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A landscape based hydroecological-economic tradeoff analysis on the impacts of cascading dams in India

Anjana Ekka
अंजना एक्का

LARGER IS NOT ALWAYS BETTER: A LANDSCAPE-BASED HYDROECOLOGICAL-ECONOMIC TRADEOFF ANALYSIS OF THE IMPACTS OF CASCADING DAMS IN INDIA

LARGER IS NOT ALWAYS BETTER: A LANDSCAPE-BASED HYDROECOLOGICAL-ECONOMIC TRADEOFF ANALYSIS OF THE IMPACTS OF CASCADING DAMS IN INDIA

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Dedicated to my parents

Preface

Since the start of the modern era, human beings have been pushing their evolutionary boundaries by defying the laws of nature and replacing them with intelligent designs. We have mastered our surroundings by building cities, establishing empires, increasing food production, and creating far-flung trade networks. But did we reduce the amount of suffering on the planet? No doubt, we have made some real progress as far as human beings are concerned with the reduction of famine, war, and plague. However, the situation is deteriorating faster than before. For seeking more comfort and amusement, we are consequently wreaking havoc on our fellow animals and on the surrounding ecosystem. The river is one of the prominent players in our ecosystem is also depleting day by day which is a major concern for the present and the future.

When I first began my research career in Inland open waters, I got a chance to travel extensively across the rivers of India. To name a few, the Narmada, Mahanadi, Brahmaputra, and the oxbow lakes of the Gangetic plains. During my travel, I found that each river resource has the same story of fragmentation, water diversion, aquatic invasives, pollution, and wetland encroachment. By exploiting rivers for our needs such as hydropower, irrigation, and drinking water, we endanger the river's resilience beyond a critical juncture where regeneration is impossible, potentially destroying our rivers forever.

So, do we have to stop using rivers? The hard reality is that rivers can manage without us but we couldn't manage without them. Our survival depends on rivers and therefore it must be used more wisely. Through my research, I have come to understand the intricate web of relationships that exist within the river landscape-how the health of these ecosystems is intimately linked to the well-being of the communities that depend on them.

Managing rivers at the basin level is crucial for ensuring the sustainable use of water resources and maintaining the health of river ecosystems. The concept has been in theory for so long. With the new technological innovation, the time has come to bridge the gap between theory and practice, ensuring the long-term sustainability and vitality of our invaluable river ecosystems.

Hope you enjoy reading this dissertation as much as I enjoyed researching and writing it.

Anjana Ekka

Delft, 2024

Inhoudsopgave

SUMMARY

The natural flows of rivers have been heavily modified in the process of development and economic growth across the basins of the world. This hydrological change affects river ecosystems and their provision of diverse services to society, threatening biodiversity and sustainable basin development. Reservoir construction is one major human activity causing such modification to the river landscape that has largely affected delivery of ecosystem services. This study is motivated to understand how varying patterns of dam development in a basin affect the river flow regime, differentially impacting the provision of river ecosystem services. Focusing on the Upper Cauvery basin in India, the study has developed an integrated modeling analysis examining the ecological and economic impact of varying levels of dam development.

In this study, a modeling framework was developed that links a landscape based hydrological model to tradeoff analysis and that allows for a quantitative assessment of the hydrological-ecological-economic effects of alternative reservoir configurations in a virtual experiment. First, a literature review was conducted to understand the ecological, economic and social impact of anthropogenic modifications of the river landscape. Then, the impacts of dams on river flow regimes were analyzed for the Upper Cauvery basin where the data is available for periods after the construction of dams. Four major reservoirs (Harangi, Hemavathi, Kabini, Krishna Raj Sagara) of varying size, storage capacity and command area were selected for the study. A landscape-based hydrological model, FLEX-Topo, was developed to model the flows contributed by the upstream and downstream areas of the considered reservoirs. Separate models were developed for individual reservoirs to simulate the flow from reservoir operation. The hydrological model was integrated with the reservoir models, and the flows downstream of corresponding reservoirs were calibrated. For each reservoir, the modelled flow regimes with and without reservoirs were then compared using Indicators of Hydrologic Alteration (IHA) to understand the degree of flow modification by the reservoirs. To understand the degree of flow modifications by reservoirs, the study simulates and compares flow regime based on IHA for different scenarios of reservoir development, including no reservoir, single reservoir, and multiple reservoirs.

The integrated hydrological-reservoir model was further linked to ecological and economic analyses. A total of 16 different combinations of spatially located reservoirs were generated by removing one or more reservoirs from all possible combinations in a virtual experiment. The combined hydrological impacts of the 16 different combinations of the four reservoirs were quantified using IHA. The biophysical quantification of two major ecosystem services supported by the river, namely fish diversity and crop production, were then estimated, and a production possibility frontier was outlined to capture the tradeoff between the two considered ecosystem services.

The results show that the average monthly flow in the Upper Cauvery basin is greatly influenced by reservoir operations and subsequent water abstraction in the basin. When individual reservoirs were compared, the year-round reduction in monthly flow was seen across all the sub-basins. When all reservoirs were integrated, the largest storage dam in the cascade has a negative impact on mean annual flow and the annual extreme conditions of minimum and maximum flows. Reservoirs used for both hydropower and irrigation have less effect on low flow pulses and low flow duration than reservoirs used only for irrigation. The combined ecological and economic impacts of multiple reservoirs as represented by the production possibility frontier revealed that large dams that do not maximize the value of water stored, i.e. by growing low value crops in smaller command areas, affect both fish species richness and the economic value of agricultural production adversely. Such reservoirs are least favorable, as they are strictly Pareto inferior to other combinations. In contrast, smaller reservoirs on tributaries (away from the main river stem) that grow high-value crops and maximize the value of water stored are Pareto superior and thus preferred.

The reservoirs are critical for economic development though they significantly affect river flow regimes. The modelling approach presented here can be used to inform operation of reservoirs so that ecologically important flow regimes (e.g., high and low flow percentiles) essential to sustain biodiversity can be maintained. Linking hydrological modelling with trade-off analysis can further contribute towards better understanding of the provision of ecosystem services at basin scale and can help water managers to make informed decisions on, say, dam removal, prioritization of river channels for dam construction, and optimization of dam operations and basin development, so as to balance the provision of multiple ecosystem services.

SAMENVATTING

De natuurlijke stroming van rivieren is sterk gewijzigd in het proces van ontwikkeling en economische groei in de stroomgebieden over de hele wereld. Deze hydrologische veranderingen hebben invloed op rivierecosystemen en hun diensten aan de samenleving, terwijl ze een bedreiging vormen voor de biodiversiteit en duurzame ontwikkeling van het stroomgebied. Reservoirconstructie is een dergelijke wijziging in het rivierenlandschap die heeft geleid tot een slechte levering van ecosysteemdiensten. Dit onderzoek heeft tot doel te begrijpen hoe verschillende patronen van damontwikkeling in een stroomgebied verschillende effecten hebben op het rivierstroomregime en daarmee op de levering van ecosysteemdiensten. Het onderzoek richt zich op het bovenste stroomgebied van de Cauvery in India en heeft een geïntegreerde modelleringsanalyse ontwikkeld om de ecologische en economische impact van verschillende damontwikkelingen te onderzoeken.

Bij dit onderzoek werd een modelleringsconcept ontwikkeld dat een op landschap gebaseerd hydrologisch model (FLEX-Topo) verbindt met trade-off analyse, waardoor een kwantitatieve beoordeling van de hydrologisch-ecologisch-economische effecten van alternatieve reservoirconfiguraties mogelijk is. Het hydrologische model werd geïntegreerd met de reservoirmodellen en de stromen stroomafwaarts van de bijbehorende reservoirs werden gekalibreerd. Voor elk reservoir werden de gemodelleerde stroomregimes met en zonder reservoirs vervolgens vergeleken met behulp van de Indicatoren van Hydrologische Verandering (IHA)-methode om het niveau van stroomverandering door de reservoirs te begrijpen.

Het geïntegreerde hydrologische-reservoirmodel werd verder gekoppeld aan ecologische en economische analyses. In totaal werden 16 verschillende combinaties gegenereerd door één of meer reservoirs te verwijderen uit alle mogelijke combinaties. De biologische kwantificering van belangrijke ecosysteemdiensten, ondersteund door de rivier, zoals vis en gewasproductie, werd vervolgens geschat en een productiemogelijkheidsfrontier werd gekwantificeerd om de trade-off tussen de overwogen ecosysteemdiensten vast te leggen. De gecombineerde ecologische en economische impact van meerdere reservoirs zoals weergegeven door de productiemogelijkheidsfrontier toonde aan dat grote dammen die de waarde van opgeslagen water niet maximaliseren, bijvoorbeeld door het verbouwen van minder waardevolle gewassen in kleinere gebieden, zowel de rijkdom aan vissoorten als de economische waarde van landbouwproductie negatief beïnvloeden. Dergelijke reservoirs zijn het minst gunstig, omdat ze strikt Pareto-inferieur zijn aan andere combinaties. Daarentegen zijn kleinere reservoirs op zijrivieren (weg van de hoofdstroom van de rivier) die waardevolle gewassen verbouwen en de waarde van opgeslagen water maximaliseren Pareto-superieur en dus de voorkeur. Het koppelen van hydrologische modellering aan trade-off analyse kan verder bijdragen aan een be-

ter begrip van de levering van ecosysteemdiensten op bekkenniveau en kan watermanagers helpen bij het nemen van betere beslissingen over bijvoorbeeld het verwijderen van dammen, prioritering van rivierkanalen voor damconstructie, en optimalisatie van damoperaties en bekkenontwikkeling, om zo een evenwicht te vinden in de levering van meerdere ecosysteemdiensten.

सारांश

बड़ा हमेशा बेहतर नहीं होता

भारत में कैस्केडिंग बांधों से उत्पन्न जल–पारिस्थितिक–आर्थिक प्रभावों का भू–दृश्य आधारित विश्लेषण।

विश्व में समग्र और आर्थिक विकास के कारण, नदियों के प्राकृतिक प्रवाह में भारी बदलाव देखा गया है। ये हाइड्रोलॉजिकल परिवर्तन मुख्य रूप से नदियों के पारिस्थितिक तंत्र और मानव जाति को विविध सेवाएं प्रदान करने के प्रावधानों को प्रभावित करते हैं लेकिन, साथ ही साथ ये नदी बेसिन की जैव विविधता और उसके सतत विकास को भी खतरे में डालते हैं। जलाशय किसी भी नदी–निर्माण परिदृश्य के संशोधनों में से एक है जिसके कारण इन पारिस्थितिक तंत्रों से खराब सेवाएं प्राप्त हो रही हैं। हमारा अध्ययन यह समझने के लिए प्रेरित करता है कि कैसे नदी बेसिन में बांध विकास के अलग–अलग पैटर्न नदी के प्रवाह और नदी पारिस्थितिकी तंत्र से उत्पन्न सेवाओं के प्रावधानों को प्रभावित करते हैं। भारत में ऊपरी कावेरी बेसिन पर ध्यान केंद्रित करते हुए, इस अध्ययन ने विभिन्न बांधों के विकास से उत्पन्न पारिस्थितिक और आर्थिक प्रभावों की जांच करते हुए एक एकीकृत मॉडलिंग विश्लेषण विकसित किया है। यह एकीकृत मॉडलिंग विश्लेषण एक आभासी प्रयोग द्वारा वैकल्पिक जलाशय विन्यास के हाइड्रोलॉजिकल–पारिस्थितिक–आर्थिक प्रभावों के मात्रात्मक मूल्यांकन के लिए एक लैंडस्केप आधारित हाइड्रोलॉजिकल मॉडल को व्यवसाय आधारित विश्लेषण से जोड़ता है। जलाशयों के अपस्ट्रीम और डाउनस्ट्रीम क्षेत्रों के प्रवाह को समझने के लिए एक लैंड–स्केप आधारित हाइड्रोलॉजिकल मॉडल, FLEX और Topo का उपयोग किया गया। इस प्रकार प्रत्येक जलाशय के लिए अलग–अलग मॉडल विकसित किए गए। हर हाइड्रोलॉजिकल मॉडल को एक जलाशय के साथ एकीकृत किया गया और संबंधित जलाशयों के डाउनस्ट्रीम प्रवाह को कैलिब्रेट किया गया। प्रत्येक जलाशय के लिए, प्रवाह–परिवर्तन की स्थिति को समझने के लिए जलाशयों के साथ और जलाशयों के बिना प्रतिरूपित प्रवाह–व्यवस्थाओं की तुलना हाइड्रोलॉजिकल परिवर्तन (आईएचए) विधि के संकेतकों का उपयोग करके की गयी। उसके उपरांत एकीकृत हाइड्रोलॉजिकल–जलाशय मॉडल को पारिस्थितिक और आर्थिक विश्लेषण से जोड़ा गया। एक आभासी प्रयोग में सभी संभावित संयोजनों में से एक या एक से अधिक जलाशयों को हटाकर कुल 16 विभिन्न संयोजन उत्पन्न किए गए। आईएचए का उपयोग करके चार जलाशयों के विभिन्न संयोजनों के संयुक्त हाइड्रोलॉजिकल प्रभावों का मात्रात्मक अध्ययन किया गया। जिससे नदियों द्वारा समर्थित प्रमुख पारिस्थितिक तंत्र सेवाओं की जैव–भौतिक मात्रा का अनुमान लगाया गया, उदाहरण के लिए–मत्स्य पालन और फसल उत्पादन। ताकि पारिस्थितिकी तंत्र सेवाओं और ट्रेडऑफ के लिए एक उत्पादन संभावना सीमा निर्धारित की जा सके।

परिणामों से पता चलता है कि ऊपरी कावेरी बेसिन में औसत मासिक–प्रवाह अधिकतर जलाशय के संचालन से प्रभावित होता है और बेसिन से जल निकासी का कारण बनता है। जब अलग–अलग जलाशयों की तुलना की गई, तो यह देखा गया कि है सभी उप–बेसिनों में मासिक–प्रवाह में पुरे वर्ष कमी रहती है। जब सभी जलाशयों के डेटा को एकीकृत किया गया तो यह देखा गया कि संयोजनों में सबसे बड़ा बांध भी औसत वार्षिक–प्रवाह पर नकारात्मक प्रभाव डालता है जबकि न्यूनतम और अधिकतम वार्षिक–प्रवाह की स्थितियाँ नकारात्मक रूप से प्रभावित होती है। बडे जलाशयों का अधिकतम उपयोग जलविद्युत उत्पादन के लिए किया जाता रहा है परन्तु कृषि क्षेत्रों में सिंचाई के लिए कम जल प्रवाह और जल प्रवाह अवधि पर सामान्यतः ध्यान नहीं दिया जाता, और देखा गया है की छोटे जलाशयों का उपयोग सिंचाई के लिए ही अधिकतर किया जाता है। सभी उत्पादन संभावनाएं और जलाशयों के संयुक्त पारिस्थितिक तंत्रों के विश्लेक्षण और आर्थिक प्रभाव यह बताते है कि बड़े बांध, जो संग्रहित जल के अधिकतम स्तर को बरकरार नहीं रख पाते है, वहां निम्न आर्थिक स्तर पर छोटी फसलों को पैदा किया जाता हैं और ये समृद्ध मत्स्य प्रजातियों पर प्रतिकूल प्रभाव डालती हैं। ऐसे जलाशयों को सबसे कम मान्यता दी जाती है और उन्हें अन्य संयोजनों से कम आँका जाता है। इसके विपरीत, सहायक नदियों (मुख्य नदी धारा से दूर) के पास बने छोटे जलाशयों को उच्च आर्थिक स्तर वाली फसलों के लिए बेहतरीन माना जाता हैं। इनमें संग्रहीत जल स्तर अधिकतम सीमा तक रखा जाता है इसलिए इनको सबसे पसंदीदा जलीय स्रोत भी माना जाता है। जलाशय किसी भी देश के आर्थिक विकास के लिए महत्वपूर्ण माने जाते हैं, हालांकि वे नदी–प्रवाह व्यवस्थाओं को बहुत ज्यादा प्रभावित करते हैं। हमारे द्वारा यहां प्रस्तुत मॉडलिंग दृष्टिकोण का उपयोग जलाशयों में संचालन इंजीनियरिंग नियमों पर सुझाव देने के लिए किया जा सकता है ताकि प्रवाह व्यवस्था (जैसे उच्च प्रवाह प्रतिशत और निम्न प्रवाह प्रतिशत), जो पारिस्थितिक रूप से जैवविविधता के लिए महत्वपूर्ण है, उसको बनाए रखा जा सके। आर्थिक प्रभावों के विश्लेषण और हाइड्रोलॉजिकल मॉडलिंग को जोड़ने के पश्चात बेसिन के पैरामीटर पर पारिस्थितिक तंत्र की सभी सेवाओं को बेहतर तरीके से समझा जा सकता है जिससे जल–प्रबंधक अधिकारीयों को बांध को हटाने, बेसिन के अधिकतम विकास के लिए बांध के सुचारु संचालन, बांध निर्माण के लिए नदी चैनलों की प्राथमिकता और अनुकूलनता निर्धारित करने के लिए बेहतर निर्णय लेने में बहुत सहायक हो सकते है जिससे पारिस्थितिकी तंत्र से जुडी सभी सेवाओं में एक संतुलन स्थापित किया जा सके।

1

INTRODUCTION

Every river tells a story
Of human civilization and their ways
Lived near rivers for centuries and days
Whispering tales of wonders
The alluring beauty and thrilling adventures
From headwater to delta, its journey so long
A symphony in streams, pure and strong

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Ekka A, Jiang, Y., Pande, S., van der Zaag, P., (2024). *How economically and environmentally viable are multiple dams in the upper Cauvery Basin, India? A hydro-economic analysis using a landscape-based hydrological model* Hydrology and Earth System Sciences, 28 (14),3219-3241.

1.1. INTRODUCTION

From headwaters to deltas, healthy rivers provide all the necessities for the survival of mankind(Agoramoorthy, 2015). Rivers have multiple dimensions (lateral, vertical, longitudinal) connected (Ward, 1994) to the flow regime which divides the river catchment area (Ward, 1994)into different interconnected ecosystems (habitat) comprising ecological, social and cultural sub-systems (Hand et al., 2018). TThese ecosystems provide a wide range of direct and indirect benefits to human beings (Bishop et al., 2010). Ecosystem services, such as hydropower, irrigation, drinking water supply, fisheries, breeding ground for aquatic wildlife, sanctuary reserves, form the lifeline of many stakeholders (Sarkar et al., 2015). All ecosystem services of river are governed by the flow regime (Gopal, 2016) and the flow regime is influenced by many biotic and abiotic factors and interactions between them which includes topography, land cover, climate and anthropogenic modifications (Grizzetti et al., 2016).

In recent decades, the demand for water has increased (Alcamo et al., 2017). The huge investments in water technology for harnessing the societal benefit from river water have resulted in substantial hydrological alterations of rivers (Vörösmarty, 2010). The constructions of dams and river linking projects are considered as one of the highest forms of modification of river flow (Forslund et al., 2009). The modification of the natural river flow caused numerous effects on the ecological status of rivers (Poff et al., 1997),and disturbed the natural biological cycle of aquatic species (Lakra et al., 2011; Ziv et al., 2012) In India, construction of barrages on the Ganges river has drastically reduced the Gangetic fish species population (Sinha and Khan, 2001). Services provided by the river ecosystem in the form of fisheries support the livelihood of millions of fisher's communities (Lakra et al., 2011; Sarkar et al., 2015) It is the tribal, marginal farmers, and landless labourers who depend on these ecosystem services for their survival. In the process of construction of dams, often the common property resources were negatively affected making people more vulnerable (Fernandes, 2008). They depend mostly on the goods and services provided by these ecosystems for their livelihood and may suffer more when the ecosystems degrade (Silvius et al., 2000; Mainka et al., 2005; Emerton and Bos, 2004; Pearce et al., 2006; Arthington et al., 2006).

Alteration of river water has benefited human development in many ways (Lehner et al., 2011) but it impaired the ecological integrity of rivers (Lehner et al., 2011) (Karr, 1991). Incorporation of human needs doesn't mean that only humans can benefit from rivers, but it also emphasizes the need for making a balance between ecological integrity and human values. Linking anthropogenic pressure, ecological status and ecosystem services (Grizzetti et al., 2016) is important for a more holistic management of river ecosystems.

1.2. ECOSYSTEM SERVICES IN RIVER LANDSCAPES

The term 'ecosystem services' emerged in the early 1980s to understand the biophysical importance of ecosystem processes in terms of human wellbeing (Daily et al., 1997; Costanza et al., 1997). Diverse definitions of ecosystem services have been provided (Costanza et al., 1997; Daily et al., 1997; Millennium Ecosystem Assessment, 2005; Fisher et al., 2009) that have evolved around providing benefits to humans directly or indirectly (Millennium Ecosystem Assessment, 2005; Costanza et al., 1997; De Groot et al., 2002), while mainly focusing on the provision of human wellbeing (Boyd and Banzhaf, 2007; Daily et al., 1997; TEEB, 2010). The most widely accepted classification of ecosystem services was given by Millennium Ecosystem Assessment (2005), which recognizes the ecological and socio-cultural importance of ecosystem services. It divides the ecosystem functions and services into provisioning services, regulating services, cultural services and supporting services. Later, Fisher et al. (2009) suggested categorizing ecosystem services based on ecosystem processes and the ecology-society link of ecosystem services. TEEB (2010) highlighted the importance of biodiversity and habitat services of the ecosystem. Similarly, the Attwood et al. (2014) research program emphasized the interaction between agricultural landscapes and water systems for providing ecosystem services.

Ironically, there is little coherence in the definitions and classifications of ecosystem services. The understanding of ecosystem services has purely been based on human intentions for conservation and diverse interests of different stakeholders (Gunton et al., 2017). Very often, river ecosystem services are considered as river flow-dependent ecosystem services (Brauman et al., 2007; Simons et al., 2017), which assumes that flow regimes directly produce ecosystem services. No doubt, water is a vital component that contributes to the processes that generate ecosystem services and provides critical connections within the ecosystem. It is an important ecosystem product, as well. But the role played by various biophysical processes, its interaction over multiple spatial and temporal scales in ecosystem functioning and provisioning of ecosystem services has often been ignored (Dollar et al., 2007; Grabowski and Gurnell, 2016; Tomscha et al., 2017). The landscape, groundwater and river flows act as one integrated unit for providing ecosystem services (Maes et al., 2016).

1.3. Linking Ecosystem services with co-evolution of the river landscape

Stream ecologists have long acknowledged the significance of river landscape on the river flow regime (Hynes, 1975; Frissell et al., 1986; Allan and Castillo, 2007). However, the notion that river landscapes act as a "biophysical template"that produces most of the ecosystem services has often been overlooked (Tomscha et al., 2017) that produces most of the ecosystem services. No doubt, flow regimes are important in this regard (Gopal, 2016) as they are influenced by many biotic and abiotic factors and interactions within a river landscape Allan (2004); Grizzetti et al. (2016). Primarily, landscapes are the result of co-evolution of climate, topography, vegetation and geology (Caylor et al., 2005; Savenije, 2010; Gao et al., 2009; Grizzetti et al., 2016)) and are considered a prominent feature of river basins (Caylor et al., 2005; Savenije, 2010; Winter, 2001; Thoms et al., 2018).

To understand the interactive process by which patterns of climate, topography, vegetation, and geology including soils are coupled in landscape arrangement and dynamics (Caylor et al., 2005), geomorphological, hydrological and ecological characteristics of a river basin within a hierarchy of spatial and temporal scales needs due consideration.

From the macro to microscale level, the hierarchical structures of the geomorphological, hydrological, and ecological components provide a conceptual paradigm to understand the linkages of various biophysical processes in a river ecosystem and its link with ecosystem services.

