift FFI: Flood Flow Interval FH: Flow Health

The PVL score calculation depends on the threshold of the reference flow (1 percentile). Changing the threshold to a higher percentile would result in score ‘zero’ for a higher number of test years. In the case of an over abstracted river like Chalakudy, how the PVL score varies when the threshold percentile is reset to a higher value is also important. This is discussed in the next section with a set of model outputs obtained while using different threshold percentiles.

SFS scores indicate that flow pattern has been partly reversed. Shifting of the high and low flow seasons to other times of the year is not a favourable condition for the survival of many species and indicates environmental degradation. Except for the two years of the test period, shifting of flows has been significant. FFI scores have not been reduced to zero in the test period. It implies that the floodplain ecosystem health has not been severely impacted, despite the shifting of the seasons. However, these scores are based on the default flood frequency of 4 years. FFI scores obtained for reduced flood frequency is discussed in the next section. Overall, FH scores for the test period indicate significant hydrologic alteration and environmental degradation which is in line with the results from the IHA analysis.

5.2.2.2 Case 2: Custom Selected Thresholds Analysis

The setting of lower range threshold to 40 percentiles has reduced the overall FH score considerably (Table 5.4 and Figure 5.8). Figure 5.8 gives the comparison of FH scores for the two cases- low range percentile as 25 and 40. Overall FH scores in all the years (for low range percentile as 40) are less than 0.5. Changing the PVL threshold to 10 percentile has resulted in a very large deviation from the reference during one-third of the test years. The comparison of PVL for both the default threshold and custom threshold are given in Figure 5.9. Changing the flood frequency to three years has resulted in zero FFI score in the year 2013. It implies that the default interval of 48 months between threshold floods is the general pattern of flooding and inundation occurred during the reference period.

Table 5-4: Test Year FH Scores for Custom Selected Thresholds

Year	HF	HM	LF	LM	PH	PL	PVL	SFS	FFI	**FH**
2006	0	0	0	0	1	0.73	0.33	0.34	1	**0.3**
2007	1	1	0	0	1	0.45	0.17	0.34	1	**0.49**
2008	0	0	0	0	1	0.09	0	0.1	1	**0.15**
2009	0.37	0.99	0	0	1	0.45	0.17	0	1	**0.37**
2010	0	0	0	0	1	0.18	0.17	0	0.86	**0.15**
2011	0.75	0.65	0	0	1	0.64	0.17	1	0.53	**0.47**
2012	0	0	0	0	1	0	0	0.38	0.19	**0.07**
2013	1	1	1	0	1	0	0	1	0	**0.5**

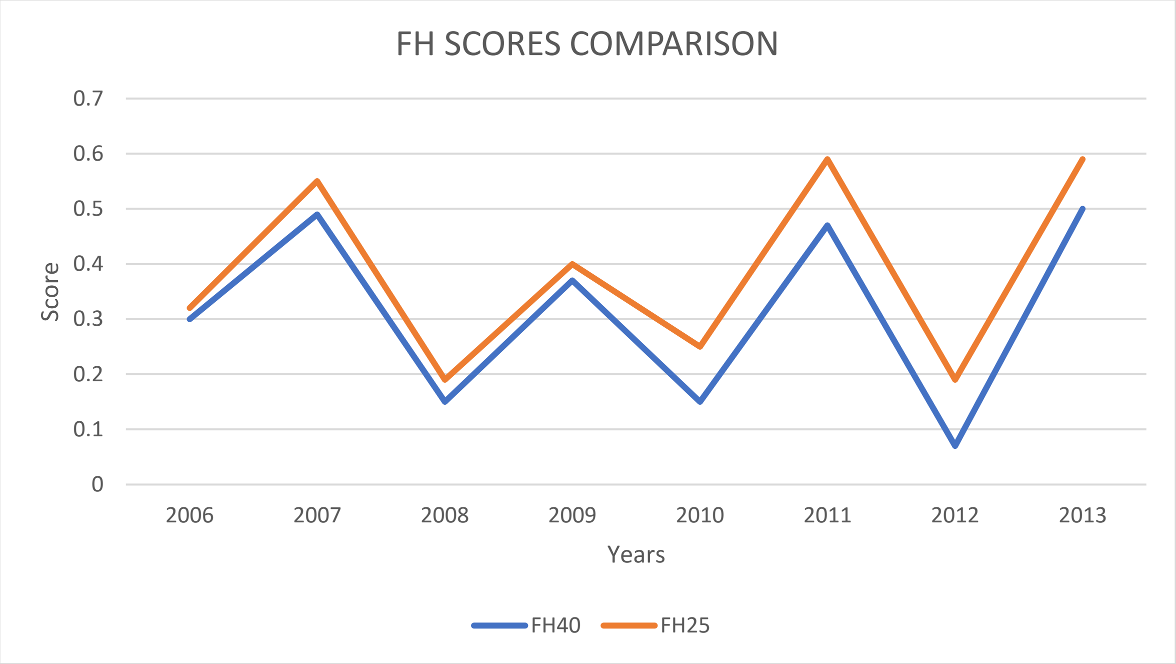


Figure 5-8: Comparison of FH Scores for Custom and Default Thresholds

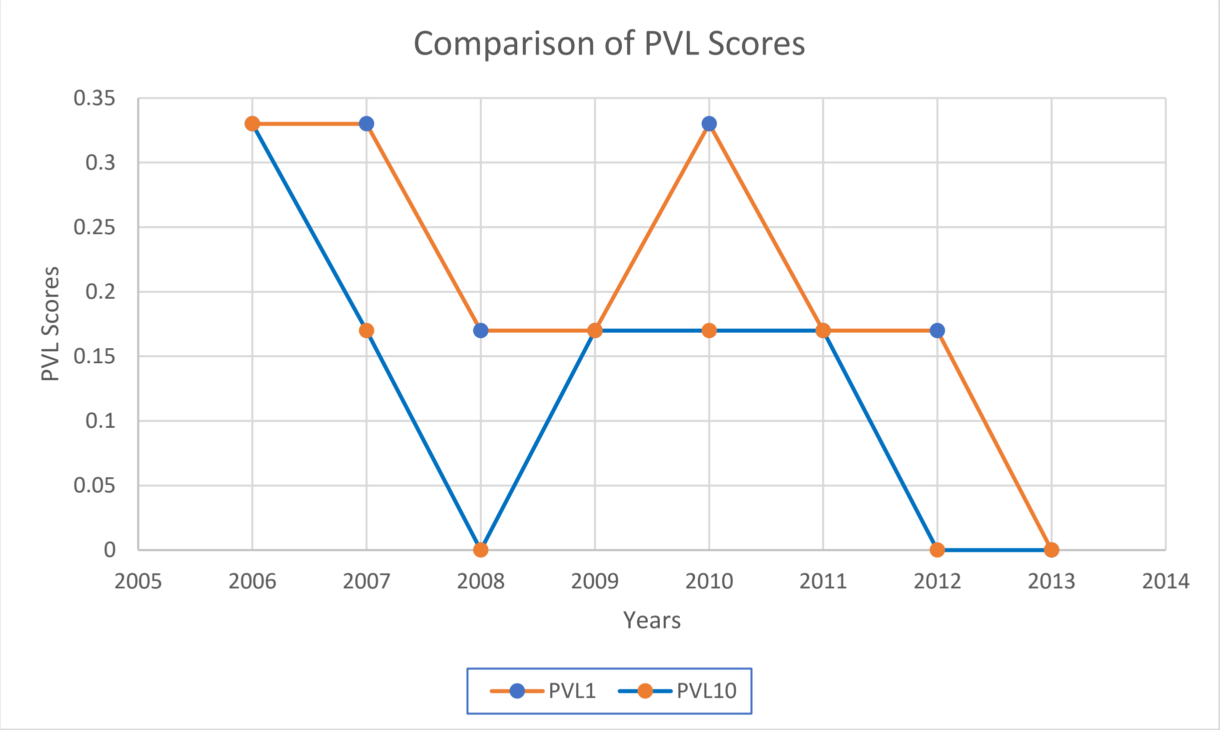


Figure 5-9: Comparison of PVL Scores for Default and Custom Selected Thresholds

5.2.3 E flows Regime Modelling

In this section, the results of E Flows regime modelling using Flow Health are presented. The results of three distinct cases are discussed here. First one of these cases is the result of the application of Design Flow tool of Flow Health using Wetted Perimeter method. Second and third cases are the results of the application of Minimum Monthly Flows Tool of Flow Health for the default and custom selected thresholds.

5.2.3.1 Design Flow Tool Results

Design flow method of monthly E-flow regime can choose any values for the monthly flows, perhaps derived by a different approach. In this section, the wetted perimeter method is used to make a preliminary estimate of E-flows. As indicated earlier, this is a very primitive method of estimation. The river cross section at Arangali site was surveyed using Total Station and is plotted in Figure 5.10. The cross section are measured based on an arbitrary benchmark and hence, negative values do not have any significance. Nevertheless, the riverbed level might have gone below the original bed level some years back due to anthropogenic and natural reasons. Cross section profile during Pre-Monsoon and Post Monsoon have been plotted to compute the average wetted perimeter. Based on the stage-discharge relationship already established at this site, a graph (Figure 5.11) is plotted. The discernible breakpoint in the wetted perimeter – discharge relationship has given an estimate of 100 m^3/s. It may be noted that Fig.5.11 shows the wetted perimeter response (the rate of change of wetted perimeter) Vs the discharge in order to discern the breakpoint easily.

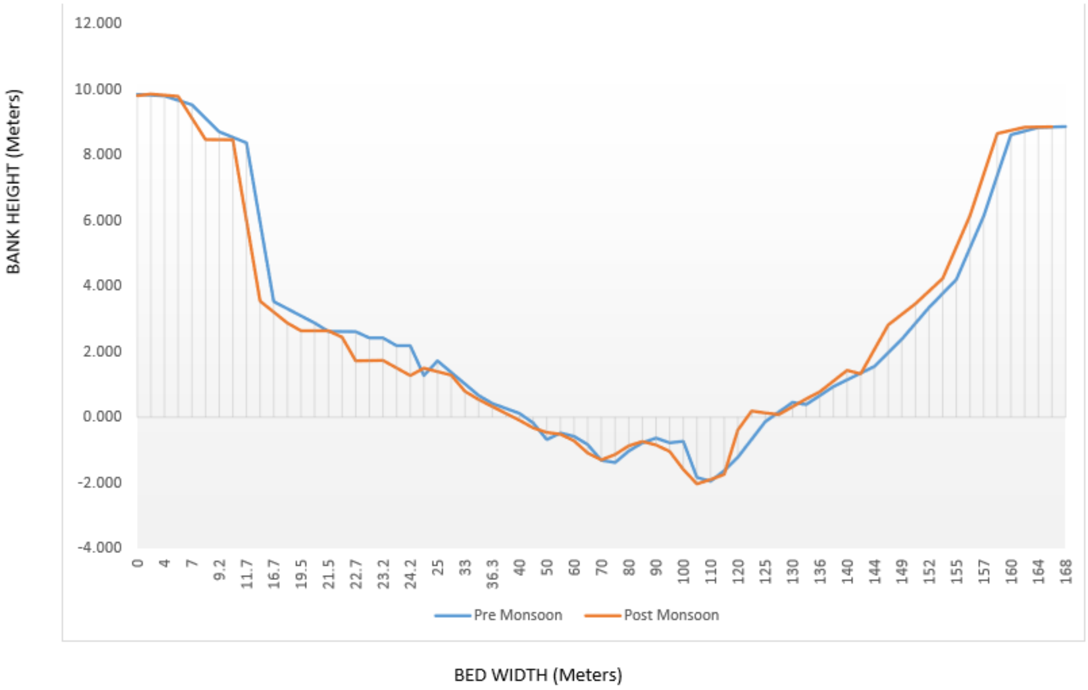


Figure 5-10: River Cross Section

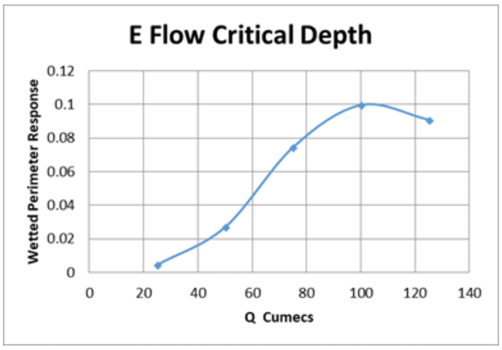


Figure 5-11: Wetted Perimeter Method

As discussed in section 3.6.1.1, Flow Health can be used to design a monthly E-flow regime based on the principle of achieving a certain percentage of the mean reference flow. This method also offers the facility of inputting the E-flow requirement value, estimated using a different approach, i.e., Wetted Perimeter Method. In this section, Flow Health is now employed with the expected discharge of 100 m^3/s to suggest a monthly flow regime. It is also used to check the FH score and is obtained as 0.82. But this monthly flow regime is costly as can be seen from Table 5.5 and Figure 5.12. It implies that the estimate of E-flow by wetted perimeter method is very high and the additional requirement is in the order of 1231Mm^3. This much extra volume of water cannot be provided, and hence it becomes practically impossible and not economically viable to use this method for E-flow regime design. However, the FH scores that can be achieved for a range of lower threshold discharges can also be computed using the design flow method.