At a macro level, the most visible feature is a catchment. It is an area of land that is drained by a river network to its outlet point. The interactions between land and water occurs in the catchment via the hydrological cycle in the form of precipitation. A catchment can be divided into various landscape units based on topography and geological characters. Conceptually, landscape units are formed with similar geomorphological and hydrological characteristics(Forman and Godron, 1986). Each landscape unit exhibits unique geomorphological, ecological, and hydrological behaviour. At the microscale, rivers are divided into river segments, reach and geomorphological units. River segments are sections of a river network that form channels and are delineated based on valley gradient, tributary confluences, and valley confinement (Grabowski et al., 2014). Similarly, reach is a section of a river at which process-form interactions occur that result in the development of geomorphological characteristics, geometric patterns and landforms in the channel and floodplains such as gravel bed, meanders, gravel, bars and oxbow lakes(Newson and Newson, 2000; Grabowski et al., 2014). Reaches are primary indicators of ecological function, habitat characteristics and species assemblages (Newson and Newson, 2000; Grabowski et al., 2014; Thorp et al., 2006). Within a reach, various micro and meso habitats are formed within geomorphic units which are formed in association with vegetation (e.g., plants, wood) or sediments including different river elements at the microscale.

The structural configuration of a river system explains the arrangement of various geomorphological components based on hierarchies. These components are connected and interact with each other as an integrated system through hydrological connectivity. The structural and functional features of a river system are the fundamental basis of hydrological connectivity. The geomorphic subsystems provide the structural basis for a landscape. The functional aspects consist of the hydrological and ecological functioning of the system. Abiotic and biotic agents act as drivers and carriers of this functioning. Various ecological processes respond to the drivers of change, leading to a set of ecosystem functions. For example, at catchment and landscape scale, the river ecosystem is interconnected by blue water (liquid water), and green water (water vapour) flows which contribute to the biophysical processes that generate ecosystem services (Falkenmark and Lannerstad, 2004; Rockström et al., 1999). Both blue water and green water contribute to the consumptive use of water. The consumptive use of blue water withdrawn from reservoirs, river streams, or groundwater in the form of irrigation, water supply for domestic and industrial use are always highlighted as provisioning services in ecosystem service research. But, the consumptive use of green water, which flows back to the atmosphere in vapour form contributes towards ecosystem resilience and generation of ecosystem services in the long run and at large spatial scales (Rockström et al., 1999). The ability of ecosystem processes to modify the available water flow is essential for the production of ecosystem services. (Rockström et al., 1999). At catchment scale, the interconnections between climate, topography, vegetation, and soils lead to the spatial distributions of soil moisture, evapotranspiration, and vegetation within the basin (Caylor et al., 2005; Dollar et al., 2007).Therefore, water plays a crucial link between hydrological and biogeochemical processes through its controlling influence on regulating ecosystem functions like transpiration, runoff generation, carbon assimilation, and nutrient absorption by plants.

1.4. RESEARCH QUESTION TO BE ANSWERED

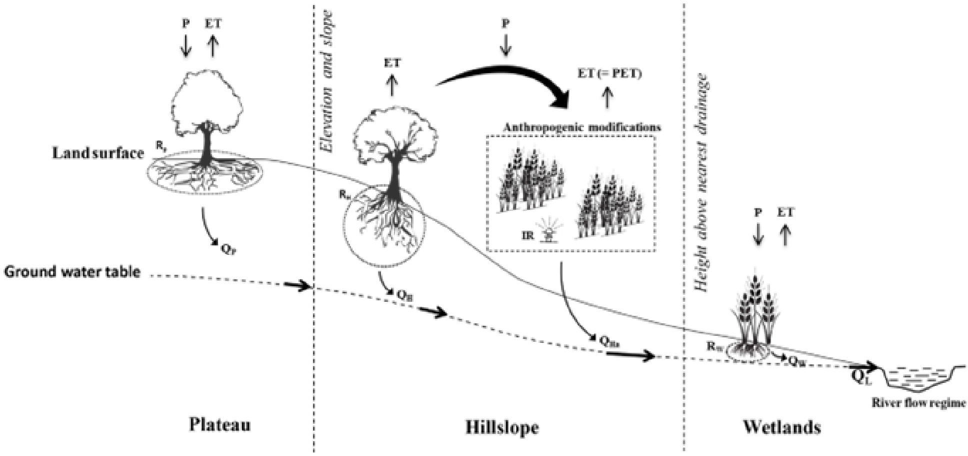
Keeping in view the above facts, this study examines the ecological, economic and social value of ecosystem services maintained by a flow regime of rivers and analyzes the impact of flow change on the value of ecosystem services through integrated assessment using both qualitative and quantitative techniques including hydro-economic modelling. Therefore, the following research questions were formulated for understanding the social-ecological and economic connection between ecosystem services and their tradeoffs under alternative scenarios for river basin management

1. What is the specific contribution that the present flow regime makes to social, ecological, and economic services of a river ecosystem?
2. How do modifications of the river landscape affect the river flow regime?
3. What are the tradeoffs among economic, social, and ecological services of rivers?
4. How can economic and social welfare be maximized while maintaining the ecological health and function of rivers?

1.5. THE LANDSCAPE FRAMEWORK

Since the landscape determines the river flow regime on which ecosystem services depend, understanding the catchment behaviour is an essential step towards understanding the impact of various biophysical processes on ecosystem services. Therefore, a landscape-based hydrological model is required, which could be close enough to mimic the real river landscape behaviour. According to Savenije (2010), topographic characters like elevation, slope, and height above the nearest drainage are the main characteristics which determine different landscapes and generate different runoff (see figure 1.1). By determining the landscape features, the change in the flow regime can be predicted by creating various water demand scenarios in the basin.

The river flow regime acts as a biophysical constraint, which limits the production of different ecosystem services which give rise to tradeoff. King et al. (2015) and Cavender-Bares et al. (2015) has used the production possibility curve to analyze the tradeoff in terms of two-dimension of ecosystem services, i.e., biophysical constraints and divergent stakeholder's preference.On the production side, there is a possible combination of



Figuur 1.1: Conceptual representation of the landscape framework.The river basin is divided into different landscape based on topographic features. The elevation and slope divides hillslope and plateau. The height above the nearest drainage differentiate wetlands from plateau and hillslope. The precipitation (P) is divided into infiltration, transpiration (ET) and runoff. Each landscape exhibits different runoff mechanism (Q_P, Q_H, Q_W) based on topographic features and root zone storage capacities (Rp, RH, RW). All three landscapes are connected by ground water flow (QL) which contributes towards the river flow regime. The anthropogenic modification of landscape (eg. converting forests into agricultural land and providing irrigation (IR) to the crops) will change the root zone storage capacity (RH_a) of the landscape. These landscape characteristics can be incorporated in hydrological model to predict flow regime.

ecosystem services that can be produced with the existing river flow regime and therefore the linking of production function frontier with landscape hydrological model provides scope for incorporating regulating services and supporting services like biodiversity, water quality, soil productivity in tradeoff analysis, which are often neglected in ecosystem services research. It requires establishing an empirical relationship of ecosystem services with river flow regime at different spatial and temporal scale, which are depended on an understanding of interlinkages with the river ecosystem.

The river flow regime acts as a biophysical constraint, which limits the production of different ecosystem services which give rise to tradeoff. (King et al., 2015)) and (Cavender-Bares et al., 2015) have used the production possibility curve to analyze the tradeoff in terms of two dimensions of ecosystem services, i.e., biophysical constraints and divergent stakeholder's preference. On the production side, there is a possible combination of ecosystem services that can be produced with the existing river flow regime and therefore the linking of production function frontier with the landscape hydrological model provides scope for incorporating regulating services and supporting services like biodiversity, water quality, soil productivity in tradeoff analysis, which are often neglected in ecosystem services research. It requires establishing an empirical relationship of ecosystem services with river flow regimes at different spatial and temporal scale.

1.6. What is this thesis about?

The concept of ecosystem services can play a crucial role in river basin management by providing a framework to understand and evaluate the benefits that ecosystems offer to human well-being. By recognizing and quantifying the various ecosystem services that rivers provide, decision-makers can make informed choices regarding resource management and prioritize sustainable practices for the benefit of future generations.

I attempted to address the issue of river ecosystem services in this thesis by combining both biophysical and socio-economic aspects in river basin management. Hydrological modelling and economic analysis, both are powerful tools. Hydrological modelling helps in understanding the physical processes within a river basin, whereas economic analysis helps in assessing the socio-economic value of ecosystem services provided by rivers, enabling the implementation of effective and sustainable management strategies that safeguard ecosystem services for future generations.

Chapter 2 of this thesis conducts a comprehensive literature review to gain a deeper understanding of river landscapes from an ecosystem service perspective. The review involved gathering detailed information about the evolutionary processes shaping river landscapes and their role as biophysical templates for the production of ecosystem services. Additionally, it explored the impact of anthropogenic activities on these ecosystem services. By synthesizing the existing literature, this chapter identifies gaps in knowledge and highlights the open questions that need to be addressed in the thesis. Furthermore, it provides a roadmap for the strategies and approaches to be employed in order to offer possible explanations and contribute to the advancement of understanding in this field.

Chapter 3 examines the biophysical aspect of ecosystem services, specifically the production of river flow regimes. In order to understand this process, the Flex-Topo model was adopted to simulate the stream flow behaviour within the Cauvery River basin in India. The model was utilized to replicate the natural flow patterns, taking into account the complex interactions between precipitation, evapotranspiration, and runoff. Additionally, the study incorporated the presence of dams as anthropogenic modifications and evaluated their impact on the river flow regime. By utilizing this modelling approach, Chapter 3 aimed to enhance our understanding of how human interventions, such as dam construction, influence the natural flow dynamics of rivers and subsequently affect the provision of ecosystem services.

Chapter 4 builds on the previous chapter to analyze the trade-offs associated with the impacts of multiple dams by analyzing the economic and environmental performance of different combinations of spatially located reservoirs of varying sizes in the Upper Cauvery River basin.

Chapter 5 synthesizes the findings and insights from this study, acknowledges its limitations and outlines potential avenues for future research.

2

ANTHROPOGENIC MODIFICATIONS AND RIVER LANDSCAPE

The river once ran free and wild
They are now altered and defiled
The anthropogenic modifications we made
changed the river course what nature laid
So let's listen to the rivers, what they have to say
To conserve them in every possible way

Parts of this chapter are based on:

Ekka A, Pande, S., Jiang, Y., and der Zaag P. V. (2020). *Anthropogenic modifications and river ecosystem services: a landscape perspective.* Water, 12 (10), 2706.

2.1. RIVER LANDSCAPE AND ECOSYSTEM SERVICES

River landscapes are interconnected complex, dynamic, interacting social–ecological system (Hand et al., 2018; Dunham et al., 2018).From headwaters to deltas, healthy rivers provide all the basic necessities for the survival and developmental needs of mankind (Millennium Ecosystem Assessment, 2005). In recent decades, the survival of many rivers is at stake due to huge water diversions for human needs. Significant hydrological alterations are results of large investments in water technologies and infrastructures for irrigation and hydro-power across the globe as well as land-use change (Vörösmarty et al., 2010). Modifications to a river landscape are the result of divergent preferences and the choices of different stakeholders. Anthropogenic use of land and water, while benefiting human development, has damaged the delivery of ecosystem services (ESs) (Stewardson et al., 2017; Bridgewater et al., 2017; Postel and Richter, 2012; Datry et al., 2018; Grizzetti et al., 2016; Roobavannan et al., 2017). These modifications either directly impact ecosystem functions or accelerate natural processes that affect river-flow regimes and thus ES production. Ecosystem loss as a consequence of hydrological alterations because of flow-magnitude and -timing changes is well-documented (Poff et al., 1997; Rosenberg et al., 2000). Many water-resource managers consider artificial impoundments as a significant cause of hydrological alterations (McCully et al., 1996; RenÖFÄLt et al., 2010; Poff et al., 1997). Large dams are not the only causes of hydrological alterations. For example, land-cover changes can lead to changes in how a catchment partitions rainfall into evaporation and runoff (Kanade and John, 2018). The diversion of water by the exploitation of aquifers, changes in land-use patterns, subsurface modifications, and inter-basin water transfer are examples of the forms of anthropogenic modification that cause hydrological alterations (Rosenberg et al., 2000; Kumar et al., 2005; Dang et al., 2016; Zhang et al., 2018; Stewardson et al., 2017). The addition of contaminants and nutrient enrichment in rivers on the river-segment scale can modify the natural flow regime (De Girolamo et al., 2015; Stewardson et al., 2017). At reach level, sand mining and stream channelization cause geomorphic and hydrological changes. When human-induced drivers change the dynamics and complexity of a river ecosystem, they cause large-scale environmental problems that diminish ecological functions in the lower river reach, resulting in a decline in ecosystem services provided by rivers.

Consequently, the benefits derived from river ecosystems services are not only consumed in a place where they are produced but often consumed elsewhere. For example, hydro-power is generated along a river, but it is transported far from the river to benefit people across the river landscape, including urban areas, and beyond. Services like water supply is either used for fulfilling basic needs (e.g., drinking) or for economic needs (e.g., industrial use of water) between upstream and downstream users. These spatiotemporal connections emerge from the typology of a river network and utilization of water according to human preferences (Gandhi, 2003; Gunton et al., 2017). Therefore the use, or abuse, of water or land resources in one part of the basin can influence water availability and provisioning of services in other regions because river ecosystems are complex systems linked dynamically across spatial and temporal scales of interactions (Rockström et al., 1999). For example, land-use and land-management decisions (Guswa et al., 2014), which are sometimes dependent on water needs of associated activities (Rockström et al., 1999), often lead to alterations of the river flow, evaporation, and transpiration regimes (Guswa et al., 2014), thereby altering diverse ecosystem services within the basin and beyond.

Acknowledging the interconnectedness between various biophysical and social systems of a river landscape, we undertook an interdisciplinary review to understand how anthropogenic activities propagate through the landscape to influence and impact ES production. To narrow down the scope of the review, we focused only on the following seven types of anthropogenic modifications: (1) dams, (2) stream channelization (3) inter-catchment water transfer, (4) sand mining, (5) groundwater abstraction, (6) changes in land-use patterns, and (7) subsurface modifications.

This review aims to synthesize knowledge on changes in ecosystem processes and functions concerning anthropogenic landscape modifications (Figure 2.1). Through various examples, we advance our understanding of how river ESs largely depend on the effective functioning of biophysical processes that are linked with geomorphological, ecological, and hydrological characteristics of the river landscape, and how anthropogenic modifications of river landscapes cause imbalances between social, economic, and cultural uses of ESs, making river landscapes more vulnerable and less resilient.

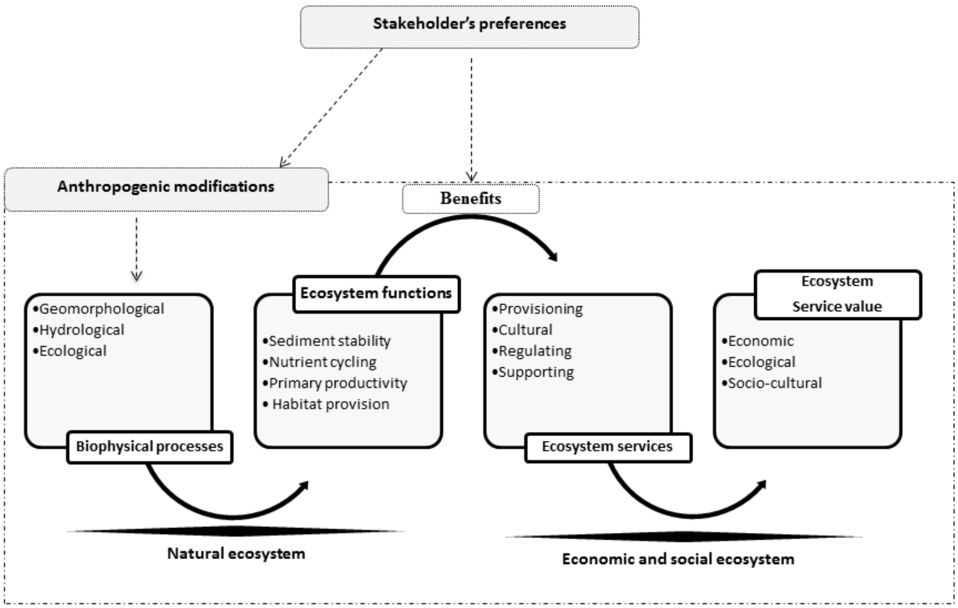
The rest of this chapter is organized as follows. The importance of linking landscape features with ecosystem services is discussed in Section 2.3. Then, we review the potential anthropogenic modifications and classify the diverse mechanisms that affect various biophysical processes of interest to ES production in Section 2.4. We also provide an overview of anthropogenic modifications and their influence on economic, ecological, and socio-cultural aspects of ecosystem services (Section 2.6). Further, emergent challenges are discussed in Section 2.7 followed by the conclusion (Section 2.8). This will help to better understand the role of spatiotemporal connections of the river landscape in ecosystem service assessment and to develop long-run strategies to promote the resilience and sustainable management of river-basin resources.

2.2. Review Approach

This section is divided into following sub sections-

2.2.1. Literature Search

We performed a systematic search of the peer-reviewed literature following the PRISMA method (Moher et al., 2009) to identify evidence of the impact of anthropogenic modifications on river landscapes that impact ESs. On the basis of the anthropogenic drivers selected for study, we searched the electronic database Scopus with keywords such as "river", "basin/catchment/watershed", and "ecosystem services" against each type of anthropogenic modification (Table 2.1). On the basis of this search, 1092 references were retrieved. Duplication were removed and only peer-reviewed articles written in English were selected for the review (n = 915). We then scrutinized the title and abstract of each publication to fit references with the aim of our search, and to include references related with anthropogenic modifications for further analysis (n = 667). For this subsample, articles were scrutinized on the basis of the following criteria: (1) specific reference to ecosystem services, ecosystem processes, or functions; and (2) papers specifying evidence of hydrological, ecological, and geomorphological components of the impact on



Figuur 2.1: An overview of anthropogenic modifications on river ecosystem services (ESs).

river landscapes.

2.2.2. Assessment Criteria

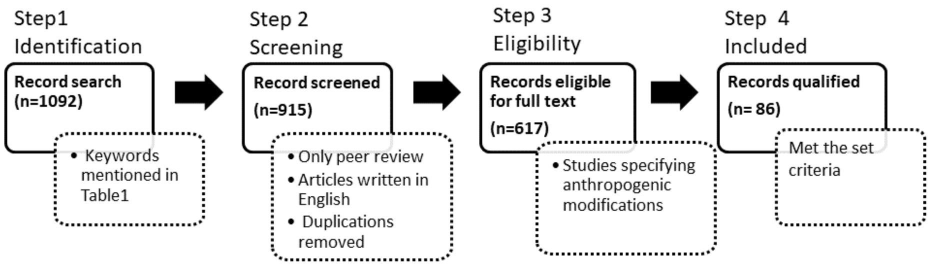
A total of 86 references were selected to map the evidence of the impact of anthropogenic modifications on river ecosystem services. An overview of the number of papers under each type of modification is given in Figure 2.2. Subsequently, we cataloged and classified papers indicating the ecohydrological or geomorphological changes in river ecosystems in connection with ecosystem responses. Not all studies explicitly referred to the classification of ESs. For example, exotic species are an indicator of species diversity, contributing to supporting services. Therefore, we used ESs classified by (Millennium Ecosystem Assessment, 2005), and the Common International Classification of Ecosystem Services (CICES) by (Maes et al., 2016) to establish connections between ecosystem responses and ESs (Table 2.3).

2.3. Linking Ecosystem Services with River Landscape Features

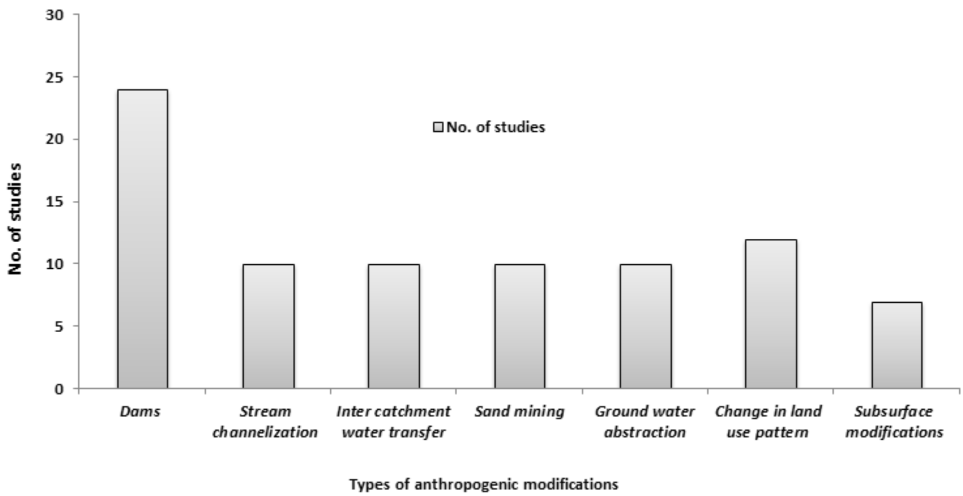
“In every respect, valley rules the stream” (Hynes, 1975). Stream ecologists have long acknowledged the significance of river landscape on the river flow regime (Hynes, 1975; Frissell et al., 1986; Allan and Castillo, 2007). However, the notion that river landscapes act as "biophysical templates"(Tomscha et al., 2017) that produce most of the ecosystem services has often been overlooked. No doubt, flow regimes are important in this regard (Gopal, 2016) but the flow regime itself is influenced by many biotic and abiotic factors and

Tabel 2.1: Different keyword combinations for the literature search before inclusion criteria were applied.

Impact Type	**Different Keyword Combinations with 'Ecosystem Services' and 'Impact'**	**No.of Papers**
Dams	Dam, damming	255
Stream channelization	Channelization, drying of swamps, canals, wetland drainage	202
Inter-catchment water transfer	Inter-catchment water transfer or inter-basin water transfer	16
Sand mining	Sand mining	18
Groundwater abstraction	water abstraction	33
Change in land-use pattern	urbanization, deforestation, agricultural practices	538
Subsurface modifications	mining, metro rail, urban karst	30



Figuur 2.2: Flow diagram of review approach following the PRISMA method.



Figuur 2.3: Number of studies reported under each anthropogenic-modification type after inclusion criteria were applied.

interactions within a river landscape (Allan and Castillo, 2007; Grizzetti et al., 2016). Primarily, landscapes are the result of co-evolution of climate, topography, vegetation, and geology (Caylor et al., 2005; Savenije, 2010; Gao et al., 2017; Grizzetti et al., 2016) and are considered a prominent feature of river basins (Caylor et al., 2005; Savenije, 2010; Winter, 2001; Thoms et al., 2018; O'Sullivan et al., 2019).

To understand the interactive processes by which patterns of climate, topography, vegetation, and geology, including soils, are coupled in landscape arrangements and dynamics (Caylor et al., 2005), due consideration needs to be given to geomorphological, hydrological, and ecological characteristics of the river basin within a hierarchy of spatial and temporal scales. Given the complexity of riverine ecosystems, the hierarchical structures of the geomorphological, hydrological, and ecological components (Grabowski et al., 2014) help to understand the linkages of various biophysical processes in a river ecosystem and production of ecosystem services.

The geomorphic subsystems provide the structural basis to a river landscape. The functional aspects consist of hydrological and ecological functioning of the system. Abiotic or biotic agents act as drivers and carriers of this functioning. Various ecological processes respond to these drivers, leading to a set of ecosystem functions (Dollar et al., 2007). From headwater to the delta, the physical variables within a river system present a continuous physical-geomorphic gradient for ecosystem functions (Vannote et al., 1980; Ward, 1989; Tomscha et al., 2017). The model of river ecosystem synthesis proposed by Thorp et al. (2010) and Thorp (2014) suggests that levels of ecosystem services provided by riverine landscapes depend on hierarchically arranged hydrogeomorphic patches from the valley to reach scales, known as functional process zones. At each level of spatial scale, the geomorphic structures such as channel width, instream cover, and channel depth, form landform attributes associated with habitat and niche complexity of river systems and processes (Dollar et al., 2007). These structures influence the habitat template of rivers and thus the number of functional micro- and macro-habitats (Thorp et al., 2006). These habitat templates assimilate the biota, and biological interactions, including physical and chemical processes, that collectively determine production of ecosystem services like species diversity, climate regulation, and food production (Grabowski and Gurnell, 2016; Thorp et al., 2010; Keele et al., 2019).

At catchment and landscape scale, the river ecosystem is interconnected by blue water (liquid water) and green water (water vapor) flows which contribute to the biophysical processes that generate ecosystem services (Falkenmark and Lannerstad, 2004; Rockström et al., 2010). Both blue and green water contribute to the consumptive use of water. The consumptive use of blue water withdrawn from reservoirs, river streams, or groundwater in the form of irrigation, water supply for domestic and industrial use is always highlighted as provisioning services in ecosystem service research. The consumptive use of green water, which flows back to the atmosphere in vapor form, contributes towards ecosystem resilience and the generation of ecosystem services in the long run and at large spatial scales (Rockström et al., 1999). The ability of ecosystem processes to modify the available water flow is essential to produce ecosystem services (Rockström et al., 1999). The interconnections between climate, topography, vegetation, and soils lead to the spatial distributions of soil moisture, evapotranspiration, and vegetation within the basin (Caylor et al., 2005). Patterns of plant rooting depth bear a strong topographic and hydrologic signature at landscape to global scales (Fan et al., 2015), which control the distribution of the total soil water content and soil losses, including leakage and runoff (Caylor et al., 2005). Therefore, water plays a crucial link between hydrological and biogeochemical processes through its controlling influence on regulating ecosystem functions like transpiration, runoff generation, carbon assimilation, and nutrient absorption by plants.

The capacity of ecosystem functions to provide ecosystem services is thus a result of interactions between various geomorphological, hydrological, and ecological processes over multiple spatial and temporal scales (Grabowski and Gurnell, 2016). It may be physical (e.g., bioremediation), chemical (e.g., mineralization, calcification), or biological (e.g., photosynthesis, larval dispersal). For example, the ecosystem functions of primary productivity help in maintaining species diversity, which in turn provides provisioning services of food and raw materials. Similarly, the sediment stability functions of ecosystems support sediment transfers in river channels from upstream to downstream. This sustains soil productivity and food productivity for human beings.

2.4. Impact on Ecosystem Services

The anthropogenic modification of a river landscape on multiple spatial scales impacts the supply of ESs, posing a threat to human well being. Hydrological alterations that result from the provision of water to developmental activities have changed the ecosystem structures and processes of river flows (Nilsson and Berggren, 2000). The social and ecological impacts of hydrological alterations caused by dams were widely reported (McCully et al., 1996; RenÖFÄLt et al., 2010; Poff et al., 1997; Kirchherr et al., 2016). The remainder of this section investigates ecohydrological or geomorphological changes in connection with ecosystem responses to anthropogenic modifications of river landscapes on various scales, and how this affects ES production (Table 2.3).

2.4.1. Inter-basin Water Transfer

On a catchment level, there are numerous examples of global anthropogenic modifications in the form of inter-basin water transfers, especially in Australia (Ghassemi and White, 2007), the USA (Ghassemi and White, 2007), Asia (Iyer, 2014), and South Africa (Muller, 1999). Inter-basin water transfers redistribute water resources from water-abundant regions (donors) to water-short regions (recipients) to alleviate water shortages and facilitate developmental activities in the recipient basin (Davies et al., 1992; Gupta and van der Zaag, 2008). Vast engineering structures on both sides of the conveying channel system cause changes in geomorphological features e.g., channel geometry, channel width, and sedimentation and siltation problems (Kibiiy and Ndambuki, 2015). This further causes stream-flow reduction in both donor and recipient streams, which decreases water availability (Hey, 1986), negatively impacting the riverine ecology and fisheries (Joshi et al., 2017; Lakra et al., 2011). It modifies habitat environments and provides pathways for the invasion and establishment of exotic species (Gallardo and Aldridge, 2018). For example, the number of migratory salmon was reduced after the implementation of the central valley project in the United States as it blocks the downstream movement of

Tabel 2.2: Impact of anthropogenic modifications on ecosystem response concerning ES

Types of modification	Eco-hydro-geomorphological changes	Ecosystem response	ES affected
Catchment scale			
Inter-Basin water transfer	Change in channel and width, river erosion and inundation of land	Stream flow reduction [1,2]	Water availability
	Exchange of aquatic species	Reduction of native species [3,4,5]	Species diversity
		Loss of aquatic diversity[6,7,8,9]	
		Homgenization and bioinvasion [10]	
Landscape unit scale			
Land use Impact	Low evapo-transpiration and precipitation	Alters runoff patterns [19,20,21]	Micro-climate regulations
	Surface soil erosion and increase surface runoff	Reduce infiltration and base flow [11, 12,13,14]	Groundwater recharge
	Discharge of agricultural contaminants	Stream flow contamination [22]	Water quality
	Loss of riparian zones	Reduction in area of wetlands [15]	Wetland productivity
	Loss of swamps and marshy areas	Loss of habitats[16,18]	Species diversity
	Loss of forest area	Alters surface runoff [24]	soil formation
Subsurface modification	Hydrological barrier to natural flows	Decrease infiltration[27,28]	Groundwater recharge
	Subsurface soil disturbance and accumulation of runoff in large depressions	Alters annual surface flow [25,26]	Micro-climate regulations
	Discharge of urban karst contaminants	Water contamination[29,30,31]	Water quality
Abstraction of ground water	Increase in salt water intrusion	Decrease water productivity[35,36,37]	Water supply
	Land subsidence	Unavailability of water[32,33,34]	Water supply
	Flow reduction in natural spring	Impact on groundwater terrestrial ecosystem [38]	Species diversity
	Reduced stream flow	Fish assemblage and habitat availability [39,40,41]	Species diversity
Segment scale			
Stream channelization	Bank erosion and change in nutrient concentration	Decrease water productivity [42,43,44,45]	Water supply
	Heterogeneity of river bed substrate	Impact on aquatic organisms[26,48,52]	Species diversity
	change in flow velocity and hydropeaking	Impact on riparian micro invertebrates [26,48,52]	Species diversity
Damming	Change in flow regime	Decline in fish abundance [65,66,67]	Species diversity
		Decrease in aquatic flora and fauna[68,69,70]	Species diversity
	Conversion of lotic to lentic environment	Growth of exotic species [71,72]	Species diversity
	Salinization and waterlogging	Water quality [73,74]	Species diversity
	Fragmented habitats	Phytoplankton composition [75]	Species diversity
		Zooplankton diversity [76]	
	Change in sediment transportation	Nutrient fluxes and biogeochemical cycle [53,54]	Micro-climate regulations
		GHG gases [55]	
	Loss of connectivity with deltaic and riparian zone	Loss of riparian and aquatic vegetation[56,57]	Species diversity
		Reduction in agricultural productivity[58]	Food production
		Obstruct fish migration[29]	Species diversity
		Aquatic food web [60,61]	Species diversity
		Aquatic breeding habitat[62,63,64]	
Reach scale			
Sand mining	River bed stability and bank erosion	Loss of productive area for cultivation [77,78]	Food production
	Sediment deposition	Loss of deep pools[79,80]	Species diversity
		Impact on food web [81,82]	Species diversity
	Change in sediment composition	Impact on benthic community[28,86]	Species diversity
	Bathymetric changes	Change in water levels[83,84]	Water availability

2

fish(Ghassemi and White, 2007).

2.4.2. Changes in Land-Use Patterns

Change in land use and land cover due to urbanization, deforestation, and agricultural practices have impacted the water balance. Expanded impervious surfaces, compaction, and soil modification resulting from urban development such as parking lots, roofs, sidewalks, and driveways can have enormous repercussions on the hydrologic cycle and corresponding water quality (Liu et al., 2017; Gwenzi and Nyamadzawo, 2014). Deforestation is also one of the most evident forms of anthropogenic impact on land surfaces (Crowther et al., 2015). It affects the microclimate on a regional level, impacting precipitation and evaporation, therefore altering runoff patterns (Kanade and John, 2018). The impact of land-use/land-cover changes may not be visible in the short term, but long-term impact has been observed (Melland et al., 2018) to decrease the value of regulating services (Tolessa et al., 2018).

2.4.3. Subsurface Modification and Tunneling Work

Impact-assessment studies on subsurface anthropogenic modifications and tunneling work on aquifer hydrogeology are limited, but have gained much attention (Pujades et al., 2015; Lilly and Ravikumar, 2018; Wang et al., 2017). Subsurface modifications include mining activities, tunnel excavation for metro lines, underground thermal-energy storage (UTES), and gas pipes, and create hydrogeological barriers to natural groundwater flows (Bernagozzi et al., 2015; Zheng and Diao, 2016; Pujades et al., 2015).
Human-made, highly connected subsurface pathways like sewer pipes, potable water pipes, and stormwater infiltration channels (Kaushal and Belt, 2012; Bonneau et al., 2017), known as "urban karsts", impact groundwater hydro-geomorphological processes that deteriorate groundwater quality by contaminating adjacent surface and groundwater bodies (Bonneau et al., 2017; Casey et al., 2013; Li et al., 2009).

2.4.4. Groundwater Abstraction

Another important type of subsurface modification is groundwater abstraction. Globally, around 38% of irrigated areas are groundwater based (Siebert et al., 2010). The excessive abstraction of groundwater results in widespread decline in groundwater storage, which not only affects the water supply, but also accelerates saltwater intrusion and causes land subsidence (Chatterjee et al., 2006; Yang et al., 2017), impacting water availability in the long run. Abandoned open-cast mines alter hydrological watershed processes by decreasing annual surface flow and water yield because of surface-soil disturbance and the accumulation of surface runoff in large depressions (Shinde et al., 2017; Steyn et al., 2019).

2.4.5. Damming

On the segment scale, the construction of a dam across a river converts a river segment of a natural watercourse into stagnant water (Gopal, 2016). The lacustrine environment of impoundments reduces the habitat availability of species dependent on riverine-forest and riparian ecosystems (Douglas et al., 2016). Changing water levels upstream creates unstable habitat conditions that disturb the life cycle and reduce the growth rate of aquatic species (Freeman et al., 2007). Consequently, species diversity is altered, which impacts provisioning services. Sediment depositions downstream directly impact channel morphology in the form of width narrowing, channel deepening, and arresting flow within the channel (Pal, 2016). This further impacts the water quality and composition of biotic communities, which influences supporting and regulating services. River damming also impacts the functions of the nutrient and biogeochemical cycle by changing the composition of silica and carbon cycles (Ma et al., 2017).

2.4.6. STREAM CHANNELIZATION

Similar to damming, stream channelization alters the landscape by cutting and dredging sediments. Small streams are widened and straightened for agriculture and water conveyance, whereas large rivers are modified for navigation, flood control, and floodplain development. Stream channelization impacts the fluvial geomorphology, energy conditions, and sediment-transport potential of rivers, making the modified channel unstable, which aggravates bank erosion (Rhoads et al., 1990; Zheng et al., 2018). It also alters the nutrient dynamics of river-flow regimes by decreasing nutrient concentrations and other biologically reactive solutes that regulate ESs by stimulating primary production, thereby affecting water quality and ecosystem health (Niswonger et al., 2017; Kunz et al., 2017).

2.4.7. SAND MINING

Urban expansion and infrastructure development have led to increased mining activities (Torres et al., 2017; Sreebha and Padmalal, 2011). The indiscriminate mining of sand and gravel from river beds, inland dunes, and floodplain areas has caused extreme damage to river-basin environments and their ecodiversity (Torres et al., 2017). In channel sand mining significantly impacts channel morphology (Barman et al., 2019; Hegde et al., 2008; Zhang et al., 2018). On the reach scale, sand and gravel mining over the deposition rate results in low infiltration and excessive riverbank erosion, which affects sediment transportation (Hegde et al., 2008). The rapid extraction of sand and gravel from riverbeds also influences hydrological processes by increasing evaporation rate and reducing groundwater recharge, leading to the failure of irrigation wells in surrounding areas (Hegde et al., 2008). Thinner superficial fluvial layers in mining areas, as a result, often lead to lower longitudinal and lateral hydrologic connectivities (Kompanizare et al., 2018). Extensive sand mining places enormous burdens on fish habitats, migratory pathways, ecological communities, and food webs (Torres et al., 2017; Yoo et al., 2018; Kobashi and Jose, 2018).

2.5. THE ECOLOGICAL AND SOCIO-CULTURAL ASPECT OF ECOSYSTEM SERVICES AND HUMAN WELL BEING

Many landscape modifications simultaneously interact, making it difficult to separately determine the impact of each. Such modifications have multiple effects on ES and human well being (Torres et al., 2017). Landscape modifications cause multifaceted and overlapping forms of impact on hydrological, ecological, and geomorphological components of the river basin, bringing complex changes in ecosystem processes, and affecting ecosystem functions. These drivers can impact one or more ES, and lead to interactions between ESs (Bennett et al., 2009; Pope et al., 2016). For example, damming destroys ecological and social habitats upstream due to submergence; downstream, it impacts habitats by reducing flow towards wetlands and floodplains. Consequently, it leads to a decrease in floodplain productivity affecting food and raw-material supply to people Singh (2009).

Likewise, land-use/land-cover changes associated with agricultural practices (Gebremicael et al., 2018), deforestation, and urbanization tend to decrease the infiltration rate of the land surface, which minimizes groundwater recharge and increases surface runoff. Simultaneously, such changes in land use reduce evapotranspiration, which affects microclimate regulation. Changes in land-use patterns accelerate the impact of climate change on ESs (Kaushal et al., 2017; Bai et al., 2019). The combined effect of climate change and land use has significant inhibitory impact on ecosystem functions, like water retention, nitrogen export, and phosphorus export (Bai et al., 2019; Hao et al., 2019), which weaken ES production. The relative importance and combined influences of landscape modification also depend on spatial scale and landscape composition (Bai et al., 2019). When regulating and supporting services are affected, this slowly influences the availability of provisioning and cultural services (Brauman et al., 2007).

These interactions result in tradeoffs and synergies between ESs (Jorda-Capdevila and Rodríguez-Labajos, 2015; Pope et al., 2016). Tradeoffs between stakeholders on a spatiotemporal scale for river ESs are not independent, but instead exhibit complex interactions that depend on the nature of irreversibility of the ecosystem (Bennett et al., 2009; Deng et al., 2016). This creates imbalances between economic, ecological, and social–cultural ES uses, threatening the ecological and social integrity of the catchment in the long run (Table **??**). For example, a study by (Intralawan et al., 2018) on tradeoffs between water use, food-security supply, and energy production for hydro-power projects in the lower Mekong basin concluded that the ecological cost (sediment/nutrients), social cost (loss of capture fisheries), and other mitigation costs were greater than the benefits from electricity generation, improved irrigation, and flood control, which are mainly economic-benefit-oriented (see also (Matthews and McCartney, 2018)). The high demand for provisioning services such as water supply, irrigation, and hydro-power deteriorates the integrity of ecological processes that affect river-basin regulatory and supporting services.

2.6. The Ecological and Socio-Cultural aspect of Ecosystem Services and Human Well Being

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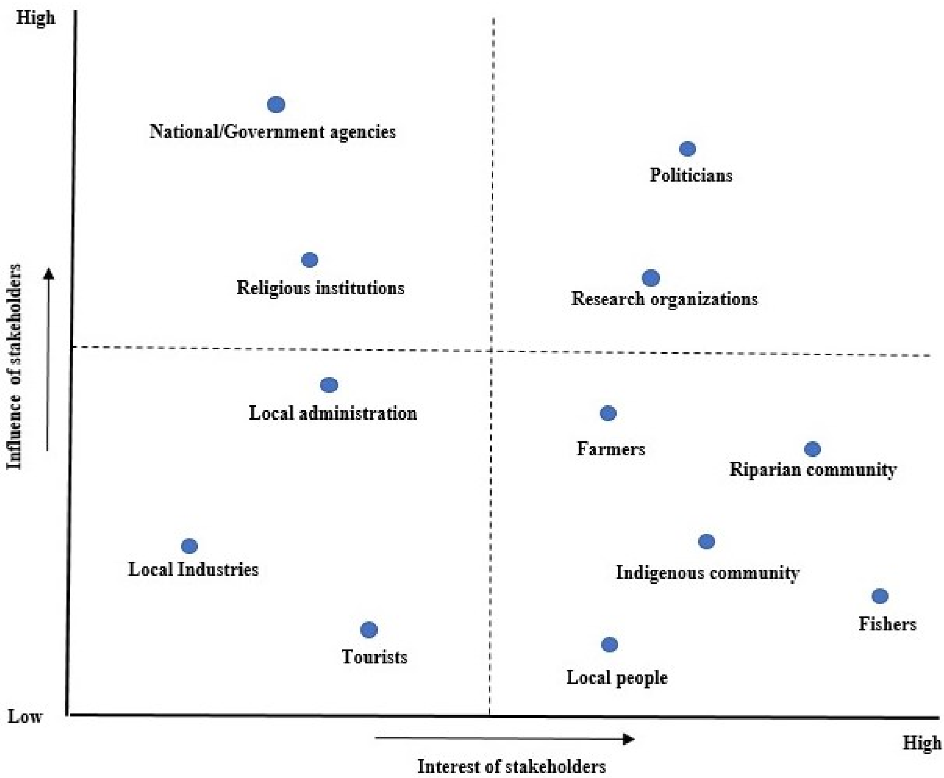
Landscapes are the signatures of ecological, economic, social, and cultural interactions (Marques et al., 2019, 2018). The modification of river landscape impacts the landscape features having prime importance in the life of the indigenous people and riparian population (Marques et al., 2019, 2018). The religious belief, folklore, customs, and traditions of these people are closely entwined and are influenced by riverine landscapes.

The power matrix of the stakeholders plays an important role in utilization of ecosystem services. Grimble and Wellard (1997) define stakeholders as all those who affect or are affected by the policies, decisions, and actions of the system. They can be individual, communities, social groups, or institutions of any size, aggregation, or level in a society (Figure 2.4). Some stakeholders, which include institutions, government agencies, and policy makers, have more power to carry out modifications on river landscape compared

Tabel 2.3: [-15]Influence of river-landscape modifications on economic, ecological, and socio-cultural ES aspects. The signs (+) and (−) indicate positive and negative influence on ecosystem services, respectively.

Anthropogenic Modifications	**Ecosystem Services** **Economic**	 **Ecological**	 **Socio-Cultural**
Inter-basin water transfer	Uninterrupted water supply for irrigation (+) Navigation (+)	Species diversity (−) Habitat provision (−)	Displacement (−) Livelihood (−) Tourism (±) Aesthetics (−)
Change in LULC	Urbanization (+) Living space (+) Agricultural use (+)	Microclimate regulation (−) Groundwater recharge (−) Floodplain connectivity (−) Habitat provision (−) Species diversity (−)	Livelihood (−) Aesthetics (−) Tourism (−)
Subsurface modifications	Urbanization (+) Living space (+) Transportation (+)	Groundwater recharge (−)	–
Groundwater abstraction	Water supply for industrial, domestic, and agricultural use (+)	Groundwater recharge (−) Saltwater intrusion (−)	–
Stream channelization	Irrigation (+)	Ag. productivity (−) Water logging (−)	–
Damming	Hydro-power (+) Irrigation (+) Water supply (+) Fisheries(±)	Fish migration (−) Sediment flow (−) Water logging (−) Water quality (−) Ag. productivity (−) Species diversity (−) Floodplain connectivity (−)	Flood control (+) Displacement (−) Livelihood (−) Tourism (±) Aesthetics (−)
Sand mining	Input material for construction (+)	River-bed instability (−) Bank erosion (−) Soil formation (−) Groundwater recharge (−) Species diversity (−)	Aesthetic (−)

to stakeholders having low power in the matrix (e.g., fishers, indigenous people, local people). River water diverted by influential stakeholders may obstruct the freely accessible benefits (e.g., livelihood, tradition, and aesthetics) of less powerful people (Felipe-Lucia et al., 2015). Power asymmetries among stakeholders create social conflict and can affect stakeholders' well being. For example, the construction of dams for harvesting water for irrigation and hydro-power has resulted in the displacement of many people, especially marginal farmers, forest dwellers, riparian, and indigenous communities (Kirchherr et al., 2016; Ramanathan, 1996). The livelihood support gradually declines due to displacement by dams resulting in shifting of the occupation and migration of the community (Ramanathan, 1996). Similarly, stream channelization and water diversion create conflicts between different upstream and downstream users (Daw et al., 2011). Therefore, ecosystem service research should be informed with detailed understanding of linkages of ecosystem services with landscape signatures including socio-ecological interaction between them.



Figuur 2.4: The influence–interest matrix of riverine stakeholders

2.7. Emergent Challenges for Ecosystem Service Valuation

Anthropogenic modifications on river landscape are the result of divergent human preferences and choices by different stakeholders. The study fills some knowledge gaps of biophysical linkages of river landscape and its importance in the delivery of ecosystem services. Understanding the critical linkages between river landscape and ecosystem delivery is crucial for ecosystem service assessment and can foster restoration strategies.

Linking anthropogenic pressure, ecological status, and ecosystem services is important for holistic management of river ecosystem service (Grizzetti et al., 2016; Keeler et al., 2012). In a monetary-based economy, so far, ecosystem service valuation acted as an important tool for ecosystem service assessment, but the framework is not able to quantify the ecological and social value of ecosystem services (Gunton et al., 2017). Therefore, further research needs to explore the value of ecosystem services not only based on monetary value but also the ecological and socio-cultural values should be given due consideration. Moreover, the trade-offs and synergies among river ecosystem services at spatial and temporal scales need to be investigated in detail. Ecosystem services are considered as a part of socio-ecological system; therefore, knowledge of relationships among ecosystem service at the landscape level is important to avoid unwanted tradeoff and to exploit synergies (Bennett et al., 2009). The goal of future direction in ecosystem service assessment should be to consider ecosystem services from the landscape perspective. It requires integration of various disciplines to understand landscape complexity and system response. Furthermore, the incorporation of stakeholders' participation, local knowledge, and locally spatial characteristics needs to be assimilated into the process of ecosystem service assessment in river basins.

2.8. Conclusions

Human interventions in the landscape are evident across river basins. Landscapes are experiencing significant changes challenging the ecological and social integrity of rivers. Our review demonstrated that ES quality and quantity largely depend on the effective functioning of biophysical processes, which are again linked with the geomorphological, ecological, and hydrological characteristics of river basins. The critical challenge is a more holistic representation of the river landscape in ecosystem service research which is constrained by the understanding of ecosystem structure and functions, and its relationship with ecological, economic, and socio-cultural values of ecosystem services contributing towards ecosystem resilience and sustainability (De Groot et al., 2010; Dunham et al., 2018). This chapter shows that ecosystem service research should be considered from a holistic landscape perspective. Ecosystem service assessment with greater sensitivity to the responses and the interaction between biophysical and socio-economic processes could help water managers and researchers striving for a welfare-maximizing equilibrium between demands for river-based ESs and modifications of river landscapes without damaging the structural and functional connectivities of the river basin.

3

Dam-induced hydrological alterations

As we build our dams so high
We change the river flow and watch it dry
Flex-Topo models may provide
A way to understand the river's tide
With simulation and analysis
We can predict the flow regime changes
And use this information
For sustainable practices and knowledge exchanges

Parts of this chapter are based on:

Ekka A, Keshav S., Pande, S., van der Zaag, P., Jiang, Y (2022). *Dam-induced hydrological alterations in the upper Cauvery river basin, India* Journal of Hydrology: Regional Studies,44,101231.

3.1. INTRODUCTION

Worldwide, dams have been constructed to meet growing human needs. No doubt, dams have provided many economic benefits in the form of water supply, hydropower, and food production, which has boosted economic growth and human wellbeing. Around the world, nearly 63 per cent of the free-flowing rivers have been affected by reservoir operations, impairing the ecological functioning of the basins (Grill et al., 2019). As a result, the ecology of both the upstream and downstream areas of the dams is impacted (Crossman and Pollino, 2018).

The construction of a dam across a river converts a river segment of the natural watercourse into stagnant water (Gopal, 2016). This changes the hydrological regime of the river in terms of magnitude, frequency, timing, duration, and rate of change in flows. Such alterations in flow regimes influence the ecological processes that impact the functioning of ecosystem services (RenÖFÄLt et al., 2010; Brauman et al., 2007). For example, the longitudinal and lateral connectivity is interrupted by dams and barrages resulting in fragmented biotic communities (Crook et al., 2015). The reduced flows of sediment, nutrients, and freshwater inputs into estuaries and coastal zones decrease the nutrient composition, phytoplankton composition and zooplankton diversity and impact the aquatic food web (Domingues et al., 2012; Simões et al., 2015; Van Cappellen and Maavara, 2016). Such disturbances of the aquatic food web decrease the productivity of estuarine and coastal habitats. The dams have also displaced 40 to 60 million people over the last 60 years (https://www.internationalrivers.org/human-impacts-of-dams). As a result, large dams have come under harsh criticism worldwide from environmental scientists, human rights activists, economists, and intellectuals. Large dams have gained notoriety for the detrimental environmental and social impacts that they cause, and the huge economic burden of their costs (Bhatnagar, 2004).