Similarly, the possibility of obtaining a lower threshold discharge from other cross-sections of this river with discernible breakpoints can also be explored. These options would provide the other E-flow regimes that can also be considered. However, such an option is not attempted considering the large gap between the current availability and requirement (even if a 20 to 30 % reduction is available).

5.2.3.2 Minimum Monthly Flow Tool – Default Thresholds Results

Target FH score 1

Flow health provides two methods viz., minimum monthly flow and design flow for the computation of E-flows. The results of the design flow method, as discussed in the previous section, are found to be practically impossible to implement. The Minimum Monthly Flow method derives the E-flow regime based on achieving specific target scores for the nine indicators or overall FH score. The highest target is a flow regime that scores one on every indicator. This would represent a very low-risk E-flow regime.

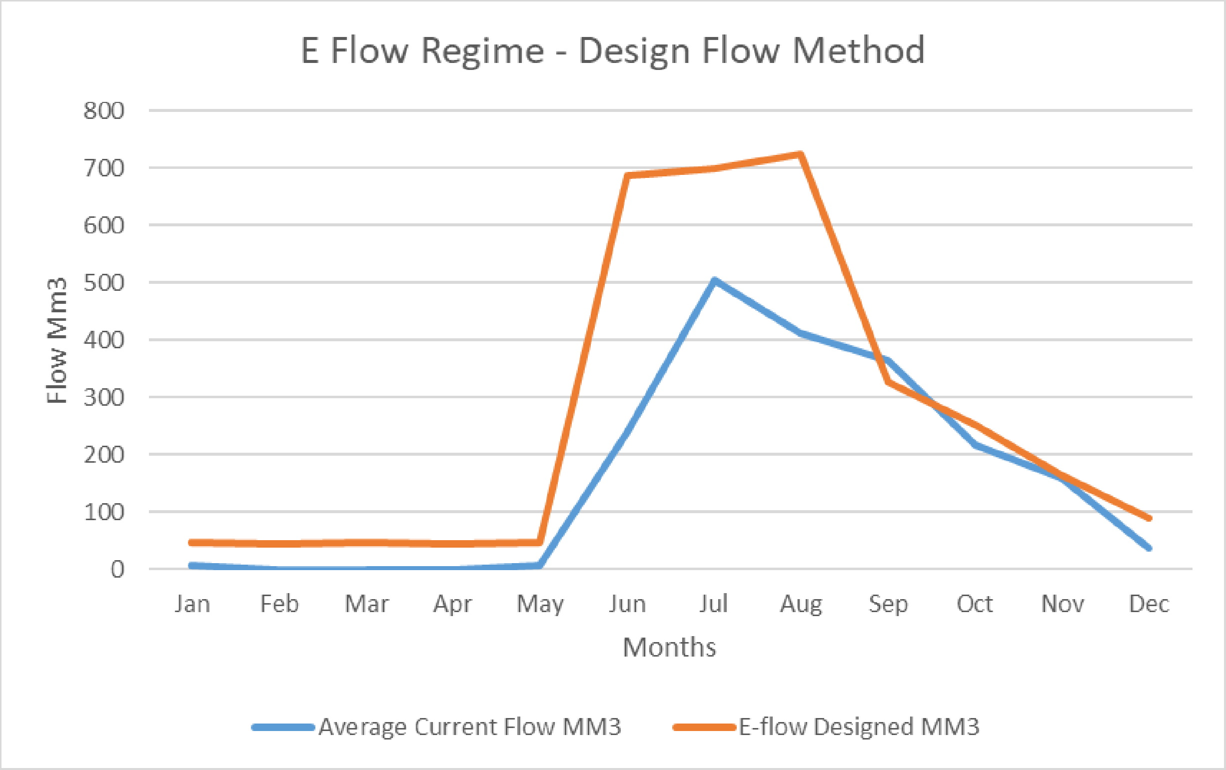


Figure 5-12: Design Flow - E Flow Regime

Table 5-5: E Flow Regime Using Design Flow Method

Months	**Average Current Flow Mm^3**	**E-flow Designed Mm^3**	**Additional Flow requirement Mm^3**
Jan	6.74	47.86	41.12
Feb	0.00	43.90	43.90
Mar	0.00	47.43	47.43
Apr	0.00	45.76	45.76
May	6.15	47.82	41.67
Jun	238.53	687.27	448.73
Jul	504.18	699.66	195.48
Aug	413.09	724.41	311.32
Sep	363.35	327.57	-35.78
Oct	217.83	252.12	34.29
Nov	159.43	163.90	4.47
Dec	36.05	88.90	52.85
Total	**1945.35**	**3176.59**	**1231.24**

The Minimum Monthly Flow that is required to meet environmental flow regime considering the target FH score as one is first attempted in this section. Monthly environmental flow regime that is designed by Minimum Monthly Flows is compared with the current flows and is shown in Table 5.6 (Columns 2 and 4). Additional flow volume required to meet this regime in a year is 92 Mm^3 (column 5 of Table 5.6). The deficit and surplus across the twelve months are shown in Figure 5.13. Extra flow volume required for keeping an FFI score of 1 and a return period of 4 years is shown separately in the Figure 5.14. Additional flow volume required for this score of FFI is 221 Mm^3 in the month of July. However, the net additional requirement of July is only 67.84 Mm^3, which is the difference between current flows and the algebraic sum of requirement for other parameters. (Figure 5.14 is the model output modified with appropriate legends and numerical values for better readability)

Table 5-6: Monthly E Flows Regime for Target FH Scores 1 and 0.8 under Default Thresholds

1	2	3	4	5	6
Months	FH1- E-flow Designed Mm^3	FH0.8- E-flow Designed Mm^3	Average Current Flow Mm^3	FH1- E-flow Additional Requirement (2-4) Mm^3	FH0.8- E-flow Additional Requirement (3-4) Mm^3
Jan	40.44	39.99	6.74	33.70	33.25
Feb	35.66	36.58	0.00	35.66	36.58
Mar	39.61	40.31	0.00	39.61	40.31
Apr	36.74	36.95	0.00	36.74	36.95
May	28.43	28.35	6.15	22.28	22.20
Jun	240.20	238.29	238.53	1.67	-0.24
Jul	572.02	572.87	504.18	67.84	68.69
Aug	409.88	428.02	413.09	-3.21	14.93
Sep	210.10	202.26	363.35	-153.25	-161.09
Oct	206.36	195.46	217.83	-11.47	-22.37
Nov	145.17	138.41	159.43	-14.26	-21.02
Dec	72.76	71.35	36.05	36.72	35.30
Total	2037.37	2028.86	1945.35	92.02	83.51

Target FH score 0.8

Minimum monthly flows for a target FH score of 0.8 is designed next. Monthly environmental flow regime designed based on Minimum Monthly Flows is compared with the current flows and is shown in Columns 3 and 4 of Table 5.6. Additional flow volume required to meet this regime in a year is 83.51 Mm^3 (Column 6 of Table 5.6). The deficit and surplus across the twelve months are shown in Figure 5.15.

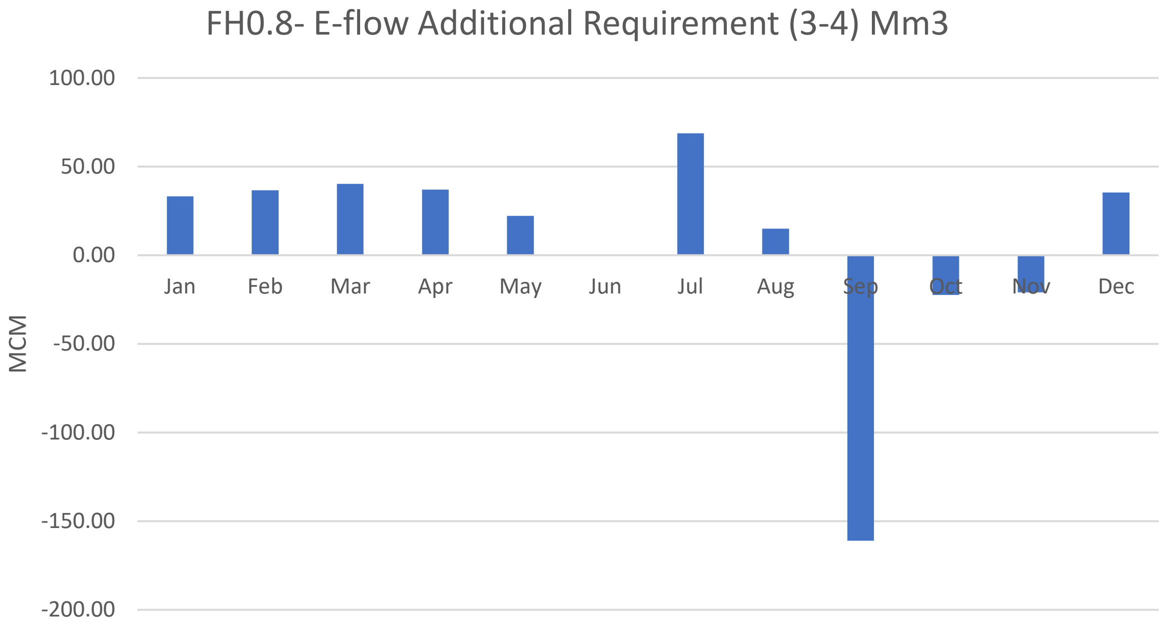


Figure 5-13: Additional Flow volumes required in each Month for an FH Score of 1. Negative values indicate the surplus flows which can be used to partially meet the deficit flows, if stored appropriately.

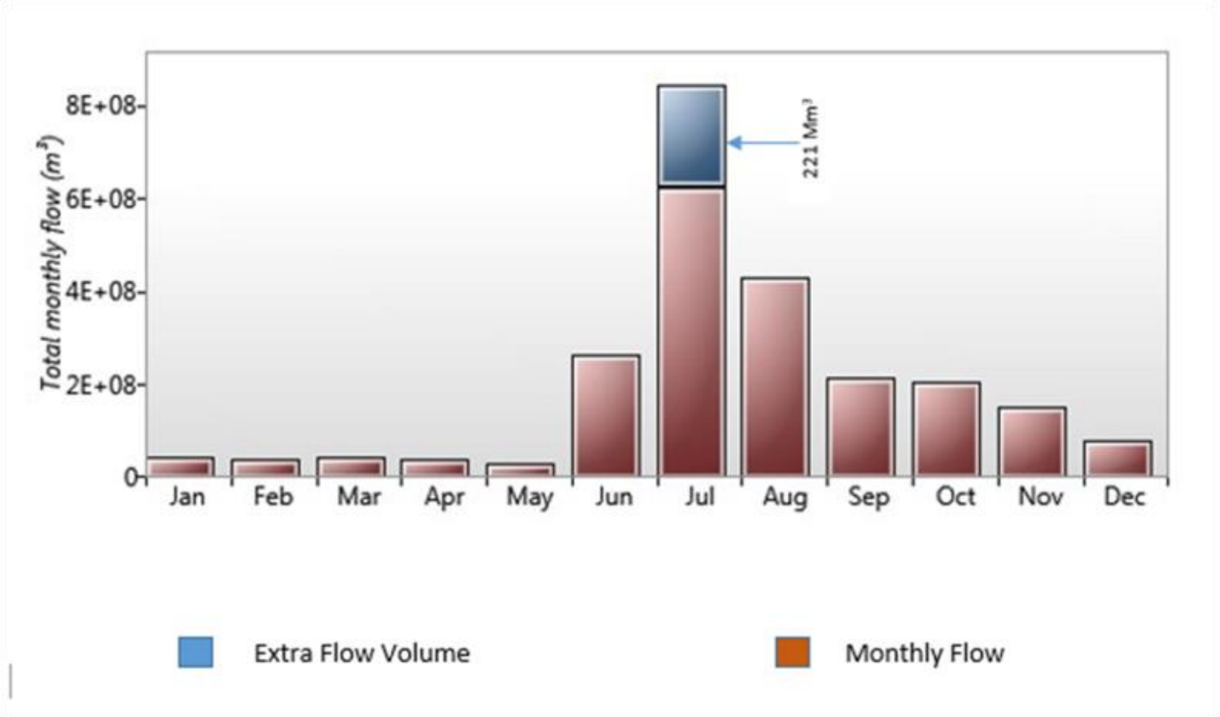


Figure 5-14: Flood Flow requirement

5.2.3.3 Minimum Monthly Flows Tool – Custom Selected Thresholds Results

Target FH scores 1 and 0.8

Now, the designing of E-flow regime for the custom thresholds is carried out. For a target FH score of 1 and 0.8, the minimum monthly flows method has suggested an additional flow requirement of 391Mm^3 and 193 Mm^3 respectively. The minimum monthly flow regimes based on custom thresholds are given in Table 5.7. Custom selected thresholds imply stringent standards, and naturally, the additional flow requirement is very high. It also means that practically no water is available for interbasin transfer if these standards are followed strictly.