In India, several multipurpose dams have been constructed such as Bhakra Nangal, Nagarjunasagar, Kosi, Chambal, Hirakud, Kakrapar and Tungabhadra dams to harness water for developmental needs. These dams were built for multipurpose uses such as hydropower, irrigation, and domestic water supply and have been seen as a sign of development and economic growth (Klingensmith, 2003). According to the National Registry for Large Dams (NRLD), in 2016 a total of 4,877 dams were built in India and 313 dams were still under construction. The Cauvery River is one such peninsular river that has been intensely altered by reservoirs, barrages, canals, and anicuts (masonry check dams constructed across streams to divert water) in response to rapidly growing water demands for irrigation, household consumption, and power generation (Vanham et al., 2011). While the construction of the reservoirs has helped to expand the irrigated areas in the basin, securing water availability during water stress which the river runs), leading to conflicts among the states sharing the rivers (Iyer, 1994; Shah, 1993; Janakarajan, 2016).

Extensive damming has also led to poor delivery of ecosystem services. Degradation in water quality is being reported extensively (Solaraj et al., 2010; B, 2016). Regulating services such as sediment transport have been adversely affected, which in turn has impacted freshwater ecosystems(Vaithiyanathan et al., 1992). For example, changes in aquatic species composition are being observed due to the changes in sediment loads because of the construction of the reservoirs (Venkatachalapathy and Karthikeyan, 2015; Dhanakumar et al., 2015). Moreover, the population of migratory fish species such as *Tor spp*, *Lates calcarifer*, *Bagarius bagarius*, and *Anguilla spp* has declined due to reduced flow rates in the river (Raj, 1941).

These are some examples that underline the necessity to assess the degree to which hydrological flows are altered, i.e., deviated from the natural flows, by the construction of dams in a basin such as that of the Cauvery basin. This study is motivated by this need for a systematic assessment of hydrological alterations by the construction of major dams in the Upper Cauvery basin. However, such an assessment requires sufficient hydrological data for the periods of pre and post reservoir construction, which is often not possible. The objectives of this study are therefore to i) develop and implement a robust human-influenced hydrological model that can reliably simulate pre reservoir hydrological regimes and ii) deploy a systematic assessment of pre and post reservoir flow regime changes in the basin.

Many studies of dam-induced alterations have used Indicators of Hydrological Alterations (IHA) to evaluate the hydrological impacts of dams on flow regime characteristics (Gierszewski et al., 2020; Pal et al., 2019; Lu et al., 2018; Mittal et al., 2016; Song et al., 2020; do Vasco et al., 2019; Fantin-Cruz et al., 2015; Pyron and Neumann, 2008). Before 1990, methods such as field surveys and ground photograph analyses were used to assess the impact of impoundments on river channels (Knighton, 1988). Statistical analysis including the non-parametric Mann-Kendall (MK) method (Yan et al., 2010), Pettitt's test, and flow-duration analysis (Ma et al., 2017) were also used to contrast the flow regimes before and after hydraulic interventions. Geomorphic Change Detection (GCD) tools (http://gcd.riverscapes.xyz/) have also been used to qualify topographic or morphological changes after an impoundment () (Wheaton, 2015). However, a more systematic assessment of flow changes is provided by the Range of Variability Approach (Richter et al., 1996) and associated with it are the Indices of Hydrological Alteration (IHA) framework (Richter et al., 1996). The IHA method takes daily streamflow values and characterizes a flow regime in terms of five ecologically significant factors: magnitude, duration, frequency, timing, and the rate of change of flows (Page et al., 2005).

Even though the IHA method provides a systematic assessment of flow changes due to hydraulic interventions, only a few studies of Indian rivers have used it. See for example the studies for the Kangsabati river(Mittal et al., 2014), the Krishna River (Kumar and Jayakumar, 2020)and the Dikrong river(Borgohain et al., 2019). This paper, therefore, applies the IHA method to systematically evaluate the impacts of major dams in the Upper Cauvery. However, the information on river flows, which is needed for IHA, is not available for periods before the construction of the dams. Robust hydrological modelling of basins with and without the reservoirs, which enables the analysis of how river flows are impacted by modified landscapes due to human interventions, is therefore additionally needed (O'Sullivan et al., 2019).

Different types of hydrological models have incorporated reservoir models or reservoir operations to simulate stream flows (Mateo et al., 2014; Li et al., 2019; Tehrani et al., 2021). Distributed models like DHSVM and CREST-snow have been used that combine reservoir operation modules to simultaneously assess the impacts of climate change and reservoir operations on the flow regimes (Li et al., 2019; Han et al., 2019). These models incorporate reservoir operations and are capable of taking spatial heterogeneity into account but often are data intensive in their representation of changing landscapes and the impacts on river flow regimes. For example, the SWAT model accounts for spatial heterogeneities by combining distributed data on soil, land cover and elevation and has been used to simulate hydrological regimes regulated by reservoirs at the basin scale (Sulis et al., 2009; Wang and Xia, 2010; Babur et al., 2016). In addition to the data and computational intensity of such models, if the impacts of reservoirs are to be estimated on data that is available only after the reservoirs have been constructed then another key consideration is the transferability of models in space and time (Gao et al., 2016).

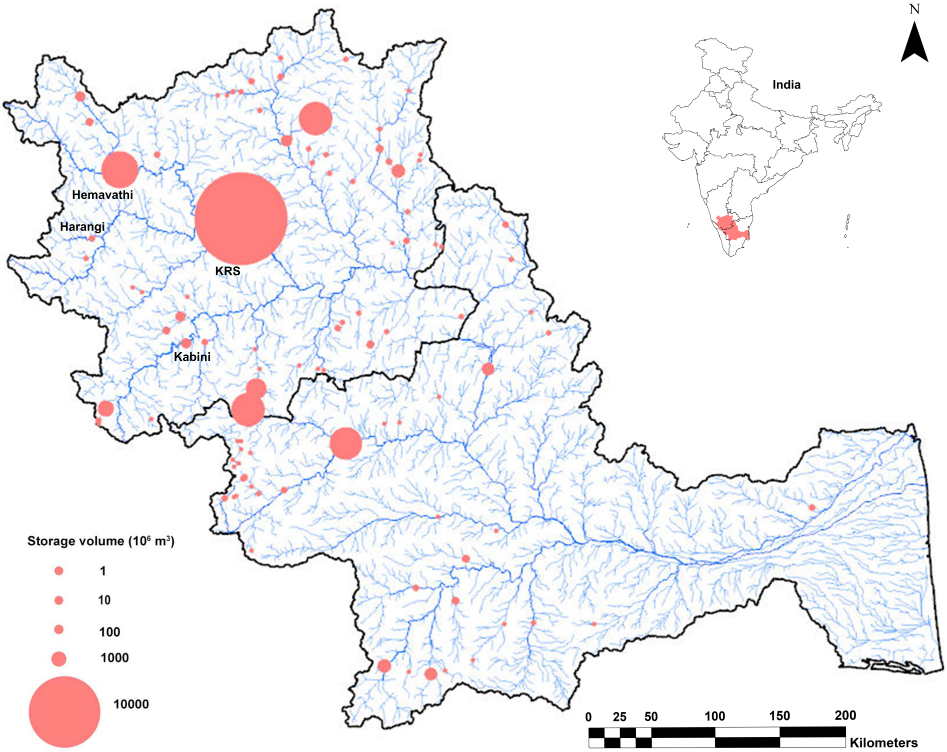
Well-constrained model structures are therefore needed to perform pre-and post-reservoir assessments, especially in regions such as Cauvery where low-resolution data is often available and no records of flow regimes exist prior to the construction of the reservoirs. This motivates the use of a topography-driven rainfall-runoff model (Flex-Topo model) which is neither computationally expensive nor data-intensive. It determines well-constrained model structures corresponding to the dominant hydrological processes in a catchment (Gao et al., 2014) that can be reliably transferred in space and time (Gao et al., 2016; Nijzink et al., 2016). The study then integrates the Flex-Topo model with the IHA method to assess the impacts of hydrological changes due to the construction of four major dams in the upper Cauvery River basin.

This chapter is organized as follows. The study area, along with reservoir details are described in the next section. The methodology that incorporates reservoir operations in a topography-driven rainfall-runoff model and its calibration are then discussed (section 3.3. The results are subsequently presented (section 3.4). The paper concludes with a discussion on the impacts of reservoirs on river flow regimes in the Cauvery River Basin (sections 3.5 and 3.6). The study will provide insight into sustainably managing water resources without hampering the socio-ecological integrity of the river systems.

3.2. DESCRIPTION OF THE STUDY AREA

The Cauvery is one of the most critical interstate rivers of southern India, lying between longitude 75°27'E to 79°54'E and latitude 10°9'N to 13°30'N. The Cauvery basin extends over the Indian states of Tamil Nadu, Karnataka, Kerala, and the Union Territory of Puducherry, draining an area of 81,155 km2 into the Bay of Bengal. Out of this, 42 per cent lies in Karnataka, 54 per cent in TamilNadu Karaikkal region of Puducherry and 4 per cent in Kerala.

There are around 96 dams constructed in the Cauvery basin during the last 1,000 years, out of which 70.30 per cent of dams have been used for irrigation purposes, 19.80 per cent for hydro-power generation, 6.93 per cent for both irrigation and hydropower generation, and the remaining 2.97 per cent dams are used only for drinking water supply. The major irrigation projects include the Cauvery delta, Hemavathi, Cauvery Mettur, Krishnaraj Sagar and Harangi.



Figuur 3.1: The location of the Cauvery basin (upper Cauvery outlined) in southern India. Also shown are the relative sizes of the dams located in the Cauvery basin based on storage volume 106m3

As Figure 3.1 shows, most of these dams are relatively small. Four major reservoirs based on size, storage capacity and command area in the Upper Cauvery basin (Figure 3.2) have been selected for the study. Table 3.1 presents a brief of the reservoirs under study.

Tabel 3.1: Brief description of the reservoirs under study

Reservoir	Year of construction	Sub-basin based on gauge location	Catchment area (106 m^2)	Gross Storage (106 m^3)	Depletion Period	Residence time (months)	Reservoir surface area to upstream area ratio	Filling period	Main purpose
Harangi	1982	Kudige	419.58	240.69	December-May	7.23	0.026	June - November	Irrigation
Hemavathi	1979	M.H. Halli	2810	1050.63	October-May	22.63	0.023	June - September	Irrigation +drinking water
Krishna Raja Sagara (KRS)	1938	Kollegal	10619	1400.31	October-May	8.68	0.010	June - September	Irrigation + drinking water
Kabini	1974	T. Narasipur	2141.90	552.74	November - May	3.57	0.026	June - November	Hydropower +Irrigation

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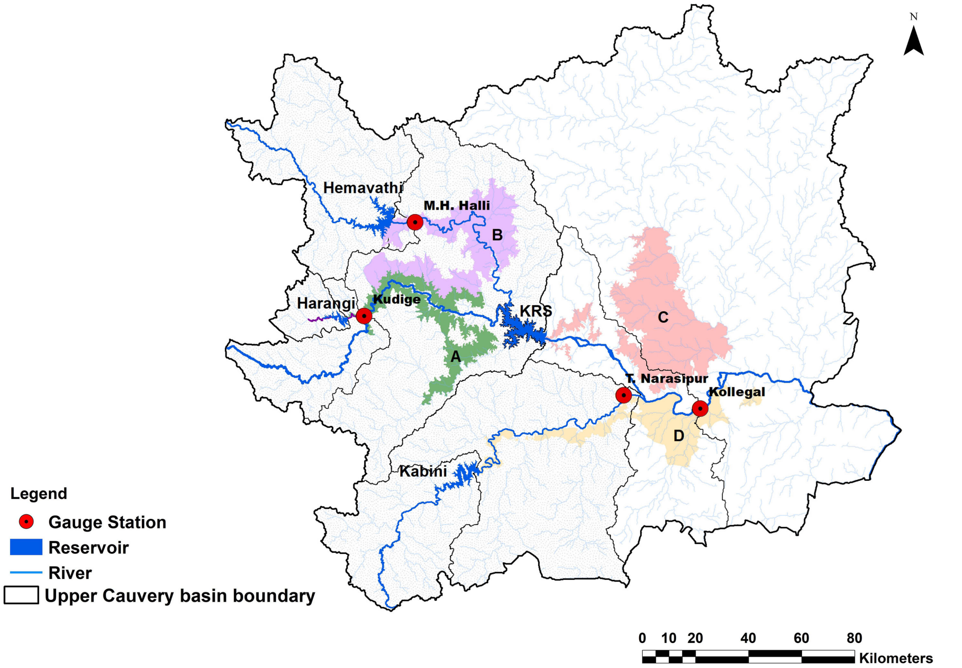
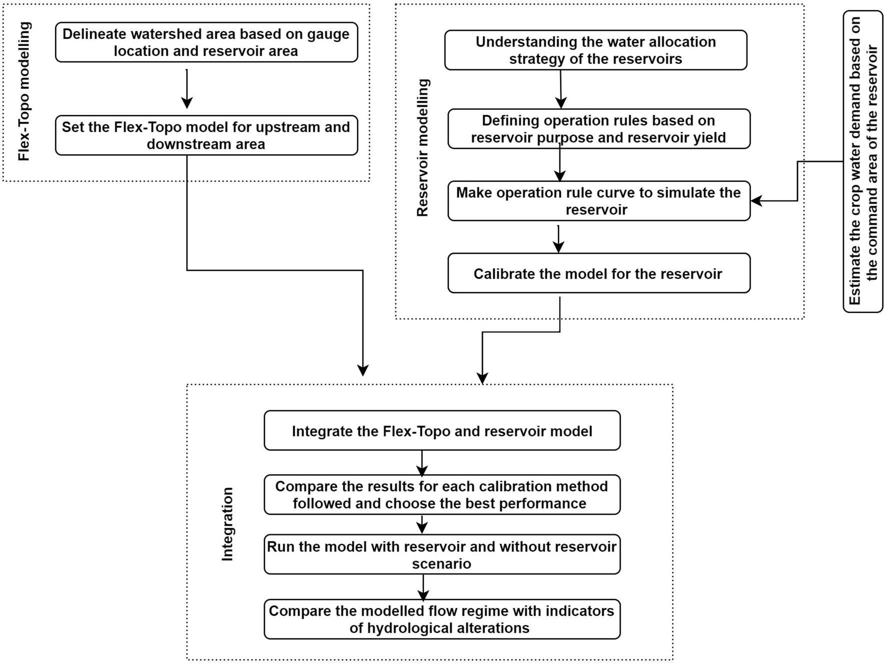


Figuur 3.2: Reservoir sites selected for study are indicated in blue colour. A, B, C and D refer to the command areas corresponding to the reservoirs; with names of reservoirs and gauging stations indicated. The sub-basins corresponding to these gauging stations are also delineated and shown in a grey outline.

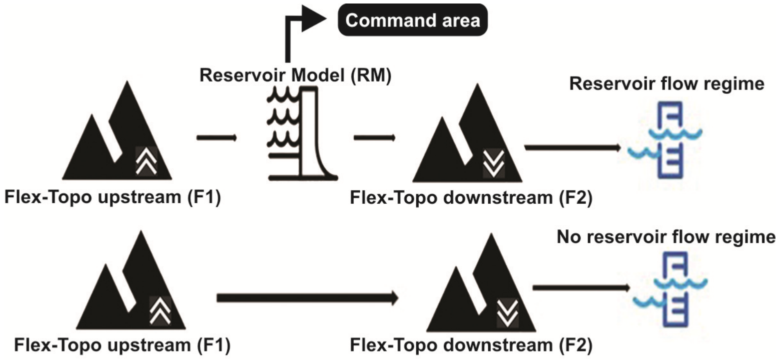
3.3. METHODOLOGY

Figure 3.3 illustrates the overall methodology. It involves modelling the reservoir operations, and the hydrology of areas upstream and downstream of the reservoir and then integrating the two to assess the effect of reservoirs on flow regimes observed downstream and thus on the delivery of ecosystem services. As a result, four sub-basins are studied delineated by the four gauging stations shown in figure 3.2. Each sub-basin is further sub-divided into two parts, corresponding to the areas upstream and downstream of its reservoir. figure 3.4 further shows the modelling concept. F1 and F2 represent the Flex-topo models for upstream and downstream areas of a reservoir contributing to flow at a gauge station (GS), whereas RM and CA represent the reservoir model and associated command area respectively. The flow is measured at the downstream gauge station (GS). In the event of reservoir integration, the outflow from F1 becomes the reservoir's inflow, and the outflow from RM enters F2, after which the outflow from F2 is calibrated at GS. If the reservoir is removed, the outflow from F1 is combined with the outflow from F2, which then forms the outflow at GS.



Figuur 3.3: Overall methodology for analyzing the impact of reservoirs on flow regimes

Further, indicators of hydrological alterations, which are based on river flow characteristics, are used to understand the impact of reservoirs on the river flow regimes. The IHA method is simple to use and provides valuable information related to flow alternations and helps to assess the potential impacts that flow alterations may have on the river ecosystem.



Figuur 3.4: Modelling concept: Upstream and downstream contributing areas of the gauging station (GS) are modelled as F1 and F2 respectively. The top row shows how the reservoir model (RM) that contributes to irrigating a certain Command area is integrated with F1 and F2 and calibrated. To simulate the pre-dam situation, RM is removed from the calibrated model, along with its contribution to irrigate the Command area

3.3.1. THE FLEX-TOPO MODEL

Topography based landscape hydrological model, FLEX-Topo, is used (Savenije, 2010)). Topography is one of the main characteristics of the river landscape, which emerges from the co evolution of vegetation and soil with climate (Savenije, 2010; Gao et al., 2014). As a result, it determines dominant hydrological processes in a catchment (Gao et al., 2014) and has been used as a strong constraint in determining and transferring the model structures in space and time (Gao et al., 2016; Nijzink et al., 2016). The model simulates the response of catchments based on different hydrological response units (HRUs). It approximates the river landscape hydrological behaviour by delineating catchments into different functional hydrological response units, e.g., wetland, hillslope, and plateau (Gharari et al., 2014). The novelty is that the model structure depends on landscape classes determined mainly by topography, which can include geological, geomorphological, or land-use classification (Savenije, 2010; Gao et al., 2014). The parsimonious model has proven to be transferable to data-scarce basins because its model structure is constrained by topography, relying less on data to calibrate parameters, and is robust in its simulations of flows under changing land-cover patterns (Savenije, 2010; Gao et al., 2014).

THE LANDSCAPE CLASSIFICATION

Topographic features like DEM, slope and Height Above the Nearest Drainage (HAND) are used to make the three broad classifications. The slope and HAND are processed in ArcGIS using DEM (80 m resolution). The overall watershed area was delineated based on gauge location. Again, the watershed area for F1 is delineated based on dam location. The F1 area is clipped from the whole watershed to get F2. For each F1 and F2, the raster data set including DEM, slope, HAND, and basin boundary are clipped and exported to Matlab for further analysis. Thresholds are selected to distinguish between the three landscape classes. Locations with HAND > 5 m and slope <11 per cent is classified as a plateau, locations with HAND > 5m and slope >11 per cent is considered as hillslopes and locations with HAND <5 m are considered as wetlands (Gharari et al., 2011). The classified maps are then compared with land use maps and five HRUs (Hillslope forests, Hillslope crops, Plateau forests, Plateau crops, Wetlands) are determined based on the percentage of landscape classes for the upstream (F1) and downstream (F2) areas of the reservoir for each sub-basin.

THE MODEL STRUCTURES

The FLEX-Topo model structure is graphically presented in Figure 3.5, while the description of the variables of each hydrological response unit of the FLEX-Topo model is given in Table 3.2.

Tabel 3.2: Brief description of the various variables linked to the FLEX-Topo model

Variables	Description
P	Rainfall
P_eHF, P_eHC, P_ePF, P_ePC, P_eW	Effective rainfall
S_iHF, S_iHC, S_iPF, S_i PC ,S_iW	Interception reservoir for hillslope forest, hillslope crop, plateau forest, plateau crop, and wetlands.
S_uHF, S_uHC, S_uPF, S_uPC, S_uW	Unsaturated reservoir for hillslope forest, hillslope crop, plateau forest, plateau crop, and wetlands.
S_f HF, S_f HC, S_fPF, S_f PC, S_fW	Fast reservoir for hillslope forest, hillslope crop, plateau forest, plateau crop, and wetlands
E_iHF, E_iHC, E_i PF, E_i PC, E_i W,	An interception from hillslope forest, hillslope crop, plateau forest, plateau crop, and wetlands
E_a HF, E_a HC, E_a PF, E_a PC, E_a W	Transpiration from hillslope forest, hillslope crop, plateau forest, plateau crop, and wetlands
Q_f HF, Q_f HC, Q_f PF, Q_fPC, Q_f W,	Runoff from fast reservoirs
S_i,max	Storage capacity of the interception reservoir
Ce	Fraction of S_u,max
S_u,max	Maximum capacity of the unsaturated zone (Equivalent to the soil moisture capacity in the root zone)
	Spatial heterogeneity in the catchment
D	Splitter to separate recharge from the preferential flow
C max	Capillary rise
K_f	Recession coefficient between the fast and slow reservoir
P_{max}	Maximum percolation rate
R_f, P	Sub-surface flow
R_p, P	Recharge in groundwater

Rainfall P (mm d^{-1}) is first partitioned between interception evaporation E_i (mm d^{-1}) and effective rainfall P_e (mm d^{-1}) based on a threshold Si_{max} (mm). Effective rainfall is partitioned between water retention in the soil and yield runoff R (mm d^{-1}), based on the root zone storage capacity $Su_{,max}$(mm) and a shape parameter (-). Plant transpiration E_t (mm $_{-1}$)) is calculated based on potential evaporation E0 (mm $^{-1}$)), a soil moisture threshold parameter C_c (-) and the relative soil moisture S_u/S_u,max). The generated runoff is further partitioned between a fast component R_f (mm d1) and a slow component Rs (mm d^{-1}) through a separator D (-). A lag function is applied to simulate the lag time T (d) between peak flow and storm event. Two linear reservoirs with different time constants K_f (d) and K_s (d) are used to calculate the fast and slow runoff. The total runoff

Q_m (mm d^{-1}) is the sum of the fast component Q_f(mm d^{-1}) and the slow component Q_s (mm d^{-1}).

The FLEX-Topo model classifies a landscape into different hydrological response units (HRUs) based on the elevation (DEM), slope and Height Above Nearest Drainage (HAND). The landscape is first divided into Hillslope, Plateau and Wetland and the classification is then compared with land use maps. More than 50 per cent of the area in the Cauvery basin is dominated by field crops followed by plantation crops and evergreen forests. The hillslope is characterized by comparatively larger root zone capacities due to deeper groundwater levels and perennial forest. But the land use pattern of the Cauvery basin has been heavily modified by agriculture. Five HRUs are then determined based on the percentage of landscape classes for the upstream and downstream areas of the reservoir for each sub-basin (Figure 3.5).The main difference between these five HRUs is the structure of the unsaturated root zone reservoir (S_u).Patterns of plant rooting depth bear a strong topographic and hydrologic signature at landscape scales ((Fan et al., 2017)). Therefore, The S_u,max for hillslope forest and plateau forest have comparatively larger root zone capacities than hillslope crops and plateau crops. In the wetlands, the root zone storage capacity (S_u,max,W) is relatively low due to the shallow groundwater table. The five landscape units are connected to a common groundwater reservoir, recharged by hillslopes forest (R_{sl},max,HF), hillslopes crop (R_{sl},HC), plateau forest (P_p, P_F), plateau crop (P_p, P_c) and capillary rise (CR) from the wetlands. The model parameter ranges used during the calibration of the model are given in Table 3.3 and are set by optimization.