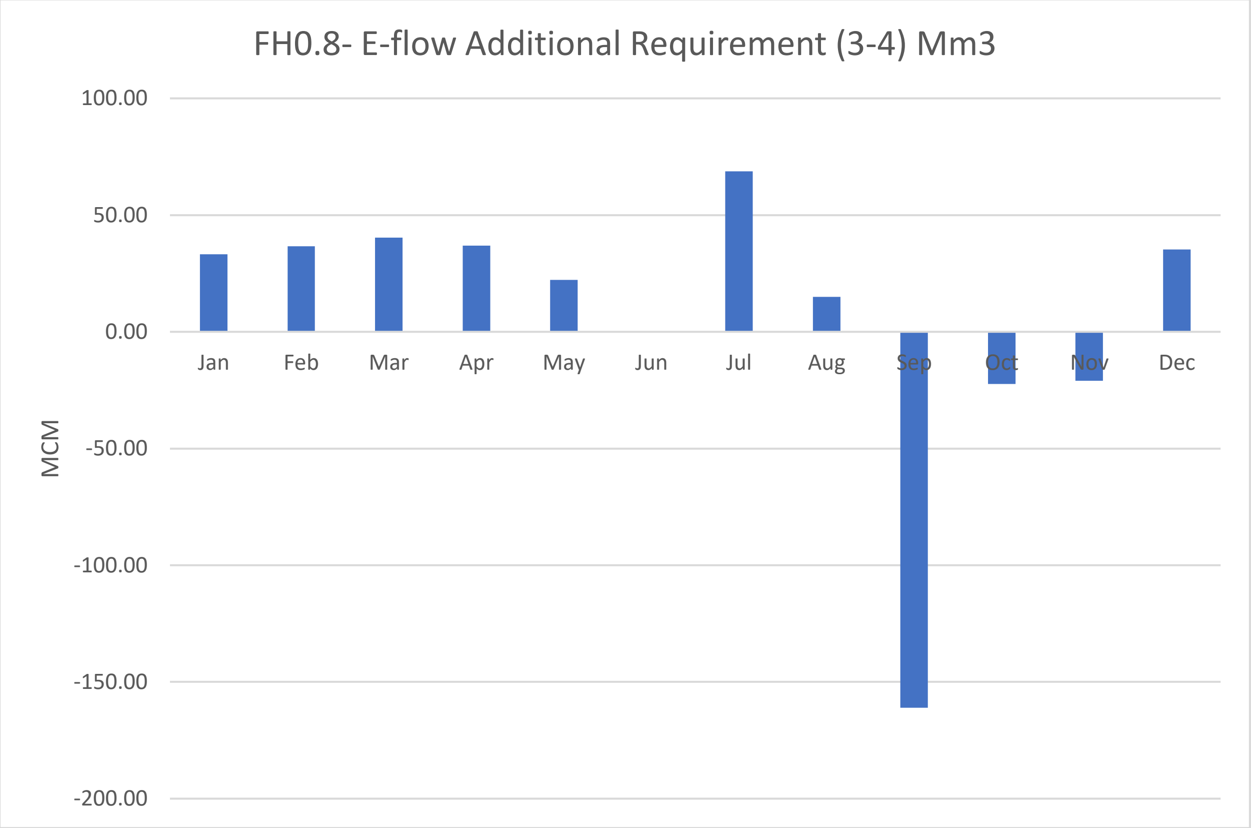


Figure 5-15: Additional Flow Volumes Required in each Month for an FH Score of 0.8. Negative values indicate the surplus flows which can be used to partially meet the deficit flows, if stored appropriately.

Table 5-7: Monthly E Flows Regimes for Target FH Scores 1 and 0.8 under Custom Selected Thresholds

1	2	3	4	5	6
Months	FH1 - E-flow Designed MM^3	FH0.8 – E-flow Designed MM^3	Average Current Flow MM^3	FH1- E-flow Additional Requirement (2-4) Mm^3	FH0.8- E-flow Additional Requirement (3-4) Mm^3
Jan	47.01	40.77	6.74	40.28	34.04
Feb	42.31	36.69	0.00	42.31	36.69
Mar	46.83	40.61	0.00	46.83	40.61
Apr	41.97	36.40	0.00	41.97	36.40
May	32.64	32.64	6.15	26.49	26.49

1	2	3	4	5	6
Jun	284.46	246.71	238.53	45.93	8.18
Jul	673.57	608.25	504.18	169.39	104.08
Aug	467.53	416.27	413.09	54.43	3.18
Sep	233.86	233.86	363.35	-129.49	-129.49
Oct	221.67	211.92	217.83	3.84	-5.91
Nov	161.72	151.75	159.43	2.29	-7.68
Dec	82.22	82.22	36.05	46.17	46.17
Total	2335.80	2138.11	1945.35	390.44	192.76

5.2.4 Summary of E Flows Modelling Results

The E Flows requirement of Chalakudy basin can be computed in three ways. Firstly, the Design Flow method with wetted perimeter application is used. Secondly, the default thresholds of Flow Health are used. Thirdly, the custom selected thresholds are used. The results obtained under these three methods are significantly different because different standards are being used in each method. Results obtained in the first method are over-estimated values of E Flows, practically difficult to implement. For the practical purpose of river management, the E Flows regime designed using default thresholds with target FH score 1 appears to be more reasonable. It requires an additional flow volume of only 92 Mm^3.

The additional flow volume required to maintain E Flows regime with FH score 1 and 0.8 under the custom thresholds are 390.4 Mm^3 and 192.7 Mm^3 respectively. This scheme requires a substantial volume of water. Restricting the E Flow regimes to either of these two would make the IBWT under PAP practically impossible. For the sake of maintaining E Flows, revoking a water-sharing pact on IBWT is not possible in the current socio-political scenario of the basin. Therefore, the E Flows regime designed using default thresholds appears to be more reasonable. Nevertheless, a final decision on this should come out of the stakeholder engagement process.

5.3 Decision Making Tool for Sustainable Water Sharing

While discussing the results of evaluation of water sharing pattern of Parambikulam sub-catchment (subsection 4.4.5), it was mentioned that the dependable flow on which the sharing must be based on, was not assessed realistically. The need to re-estimate the dependable flows using a reasonably long period data to design a sustainable water sharing pattern was also emphasised in this subsection. A decision-making tool that can be used for this purpose is developed and discussed in the subsequent section.

5.3.1 Evolution of the decision-making tool

This tool is designed in such a way that it incorporates a rigorous methodology to account the uncertainties of future climate and its impact on runoff. One of the significant outcomes of the study is the development of decision-making tool which can be utilised in the Indian context where the availability of data is limited. There are four distinct operational phases in the application of this tool as shown in Figure 5.16.

1. In the first phase, a suitable rainfall-runoff model is calibrated using the historicalal climate data and historical runoff data (blue connector path in Figure 5.16). The model is then used to simulate the runoff from other easily obtainable/synthetic climatic data.
2. In the second phase, the Stochastic Climate Library (SCL) of eWater Toolkit is used to generate stochastic climate data. The calibrated rainfall-runoff model is used to predict the runoff for this climate data. (green connector path in Figure 5.16).
3. In the third phase, the Monte Carlo simulation of runoff using historicalal climate data is carried out to predict other sets of runoff (red connector path in Figure 5.16).
4. The fourth phase incorporates the baseline climate change scenario of this catchment portrayed in India’s second national communication to United Nations Framework Convention on Climate Change (UNFCCC) into the predicted runoff (pink connector path in Figure 5.16) (Gosain et al., 2011, Ministry of Environment and Forests Government of India, 2012).

By using this tool, it is possible to generate runoff data set for reasonably good length. Tool can also incorporate actual climate change study results as shown in Figure 5.16. It can facilitate informed decision making on dependable runoff which shall be the basis of sharing pattern.

5.4 Sustainable Water Sharing Model for Parambikulam Sub Catchment

In this section, the Decision-Making Tool developed in the previous section is applied to Parambikulam sub-catchment to demonstrate its application. Results of running four different phases of this tool are discussed subsequently. This is followed by the discussion of the result of a sustainable water sharing model for the sub-catchment.

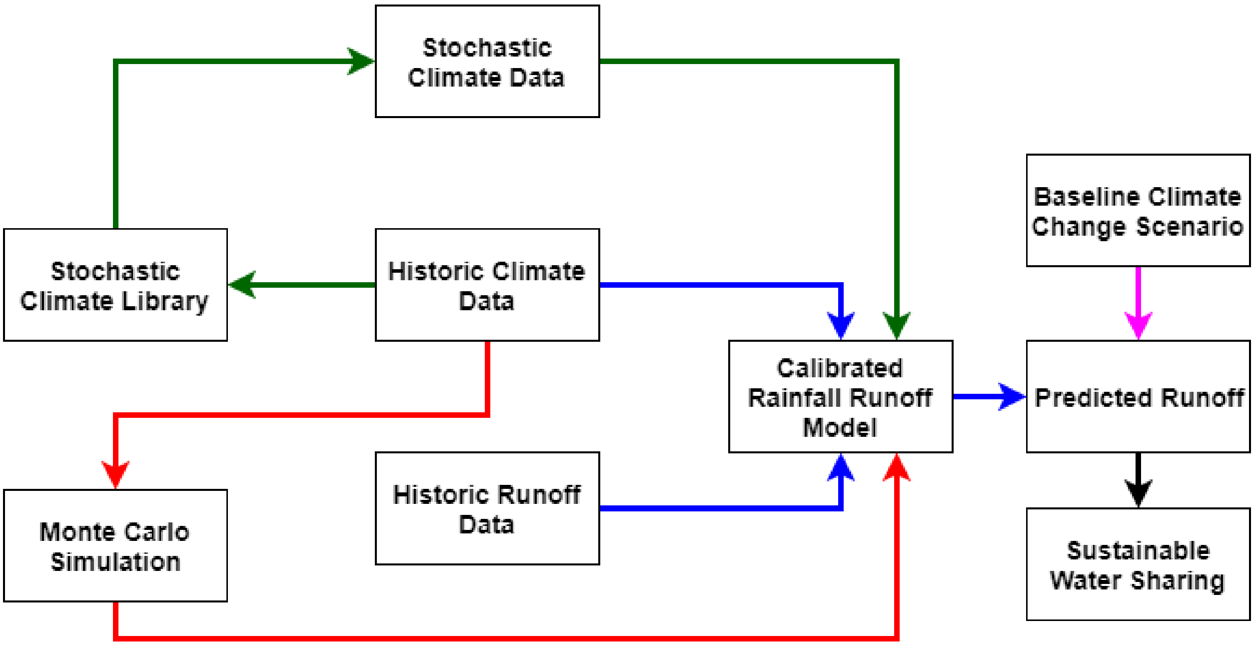


Figure 5-16: Decision-making Tool for Sustainable Water Sharing

5.4.1 Calibrated rainfall-runoff model

The first phase of the Decision-Making Tool is the calibration of an appropriate rainfall-runoff model. Daily time series of rainfall, PET and observed runoff from 1987 to 2012 are the input data. Using the Theisen Polygon method, the average rainfall of this sub-catchment was worked out as shown in Figure 5.17.

An appropriate rainfall-runoff model was selected such that the maximum NSE values were obtained for calibration and verification. All the five models available within the eWater toolkit RRL viz, SimHYD, SMAR, TANK, AWBM, Sacramento were primarily tested for its NSE values, and the best value obtained for each model was taken for comparison. This was done by running each model for all the available optimisation methods but keeping the primary objective function as NSE. These best value results of NSE are presented in Table 5.8. From these results, it can be concluded that Sacramento has performed better than all other models.

Table 5-8: Comparison of Different Models' NE Values

NSE Values	SimHYD	SMAR	TANK	AWBM	Sacramento
Calibration	0.832	0.739	0.777	0.833	0.853
Verification	0.809	0.522	0.762	0.833	0.840

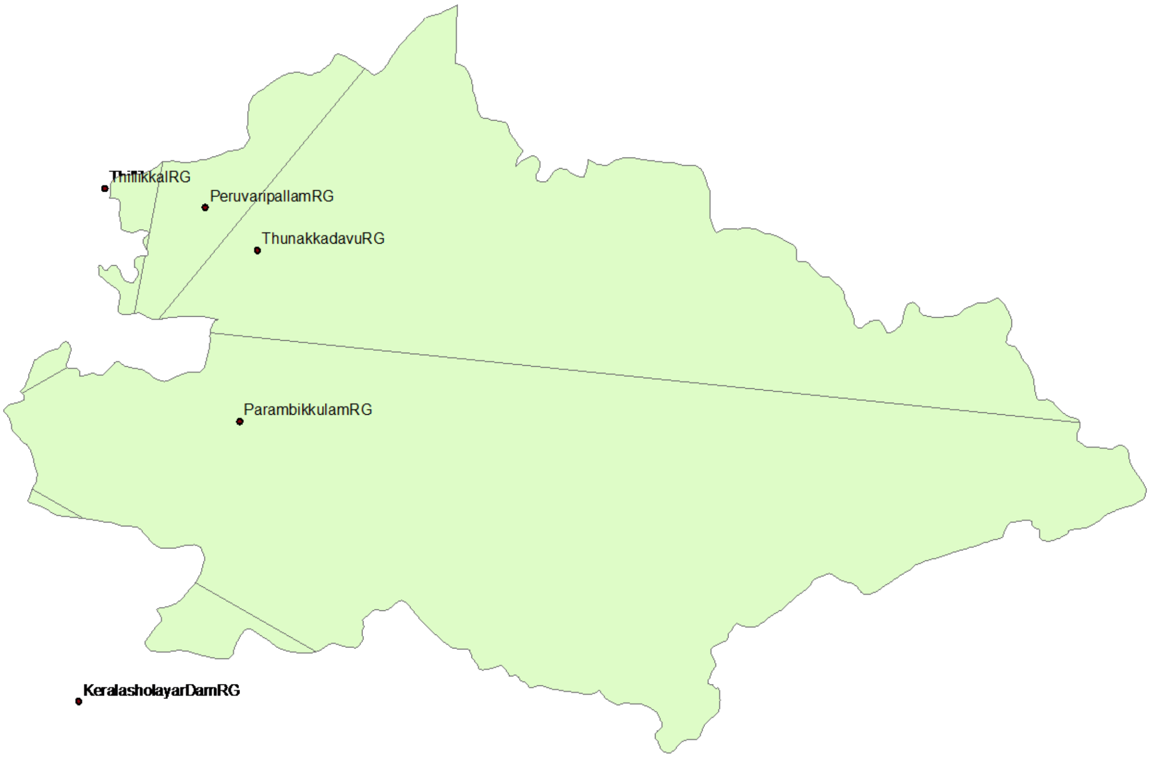


Figure 5-17: Theisen Polygon for Average Rainfall Computation

The scatter plot of Sacramento calibration and verification results are presented in Figure 5.18. Model calibrated using the initial eight years' data and verified with the following four years data. The calibration was carried out using the NSE as the objective function, and multi-start pattern search algorithm was used for the optimisation of the model parameters. The optimised parameter values of calibration as viewed in the model output are directly reproduced in Table 5.9. It may be noted that the calibration and verification of NSE values are in the same range (calibration 0.853 and verification 0.84) and hence the model exhibits a stable behaviour. These ranges of values are obtained despite the lack of rainfall gauging stations in the upper region of the catchment (as can be seen in Figure 5.18) and hence the model performance can be considered as very good.

To have a better insight into the model performance, the model output of total monthly flows from 1994 to 2005 are presented in Figure 5.19 along with actual monthly flows. The model output and actual output match reasonably well. However, some of the peak values after 1999 overestimates the observed ones, may be due to change in the pattern of rainfall. Figure 5.20 gives the scatter plot of the monthly flows. Its spread is distributed evenly about the 45-degree line, indicating the lack of bias in the model output. The actual flows in the catchment are observed using the stage discharge relationship established in the exiting open channel.

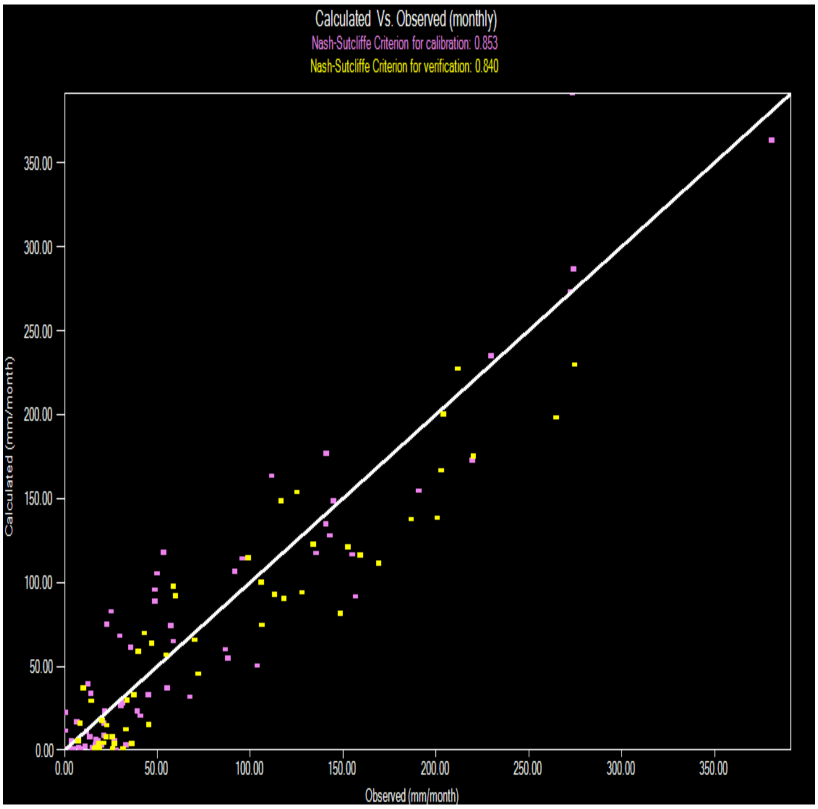


Figure 5-18: Sacramento Calibration Results

Table 5-9: Calibration results

Pattern Search Multi-Start
==================
Number of starts 4
Maximum number of iterations per search30
==================
TIME.Models.Sacramento
Objective value (Nash-Sutcliffe Criterion) : 0.852862157737161
Adimp 0.00328198084760548 0 1 False 2
Lzfpm 48.6515119595693 0 50 False 0
Lzfsm 49.7285127242694 0 50 False 0
Lzpk 0.0379368734024171 0 1 False 2
Lzsk 0.0414944099921241 0 1 False 2

Lztwm 393.713323228859 0 400 False 0
Pctim0.0673801774240007 0 1 False 2
Pfree 0.998304697334909 0 1 False 2
Rexp 0.121510686293017 0 3 False 2
Rserv 0.300000011920929 0 1 True 2
Sarva 0.00999999977648258 0 1 True 2
Side 0 0 1 True 2
Ssout 0.00100000004749745 0 1 True 2
Uzfwm 77.9582258099496 0 80 False 0
Uzk 0.099003251059448 0 1 False 2
Uztwm 39.7266437391409 0 100 False 0
Zperc 8.31919574007354 0 80 False 0
Calibration Statistics:
Performed a total of 1664 runs and 1664 objective function evaluations in 0h 1min.57 s

Even then, the stage discharge relationship can show some variation for extremely low flows and extremely high flows. The loop rating effect of Stage-Discharge curve during unsteady flow can also cause this effect. Since the prediction aims at the volume rather than peak values, a cumulative plot of the model output and actual discharges are given in Figure 5.21. The cumulative plot of total flow both from the model output and actual flow, match well, though there is slight variation in between.

The plot indicates that the total volume of computed and actual flow match well and shows the model stability. Hence, from these three figures, it can be concluded that the simulated flow follows the same pattern as that of the observed flow though there is a slight deviation in the average flow values. It implies that the Sacramento model was able to capture the rainfall-runoff behaviour of the sub-catchment and hence can be effectively used for predicting the runoff from rainfall and other data.

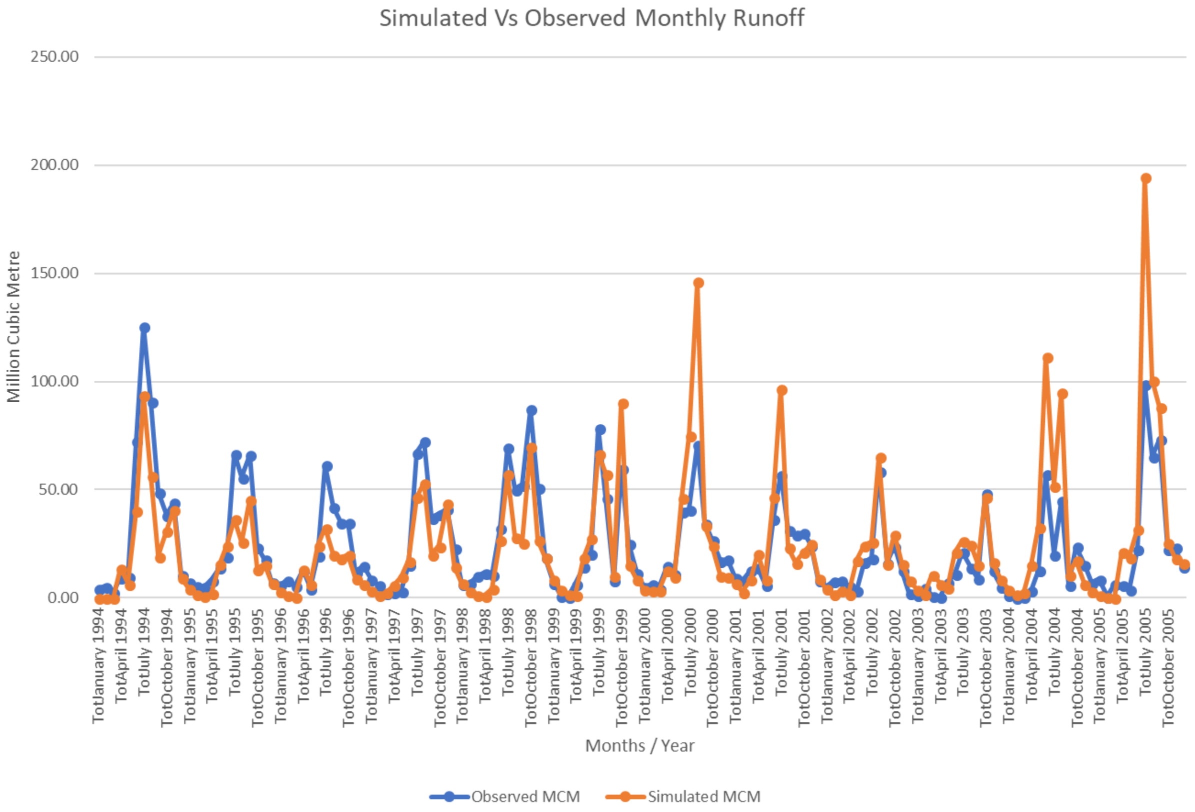


Figure 5-19: Simulated and Observed Monthly Totals

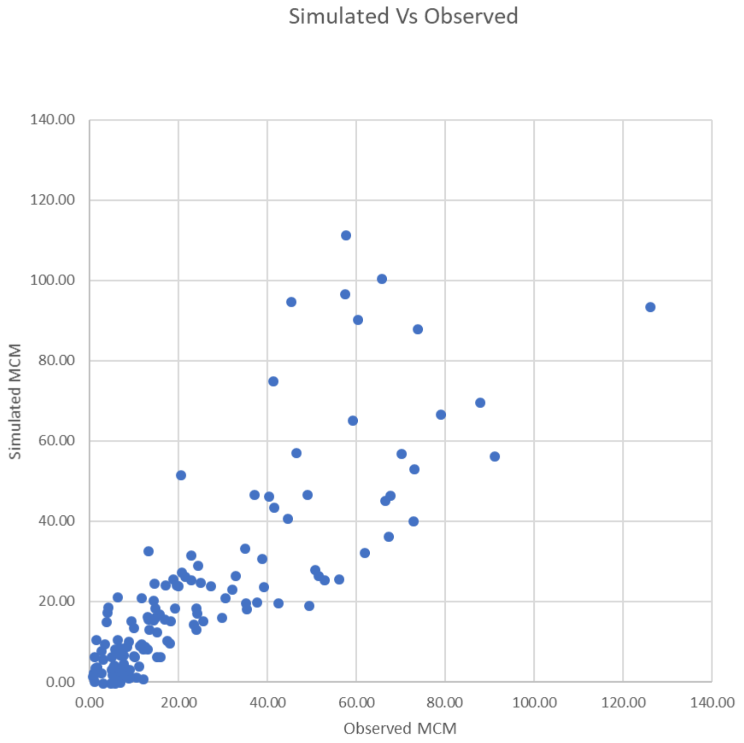


Figure 5-20: Scatter Plots of Observed and Simulated Monthly Flows

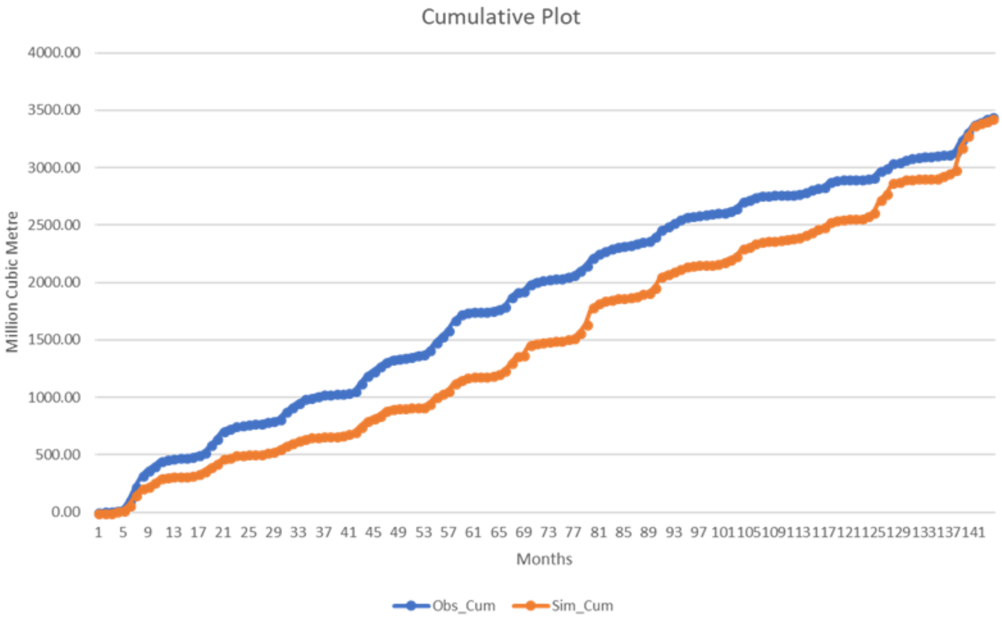


Figure 5-21: Cumulative Plot of Observed and Simulated Outflows

5.4.2 SCL simulation

The second phase of the decision-making tool (Figure 5.16) is to generate stochastic climate data and to predict the runoff corresponding to this data using the Sacramento model (calibrated in the previous section). Stochastic rainfall data is created using the observed daily rainfall from 1987 to 2012. Two replicates of rainfall, created using SCL, are presented in Figures 5.22 and 5.23. The observed rainfall is also shown alongside to appreciate the difference between them.