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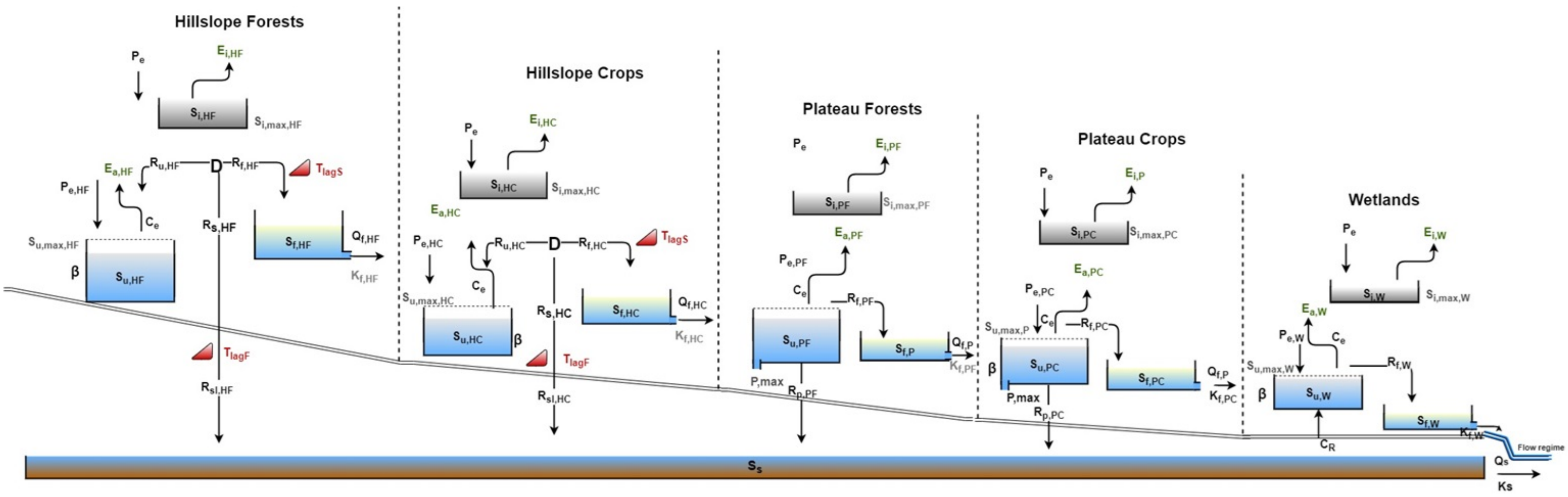
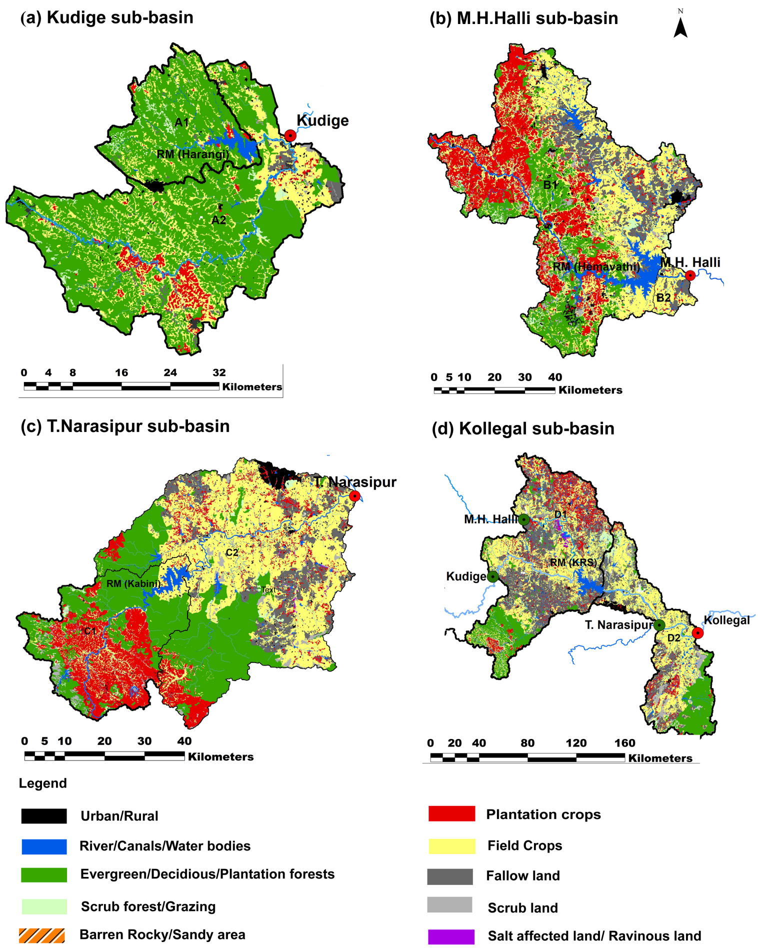


Figuur 3.5: The FLEX-Topo model structure used, showing that different landscape-land use classes have different model structures. All such structures additively contribute to the outflow

3

Tabel 3.3: Model parameters prior ranges. These define the feasible range within which parameters are calibrated

Parameters	Parameter Range				
	Plateau crop	Plateau forest	Hillslope crop	Hillslope forest	Wetlands
Imax [mm day^{-1}] (Storage capacity of the Interception reservoir)	1-8	6-10	1-8	6-10	1-5
Ce [-] (Fraction of Su, max)	0.1-1	0.1-1	0.1-1	0.1-1	0.1-1
Sumax [mm] (Maximum soil moisture capacity in the root zone)	100-500	100-1000	100-500	100-1000	10-100
[-] (Spatial heterogeneity in the catchment/shape parameter)	0.1-5	0.1-5	0.1-5	0.1-5	0.1-5
Pmax [-] (Maximum percolation rate)	0.1-5	0.1-5	-	-	-
D [-] (The splitter)	-	-	0-0.5	0-0.5	-
CRmax [mm/day] (Capillary rise)	-	-	-	-	0.01-1
Kf [d] (Recession coefficient of the fast reservoir)	0.005 -1	0.005 -1	0.005-1	0.005-1	0.005-1
Catchment parameters					
Ks [d] (Recession coefficient of the slow reservoir)	0.0001-0.01				
Tlag [d] (Time lag between the storm and peak flow)	0.1– 30				
Frac 1 [-] (Fraction of forests cover)	The value is fixed (0 -1) based on the percentage of forest area in the sub-basin				
Frac 2 [-] (Fraction of Irrigation)	The value is fixed (0 -1) based on the percentage of Irrigated area in the sub-basin				



Figuur 3.6: Landcover map shown for each basin. Also shown are the reservoirs, and the corresponding upstream and downstream areas. The three entities are connected to model the stream flows at the reported gauge stations indicated in the red dot. The outflows from Kudige, M.H. Halli and T. Narasipur sub-basins are added to the Kollegal sub-basin at the gauging stations indicated by the green dots (shown in Figure d)

RESERVOIR INCLUSION IN THE FLEX-TOPO MODEL

Separate FLEX-Topo models are created for the contributing areas corresponding to the inflow points to the reservoirs and river reaches between the reservoir outflow points and downstream flow gauging stations. Figure 3.4 illustrates it in greater detail, where for each reservoir case upstream area F1 and downstream area F2 are modelled separately. A separate reservoir operation model is created for each reservoir. Thus, for each basin with a reservoir, FLEX-Topo for F1 models the inflow to the reservoir. The operation model of the reservoir then determines inflow to area F2, and the FLEX-Topo model for this area then determines the outflow at the downstream gauge station. The outflows from Kudige, M.H. Halli and T.Narasipur sub-basins are treated as inflows to the Kollegal sub-basin at their respective gauging stations (See figure 3.2). An attenuation factor ranging between 0 and 1 is considered to account for any water loss from the outflow of the reservoir to the gauge station for which the outflow is being modelled.

RESERVOIR OPERATION AND MODELLING

The operation of the multi-purpose reservoir is governed to meet the demands of end-users, according to the priorities for allocation. In general, five primary zones of reservoir storage are considered when operating multi-purpose reservoirs. Storage above the flood control zone between full reservoir level and mean water level is known as spill zone. This storage is occupied mostly during high floods, and the releases from this zone consider trade-offs between structural safety of the dams and downstream flood damages. The flood control zone is the temporary storage for alleviating downstream flood damages. This zone is emptied as soon as possible to negotiate the next flood events. The conservation zone is situated between FRL and dead storage levels. This storage is used for the conservation of water for meeting future demands. The buffer zone is used to satisfy only very essential water needs in case of extreme situations. The dead storage zone refers to the storage meant to absorb sediments entering the reservoir. It is not meant to release water and is therefore considered a dead storage zone. The water allocation zones are crucial for the operation of reservoirs.

Reservoir operation is modelled using a shortage rule curve based on water demand for each reservoir. Depending on the end-user demand that a reservoir is catering to, the following conservation of mass equation is modelled for each time step:

$$\frac{S_{t+1} - S_t}{\triangle t} = I_t + P_t - E_t - O_t - (L_t * D_t) \tag{3.1}$$

S_t = storage, I_t = Inflow, E_t = Evaporation on reservoir surface, P_t = Precipitation on reservoir surface, D_t = demand for reservoir water, L_t = fraction supply of the demand for the reservoir on day t and $\triangle t = 1$ day.

OPERATION RULE CURVES

The reservoir operations are based on shortage rule curves which define zones within which specified proportions of the demand are supplied (Basson et al., 1994). These supply zones in turn depend on reservoir functions, which include flood control, irrigation, hydropower, and water supply. Three operating rule curves for 100 per cent demand-supply (L=1.0), 80 per cent demand-supply (L=0.8), and 50 per cent demand-supply (L=0.5) are used to obtain four operating zones, i.e., spill zone, flood control zone, conservation zone and buffer zone. The operating rule curve is defined based on trigonometric functions developed by Ndiritu and Sinha, 2009 as indicated below:

$$L_{\ell,j} = \tau + (3-1)w + a(sin(2\pi(\frac{t}{365} - \ell))) \tag{3.2}$$

Where, $L_{\ell,j}$ is the operation rule curve for different fraction of demand-supply level for the t th time step ($t = 1,2,3....365$),

τ = Translational Parameter
w =Width parameter
a =Amplitude parameter
ℓ = Lag parameter

Tabel 3.4: Description of variables and parameter ranges for Irrigation and Hydropower reservoirs

Parameter	**Irrigation**	**Hydropower**
Translation [τ]	0-1	0-1
Width [w]	0-0.5	0-0.5
Amplitude [a]	0-1	0-1
Lag [ℓ]	0-1	0-1
Storage initial [S_t, m^3]	Min storage – Max storage (m^3)	Min storage – Max storage (m^3)
Reference level [rl, m^3]	-	Min level – Max level (m^3)
Storage threshold [up, m^3]	-	Min storage – Total storage (m^3)
Initial storage level [S_t level, m^3]	-	Min level – Max level (m^3)

The parameters for irrigation and hydropower in the model include translation, width, amplitude, and lag, all ranging between 0-1, showing the flexibility in adjusting these variables (Table 3.4). Storage parameters like initial storage and storage thresholds are set based on minimum and maximum storage levels specific to each reservoir. The reference level and initial storage are defined for hydropower, guiding reservoir management within these limits.

Table 3.5 outlines the assumptions used in the reservoir model for irrigation and hydropower operations. For irrigation, flow thresholds are based on the maximum outflows recorded during the study, and the outflows are constrained by storage levels in relation to the 100 percent operating curve. For hydropower, water levels are maintained below a reference level, and any excess storage above this level is released. The storage threshold is calibrated to ensure that if storage exceeds this limit, all incoming flows are directed downstream to balance supply and demand effectively.

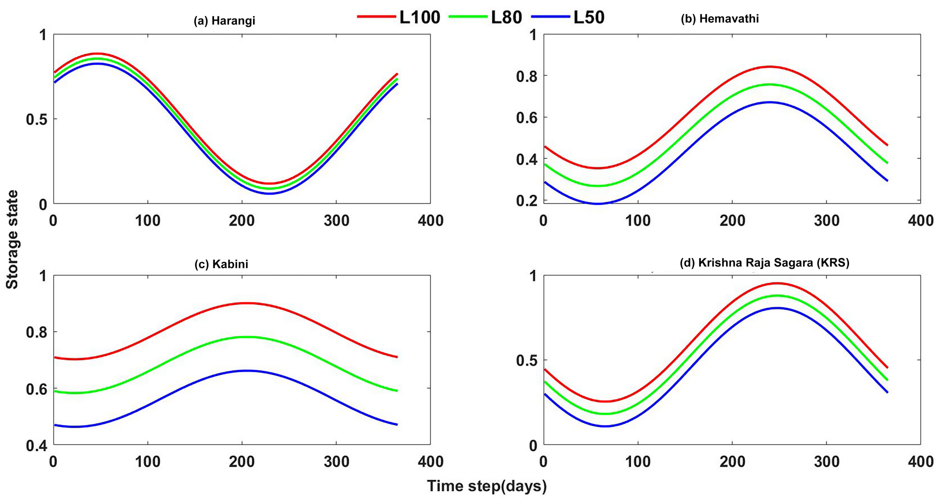
Tabel 3.5: Assumptions for applying operation rules in the reservoir model

Irrigation	Hydropower
Flow thresholds on reservoir outflows are considered, which is the maximum of the outflow data of the study period.	The level of water should not be above the reference level (rl). If the level is above the reference level, the amount above the storage at the reference level becomes outflow.
If the storage in the reservoir is in the 100% supply zone, the outflow from the reservoir is considered to be equal to the storage in excess of the 100% operating curve. However, constraints are put on the outflow, such that it cannot be greater than the flow threshold defined above for that reservoir.	The outflow at any time should not be equal to the flow threshold, which is the maximum of daily outflows from the data of the study period.
	The storage threshold is calibrated, and it is made sure that if the reservoir storage is above the storage threshold, all the inflow to the reservoir from the contributing area is released downstream. Below the 100 per cent operating curve, demands are met according to the supply zone that reservoir storage is in

The four supply zones derived from three operating rule curves serve as the metric to determine the extent to which demands are met all year round. The demand is then calculated on a daily time step and depending on the purpose of the reservoir with respect to the three operating rule curves. Based on the purpose of the reservoir (irrigation or hydropower) as defined in the shortage rule curve, different levels of demand are satisfied. Fulfilling the different levels of demand is subjected to multiple reliability constraints of demand and reservoir storage state and optimization is carried out using the Non-Dominated Sorting Genetic Algorithm (NSGA-II) optimization method. The reservoirs in the Kudige sub-basin serve the sole purpose of meeting the irrigation demands. The Hemavathi and Krishna Raja Sagara in M.H. Halli and Kollegal sub-basins are used for irrigation and drinking purpose. The Kabini reservoir in the T. Narasipur sub-basin is used for both irrigation and hydropower production. The area capacity curve for the Kabini reservoirs is estimated to maintain the water level around the reference level using the least square fitting method.

The shortage rule curve is developed using the maximum and minimum storage values available during the study period for each reservoir to manage water availability effectively. It defines the storage thresholds at which water shortages might occur, guiding reservoir operations to maintain sufficient water levels and avoid shortages during critical periods.

The shortage rule curves of different reservoirs studied are shown in Figure 3.8. The L50, L80 and L100 refer to 50 per cent, 80 per cent and 100 per cent supply of demand. For Hemavathi, Harangi and KRS reservoirs, the storage state of the reservoir can decrease below 20 per cent to fulfil the irrigation demands but cannot go below the L50 curve as this is the critical limit that determines whether to cut back the water for irrigation or any kind of public use. To maintain the function of flood control, the upper limit curve will not be changed for all the reservoirs. In the case of the Kabini reservoir, which is used for hydropower production, the lower limit defines the hydropower generation and therefore the lower limit (L50) will always be more than 40 per cent of the storage state. Harangi is a smaller reservoir compared to the other three reservoirs used in the study. Its limited storage capacity significantly affects the shape and behaviour of its rule curves



Figuur 3.7: The calibrated shortage rule curve of reservoirs under study. The x-axis shows days of a year whereas the y-axis shows the fraction of total available storage (dimensionless storage state).

CROP WATER REQUIREMENT

The estimation of crop water requirement is vital to schedule irrigation based on available water resources (Hargreaves and Samani, 1982). This also determines the water demanded from the reservoirs and influences its mass balance based on its operation rule. The yield potential of crops depends on the climate, crop type and the water demand satisfied in the different growth stages of the crops.

The impact of crop type and growth stage on crop water needs is captured by its crop coefficient and determines crop-specific water demand as a function of potential evapotranspiration (Allen et al., 1998). The crop coefficients vary across regions and depend on the duration of different crops grown, therefore the K_c values for each crop grown in the study area are taken from peer-reviewed literature ((Allen et al., 1998; Mohan and Arumugam, 1994). The crop-specific evaporative water demand is then calculated based on the following formula:

$$ET_a = ET_o \times K_c \tag{3.3}$$

Where,
ET_a = Crop water requirement (mm day $^{-1}$)
ET_o = Potential Evapotranspiration (mm day $^{-1}$)
K_c = Crop Coefficient (-)

The water requirement of the crop is supplied by rainfall (P), irrigation or in some cases, by a combination of both rainfall and irrigation (Brouwer and Heibloem, 1986). When water is supplied by rainfall, not all rainfall is effective due to various factors like climate, soil texture and depth of the root zone (Brouwer and Heibloem, 1986). Therefore, the part of the rainfall which is stored in the root zone and can be used by the plants, called effective rainfall Re, is calculated separately.

Effective rainfall (R_e) is calculated for the daily time step, following the Indian-2 method (Ali and Mubarak, 2017), which specifies that if rainfall is less than 6.25 mm day $^{-1}$ then the effective rainfall is considered zero (R_e = 0 mm day $^{-1}$ when P<6.25 mm day^{-1}). If rainfall is more than 6.25 mm day $^{-1}$ and less than 75 mm day $^{-1}$, then effective rainfall is equal to rainfall (R_e = P when 6.25mm day $^{-1}$ <P<= 75 mm day $^{-1}$). The amount of rainfall beyond 75 mm day $^{-1}$ is not considered effective as it does not become available to plants. The irrigation requirement of a crop is then calculated as the difference between crop water needs and effective rainfall. The net irrigation requirement for the study area was calculated assuming a 70 percent application efficiency of the irrigation provided(Jain et al., 2019).

3.3.2. DATA INPUT TO THE MODEL

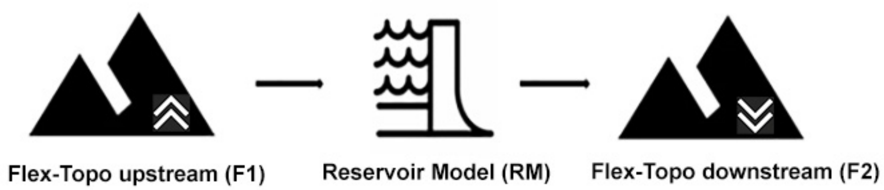
Rainfall and potential evapotranspiration are used as forcing data. Daily gridded rainfall (0.25° x 0.25°) and temperature (1° x 1°) data are obtained from the Indian Meteorological Department, Government of India ((Pai et al., 2014; Srivastava et al., 2009). The rainfall and temperature information are extracted for each sub-basin to force the FLEX-Topo model and the reservoir model. The potential evapotranspiration (ET_O) is calculated based on the Hargreaves equation (Hargreaves and Samani, 1982) considering max, mean and min temperature values.

The runoff data are acquired from the Central Water Commission, Government of India. The data on reservoirs including inflow, outflow and storage level is accessed from Karnataka State Natural Disaster Monitoring Centre, Government of Karnataka, India. (https://www.ksndmc.org/ReservoirDetails.aspx). The crop water demand is calculated using crop-coefficient.

3.3.3. MODEL CALIBRATION

The dataset from January 1991 to December 2010 is used to calibrate the FLEX -Topo models and the data set from 2010 to 2016 is used for validation. The reservoir models are calibrated using the dataset from January 2011 to December 2016 to obtain the reservoir operating rules first. The calibration of a FLEX-Topo model integrated with the reservoir of each basin is conducted in a stepwise manner.

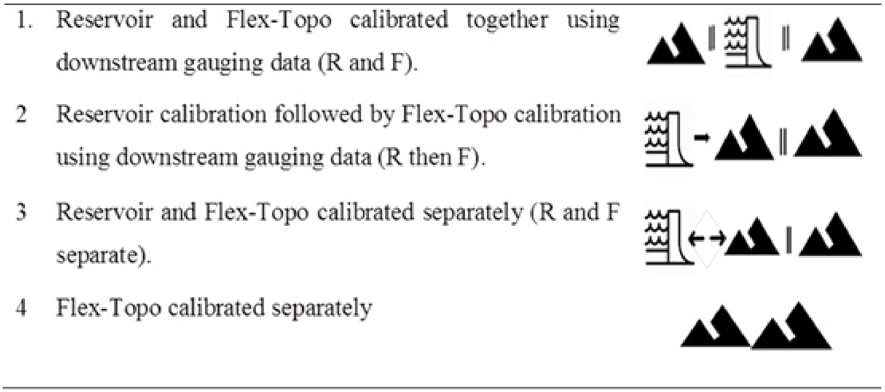
Four calibration strategies are considered for each reservoir location as indicated in Figure 3.8 and 3.9 . First (called "R and F") the integrated flex-reservoir model is calibrated using the downstream gauging station. In this calibration strategy, the model generated for each reservoir in each sub-basin is first integrated into the corresponding upstream and downstream Topo-Flex models of the sub-basin. Then the output of the system of models, i.e., the F-R-F model, is calibrated using Monte-Carlo sampling on observed streamflow at the corresponding gauging station.



Figuur 3.8: The F-R-F model conceptualization is composed of a Flex-topo model for the contributing area upstream of a reservoir (F1), a reservoir model (RM) and a Flex-topo model for the contributing area downstream of the reservoir (F2)

In the second calibration method (called "R then F") the reservoir is calibrated first, then keeping the parameters of the reservoir fixed the integrated model is calibrated using a downstream gauging station. The parameters of the reservoir model are calibrated first using the reservoir's inflow and outflow data from January 2011 to December 2016. The reservoir parameters are then fixed to the best parameter set and calibrated reservoir model is inserted in the serial system of models F-R-F, The Flex-Topo model parameters are then calibrated using data from the downstream gauging station for each sub-basin.

Third ("R and F separately"), both the reservoir model and flex model are calibrated separately. Parameters of the Flex-Topo are transferable (Gao et al., 2014). Therefore, the reservoir and the Flex-Topo model of the entire sub-basin are calibrated separately and then the calibrated parameters are used to run the system of the models (i.e., the F-R-F model).



1.	Reservoir and Flex-Topo calibrated together using downstream gauging data (R and F).
2	Reservoir calibration followed by Flex-Topo calibration using downstream gauging data (R then F).
3	Reservoir and Flex-Topo calibrated separately (R and F separate).
4	Flex-Topo calibrated separately

Figuur 3.9: The calibration performance of the reservoir models for the four reservoirs (reservoir outflow in m3 day-1)

In the fourth method, the Flex-Topo model for each sub-basin is calibrated and assessed separately to compare the results with the above three calibration methods. All the parameters are considered independent of each other. Modelled runoff corresponding to each parameter set is compared with the observed using Nash-Sutcliffe Model Efficiency (NSE) and Mean Absolute Error (MAE). The results indicated that the second calibration method (R then F strategy) performed well during the calibration and validation phase compared to the other methods, therefore, the reservoir calibration followed by the Flex-Topo calibration method is adopted for final calibration.

The spatial heterogeneity, as well as variations in land use, has been incorporated in F1 and F2 which define the model structures and fluxes of FLEX-Topo (as shown in Figure 3.6). Slope, height above the nearest drainage and land use type together defines the various model classes (or landscapes) and associated with each such 'type' of the landscape is a model structure with its unique equations (as indicated in Figure 3.5). For example, within F1 forested hillslopes have a model structure that replicates subsurface flow processes while areas that are close to river networks such as wetlands have model structures that simulate processes such as saturation excess overland flow. Further, evaporation fluxes from forested hillslopes are modelled differently from the evaporation from forested agriculture areas. Since the parameters of Flex-topo are transferable (Gao et al., 2014), the same parameters have been used, and calibrated jointly, from similar heterogeneities such as for forested hillslopes in F1 and F2. Given that topography controls the model structures, the Flex-Topo model is calibrated based on streamflow observed at the corresponding stations downstream of the reservoirs.