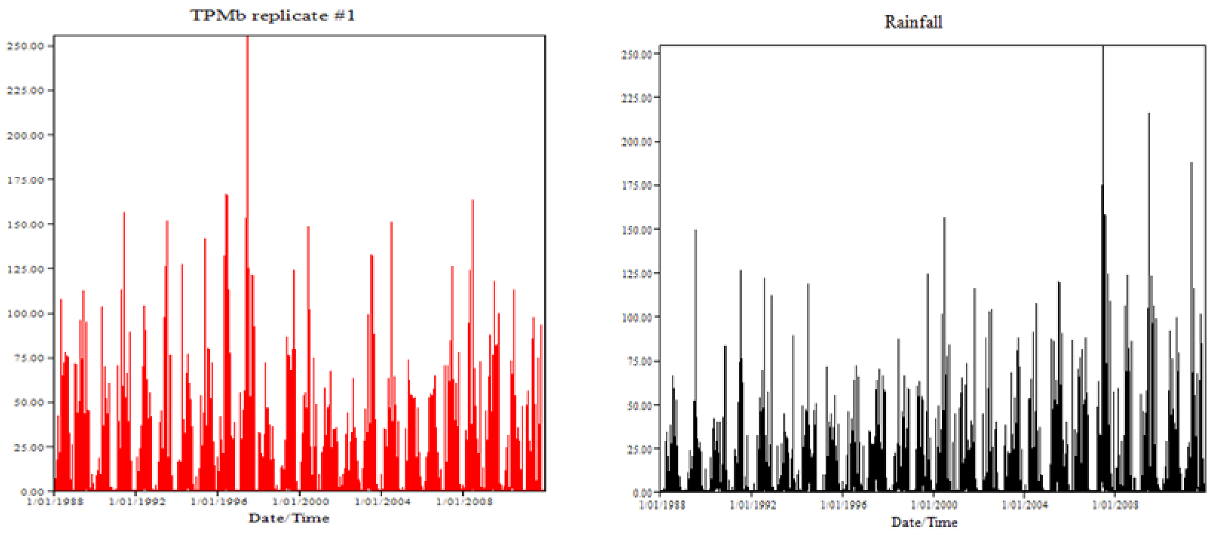


Figure 5-22: SCL Replicate 1 Rainfall and Observed Rainfall

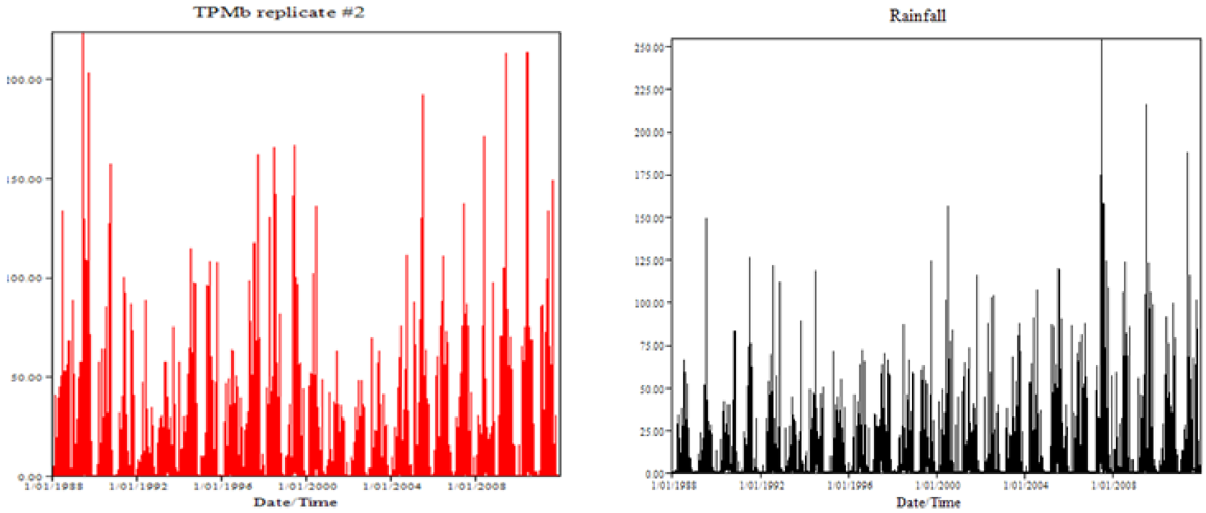


Figure 5-23: SCL Replicate 2 Rainfall and Observed Rainfall

Calibrated Sacramento model simulates the runoff for these two replicates. Simulated daily runoff is analysed using RAP, and the yearly total runoff for each replicate is shown in Table 5.10 and Figures 5.24 and 5.25. The daily runoff output of Replicates 1 and 2 are presented in Annexure (in the CD attached). Replicate 1 and Replicate 2 are the runoff simulated using typical rainfall data generated using SCL. They represent the runoff generated in the catchment due to two different rainfall patterns. They cannot be compared individually. More precisely, each replicate is representing one typical climate scenario.

Table 5-10: SCL Replicates Analyzed Using RAP

Year	Replicate 1 Runoff Mm^3	Replicate 2 Runoff Mm^3
1	373.04	927.62
2	491.09	571.18
3	237.86	219.07
4	515.86	177.89
5	679.17	178.96
6	272.54	380.04
7	202.12	448.12
8	574.02	315.96
9	609.70	554.10
10	754.67	541.49

Year	Replicate 1 Runoff Mm^3	Replicate 2 Runoff Mm^3
11	139.14	740.12
12	541.36	259.36
13	299.16	192.61
14	199.82	162.51
15	169.09	175.38
16	381.66	349.03
17	417.45	489.62
18	227.70	363.04
19	540.22	441.31
20	603.81	317.14
21	458.61	626.98

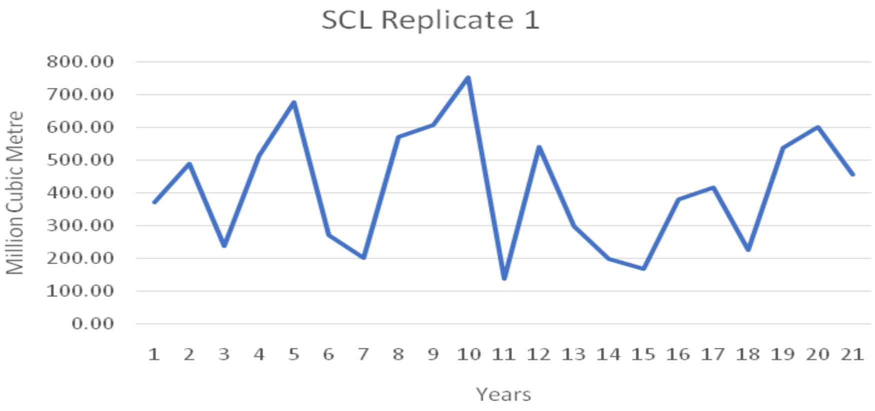


Figure 5-24: SCL Replicate 1

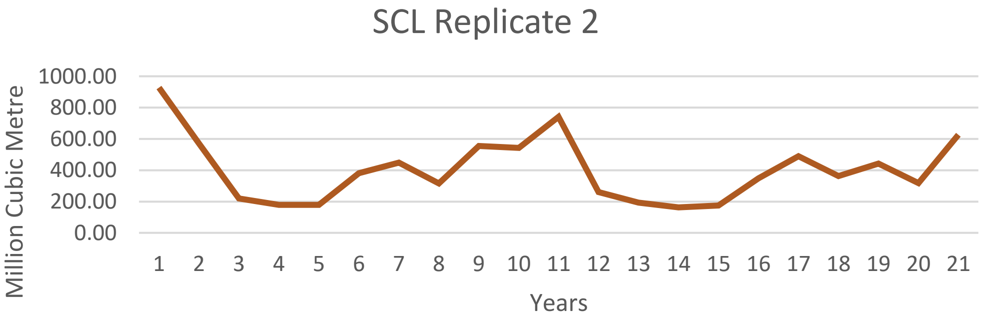


Figure 5-25: SCL Replicate 2

General statistics of these two replicates compared with that of historicalal data are also analysed using RAP, and its results are presented in Table 5.11. Most of the statistical parameters of historicalal data are significantly lower than replicates one and two which shows that the climate variability can be accounted by applying SCL data. The seasonal variations of runoff from the SCL are shown in Figure 5.26. The runoff predicted using SCL data shows the same seasonal changes as that of historical data. It shows the reliability of SCL generated runoff.

Table 5-11: Replications General Statistics

Statistic	Historical	Replicate 1	Replicate 2
Minimum	0.00	29.39	5.56
Maximum	17242.17	27686.64	66558.51
Percentile 10	0.00	77.21	49.50
Percentile 90	1904.63	1975.82	2555.38
Mean	774.16	866.08	1148.36
Median	362.18	404.31	474.07
CV	1.66	1.95	2.20
Standard Deviation (SD)	1287.83	1686.79	2521.39
Skewness (Mean/Median)	2.14	2.14	2.42
Variability	-5.26	-4.70	-5.29
Number of Zero Days	1012.00	0.00	0.00
SD of the log of daily flows (S_Log)	1.06	0.52	0.61
Lanes Variability Index (Lanes)	1.03	0.53	0.65

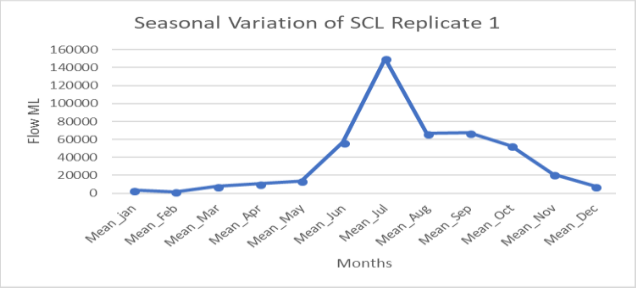


Figure 5-26: Seasonal Variation of Mean Monthly Runoff Predicted Using SCL Data

5.4.3 Monte Carlo Simulation

The third phase in the decision-making tool (Figure 5.16) is a Monte Carlo simulation of yearly runoff. Using RAP, Monte Carlo simulation of the historicalal database is taken up to generate additional sets of runoffs. Among the1000 iterations which are carried out for a span of 1 to 20 years, two iterations are randomly chosen. Runoff simulated using Sacramento model is used to generate additional 20 years data. Maximum span length of only twenty years is possible with RAP, and hence the iteration span length is fixed as twenty years. Yearly runoff for twenty years of the two iterations is analysed using RAP, and their results are shown in Table 5.12 and Figures 5.27 and 5.28. The daily runoff output of iteration 1and 2 are presented in Annexure (in the attached CD). Iteration 1 and 2 runoff values represent typical runoff possible in any two years. They are generated using the Monte Carlo simulation of historical data. These values are also representing two typical scenarios that may happen.

Table 5-12: Monte Carlo Simulated Iteration

Year	Iteration 1 Runoff Mm^3	Iteration 2 Runoff Mm^3
1	173.00	267.96
2	248.33	436.64
3	195.25	193.41
4	299.84	404.25
5	434.04	237.38
6	189.67	204.12
7	409.82	303.23
8	236.91	333.56
9	200.05	372.26
10	307.55	466.43
11	332.67	345.69
12	364.57	280.59
13	460.05	241.45

Year	Iteration 1 Runoff Mm^3	Iteration 2 Runoff Mm^3
14	355.40	404.14
15	270.80	648.47
16	246.30	542.02
17	409.39	1106.61
18	635.07	552.64
19	560.49	669.23
20	1090.52	516.79

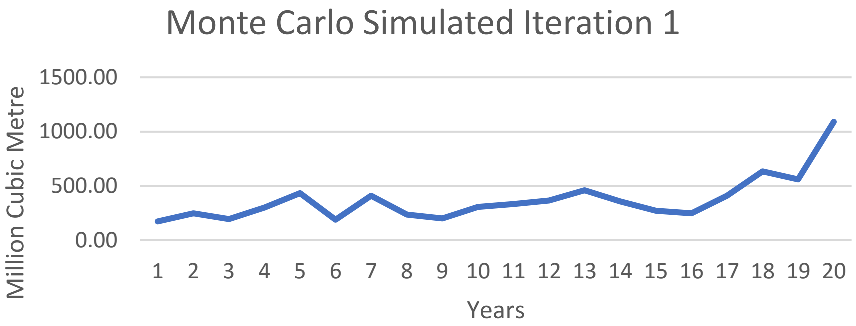


Figure 5-27: Monte Carlo Simulated Iteration 1

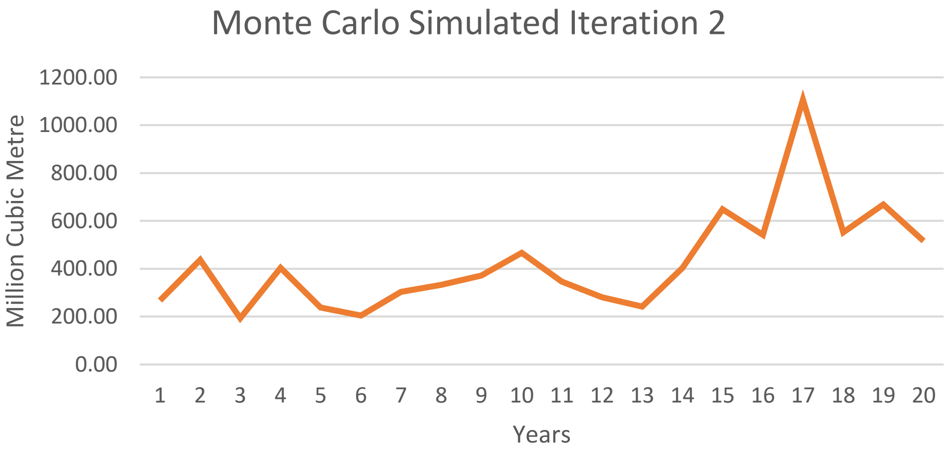


Figure 5-28: Monte Carlo Simulated Iteration 2

The general statistics of yearly runoff data (simulated in this manner) are compared with that of historical data set in Table 5.13. Most of the statistical parameters of historicalal data are significantly lower than the iterations 1 and 2, as observed in SCL data. This statistic of the climate data shows that the variability can be accounted by applying Monte Carlo Simulated data.

Table 5-13: Iterations General Statistics

Statistic	Historical	Iteration 1	Iteration 2
Minimum	0.00	0.00	5.19
Maximum	17242.17	75146.30	75146.30
Percentile 10	0.00	50.90	59.82
Percentile 90	1904.63	2136.44	2396.03
Mean	774.16	1015.58	1167.13
Median	362.18	452.24	503.69
CV	1.66	2.46	2.45
Standard Deviation (SD)	1287.83	2502.10	2862.73
Skewness (Mean/Median)	2.14	2.25	2.32
Variability	-5.26	-4.61	-4.64
Number of Zero Days	1012.00	15.00	0.00
SD of the log of daily flows (S_Log)	1.06	0.59	0.58
Lanes Variability Index (Lanes)	1.03	0.61	0.60

The runoff predicted using Monte Carlo Simulated data is also showing same seasonal variations as that of historical data. The seasonal changes of runoff predicted using Monte Carlo Simulated data are shown in Figure 5.29.

5.4.4 Baseline Climate Change Scenario

The fourth and last phase in the decision-making tool (Figure 5.16) is the adjustment of the runoff based on the baseline climate change scenario which is predicted for this catchment. The baseline climate change scenario for this sub-catchment has been predicted by the Ministry of Environment and Forests & Climate Change, India (MoEF & CC). The application of GCM and RCM for climate change analysis has not been directly carried out in this study as it has already been done by the MoEF & CC for this sub-catchment. The climate change prediction for this sub-catchment is in the range of -10% to -24 % of baseline runoff (Gosain et al., 2011, Ministry of Environment and Forests Government of India, 2012).

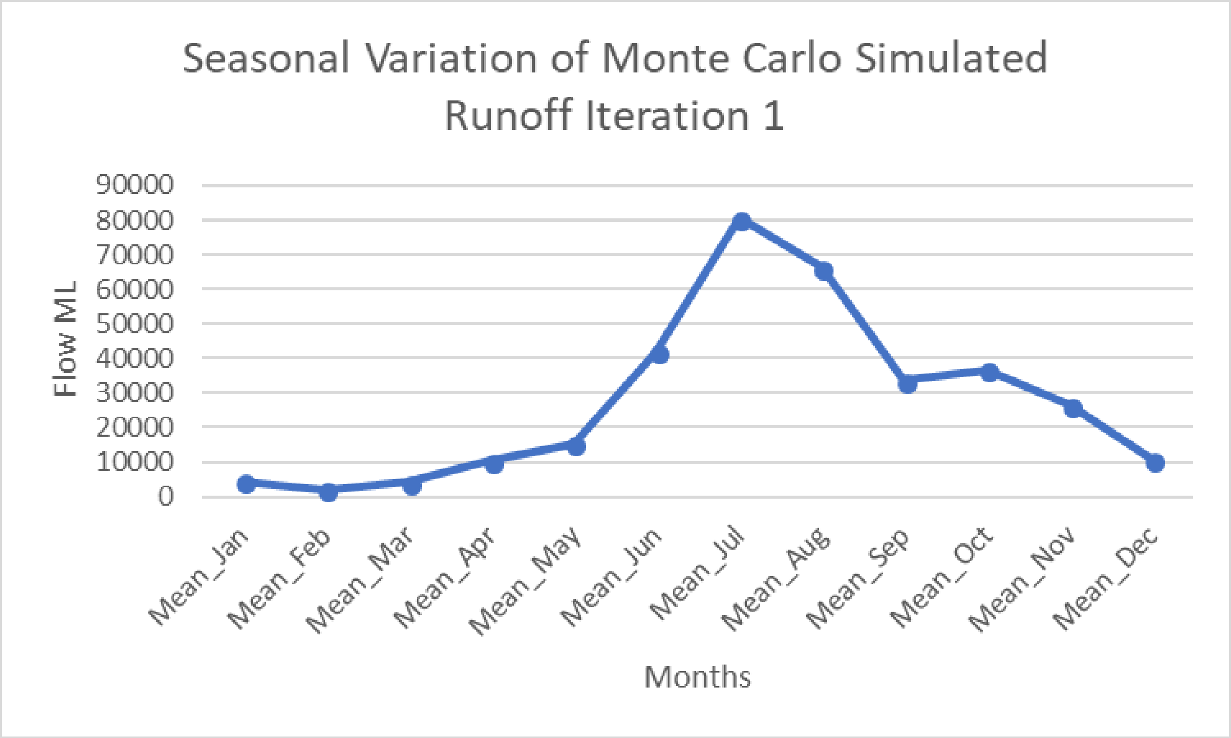


Figure 5-29: Seasonal Variation of Mean Monthly Runoff Predicted Using Monte Carlo Simulation

Baseline runoff to apply this change is estimated from the combined data set (Table 5.14) generated by pooling the historical runoff data, SCL simulated runoff data and Monte Carlo simulated runoff data. 75% dependable runoff estimated from this combined database is taken as the baseline runoff which is 241.45 Mm^3. Applying -10% to -24% change in this runoff, the expected dependable runoff values will be in the range of 183.5 Mm^3 to 217.3 Mm^3 (see Table 5.15). These three values, 183.5 Mm^3, 217.3 Mm^3 and 241.45 Mm^3, are taken as case 1, case 2 and case 3 respectively in the subsequent analysis.

5.5 Sustainable Water Sharing Model for Parambikulam Sub Catchment

The dependable runoff from Parambikulam sub-catchment, on which the sharing must base is shown in Table 5.15. As discussed in section 4.3.1, the net dependable runoff available for sharing must be ascertained from this, after setting apart the contribution towards E Flows. Results of E flow modelling of the entire Chalakudy basin is presented in section 4.5. It was concluded in this section that, an additional flow requirement of 92 Mm^3, over and above the existing current flows, is required to maintain the E flows in Chalakudy basin. The share of Parambikulam sub-catchment towards this 92 Mm^3 must be fixed to work out the dependable net flows and is estimated in proportionate to the area of this sub-catchment compared with the total area of the watershed.

Table 5-14: Combined Data Set Generated by Pooling the Historical Runoff Data, SCL Simulated Runoff Data and Monte Carlo Simulated Runoff Data

Year	Runoff Mm^3	Year	Runoff Mm^3	Year	Runoff Mm^3	Year	Runoff Mm^3
1	175.47	29	515.86	57	332.67	85	669.23
2	329.83	30	679.17	58	364.57	86	516.79
3	178.84	31	272.54	59	460.05	87	927.62
4	181.08	32	202.12	60	355.40	88	571.18
5	311.66	33	574.02	61	270.80	89	219.07
6	361.22	34	609.70	62	246.30	90	177.89
7	310.90	35	754.67	63	409.39	91	178.96
8	418.62	36	139.14	64	635.07	92	380.04
9	294.99	37	541.36	65	560.49	93	448.12
10	238.76	38	299.16	66	1090.52	94	315.96
11	359.06	39	199.82	67	267.96	95	554.10
12	380.14	40	169.09	68	436.64	96	541.49
13	312.61	41	381.66	69	193.41	97	740.12
14	295.92	42	417.45	70	404.25	98	259.36
15	227.92	43	227.70	71	237.38	99	192.61
16	159.50	44	540.22	72	204.12	100	162.51
17	186.96	45	603.81	73	303.23	101	175.38
18	165.95	46	458.61	74	333.56	102	349.03
19	361.86	47	173.00	75	372.26	103	489.62
20	236.03	48	248.33	76	466.43	104	363.04
21	451.27	49	195.25	77	345.69	105	441.31
22	203.95	50	299.84	78	280.59	106	317.14
23	289.31	51	434.04	79	241.45	107	626.98
24	320.99	52	189.67	80	404.14		
25	277.17	53	409.82	81	648.47		
26	373.04	54	236.91	82	542.02		
27	491.09	55	200.05	83	1106.61		
28	237.86	56	307.55	84	552.64		

Table 5-15: 75% Dependable Runoff Values

Category	75 % Dependable Runoff in Mm^3
Originally Estimated (As given in the agreement)	467.2
Physically Observed Historical	203.9
Modelled with Decision Making Tool without Baseline Climate Change Scenario	241.45
Modelled with Decision Making Tool with Baseline Climate Change Scenario	183.5 – 217.3

Chalakudy basin has three sub-catchments and their areas are shown in Table 5.16. Therefore, the proportionate contribution from Parambikulam sub-catchment is 26.3 Mm^3. However, this will vary according to the thresholds being used in the E Flow modelling and the targeted FH score. E Flows share under default threshold conditions for an FH score of 0.8 is 23.8 Mm^3. E Flows share under custom selected thresholds for FH scores 1 and 0.8 are 111.6 Mm^3 and 55.1 Mm^3 respectively. Accordingly, the E Flows contribution from Parambikulam sub-catchment and its net dependable runoff in the three cases are presented in Table 5.17.

Table 5-16: Areas of sub catchments in Chalakudy Basin

Sub Catchment	**Area in km^2**
Poringalkuthu	512
Sholayar	314.4
Parambikulam	331
Total	1157.4

Table 5-17: Different Cases of Net Dependable Runoff

Threshold	75% Dependable Runoff			Targeted FH Score	E Flow Share Mm3	Net Dependable Runoff Mm3		
	Case 1	Case 2	Case 3			Case 1	Case 2	Case 3
Default	183.5	217.3	241.45	1	26.3	157.2	191	215.15
				0.8	23.8	159.7	193.5	217.65
Custom Selected				1	111.6	71.9	105.7	129.85
				0.8	55.1	128.4	162.2	186.35

Case 1: Lower limit of baseline runoff with climate change scenario

Case 2: Upper limit of baseline runoff with climate change scenario

Case 3: Baseline runoff without climate change scenario

The Dependable Net Runoff (NDRO) for cases 1,2 and 3 of custom selected thresholds is substantially low. This indicates that, if E Flows are provided based on custom selected thresholds, the volume available for IBWT will be much lesser and the scope for water sharing will be limited. However, to have an insight into the sharing pattern in the IBWT, the NDRO for default and custom selected thresholds may have to be considered. This NDRO may be shared in a deterministic or stochastic manner. Two examples of each of the possible sharing under deterministic or stochastic conditions are discussed below.