The Elitist Non-Dominated Sorting Genetic (NSGA-II) algorithm is used to calibrate the model parameters ((Deb et al., 2000)). NSGA-II is a multi-objective optimization algorithm. It simultaneously optimizes multiple objectives by identifying parameters that

Tabel 3.6: Parameter setting for NSGA II optimization of the model

NSGA parameters	Reservoir calibration	Integrated FLEX-Topo Calibration
No. of Iterations	250	300
No. of decision variables	5-8	25
No. of population size	25-40	125
Population Crossover	0.7	0.7
Population Mutation	0.2	0.2
New generation selection	Elitist selection	Elitist selection
Ordering criteria	Crowding distance	Crowding distance

yield model performances that are not dominated by any other feasible parameters in the multi-objective space (Efstratiadis and Koutsoyiannis, 2010).

Two objective functions are defined and minimized simultaneously. The first objective (f1) is the negative of Nash-Sutcliffe Efficiency (NSE) and the second objective (f2) is the Mean Absolute Error (MAE).

$$f1 = \frac{\sum_{i=1}^{n}\left(Q_i^m - Q_i^o\right)^2}{\sum_{i=1}^{n}\left(Q_i^o - \overline{Q}_o\right)} \tag{3.4}$$

$$f2 = \frac{1}{n}\sum_{i=1}^{n}|Q_i^m - Q_i^o| \tag{3.5}$$

Here, Q_i^o is the i^{th} observation for the observed discharge being evaluated. Q_i^m is the value of the modelled discharge. $\overline{Q}_o$ is the mean of observed discharge and n is the total number of observations. The parameter sets calibrated for the FLEX-Topo model and the reservoir model are given in Tables 3.2 and **??** respectively.

The NSGA-II parameter setting may have different impacts on computational effectiveness. The population crossing over and population mutation plays critical roles during optimization (Wang higher fraction of the population crossing over (0.9) and a lower value of mutation value are preferred for better convergence and to prevent the population from getting trapped in local optima (Wang et al., 2019). The population size depends on the number of the decision variables calibrated in the model and keeping the population size five times the number of decision variables is considered ideal for the simulation . Since for Flex-Topo, there are 20 parameters, the population size is kept at 100. Similarly, for the reservoir model, the number of parameters is five, which translates into a population size of 25. Higher population sizes were also attempted but not used and reported for later analysis because the performance achieved was similar to the reported population sizes. The number of iterations is first tested using 50, 100, 250 and 500 iteration runs and 250 was finally chosen based on the best optimization results.

For each parameter set, the modelled run-off at stations shown in Figure 3.6 is compared with the observed runoff using -NSE and MAE (equations 4.2 and 4.3). The Pareto-front corresponding to the minimum value of -NSE and MAE as identified by the NSGA-II algorithm is considered as containing the better-performing parameter sets for each of the four basins.

3.3.4. INDICATORS OF HYDROLOGICAL ALTERATIONS

The set of Indicators of Hydrological Alteration (IHA) initially proposed by (Richter et al., 1996) is used to understand the impacts of reservoirs on the flow regimes in the Cauvery basin. The parameters considered in IHA have a strong relationship with the river ecosystem and the degree of human interferences in the form of dams, barrages, and other kinds of water diversions on flow regime can be easily estimated. The IHA are categorized into five groups in terms of the magnitude of monthly flow, magnitude and duration of annual extreme flow condition, frequency, and duration of high and low flows. In the present case study, the observed frequency corresponds to the modified flow regime due to reservoir construction and the expected frequency refers to the predicted flow regime without the reservoir.

3.4. RESULTS

TThe results are discussed under the following heads:

3.4.1. RESERVOIR CALIBRATION

The reservoirs are calibrated on a daily time scale. Due to limited data on reservoirs, all the years were used for calibration. There is no validation performed for the modelled streamflow at the reservoir outlets. The results of the reservoir calibrations are presented in Table 3.5. Within parentheses, the Pareto front ranges produced by the NSGA II algorithm are given for both -NSE and MAE. The MAE is always non-negative, and a lower value means a better prediction. The MAE value of all four reservoirs falls in the range of 0.71 to 2.92 (106 m^3 day^{-1}) which is in the acceptable range. Similarly, the NSE value was observed between 0.51 to 0.73. The NSE value above 0.50 is acceptable. Figure 3.9 compares the modelled outflows with the observed ones for the four reservoirs. It was observed that Krishna Raj Sagara (KRS) reservoir, which is the biggest reservoir among the studied sample, has fluctuating outflows during the low flow periods. The adopted operational rule curve within the reservoir models only considers water demands for irrigation or hydropower and does not model water releases for specific purposes, such as drinking water from the KRS dam. This is especially so during the low flow period that is thus not well captured by the model.

INTEGRATION OF RESERVOIRS WITH FLEX-TOPO: F-R-F MODEL CALIBRATION AND VALIDATION

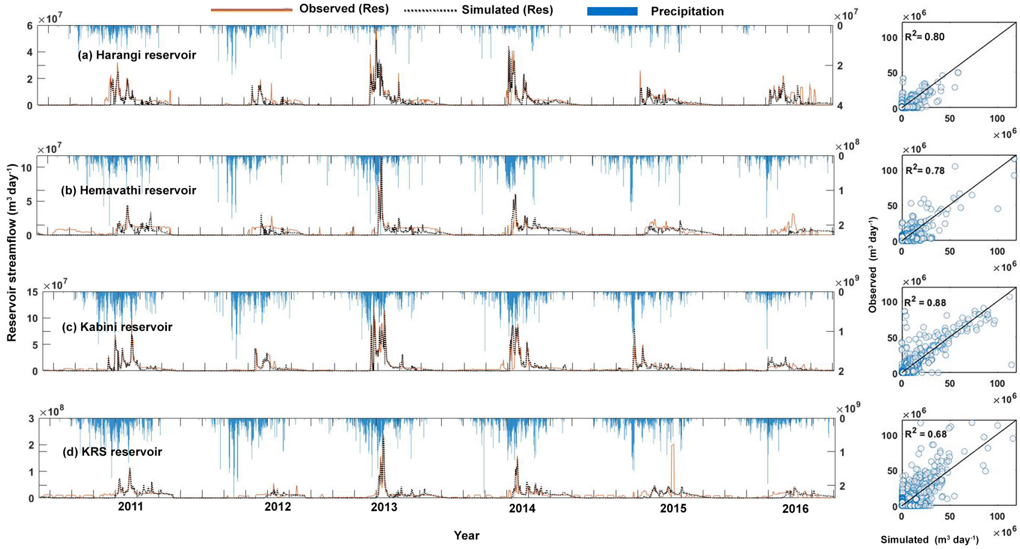
The calibration metrics of the models after the integration of corresponding reservoirs with the Flex-topo models are presented in Table 3.7 and how the modelled streamflow time series compare with the observed are shown in Figures 3.10. The figure also shows

Tabel 3.7: The model performance metrics for the calibration of the four reservoirs and the calibration and validation of the F-R-F models (i.e., the integration of calibrated reservoirs with upstream and downstream FLEX-Topo models) for the corresponding four sub-basins.

Reservoir Calibration (2011-2016)						
Reservoirs	-NSE [range]	MAE [range] (10^6 m^3 day^{-1})				
Harangi(kudige)	-0.64 [-0.65 - (-0.63)]	2.92 [2.92 -3.01]				
Hemavathi (M.H. Halli)	-0.51 [-0.52 - (-0.51)]	1.15 [1.15 -1.16]				
Kabini (T.Narasipur)	-0.73 [-0.73 - (-0.72)]	1.24 [1.24-1.24]				
KRS(Kollegal)	-0.68 [-0.67 - (-0.69)]	0.71 [0.70 - 0.72]				
F-R-F model calibration and validation						
Sub-basins	Calibration (1991-2010)			Validation (2011-2016)		
	-NSE [range]	MAE [range] (mm day-1)	PBIAS (%)	-NSE	MAE (mm day-1)	PBIAS (%)
Kudige	-0.80 [-0.81 - (-0.80)]	1.36 [1.33 -1.39]	8.54	-0.65	2.05	16.27
M.H. Halli	-0.57 [-0.57 - (-0.56)]	0.37 [0.40 -0.41]	3.24	-0.52	0.48	17.66
T.Narasipur	-0.53 [-0.53 - (-0.50)]	0.67 [0.67- 0.69]	11.62	-0.52	0.66	-42.80
Kollegal	-0.53 [-0.54 - (-0.52)]	0.92 [0.92 -0.97]	-6.23	-0.50	0.86	-57.54

the modelled stream flows that simulate the pre-reservoir cases ("No-Res") for the fours sub-basins. Here for each reservoir model that is integrated, a parameter set corresponding to a point that lies in the middle of the Pareto front in the objective space, i.e., balanced by non-dominated sets on either side, is chosen.

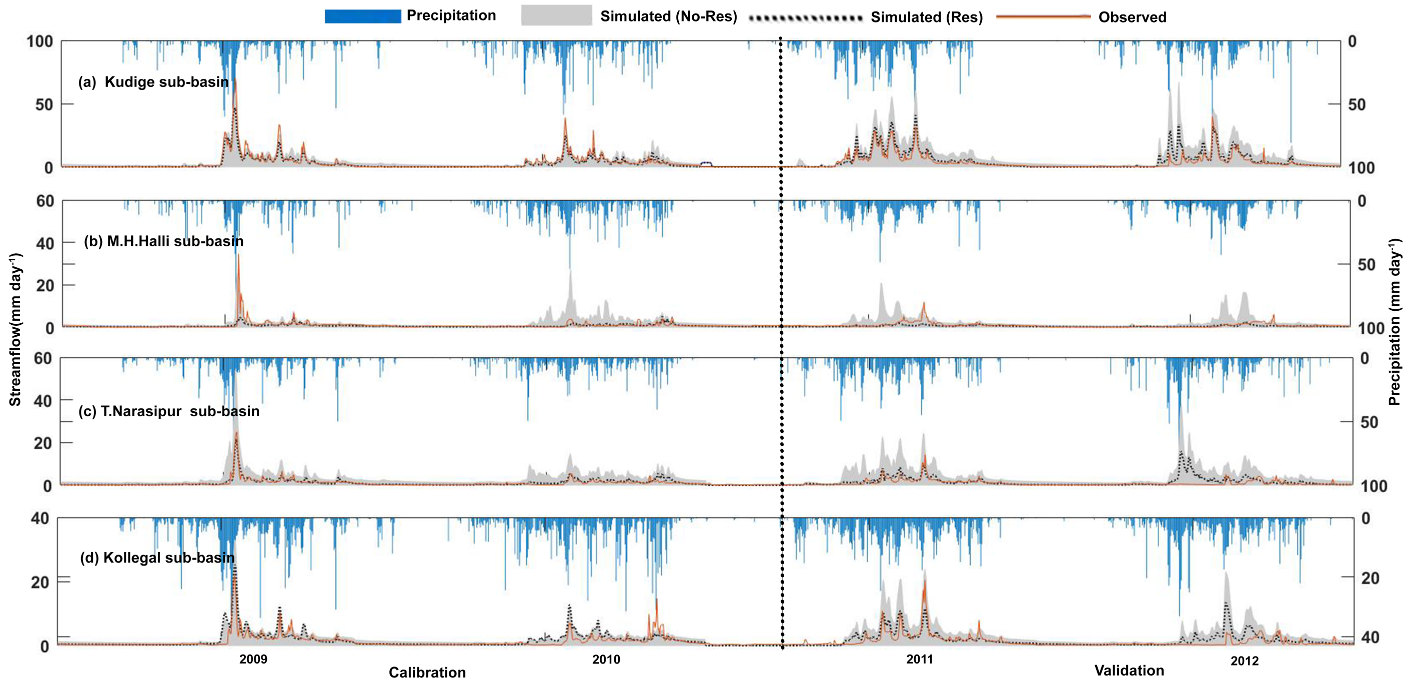
The scatter plots of the observed and modelled stream flows are shown in Figure 10. Amongst the four sub-basins, Kudige performed the best in calibration (R^2=0.90) and validation (R^2=0.81). Harangi is in the Kudige sub-basin, which is the smallest reservoir among all the reservoirs taken for the study. As indicated in Table 3.1, the residence time of the Harangi reservoir is small, which meant that the reservoir model (being a more difficult calibration problem) had little impact on the overall model performance. The R-squared of M.H. Halli, T.Narasipur and Kollegal performed in the range of 0.73 to 0.77 during the calibration phase and 0.67 to 0.74 during the validation phase. The models of all the basins therefore appear to have a bias in predicting flows, with modelled daily flows being higher than the observed-on average for T. Narasipur and Kollegal sub-basins.



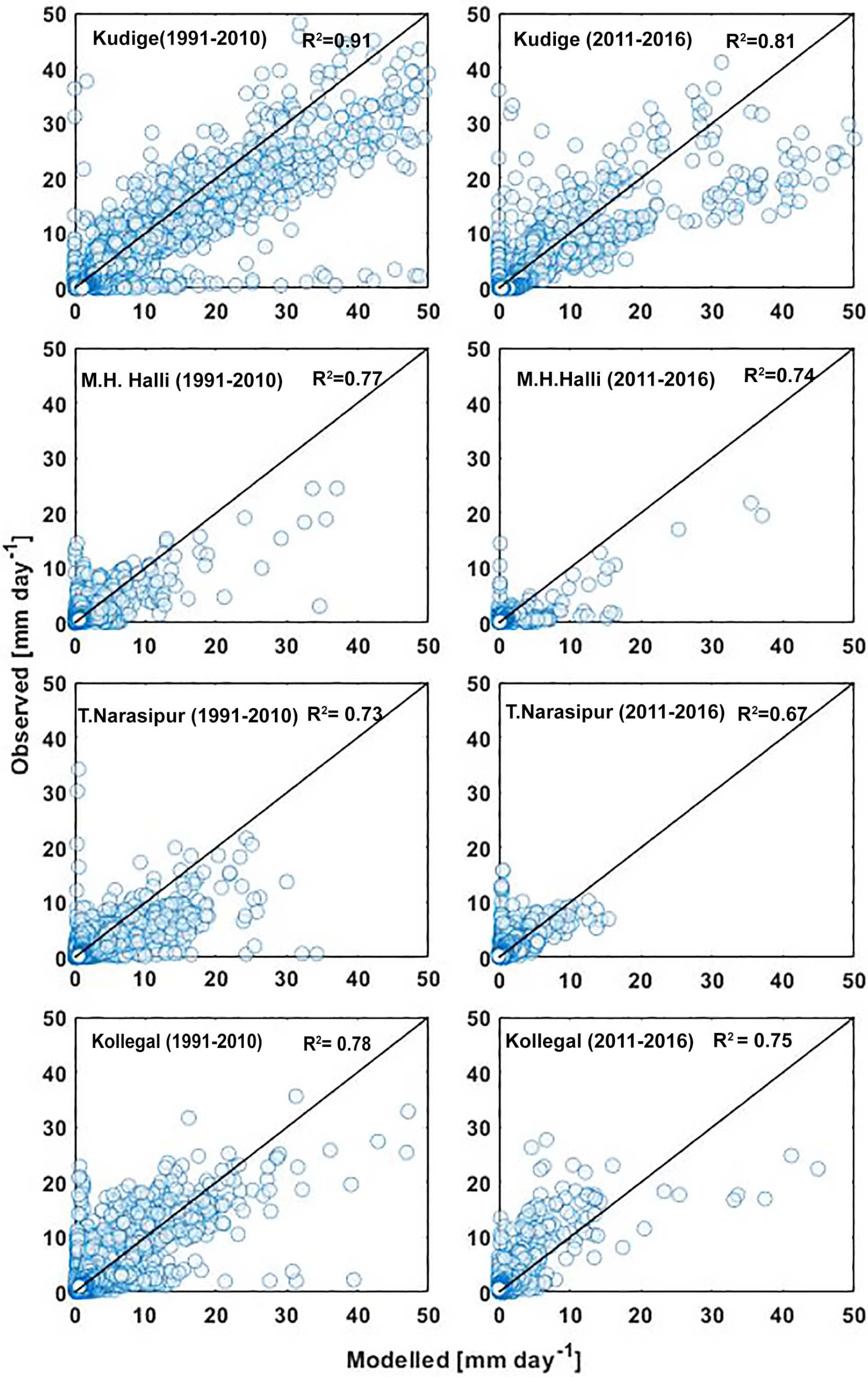
Figuur 3.10: The calibration performance of the reservoir models for the four reservoirs (reservoir outflow in m^3 day-1)

Table 3.5 reports on the performance of the calibrated F-R-F model with the observed for the four sub-basins. The NSE was observed in the range of 0.53 to 0.80 in the calibration phase and 0.50 to 0.65 in the validation phase for all the four sub-basins. The NSE value above 0.50 is considered an acceptable level of performance. Similarly, the values of MAE were observed in the range of 0.92 to 1.36 mm day^{-1} in the calibration phase and 0.86 to 2.05 mm^{-1} in the validation phase and are acceptable.

3



Figuur 3.11: The F-R-F model performance for the four sub-basins. Only four years (2009 to 2012) are presented here. Additionally, 'No-Res' represent simulations without reservoirs and 'Res' represent simulations with reservoir



Figuur 3.12: Scatter plot of the observed and modelled stream flows during calibration (left panel) and validation phase (right panel) for the four sub-basins

The PBIAS values for the calibration and validation periods are also provided in Table 3.5. It indicated that for Kuidge and M.H. Halli, the values of PBIAS are within the ±25 percent limits, which are acceptable. However, for T. Narasipur and Kollegal sub-basins the PBIAS values of the validation periods are beyond the acceptable limits.

The mostly positive PBIAS values suggest that the low flows are better simulated than the the high flows. This is also evident from Figure 3.10 where high flows are often missed, especially for the cases of Harangi, Hemavathi and Kabini reservoirs. Since the parameter sets on the pareto front that are closest to the origin are chosen for the simulations, the corresponding model simulations do not have the best possible performances in either of the two objective functions. Even though NSE is used as one of the objective functions (that is sensitive to high flows due to NSE being a quadratic function of the residuals), MAE is the other objective function that is robust to outliers (Pande, 2013a,b). This may be a reason why high flows are not as well simulated as the low flows.

IMPACTS OF THE RESERVOIRS ON THE FLOW REGIMES

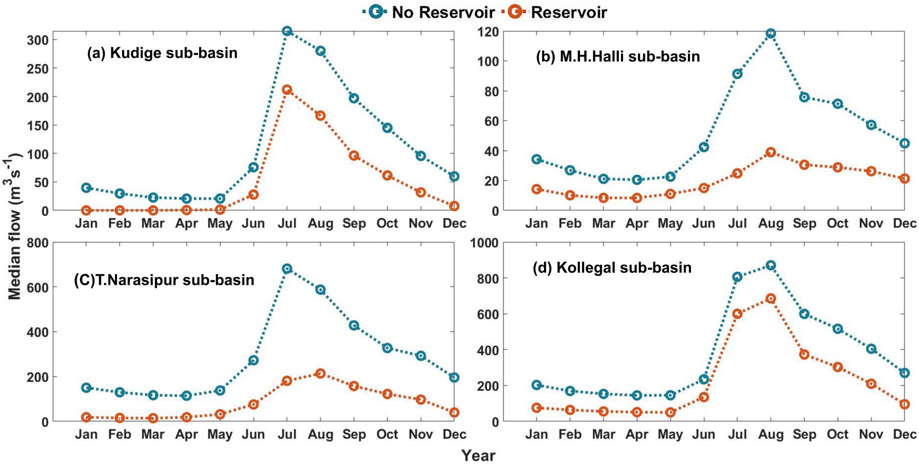
The impacts of the reservoirs on the river flow regimes are assessed using indicators of hydrological alteration (Richter et al., 1996). The calibrations of the entire basins at the gauge sites are not possible to estimate the pre-reservoir scenarios due to the lack of data before the dams were constructed. Furthermore, the calibration of the upstream models (F1) using inflow data of the reservoirs was hampered by limited data on the reservoirs itself, which were available for six years within the period studied. Therefore, the calibrated F-R-F models are used to infer the natural flow regimes by removing the reservoirs of the corresponding four sub-basins. The flow regimes simulated by the models after removing the reservoirs are used as pre-impact simulations for the corresponding sub-basins. The gauge stations, used for model calibration and validation, located downstream of the reservoirs are used to compare the pre-and post-construction of reservoirs (see Figure 3.5 for gauge station locations) and the data from the year 2001 to 2016 is used for calculating the indicators for hydrological alterations.

IMPACT ON THE MAGNITUDES OF THE MONTHLY STREAM-FLOW CONDITIONS

The median values of the monthly stream flows for the four sub-basins are given in Figure 3.13. It shows that the flows in the sub-basins were consistently reduced during all the months of the year after the reservoirs were constructed.

IMPACT ON MINIMUM FLOWS

The median values of hydrological alterations for the annual extreme flow conditions of the Upper Cauvery River basin are given in Table 3.8. The 1-day and 3-day minimum median flows were reduced significantly in all sub-basins. Zero flow days were observed only in the Kudige sub-basin in the post-impact period. The base-flow indices of all basins were reduced after reservoir constructions, except for the M.H. Halli sub-basin, where the base-flow index increased.



Figuur 3.13: The magnitudes of the monthly streamflow pre- and post-reservoir construction

IMPACT ON THE MAXIMUM FLOWS

The median values of the impact of reservoirs on maximum flows is also indicated in Table 3.6. All 1-day and 3-day maximum median flows were reduced in all sub-basins, and most significantly in the M.H. Halli and T. Narasipur sub-basins, where high-magnitude flooding was eliminated after reservoir constructions.

IMPACT ON THE FREQUENCY AND DURATION OF HIGH AND LOW PULSES

The high and low flow conditions are defined based on 75th (high pulse) and 25th flow (low pulse) percentiles. Increases in the low pulse durations are observed in the Kudige, M.H. Halli and Kollegal sub-basin which may worsen the eco-hydrological environment of the river and surrounding floodplains. A decrease in low pulse duration is observed in the T. Narasipur sub-basin. Moderate decreases in high pulse durations are observed in all the sub-basins. A decrease in high pulse duration hampers the supply of nutrients to the aquatic plants and animals and may reduce the riverine biodiversity. This means

Tabel 3.8: Indicators of hydrological alterations of extreme flow conditions

IHA parameter	Kudige (Harangi)		M.H. Halli (Hemavathi)		T. Narasipur (Kabini)		Kollegal (KRS)	
	Irrigation		Irrigation		Hydropower		Irrigation	
	No Reservoir	Reservoir	No Reservoir	Reservoir	No Reservoir	Reservoir	No Reservoirs	Reservoirs
	Extreme flow condition (m^{3}s^{-1})							
1-day minimum	15.43	0.00	17.55	7.11	97.22	12.45	127.4	44.98
3-day minimum	15.65	0.00	17.72	7.15	97.76	12.53	128.2	45.14
1-day maximum	1120.00	809.10	750.20	169.30	2450.00	877.20	3646	3027
3-day maximum	1041.00	713.90	680.9	138.5	2280.00	809.50	3474	2873
Number of zero days	0.00	90.50	0.00	0.00	0.00	0.00	0.00	0.00
Base flow index	0.14	0.00	0.26	0.30	0.30	0.12	0.28	0.16
	Frequency and duration of high and low flows (m^{3}s^{-1})							
Low pulse count (*n* times year^{-1})	4.00	2.50	4.00	4.00	2.00	5.5	2.00	2.00
Low pulse duration (days)	9.00	52.75	13.50	19.50	25.50	7.75	18.5	117.5
High pulse count(*n* times year^{-1})	5.00	6.00	4.50	3.00	5.50	3.00	6.00	5.50
High pulse duration (days)	8.00	4.50	7.00	4.00	9.00	4.00	8.00	5.00

that the supply of nutrients may have been hampered in all the sub-basins affecting riverine biodiversity.

In the context of a hydropower reservoir (Kabini), it was observed that the reservoir case has long low pulse duration than the case without a reservoir. Since a specific water level should be maintained in the hydro-power reservoir to generate electricity, water is frequently discharged from the reservoir to do so resulting in low pulse duration. In contrast to the hydropower reservoir, irrigation reservoirs (Harangi, Hemavathi and KRS) have higher low pulse durations than for its corresponding no reservoir cases. This suggests that, in comparison to hydropower reservoirs, irrigation reservoirs generate higher flow regimes. A similar reduction in low pulse duration was observed in the Yangtze River due to reservoir operation for irrigation purposes in China (Gao et al., 2018).