5.5.1 Deterministic Sharing – Option 1

In this option, the NDRO is shared between Tamil Nadu and Kerala in the ratio of 396.4: 70.8; this is the originally contemplated ratio of sharing. The entitlements of Kerala and Tamil Nadu for case 2 NDRO under default and custom selected thresholds are shown in Table 5.18 and Figure 5.30. Under the custom selected thresholds, the entitlements of Kerala and Tamil Nadu are almost one half of the entitlements under default thresholds. Under the deterministic sharing option -1, if the NDRO exceeds the values 191Mm3 or 105.7 Mm3, depending upon the threshold being selected, the extra flows are expected to flow down the sub catchment, enriching the main river.

Table 5-18: Kerala - Tamil Nadu Entitlements under Deterministic Sharing Option 1

Threshold	Case 2 NDRO Mm3	Kerala Share Mm3	TN Share Mm3
Default	191	28.94	162.06
Custom	105.7	16.02	89.68

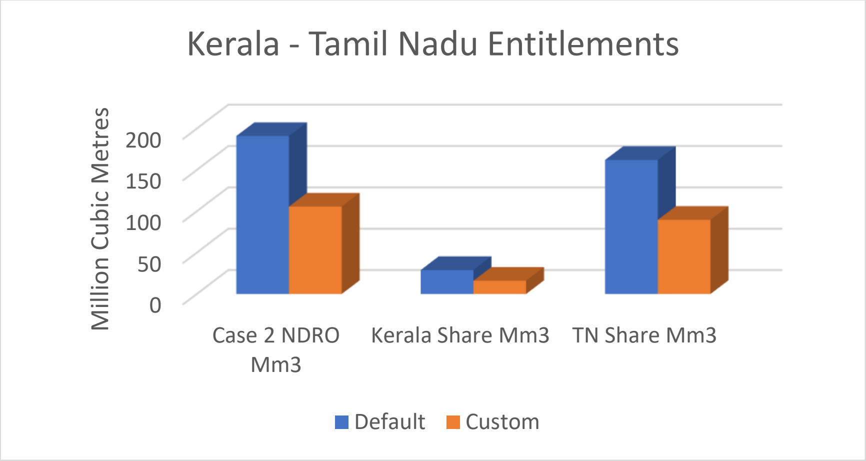
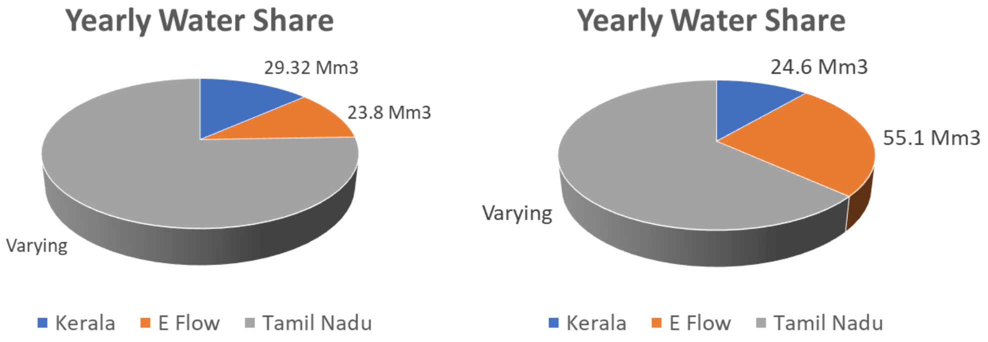


Figure 5-30: Entitlements of Kerala and Tamil Nadu under Deterministic Sharing Option 1

5..5.2 Deterministic Sharing – Option 2

In this option, Tamil Nadu is permitted to divert all the waters after ensuring E Flows contribution and Kerala’s deterministic entitlement proportional to the NDRO. In this, only Kerala’s entitlements and E Flows contribution are fixed. Tamil Nadu’s entitlement will be the flows in excess of meeting Kerala’s entitlement and the E Flows share. This will be varying. The entitlements of Kerala and Tamil Nadu for case 2 NDRO under default and custom selected thresholds of $FH_{0.8}$are shown in Figure 5.31.



E Flow Default Threshold, FH 0.8 E Flow Custom Threshold, FH 0.8

Figure 5-31: Entitlements of Kerala and Tamil Nadu and E Flows Contribution under Deterministic Sharing Option 2

5.5.3 Stochastic Sharing Option 1

In this option, the net dependable runoff after allocating E Flows is shared in the ratio 396.4:70.8 between Tamil Nadu and Kerala.

1. In each year the allocation to Kerala and Tamil Nadu will be different
2. Each month’s allocation must be computed successively
3. Each month’s share towards E Flows for an FH score of 1 or 0.8 must be worked out

This pattern will have a monthly system of sharing. Applying this pattern of sharing to the real-time data of the water year 2014-15 is demonstrated in Table 5.19 by taking default FH_1 demand for E Flows. Total runoff in the year was 268.15 Mm^3 as accumulated for 12 months. The monthly allocation of FH_1 is 2.19 Mm^3. NDRO of each month is worked out by deducting the E Flow reserve from the total run off in the month. This quantity is shared between Kerala and Tamil Nadu in the ratio of 396.4:70.8. This would facilitate distress sharing. When the NDRO of a month is varying significantly from what is normally expected, the distress will be shared by both the states. Same will be the case when surplus occurs. In the case of extreme climatic events this is particularly important.

Table 5-19: Stochastic Sharing Option 1 Applied to the Year 2014-15

Month	Total Runoff Mm^3	E Flow Reserve FH$_1$ Mm^3	NDRO Mm^3	TN Share Mm^3	Kerala Share Mm^3
Jul	53.41	2.19	51.22	43.46	7.76
Aug	70.49	2.19	68.30	57.95	10.35
Sep	39.44	2.19	37.25	31.61	5.65
Oct	23.81	2.19	21.61	18.34	3.28
Nov	10.93	2.19	8.73	7.41	1.32
Dec	4.60	2.19	2.41	2.04	0.36
Jan	9.91	2.19	7.72	6.55	1.17
Feb	2.68	2.19	0.49	0.41	0.07
Mar	16.83	2.19	14.63	12.42	2.22
Apr	8.29	2.19	6.10	5.17	0.92
May	4.54	2.19	2.34	1.99	0.36
Jun	23.23	2.19	21.04	17.85	3.19
Total	268.15	26.30	241.85	205.20	36.65

5.5.4 Stochastic Sharing Option 2

This option applies to the Decision-Making Tool for Sustainable Water Sharing (DMTSWS) in a comprehensive manner. In this case, the DMTSWS is run at the beginning of every water year after incorporating the previous years’ rainfall and runoff data. The net dependable runoff is modified in this manner as ModNDRO. In the next stage, the SWMPRO (South West Monsoon Period Runoff; June to September) of the current year is taken, and its value as a percentage of ModNDRO is assessed. Sharing ratio is decided based on this percentage range. This procedure is schematically shown in Figure 5.32.

An additional check for identifying the extreme low years is also to be performed under this option. It is carried out by considering the upstream storages also as a deciding factor. The combined net storage of Parambikulam, Thunacadavu, Peruvaripallam, TN Sholayar and Lower Nirar as on 30th September is compared with the consolidated net FRL storage of these reservoirs and is expressed as a percentage. (TN Sholayar and Lower Nirar are included in this as water can be diverted to Parambikulam sub-catchment from these two reservoirs using the IBWT network.) When this percentage is less than 65, it is identified as an extremely low year, and the sharing ratio is modified accordingly. This procedure is schematically shown in Figure 5.33. In the case of extreme low years, Tamil Nadu gets 100% of the NDRO.

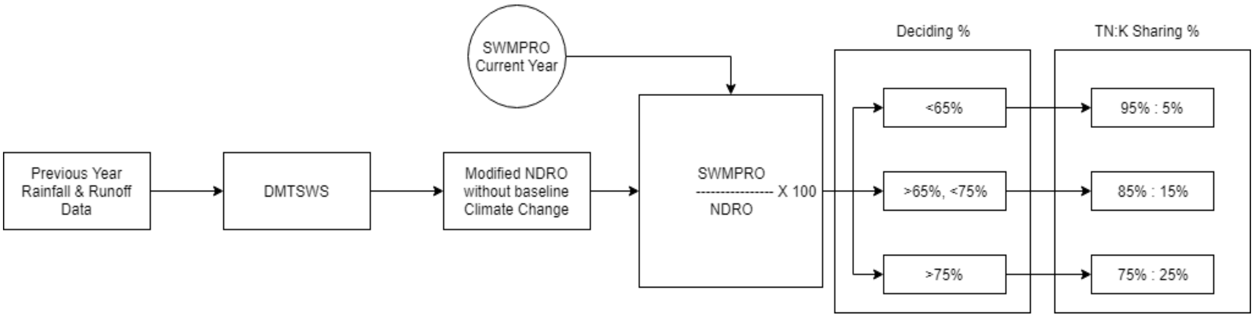


Figure 5-32: Schematic Diagram of Stochastic Sharing Option 2

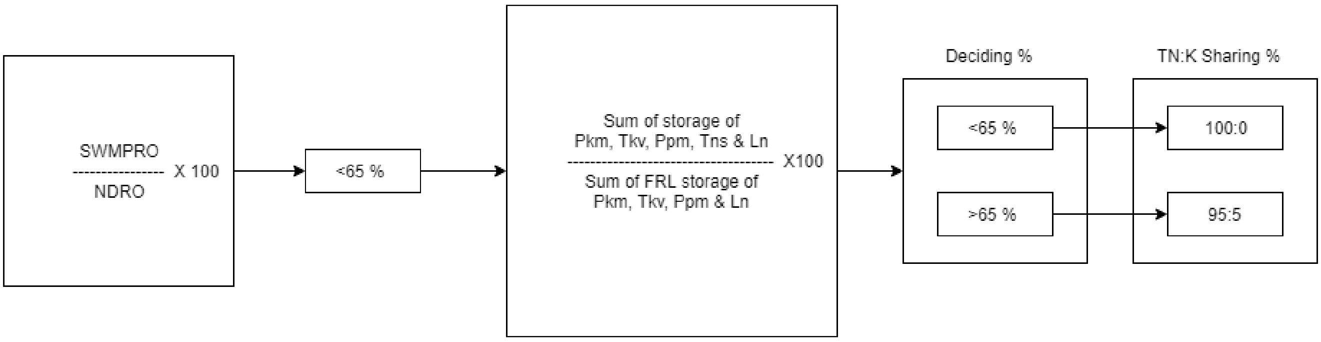


Figure 5-33: Extreme Low Year Check

Table 5-20: Stochastic Sharing Option 2 Performance Test

Year	Runoff Mm3	Mod NDRO Mm3	SWMPRO Mm3	SWMPRO/Mod NDRO %
2012-13	65.8	207.26	31.68	15.29
2013-14	314.19	207.26	251.71	121.45
2014-15	251.05	207.26	169.48	81.77
2015-16	167.06	206.02	110.86	53.81
2016-17	88.24	206.02	60.23	29.24

Performance Test

The performance of stochastic sharing option two is tested with the real-time data of 2012-13 to 2016-17. Table 5.20 shows its results. It shows that the years 2012-13, 2015-16 and 2016-17 are to be checked for extreme low year condition. These are the years in which the SWMPRO is less than 65% of NDRO. Results of extreme low year check are shown in table 5.21.

Table 5-21: Extreme Low Year Check Results

Year		PKM Mm3	TKV Mm3	PPM Mm3	TNS Mm3	LN Mm3	Sum Storage Sept 30th Mm3	Percentage of FRL Storage
2012-13		299.97	14.93	16.45	153.03	3.11	487.48	69.80
2015-16		399.52	15.63	17.37	107.46	3.14	543.12	77.77
2016-17		262.07	15.61	17.34	80.64	3.11	378.77	54.24

PKM: Parambikulam TKV: Thunacadavu PPM: Peruvaripallam TNS: Tamil Nadu Sholayar LN: Lower Nirar

Extreme low year check results show that 2016-17 is an extreme low year. Therefore, during this year, Tamil Nadu will be permitted to divert the entire runoff from this sub catchment

5.5.5 Most Sustainable Sharing Option:

Two options of deterministic sharing and two options of stochastic sharing are discussed in the previous subsections. The sustainability index (SI) of these sharing options can be assessed numerically by the equation 2.1 and hence identify the most suitable option. Numerical computation of SI is possible if all the field level utilization data of water is made available. Though the field level utilization data of water from Kerala side is available, the data from Tamil Nadu is not available. No joint gauging of these values is prescribed in the present agreement on water sharing and hence it is not mandatory on Tamil Nadu to provide this data. Values of the performance criteria like reliability, resilience, vulnerability etc. to be used in the numerical computation of SI can be assessed only if these data are available. Under these circumstances, a qualitative analysis of the situation is carried out. Because of the reasons listed below, stochastic sharing option 2 is the most sustainable one among all these four options.