3.5. DISCUSSION

The method implemented in this paper is limited by various assumptions. After discussing the assumptions and how these may be alleviated, the influence of reservoir operations on flow regimes in the Upper Cauvery are synthesized and followed by what it may imply for reservoir operations in India.

3.5.1. MODEL UNCERTAINTY AND UNDERLYING ASSUMPTIONS

The result indicates that flow regimes are clearly altered from their natural state following reservoir impoundments. Although dams differ dramatically in size, function, and location, almost all sub-basin record a reduction in median flow, minimum and maximum flows. These patterns are primarily caused by regulated reservoir operations, including storing and releasing flows for irrigation, or hydropower generation, which alters the river streamflow characteristics. Moreover, the water is being diverted for irrigation outside the basin which also contributed to altered flow regime characteristics. However, the diverted flow is not addressed in the present simulation in the sense that we assume that the irrigation water supply evaporates and does not return to the basin. This implies that the model is likely under-estimating available discharges at the sub-basin outlets and this has been reflected in the PBIAS values of T. Narasipur and Kollegal sub-basins during the validation phase.

In case of no reservoir, the command areas irrigated by reservoirs become unirrigated and the irrigated areas are reduced proportionally in the model based on the command area falling in the upstream and downstream areas of the reservoirs. Such an assumption needs to be validated, e.g., based on official records on land use types in the pre-reservoir periods.

The low flows are better simulated than the peaks. One explanation may be that the parameter sets on the pareto front that are closest to the origin are chosen for the simulations. This means that the corresponding model simulations do not have the best possible performances in either of the two objective functions. Even though NSE is used as one of the objective functions (that is sensitive to high flows due to NSE being a quadratic function of the residuals), MAE is the other objective function that is robust to outliers (Pande, 2013a,b). This may be a reason why high flows are not as well simulated as low flows.The use of additional objective functions such as log (NSE) and others based on hydrological signatures (Santos et al., 2017) may alleviate such concerns.

The reservoirs were calibrated first partly because of limited data (following the R then F calibration strategy). Only six years of daily scale time series were available for the inflows and outflows of the reservoirs, which was not deemed sufficient for the calibration and validation of the F-R-F model. Therefore, different time series are used for the calibration of Flex-Topo and reservoir models. Further, because a standard operating rule curve is used for all the reservoirs, it is acknowledged that some of the dams' specific water discharges may not have been captured by the reservoir model. Validation results also suggest that modelled flows of two reservoirs are biased. Model calibration may therefore benefit from operating rule curves inspired by specific reservoir functions and flow requirements.

3.5.2. INFLUENCE OF RESERVOIR OPERATIONS ON FLOW REGIMES IN THE UPPER CAUVERY

The study confirms that the average monthly flow in the Upper Cauvery basin is greatly influenced by reservoir operations and subsequent water abstractions in the basin. The reduction of streamflow in most of the months is likely contributing to increased scarcity of water in different seasons. The decrease in monthly flows is observed across all the sub-basins throughout the year due to reservoir operations when compared to its natural flow regimes. The different operation rules in different sub-basins have varying degrees of influence on downstream flow timing, pulse behaviour, change rate, and frequencies of flow (Wang et al., 2016).

The decrease in summer flows during the post-reservoir periods, as evident from the model results, may lead to negative effects on the aquatic habitats and migratory and reproductive biology of fish species in the downstream areas. The one-day minimum flow at Kudige was observed to be below 1 m^3s^{-1}, which before the reservoir construction was 15.43 m^3s^{-1} and at safe level. This huge reduction is harmful to the survival of aquatic organisms. The frequency and duration of high and low pulses are critical to supporting the migratory behaviour of fish during the spawning season (Wang et al., 2016). In addition, variations in fish assemblage structures have likely been affected since the structures are strongly associated with mean daily flows, base flow, number of zero-flow days and high-flow pulses (Arthington et al., 2014; Anderson et al., 2006; Perkin and Bonner, 2011). Furthermore, in the Kudige sub-basin, a period of 90 days of zero flow was recorded after the construction of the Harangi reservoir which created a stressful environment for the aquatic organisms.

In the T. Narasipur sub-basin, the natural base flow index of 0.30 was reduced to

0.12 after the construction of the Kabini reservoir. In tropical rivers, the streamflow discharge is composed entirely of the base flow through most of the dry season of the year (Smakhtin, 2001). This and extended duration of zero flow leads to the loss of lotic habitats which places aquatic species at high risk of extinction (Mallen-Cooper and Zampatti, 2020).

The frequency and duration of low pulses were also impacted across all the studied sub-basins. Decreases in low pulse durations in the Kudige, M.H. Halli and Kollegal sub-basins may worsen the eco-hydrological environment of the river and surrounding floodplains. In contrast, an increase in low pulse duration was observed in the T. Narasipur sub-basin where the hydro-power reservoir is located. The reservoir releases excess water to preserve flood control capacity from June till August, after which it releases flow to meet the power generation requirements, which then increases the low flow duration in the T. Narasipur sub-basin.

Hydrological connectivity between the river channels and floodplain is dependent on the intensities and durations of high and low pulses and determines the habitat for aquatic species in the dry and wet seasons (Wang et al., 2016). Flow pulses also provide essential carbon inputs to the riverine ecosystem and strongly support the aquatic food web (Sheldon and Thoms, 2006). Thus, floodplain ecosystems are dependent on naturally dynamic river-flow patterns (Rood et al., 2005). Changes in flow patterns directly affect the floodplain habitats, and thus biodiversity, as exemplified by the reported loss of fish and invertebrates due to dam regulations in the Paraná River basin (Agostinho et al., 2004). Dam impoundments cause salinization and waterlogging which impact the water quality (Tuboi et al., 2018). Similar cases of salinization and waterlogging were reported in the Kabini command area (Nagaraj et al., 2003).

Around 23 per cent of Karnataka's share of Cauvery water is utilized to irrigate highly intensive crops like paddy and sugarcane. Crop productivity and irrigation effectiveness are both impacted negatively by improper cropping patterns over time, which lowers profitability. Similar to this, hydraulic interventions such as dams and barrages changed the Mahanadi River delta from an agrarian system that depended on flooding to a landscape that was vulnerable to flooding (D'Souza, 2006). Since the Hirakud Dam began operating in 1958, the frequency of high floods in the Mahanadi basin has risen from once every 3.48 years to once every 3.3 years (D'Souza, 2006). Furthermore, due to silting of the reservoirs and canals, the tail-end areas do not get adequate irrigation water for the second crop thereby reducing the area for agricultural production (Kulkarni, 2020).

The reported geomorphic consequences of dams include bed armoring, changes in bedform morphology, and sediment depositions downstream that directly affect the channel morphology by narrowing widths, deepening channels and arresting flow within the channel(Pal et al., 2019). Downstream bed degradation was accelerated by amplified peak discharges from dams reported in the upper Godavari River basin (Sanyal et al., 2021). However, no such studies were reported for the Cauvery River basin.

3.5.3. IMPLICATIONS FOR INDIA

Increasingly empirical data is suggesting that dams, despite large investments, are unable to deliver on their claims (Pradhan and Srinivasan, 2022). The reservoirs are critical for economic growth though it significantly affects the river flow regimes. The costs of dam removals are huge and have both economic and social implications. However, the ill effects of the dams can be minimized by incorporating environmental flows as an integral part of dam development programs. Since irrigation reservoirs have a distinct hydrological influence over hydropower reservoirs, there may be a need to differentiate the e-flow setting based on the purpose of the reservoirs. More research should be done to compare the flow regime changes made by reservoirs serving various purposes in order to establish e-flow standards that specifically target the impact of that type of reservoir operation. More specifically, in the Cauvery River basin and other related basins where dams are already operational, the reservoir operation rules could be re-calculated to take environmental flow requirements into account, thereby reducing their negative effects.

In India, environmental flows are still not widely acknowledged (Smakhtin, 2001). Even though the Supreme Court of India has mandated a minimum flow of 10 per cent for rivers like Yamuna and Cauvery to improve its water quality (Smakhtin, 2001). the water released from various dams are not well aligned with such environmental flow requirements. There is also a lack of data on the relationships between flows and ecosystem functioning, which impedes the implementation of environmental flow assessment (Jain, 2015). Further, the existing Environmental Impact Assessment (EIA) system in India is unable to keep up with the pace of economic growth and fails to examine and mitigate the broader consequences of widespread dam-building (Erlewein, 2013). To improve the EIA, the timing and duration of low/high flow pulses should be considered during the impact assessment of dams in relation to the environmental flows. It can be more effective if the flow requirements for dry and wet years are assessed separately for different reservoir storage levels and reservoir purposes. In addition, the tradeoffs between water security of different stakeholders need to be considered during the design and construction of the dams (Pradhan and Srinivasan, 2022).

3.6. CONCLUSION

Given the present scenario of changing climate, sustainable water resource management is becoming a bigger issue. Since it is so difficult to integrate natural hydrological processes with reservoir operations, reliable forecasting of future water availability is confronted by significant hurdles. With the proposed modeling approach, the effects of dams on river flow regime can be studied even when no data is available for the period before the dam was constructed. This paper assessed such effects under data scarce conditions using a landscape-based hydrological model (FLEX-Topo) and Indicators of Hydrological Alterations (IHA) in the upper Cauvery region of India.

The study confirms that the average monthly flow in the Upper Cauvery basin is greatly influenced by reservoir operations and subsequent water abstraction in the basin. The decrease in monthly flow is observed across all the sub-basins throughout the year due to reservoir operations when compared to its natural flow regimes. Since irrigation reservoirs have a distinct hydrological influence over hydropower reservoirs, there may be a need to differentiate the e-flow settings based on the purpose of the reservoirs and future research work should be initiated to achieve this target. This can be done, for example, by using the modelling approach presented here to reverse engineer operating rules so flow regimes (such as certain high and low flow percentiles) essential to sustain biodiversity can be maintained. Further, had there been longer data time series for the inflows and outflows of the reservoirs, better outcomes could have been achieved by the proposed method. The current work also used a simple trigonometric operation rule curve for all the reservoirs. This can be improved further by employing reservoir-specific operation rule curves, which again depends on the availability of appropriate time series data. Nonetheless, the present study presents a way forward to understand the impacts of dams at the basin scale under data scarce conditions and to help basin managers in formulating strategies to allocate water for both human and environmental needs.

4

TRADEOFF ANALYSIS BETWEEN ECOSYSTEM SERVICES

Dams, marvellous and supreme
Taming the wilderness of streams
Light in the dark, the crop stands tall
Both at the cost of fishes downfall
In the world of choices we make,
There are no easy paths to take,
so let us ponder and contemplate
the tradeoff we make each day
And strive to place a balance lay
between development and river's way

Parts of this chapter are based on:

Ekka A, Jiang, Y., Pande, S., van der Zaag, P., (2024). *How economically and environmentally viable are multiple dams in the upper Cauvery Basin, India? A hydro-economic analysis using a landscape-based hydrological model* Hydrology and Earth System Sciences, 28 (14),3219-3241.

4.1. Introduction

Population growth, economic development, and climate change have necessitated the construction of water conservation projects such as dams and reservoirs to meet the societal needs for water, food, and energy among others(Suwal et al., 2020; Vanham et al., 2011). A large number of cascade reservoirs, i.e., multiple reservoir dams constructed along a river network, have already been built, and many more are in the process of construction (Suwal et al., 2020). The establishment of reservoirs and dams can alter basin hydrological conditions, particularly river flows downstream of these dams, by storing and releasing river water that can affect aquatic ecosystems in the basin.

Understanding the impact of multiple dams is important for the sustainable development of river basins. The flow regime of rivers is considered a key factor that is affected by dams while determining river ecosystem health (?Brauman et al., 2007). Many scholars have used the degree of hydrological alteration to measure the hydrological impact of dams (Gierszewski et al., 2020; Lu et al., 2018; Mittal et al., 2016; ?). While hydrological alterations from dams have basin-wide implications, impact assessment typically concentrates on river segments, assessing the impact upstream or downstream of single dam projects (Nilsson and Berggren, 2000). The assessment becomes more challenging when there are more critical ecosystems affected in the presence of divergent interests of both upstream and downstream stakeholders (Arias et al., 2014; Berga et al., 2006).

A viable configuration of dams considers factors such as stakeholder preferences and ecosystem preservation to ensure the sustainable functioning of a dam system. From a stakeholder perspective, it takes into account the preferences and needs of different parties involved, including local communities, government bodies, environmental organizations, and industries. The aim is to strike a balance among diverse interests, incorporating stakeholder preferences into the design and operation of a dam system (Kemmler and Spreng, 2007) From a phenomenological perspective, a viable configuration respects the boundaries within the ecosystem that, if exceeded, could disrupt the functioning of key components such as fish biodiversity, aquatic habitats, and downstream water quality (Kumar and Katoch, 2014). Overall, achieving a sustainable balance between societal needs and environmental protection requires careful planning, scientific analysis, and transparent decision-making processes in dam development(Kemmler and Spreng, 2007; Kumar and Katoch, 2014).

There are ecological-economic models that analyze tradeoffs between economic development and ecological conservation or among ecosystem services, but they usually consider the effect of a single reservoir(Lu et al., 2018; Rodríguez et al., 2006; Fanaian et al., 2015) or quantify tradeoffs between energy production and environmental degradation (Null et al., 2020; Song et al., 2019; Wild et al., 2019; Schmitt et al., 2018) Few studies have targeted multiple dams(Consoli et al., 2022; Van Cappellen and Maavara, 2016; Ouyang et al., 2011; Wang et al., 2019; Zhang et al., 2020). For example, Ouyang et al., 2011 studied the impact of cascade dams on stream flow, sand concentration, and nutrient pollutant discharge in the upper reaches of the Yellow river. Similarly, (Zhang et al., 2020) focused on understanding the hydrologic impact of cascade dams in a small headwater watershed under climate variability. However, there are no studies that assess the impact of multiple dams on the provision of ecosystem services at macro basin scales and at daily time steps when pre-dams data is unavailable. This study aims to fill this gap by proposing a flexible approach that can simulate the effect of multiple dams on ecosystems services and assess tradeoffs between different ecosystem services competing over river flow under different spatial configurations of dams.

In this study, we have chosen economic value of agriculture production and normalized fish diversity index based on an empirical equation of fish species richness as the indicators of ecosystem services to represent economic development and environmental sustainability respectively. The study area is the Upper Cauvery River basin in India where these ecosystem services dominate. The study aims to assess how different configurations of existing reservoirs of varying sizes in the basin perform in terms of these ecosystem services so that desirable configurations of reservoirs could be identified. Here, a desirable configuration of existing reservoirs is one that efficiently meets agricultural water demand while considering ecological sustainability better than other configurations.

The novelty of the approach is the tradeoff analysis based on model simulations that can simulate not just the effects of various configurations of existing reservoirs but also the effects of synthetic configurations of reservoirs, though the current study focuses only on existing reservoirs as a proof of concept. The approach is based on chapter 3 which presented a landscape-based hydrological model coupled with a model of reservoir operations at a daily scale, to primarily analyse the hydrological effects of single reservoirs. In the present study, the existing reservoirs of the Upper Cauvery River basin are integrated to examine their overall effects on dominant ecosystem services at the basin level. For the first time such an assessment of flow alterations due to a cascade of multiple reservoirs is being conducted at a daily time scale for a major river basin in India where pre-intervention data were not available. We will show that this approach can measure the impact of cascade dams on the provision of ecosystem services in basins at a fine temporal resolution and can analyze and optimize dam development that balances the provision of multiple ecosystem services.

This chapter is structured as follows. The methodology is discussed in section 4.2 which includes the integration of reservoirs and the construction of tradeoff between fish species richness and agricultural production. The results are subsequently presented in section 4.3, and discussed in section 4.4. The chapter concludes with possible future implications of the study for sustainable reservoir management incorporating ecosystem services-based assessments that balance environmental with socio-economic needs.

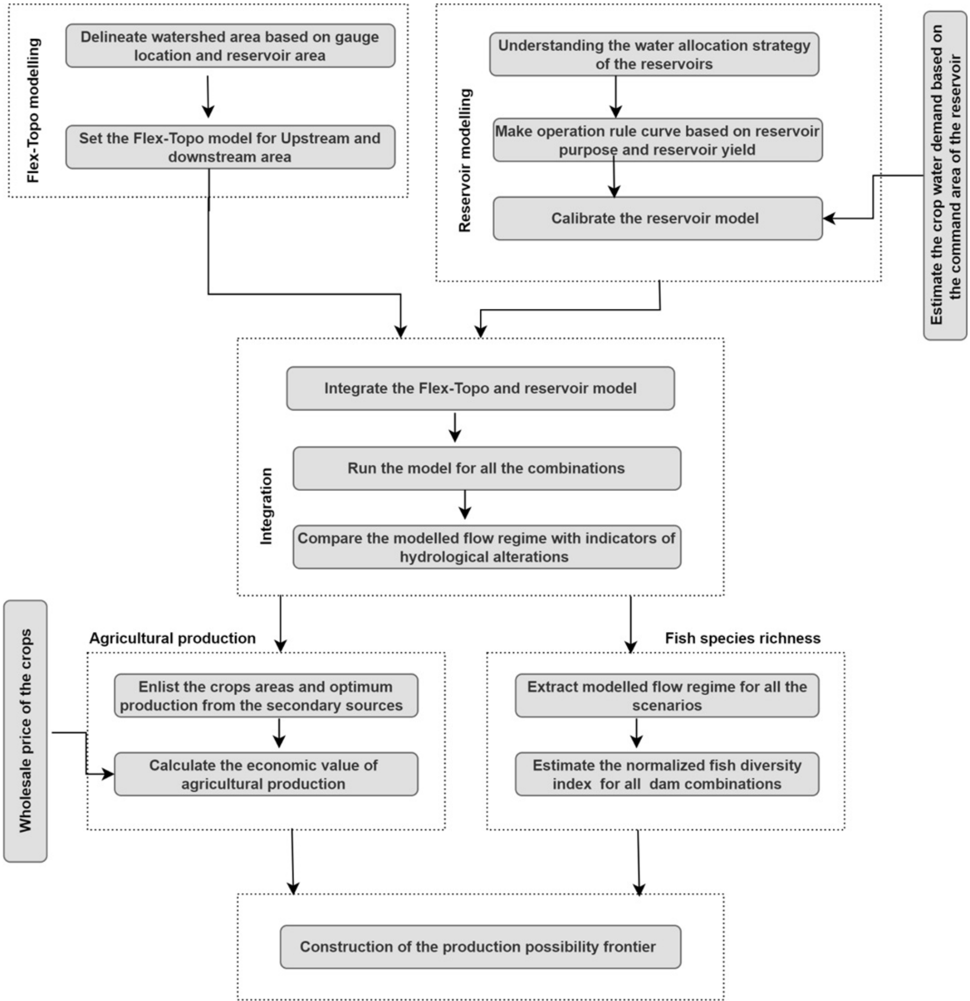
4.2. Methods

The aim of this chapter is to assess the hydrological, ecological, and economic consequences of multiple dams within the study area. To achieve this objective, a landscape based hydrological model (FLEX-Topo) was integrated with a reservoir operations model. The setup of this model was explained in detail, including its inputs, parameters calibrated and calibration results, in chapter 3. This integration involves modeling the operations of the reservoirs, as well as the hydrology of the upstream and downstream areas of the reservoirs (Figure 4.1). By integrating these models, the impact of reservoirs on the flow regimes downstream and the delivery of ecosystem services can be evaluated (see). A detailed description is given below.

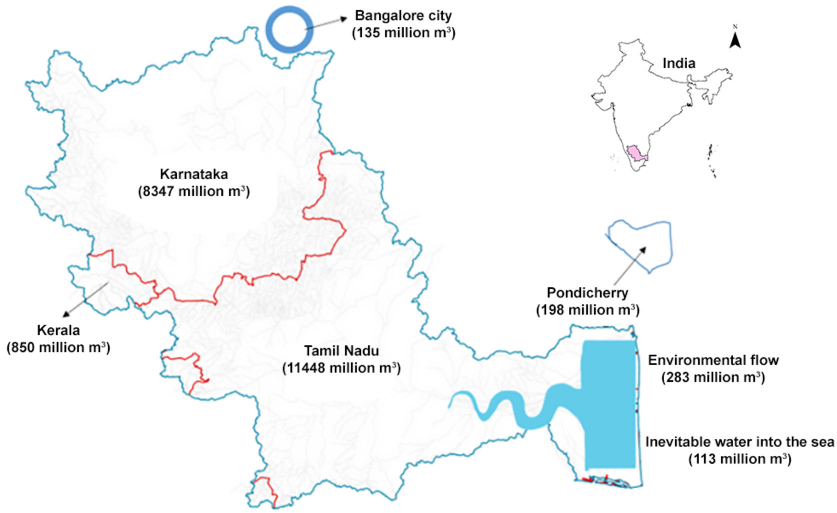
4.2.1. Description of the study area

The Cauvery River is the fourth largest river in peninsular India that originates from Talakaveri in the Kodagu district of Karnataka state India. The river has a drainage area of 81,155 km^2, which is nearly 2.7% of the total geographical area of the country (India, WRIS, 2015). The Cauvery basin extends over the Indian states of Karnataka (42%), Kerala (4%), and Tamil Nadu (54%) including the Karaikal region of Puducherry before draining into the Bay of Bengal.The states of Karnataka, Tamil Nadu, and Kerala, along with the union territory of Puducherry, all claim a share of water from the Cauvery River (see figure 4.2.)

Agricultural land is dominant in the basin, with an area of 53700 km^2 (or 66 %), which is followed by forest area at 16600 km^2 (or 21 %) Sreelash et al. (2014). Along certain stretches of the Cauvery River, extensive abstraction of water is carried out for intensive agriculture (Vedula, 1985; Bhave et al., 2018). Paddy is the most significant crop in this region, although Ragi, Jawar, and other millets are also grown in rainfed circumstances. More than 60 percent of the total population in the Cauvery basin lives in rural areas with agriculture as the main occupation and 48% of the area under cultivation(Singh, 2012).

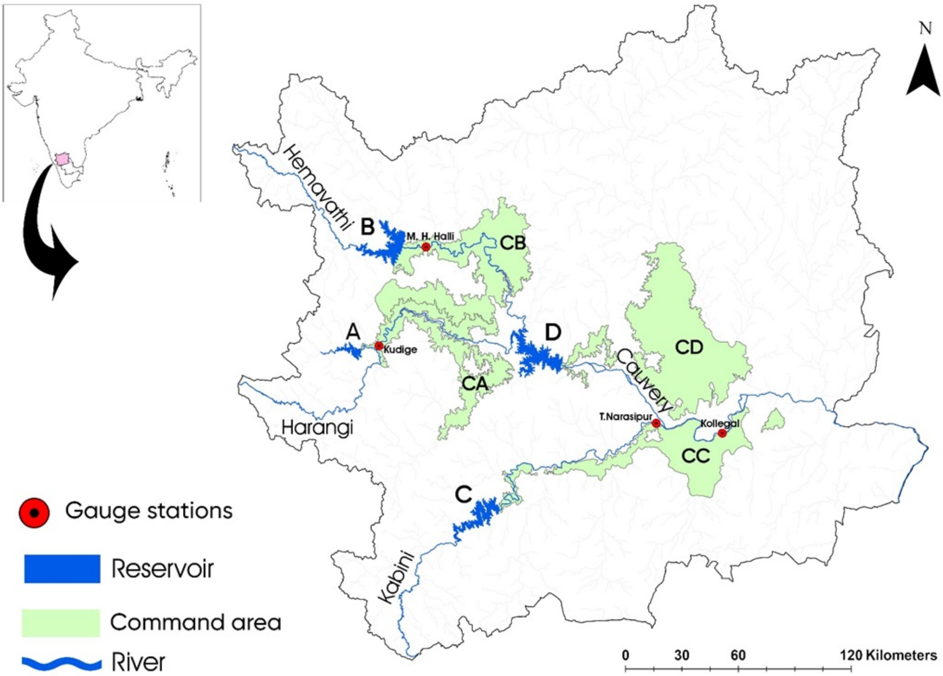


Figuur 4.1: Overview of the methodologic structure of the study

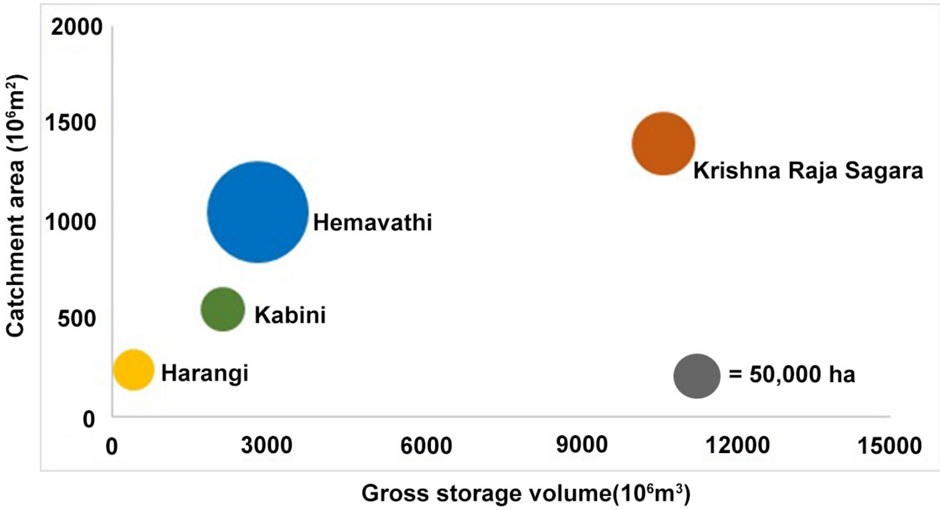


Figuur 4.2: Overview of water allocation (million m ^{3}year^{-1}) in the Cauvery basin among different states/union territories as per the supreme court Verdict in 2018.