1. Dependable flows are precisely modified under this option and are not a static one
2. Sharing is perfectly stochastic
3. Sharing is made more equitable by introducing extreme low year check
4. Dynamism is explicit in this sharing model

In the initial discourse on sustainability, it was concluded that sustainability of any policy on water sharing must be ascertained with respect to its reliability, resilience and vulnerability. The policy implied in stochastic sharing option 2 discussed here is more reliable as the dependable flows are modified every year. This is also more resilient to extreme climatic events as the sharing contemplated is stochastic. Additional incorporation of an extreme low year check reduces significantly the vulnerability. The factor of dynamism inbuilt in this sharing model also reduces the vulnerability and improves reliability and resilience. This study is concluded with the qualitative analysis of sustainability because of the unavailability of the field level utilization data in the present context. If ISWDT is constituted, numerical assessment of the SI of most sustainable water sharing option is possible, provided both the states are depositing their actual field level water utilisation data.

5.6 Summary

In this chapter, the results of fourth, fifth and sixth objectives of the research topic are discussed, and it is concluded by identifying the most sustainable water sharing option for Parambikulam sub-catchment. This model can be adopted in the following cases.

- Other sub-catchments of PAP
- Other sub-catchments of existing IBWT links
- Other sub-catchments of proposed IBWT links
- Interstate river catchments to be shared

It can also be used extensively by the ISWDT.

Chapter 6

6. SUMMARY AND CONCLUSIONS

This chapter summarises the study and provides significant conclusions. The summary is organised in the order of objectives.

6.1 Summary

Spatial and temporal variations in water availability is a major challenge in water resource management. IBWT is a technological innovation believed to be capable of addressing this challenge. Though the Government of India is actively considering many new IBWT networks, there are many problems associated with this concept. Water conflicts are predominant in the already executed IBWT networks. Significant gaps exist in the research on how an IBWT framework becomes a sustainable water sharing model. Lack of appropriate decision-making tool for the design and implementation of a sustainable water sharing model is one of the critical areas that need specific attention. Also, a suitable methodology for E Flows modelling of the basins is not available in Indian IBWT. In this study, these issues are addressed by taking a case study of PAP, Asia's largest IBWT network.

Aiming for a sustainable water sharing model for IBWT projects, the research agenda for this study has been built up with six objectives. The first objective in this research agenda is the analysis of the existing water sharing pacts from their sustainability perspective. A critical review of the proposed policy guidelines on water sharing in India, as contemplated by its Ministry of Water Resources, is taken up first. Some of the critical areas that are found to be missing or not taken care of by the proposed policy guidelines in India are discussed in this review.

Three existing global models of water sharing are analyzed in the next section. Qualitative indicators of sustainability, most relevant in the case of water sharing pacts, are initially identified to support this analysis. This identification was made based on the three postulates of sustainable water sharing as evolved from the critical review of policy guidelines on water sharing proposed in India. 'Sharing without any conflict on environment and ecosystems', 'sharing without any dispute on the resource availability constraints' and 'sharing without any disagreement on the needs of the states' are the three postulates. The five indicators of sustainability relevant to water sharing are identified. Each of these indicators was crystallised with specific parameters that can be visualised from the pact. Water sharing in

Colorado basin (USA), Murray Darling Basin (Australia) and PAP basins (India) are examined from their sustainability perspective using these qualitative indicators.

In the next section of this study, an ecohydrological framework for negotiating water sharing is evolved based on the results of the examination of existing water sharing pacts. Ecohydrology is the new paradigm for sustainability and is the premises in which this framework has been developed. Essential three components of the ecohydrological framework are suggested in this study. All these components are to be overarched by the stakeholder participation and that is an essential aspect of this framework.

A numerical analysis of PAP's water sharing is carried out in the next section. The water-sharing pattern of Parambikulam sub-catchment in the existing PAP agreement is deterministic. It provides a total quantity of 396.4 Mm^3 to Tamil Nadu. If the total yield from this sub-catchment in any year exceeds this threshold value of 396.4 Mm^3, balance quantity in that year is given to Kerala. From this, up to 70.8 Mm^3 is transferred to Bharathapuzha basin for irrigating Kerala lands in Chitturpuzha valley and the rest is released to Chalakudy basin. Estimation of the dependable flows based on the historical data, now available for a reasonably more substantial period has been worked out. The comparative analysis of various sharing patterns based on 50%, 75% and 90% dependable flows are also carried out. However, for the sharing to be more sustainable, the threshold value used for sharing shall be computed after earmarking the environmental flow requirement for the sub-catchment. E Flows modelling of Chalakudy basin, which forms the basis for fixing E Flows contribution of Parambikulam sub-catchment, is taken up in the next section of this study.

E-Flow modelling of Chalakudy basin is taken up using the hydrological metrics method. A suite of nine hydrological metrics which are of utmost ecological relevance is used for this modelling exercise. Hydrological alteration of the basin due to the construction of PAP is investigated in the first instance using IHA. Based on the historicalal data of flows into PAP reservoirs, the basin is simulated to its pristine condition. IHA is also used to analyse the impact of hydrologic alteration on specific parameters of high ecological significance like extreme low flows, 90 days minimum, 90 days maximum. The 75th percentile, Median and the 25th percentile of all these parameters in the simulated pristine scenario and the current flows scenario are appreciably different.

'Flow Health', a suite of nine hydrological metrics, is used for the actual modelling of E Flows. Using the Flow Health, the E Flows requirement of Chalakudy basin is computed in three ways. Firstly, the Design Flow method with the wetted perimeter; secondly, the default thresholds of Flow Health; and thirdly, the custom selected thresholds are used. The results obtained under these three methods are significantly different because different standards are being used in each method. Results obtained in the first method are over-estimated values of E Flows, practically difficult to implement.

The need to re-estimate the dependable flows using a reasonably larger period data to design a sustainable water sharing pattern was emphasised earlier. A decision-making tool for this purpose is developed in the subsequent section of this study. This tool is designed in such a way that it incorporates a rigorous methodology to account the uncertainties of future climate and its impact on runoff. There are four distinct operational phases in the application of this tool. In the first phase, a suitable rainfall-runoff model is calibrated using the historical climate data and historicalal runoff data. The model is then used to simulate the runoff from other easily obtainable/synthetic climatic data. In the second phase, the SCL of eWater Toolkit is used to generate stochastic climate data. The calibrated rainfall-runoff model is used to predict the runoff for this climate data. In the third phase, the Monte Carlo simulation of runoff using historical climate data is carried out to predict other sets of runoff. The fourth phase incorporates the baseline climate change scenario of this catchment portrayed in India’s second national communication to UNFCCC into the predicted runoff. By using this tool, it is possible to generate runoff data set for reasonably good length. The tool can also incorporate actual climate change study results. It can facilitate informed decision making on dependable runoff which shall be the basis of sharing pattern.

Application of the above decision-making tool to Parambikulam sub-catchment is the next phase of this study. A calibrated rainfall-runoff model for Parambikulam sub-catchment, as suggested in the first phase of the decision-making tool, is developed first. In the second step, stochastic climate data of Parambikulam sub-catchment is generated using SCL. This data is used to generate another runoff set using the calibrated rainfall-runoff model. In the third phase, the Monte Carlo simulation is applied to generate additional sets of runoff. By pooling all these, a database of 107 years is generated for this sub-catchment. 75% dependable flow is worked out using this database. The climate change as predicted in India’s second national communication to UNFCC is incorporated into this dependable flow estimation, subsequently, as suggested in the last phase of the decision – making tool. The result of dependable runoff obtained in a year is in the range of 183.5 – 217.3 Mm^3.

In the last section of this study, a sustainable water sharing model for Parambikulam sub-catchment is attempted, considering the dependable runoff and the E Flows requirement. Contribution to the E Flows requirement of Chalakudy basin from Parambikulam sub-catchment is worked out in proportion to its catchment area. Different sharing patterns for the remaining amount of water, after allocating the E Flows, are discussed in this section. These include two deterministic models and two stochastic models. Major conclusions drawn out of this study are as follows:

6.2 Conclusions

1. A critical review of the proposed policy guidelines on water sharing in India, as contemplated by the Ministry of Water Resources reveals that these guidelines are silent on the importance of ecosystem services of rivers. The most important lacuna of the guideline is that it does not stipulate specific allocations to rejuvenate the ecosystem services while sharing the water resources
2. The five indicators of sustainability relevant for water sharing are identified as ‘dependable flows’, needs assessment’, ‘E Flows’, ‘stochastic’ and ‘dynamism’. Examination of water sharing in Colorado basin (USA), Murray Darling Basin (Australia) and PAP basins (India) from their sustainability perspective using these qualitative indicators reveals that PAP’s water sharing is the least sustainable one, and the Murray Darling basin’s sharing model turned out to be the most sustainable one.
3. An ecohydrological framework is developed for sustainable water sharing. Resource limit identification, defining the needs and allocation commensurate with needs are the essential three components of the ecohydrological framework suggested in this study. The water needs for the environmental purpose are introduced as a constraint in the resource limit identification step itself. The collective definition of needs is modified based on the resource availability
4. A performance evaluation of the water sharing in Parambikulam sub-catchment using the actual data collected from the site showed that deterministic sharing pattern fixed for this sub-catchment has many problems which challenge its sustainability. Lack of realistic dependable flow estimation on which the sharing must rely on is the first one among these challenges. PAP’s water sharing is not sustainable, and that needs to be revisited in the background of the above results.

5. Estimation of the dependable flows based on the historical data, now available for a reasonably larger period, has indicated that the initially fixed value is exorbitantly biased to the higher side. This bias has resulted in making both the parties of the pact unhappy about its performance. The comparative analysis of various sharing patterns, based on the new dependable flows arrived at using historical data, has also shown that the sharing based on 75% dependable flows is more equitable compared to the sharing based on other statistics.
6. Investigation on the hydrological alteration of the basin due to the construction of PAP using IHA model showed that the hydrological alteration of the basin is phenomenal
7. For the practical purpose of river management, the E Flows regime designed using default thresholds with target FH score 1 appears to be more reasonable, and the Chalakkudipuzha, the main basin of PAP has additional flow requirement of 92 Mm^3 to meet the E Flow requirements in a year using that standard.
8. One of the significant outcomes of the study is the development of a decision-making tool which can be utilised in the Indian context where the availability of data is limited. It enables synthetic data generation, rainfall-runoff modelling and can account for climate change. The decision-making tool can facilitate sustainable water sharing. The decision-making model can be adopted in other IBWT projects, ISW projects and by the ISWDTs
9. The stochastic sharing model based on ‘SWMPRO and Extreme low year check’ is the most sustainable water sharing model for the PAP based on qualitative assessment.

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8. LIST OF PUBLICATIONS

Publications in peer reviewed international journals

1. Padikkal, Sudheer, K. S. Sumam, and N. Sajikumar. "Decision Making Tool for Sustainable Water Sharing." *Water Resources Management* 32.14 (2018): 4707-4723.

2. Padikkal, Sudheer, Kottekatt Surendran Sumam, and Neelakantan Sajikumar. "Environmental flow modelling of the Chalakkudi Sub-basin using 'Flow Health'." *Ecohydrology & Hydrobiology* (2018).

3. Padikkal, Sudheer, K. S. Sumam, and N. Sajikumar. "Sustainability indicators of water sharing compacts." *Environment, Development and Sustainability* 20.5 (2018): 2027-2042.

Publications in peer reviewed international conference

1. PADIKKAL, SUDHEER., SUMAM, K.S. & SAJIKUMAR N 2014. A Critical Review of Proposed Policy Guidelines for Sustainable Water Sharing in India. *International Conference on Integrated Water Resources Management.* Kozhikode.

2. PADIKKAL, SUDHEER., SUMAM, K.S., SAJIKUMAR N & SANKHUA R.N 2014. **Modelling Environmental Flows Augmentation for Ecosystem Conservation and Sustainable Water Sharing**. *International Conference on Integrated Water Resources Management.* Kozhikode.

9. ANNEXURE

Annexure of this thesis contains the data used in this study and the different models' outputs. It is presented in the CD attched, as the hard copy will run into more than 2000 pages. A brief description of its contents is given below. *File name with its extension is given in the brackets.*

1. PAP Interstate Agreement between Kerala and Tami Nadu (*PAP AGREEMENT.pdf*)
2. Data used in this study
   a. Gauge - Discharge Data Arangaly (*Gauge-Discharge Data Arangaly,1978-2014.csv*)
   b. Processed input data for Flow Health (*CHKDY_ARANGALY_INPUT.csv*)
   c. Unprocessed rainfall data of various rain gauge stations inside Parambikulam sub catchment (*RAINFALL DETAILS AT PKM.xlsm*)
   d. Unprocessed rainfall data of Kerala Sholayar rain gauge station outside Parambikulam sub catchment (*KS RAINFALL DATA.xls*)
   e. Input rainfall data for RRL model (*InputRainfallmmd.cdt*)
   f. Input runoff data for RRL model (*InputRunoffMLD.cdt*)
   g. Input PET data for RRL model (*InputPETmmd.cdt*)
3. Model outputs
   a. SCL Replicate 1(*SCLRep1.cdt*)
   b. SCL Replicate 2 (*SCLRep2*.cdt)_
   c. Monte Carlo Simulated Iteration 1(*span20Iter1.cdt*)
   d. Monte Carlo Simulated Iteration 2 (*span20Iter2.cdt*)