Based on the availability of the data needed for the study, the four largest reservoirs in the Upper Cauvery region by gross storage capacity are selected for investigation, including Harangi, Hemavathi, Kabini, and Krishna Raja Sagara (Figure 4.3). Among the selected reservoirs, Harangi is the smallest reservoir and Krishna Raja Sagara is the largest reservoir in terms of gross storage capacity and command area (Figure 4.4).



Figuur 4.3: An overview of the Upper Cauvery River Basin. The reservoirs in the study area are labelled as A, B, C, and D, representing Harangi, Hemavathi, Kabini, and Krishna Raja Sagara (KRS) reservoirs respectively. The labels CA, CB, CC, and CD are used to denote the respective command areas served by these reservoirs.



Figuur 4.4: Overview of selected reservoirs by catchment area and gross storage volume. The size of the bubbles is proportional to the size of the catchment areas. The grey circle indicates the size of the bubbles which is equivalent to 50,000 ha.

4.2.2. Hydrological model (The FLEX-Topo Model)

The present study utilizes a hydrological model called FLEX-Topo (see section 3.3.1) . This parsimonious modeling approach has demonstrated its ability to simulate streamflows in data-scarce basins, as its structure is constrained by topography, requiring relatively few calibration parameters, and yielding reliable flow simulations even under changing land-cover conditions (Gao et al., 2014; Savenije, 2010). The FLEX-Topo model classifies the landscape of a basin into various Hydrological Response Units (HRUs) based on elevation (Digital Elevation Model - DEM), slope, and Height Above Nearest Drainage (HAND) and HRU specific processes are modelled to simulate river flows. FLEX-Topo is then integrated with a reservoir operations model, which simulates altered flows at daily time steps (for more details, see chapter 3 and Figure 3.2).

Creation of Hydrological Response Units (HRU)

A Hydrological Response Unit or HRU represents a distinct landscape element assumed to exhibit specific hydrological responses and is accordingly modelled by FLEX-Topo. Its characteristics are influenced by both topography and land use. The topographical aspects, such as plateau, hillslope, and wetland, determine the HRU's streamflow responses to rainfall. Additionally, land use, whether forests or agriculture, impacts the HRU's surface conditions, water infiltration rates, and evapotranspiration, further shaping its hydrological response.

For the present study, the classification of landscape into HRUs involves utilizing the Digital Elevation Model (DEM), slope, and Height Above the Nearest Drainage (HAND), into three distinct classes, namely hillslopes, plateaus and wetlands. The slope and HAND data are processed using an 80-meter resolution DEM. The delineation of a sub-basin with a reservoir within is determined based on the location of a streamflow gauge downstream of the reservoir. As indicated in Figure 3.9, the area upstream of the reservoir that is contributing flow to it (known as F1) is delineated by the location of the corresponding dam. Subsequently, the area downstream of the dam directly contributing flow to the gauge (known as F2 in Figure 3.9) is obtained by clipping F1 from the entire sub-basin delineated with respect to the gauge. The HRUs are identified for both F1 and F2 contributing areas and subsequently used to execute the FLEX-Topo model for the sub-basin.

Forcing data

Rainfall and potential evapotranspiration data are utilized as the forcing data. Daily gridded rainfall data with a spatial resolution of 0.25° x 0.25° and temperature data with a resolution of 1° x 1° are obtained from the Indian Meteorological Department, Government of India (Pai et al., 2014; Srivastava et al., 2009). Runoff data is obtained from the Central Water Commission, Government of India. The information on reservoirs, including inflows, outflows, and storage levels, is accessed from the Karnataka State Natural Disaster Monitoring Centre, Government of Karnataka, India, through their official website (*https://www.ksndmc.org/ReservoirDetails.aspx*). For reservoir model calibrations, only a time series of six years of daily inflows, storage and outflows was accessible. However, extended periods of streamflow data for the corresponding downstream gauges, rainfall and temperature data for the sub-basins were available. Thus, the six-year reservoir data was used to calibrate the reservoir operations models and the other streamflow and input forcing data were utilized to calibrate the integrated FLEX-Topo and reservoir operations models.

To analyse agricultural production, the data on the cultivated area and average production of crops at the district level in the study area are sourced from the Directorate of Economics and Statistics, Government of Karnataka (https://des.karnataka.gov.in/info-2/Agricultural+Statistics+(AGS)/Reports/en). Additionally, price information for crops in each district is obtained from the website https://agmarknet.gov.in/.

RESERVOIR OPERATION MODEL

The operation of multi-purpose reservoirs is governed by the objective of meeting the demands of end-users based on certain allocation priorities. Depending on end-user demands, the following conservation of mass equation governs each time step:

$$\frac{S_{t+1} - S_t}{\triangle St} = I_t + P_t - E_t - O_t - (L_t * D_t) \tag{4.1}$$

S_t = storage, I_t = Inflow, E_t = Evaporation on reservoir surface, P_t = Precipitation on reservoir surface, D_t = demand for reservoir water, L_t = fraction supply of the demand for the reservoir on day t and $\triangle t = 1$ day.

The reservoir model is embedded in the FLEX-Topo model by using the modelled outflow from the upstream area as an inflow into the reservoir and using the reservoir outflow as an inflow in order to model the runoff at the gauge station generated out from the downstream area of the reservoir.

The reservoir operation is based on shortage rule curves that define zones within which specified proportions of the demand are covered. The reservoir operating rules determine L_t. D_t is determined based on water demand calculation for irrigating crops in command areas or for generating hydropower (see section3.3.1 for details).

4.2.3. HYDROLOGICAL-RESERVOIR MODEL SIMULATION (CALIBRATION AND VALIDATION)

The reservoir models were first calibrated using the dataset composed of inflow, outflow, storage, rainfall, and potential evapotranspiration, for the four reservoirs covering the period from January 2011 to December 2016. These were embedded into the FLEX-Topo models of the corresponding sub-basins as mentioned above and the FLEX-Topo parameters were then calibrated. To calibrate the FLEX-Topo parameters, the dataset of rainfall and potential evapotranspiration for the period January 1991 to December 2010 was used. The performance of the integrated model in different sub-basins were then validated using the dataset from 2011 to 2016.

The Elitist Non-Dominated Sorting Genetic (NSGA-II) algorithm was used to calibrate the model parameters (Deb et al., 2000). Two objective functions are defined and minimized simultaneously. The first objective (f1) is the negative of Nash-Sutcliffe Efficiency (-NSE) and the second objective (f2) is the Mean Absolute Error (MAE). Note here that when -NSE is being minimized, NSE is being maximized.

$$f1 = \frac{\sum_{i=1}^{n} (Q_i^m - Q_i^o)^2}{\sum_{i=1}^{n} (Q_i^o - \overline{Q}_o)} \tag{4.2}$$

$$f2 = \frac{1}{n} \sum_{i=1}^{n} |Q_i^m - Q_i^o| \tag{4.3}$$

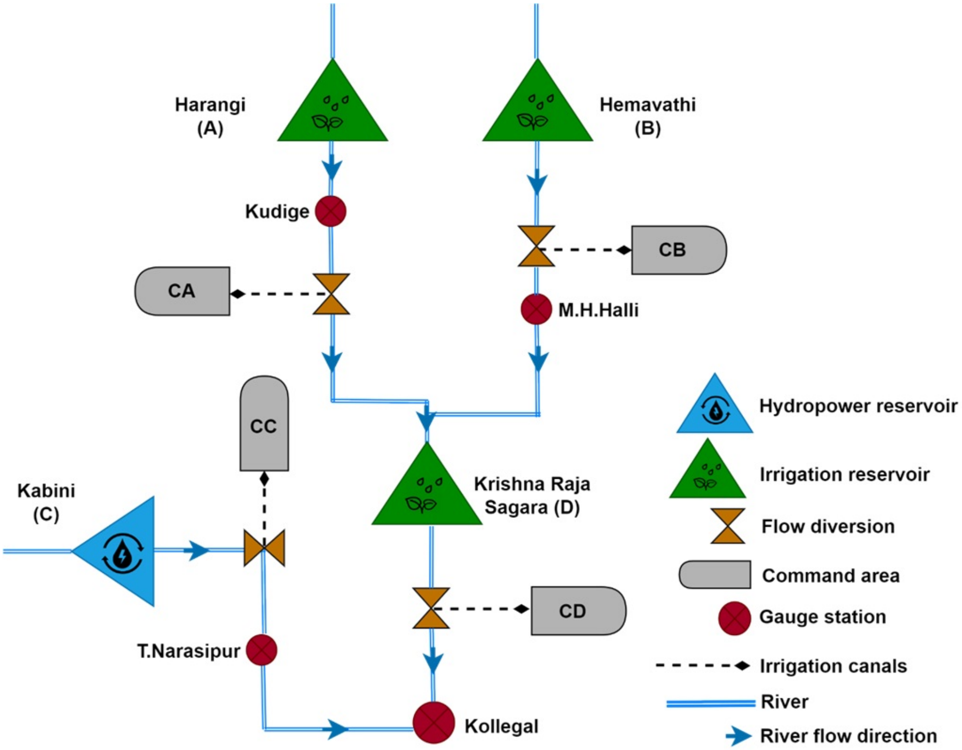
Here, Q_i^o is the i^{th} observation for the observed discharge being evaluated. Q_i^m is the value of the modelled discharge. $\overline{Q}_o$ is the mean of observed discharge and n is the total number of observations. The parameter sets calibrated for the FLEX-Topo model and the reservoir model are given in Tables 3.2 and **??** respectively.

4.2.4. SIMULATING THE EFFECTS OF DIFFERENT SPATIAL CONFIGURATIONS OF THE RESERVOIRS

Figure 4.5 shows one specific example of how the effect of various spatial configurations of reservoirs on flow regimes are simulated at the most downstream gauging station. This example considered the spatial configuration that contains all the reservoirs in the basin. The outflows from reservoirs Harangi and Hemavathi flow through the gauge stations of Kudige and M.H. Halli, respectively, and then into the KRS reservoir. Similarly, the outflow from the reservoir Kabini flows through the gauge station T. Narasipur and then joins the outflow from the reservoir KRS at the gauge station Kollegal, which is the most downstream gauging station. The integrated models corresponding to the subbasins delineated by each of the gauge stations simulate the 'altered' flows reaching at their respective stations.

For example, the sub-basin corresponding to KRS is delineated by the gauging station Kollegal. Hence the flows modelled at this station are considered, including the flows generated by contributing areas corresponding to gauge stations Kudige, M.H. Halli and T. Narasipur where corresponding modelled flows are considered. Such models of flows (with or without respective reservoirs) at the gauge stations downstream of each of the four reservoirs, instead of observed flows, are used for simulating flow regimes at the gauging station Kollegal for various possible configurations of reservoirs upstream.

A total of 16 different configurations were generated by removing one or more reservoirs from the schematic graph presented in figure 4.5 and corresponding flows were



Figuur 4.5: Showing the spatial configuration that contains all four reservoirs of the basin. A reservoir or a combination of reservoirs can be removed from this configuration to simulate correspondingly altered flow regime at Kollegal, the most downstream gauging station location. In this way the reservoirs in different spatial configurations are integrated together to assess the effect of the configuration on the flows most downstream at Kollegal. All possible configurations of the reservoirs were considered to create a total of 16 different scenarios.

modelled to simulate flow at the gauge station Kollegal (see Table 4.1) for an overview of the different configurations). The modelled flows were then compared to understand the impacts of reservoirs of varying configuration on the flow regime and, subsequently, on the production of the considered ecosystem services that are dominant in the basin (see Table 4.1).

Tabel 4.1: Comparison of different combinations of reservoirs by storage volume, purpose, sub-basin area and spatial configuration

Scenarios	Reservoir combinations	Reservoir characteristics Storage volume ($10^6 m^3$)	Purpose of the reservoir & Net Command Area (NCA)-ha	Spatial configuration
Scenario with four reservoirs (Base scenario)				
Sabcd	A+B+C+D	A: 240.69 B: 1050 C: 552.74 D: 1400.31	Irrigation - A, B, D Irrigation & Hydropower-C For individual reservoir NCA : 499215	A, B: upstream & on a tributary C: downstream & on a tributary D: downstream & on main channel
Scenario with three reservoirs				
Sbcd	B+C+D	B: 1050 C: 552.74 D: 1400.31	Irrigation - B, D Irrigation & Hydropower-C NCA: 445677	B: upstream & on a tributary C: downstream & on a tributary D: downstream & on main channel
Sabd	A+B+D	A: 240.69 B: 1050 D: 1400.31	Irrigation - A, B, D NCA: 453485	A, B: upstream & on a tributary D: downstream & on main channel
Sacd	A+C+D	A: 240.69 C: 552.74 D: 1400.31	Irrigation - A, D Irrigation & Hydropower-C NCA: 207350	A: upstream & on a tributary C: downstream & on a tributary D: downstream & on main channel
Sabc	A+B+C	A: 240.69 B: 1050 C: 552.74	Irrigation - A, B Irrigation & Hydropower-C NCA: 391133	A, B: upstream & on a tributary C: downstream & on a tributary
Scenario with two reservoirs				
Sbd	B+D	B: 1050 D: 1400.31	Irrigation - B, D NCA: 399947	B: upstream & on a tributary D: downstream & on main channel
Scd	C+D	C: 552.74 D: 1400.31	Irrigation - D Irrigation & Hydropower-C NCA:	C: downstream & on a tributary D: downstream & on main channel
Sad	A+D	A: 240.69 D: 1400.31	Irrigation - A, D NCA: 161620	A: upstream & on a tributary D: downstream & on main channel
Scb	C+B	C: 552.74 B: 1050	Irrigation - B Irrigation & Hydropower-C NCA: 153812	C: downstream & on a tributary B: upstream & on a tributary
Sab	A+B	A: 240.69 B: 1050	Irrigation - A, B NCA: 345403	A, B: upstream & on a tributary
Sac	A+C	A: 240.69 C: 552.74	Irrigation - A Irrigation & Hydropower-C NCA: 99268	A: upstream & on a tributary C: downstream & on a tributary
Scenario with one reservoir				
Sd	D	D: 1400.31	Irrigation - D NCA: 108082	D: downstream & on the main channel
Sb	B	B: 1050.00	Irrigation - B NCA: 291865	B: upstream & on a tributary
Sc	C	C: 552.74	Irrigation & Hydropower-C NCA: 45730	C: downstream & on a tributary
Sa	A	A: 240.69	Irrigation - A NCA: 53538	A: upstream & on a tributary
Scenario with no reservoir				
S0	NO	–	–	–

4.2.5. INDICATORS OF HYDROLOGICAL ALTERATIONS

The set of Indicators of Hydrological Alteration (IHA) initially proposed by Richter et al. (1996) is used to measure the effects of different reservoir configurations on the flow regime in the Upper Cauvery basin. The parameters considered in IHA have strong relationships with river ecosystems, and therefore can be used to assess the impacts of dams on the flow regime. The IHA are classified into five groups based on magnitude of monthly flows, magnitude and duration of annual extreme flow conditions, and frequency and duration of high and low flow rates. Major indicators used in the study include mean annual discharge, low flows, high flows, low pulse rate, and high pulse rate. High frequencies of flows, and alterations of it, can be considered within the IHA given that modeled flow regimes are at daily time scale. Although earlier methods of assessing the impact of impoundments on river channels have involved field surveys, statistical analyses (Yan et al., 2010), and geomorphic change detection tools (Wheaton, 2015), the IHA framework provides a more systematic assessment of changes in flows. Its application has been relatively limited in the studies of Indian rivers (Mittal et al., 2014; Kumar and Jayakumar, 2020; Borgohain et al., 2019), often due to lack of pre-dam data availability. The simulations of pre-interventions flows presented here makes this possible, especially when the data is not available.

4.2.6. TRADEOFF BETWEEN ECOSYSTEM SERVICES: CONSTRUCTION OF THE PRODUCTION POSSIBILITY FRONTIER

The production possibility frontier (PPF), also known as the production possibility curve or boundary, is a graphical representation of the different combinations of goods or services that an economy can efficiently produce given its limited resources and technology (Martinez-Harms et al., 2015; King et al., 2015; Cavender-Bares et al., 2015). It can be described as the outward boundary of the convex hull of the production set of the economy. It shows the maximum level of one good or service that can be produced in relation to the production of another good or service, given the existing resources and technology.

In the Cauvery basin, approximately 48 percent of the land is used for crop cultivation (Singh, 2009). In certain stretches of the Cauvery River, there is extensive water abstraction for intensive agriculture (Vedula, 1985; Bhave et al., 2018). This water extraction has resulted in notable changes in the composition of aquatic species, primarily due to the construction of reservoirs, and in the overall biodiversity of the river ecosystem. This tradeoff between the corresponding dominant ecosystem services that are provided by the bioeconomy of the basin is represented by a tradeoff between indicators of agricultural production value and fish species richness respectively, and conveniently represented by the PPF. The value of crop production that dominates the agricultural production value is used for the former, and a specific indicator for fish species richness, namely the normalized fish diversity index, is used for the latter.

Different spatial configurations of the reservoirs correspond to different partitioning of flows for irrigation and for aquatic ecosystems. Therefore, different pairs of crop production values and normalized fish diversity index are generated for different reservoir configurations. Since only existing reservoirs are considered, a production set is determined based on the production outputs of all possible spatial configurations of existing reservoirs. Specifically, it is defined by the convex-hull of the 16 pairs of agricultural production and normalized fish diversity index values, corresponding to the 16 possible spatial configurations of the reservoirs. The production possibility frontier is then the outward boundary of the production set. However, note that this production set can be exhaustively populated by simulating synthetic configurations of artificial reservoirs on the river network. This is left for future work.

Agricultural production

The available information on agricultural crops and their distribution is organized at the district level (the lowest administrative level within the boundaries of the states that fall in the basin where such information is available). All the calculations related to these crops are performed at this level, where a total of nine districts are considered in the analysis. The districts falling within each sub-basin of the Upper Cauvery basin are identified and their areas are determined. Subsequently, using the available data, the areas of irrigated and unirrigated land within and outside the sub-basins are calculated. Based on the known cropping patterns for each district, the crops grown are categorized into four growing seasons: kharif (June-September), rabi (October-January), summer (February-May), and perennial crops. The area dedicated to each crop within a sub-basin is determined proportionally by the acreage of different crops in each district within the sub-basin. The maximum yield under irrigated conditions and crop prices are obtained from agricultural census sources. Additionally, information on crop coefficients and crop yield response factors is gathered from published literature. An average yearly real price is estimated for each crop in all the districts within the studied basin (see Supplementary materials, Table S.8). For irrigated areas, the maximum (optimum) yield values from the literature are used to calculate crop production. However, for unirrigated areas, the reduction in yields are estimated based on the actual evapotranspiration estimates of the integrated model.

For agricultural production, the relationship between crop yield and water depends on the corresponding relative reduction in evapotranspiration (ET). The actual yield is calculated based on the following formula by (Allen et al., 1998).

$$1 - \frac{Y_a}{Y_o} = K_y \left(1 - \frac{\sum_{i=1}^{n} ET_a^i}{\sum_{i=1}^{n} ET_p^i}\right) \tag{4.4}$$

Where Y_a = actual Yield (kg ha^{-1}year^{-1}), Y_o = optimum Yield (kg ha^{-1}year^{-1}) K_y = yield response factor, ET_a^i= Total actual evapotranspiration for day i out of n days of the crop season ($^{-1}$), ET_a^i = Total potential evapotranspiration for day i out of n days of the crop season (mm day $^{-1}$).

Tabel 4.2: The Crop coefficient (K_c) and yield response factor (K_y) used to calculate the yield

	CROPS	Kc	Ky
1	**CEREAL CROPS**		
	Bajra	0.67	0.92
	Jowar	0.69	0.92
	Maize	1.06	1.25
	Paddy	1.14	1.20
	Ragi	0.69	0.90
2	**PULSES CROPS**		
	Avare	0.74	0.85
	Bengal gram (Gram)	0.90	0.90
	Black gram	0.65	0.85
	Cowpea	1.19	0.98
	Green gram	0.89	0.80
	Horse gram	0.74	0.90
	Navane	0.74	0.70
	Tur (Red gram)	0.74	0.90
3	**OIL SEEDS CROPS**		
	Linseed	0.78	0.70
	Castor	0.70	0.70
	Groundnut	0.78	0.70
	Niger seed	0.70	0.80
	Rape & Mustard	0.75	0.80
	Safflower	0.75	0.80
	Sesamum	0.75	0.95
	Soyabean	0.70	0.85
	Sunflower	0.75	0.95
4	**COMMERCIAL / FIBRE CROPS**		
	Cotton	0.88	0.85
	Sugarcane	1.58	1.20
	Tobacco	0.90	1.10
5	**PLANTATION & HORTICULTURAL CROPS**		
	Lemon	0.70	1.10
	Onion	1.19	1.10
	Tomato	1.19	1.05
	Banana	1.12	1.20
	Beans	0.93	1.15
	Brinjal	0.93	0.85
	Cabbage	1.19	0.85
	Cashewnut (Raw & Processed Nuts)	0.80	0.90
	Coconut	0.80	0.90
	Grapes	0.85	1.10
	Guava	0.69	1.10
	Mango	0.69	1.10
	Papaya	0.93	0.90
	Pomogranate	0.50	0.90
	Potato	1.09	1.10
	Sapota	0.70	0.90
	Sweetpotato	1.09	1.00
	Tapioca	1.09	0.80
	Coffee (Arabica)		
	Coffee (Robusta)		
6	**CONDIMENTS & SPICES CROPS**		
	Coriander	1.19	1.20
	Arecanut (Raw & Processed Nuts)	0.80	0.90
	Black pepper	1.19	1.10
	Cardamom	1.19	1.10
	Dry Chillies	0.95	1.10
	Dry Ginger	0.93	1.10
	Garlic	1.19	0.90
	Turmeric	1.01	0.85

Source: Compiled from Allen et al., 1998; Mohan & Arumugam, 1994.

4

The equation 4.4 presents end-of-season yield as a fraction of optimal yield that depends on how much daily evaporation is accumulated by the crops over the season compared to the respective evaporation demands (optimal evaporation). Yearly production value is obtained by multiplying the average area of each crop with average simulated yields and prices over 2011-2016. Yields are multiplied by the area cultivated with corresponding crops to calculate the agricultural output; irrigated output if irrigated else rainfed output. Total agricultural production equals the agricultural output from both rainfed and irrigated areas. The crop-specific prices are multiplied by the corresponding production output to indicate the economic value of the ecosystem service supported by the basin.

Normalized Fish Diversity Index

Aquatic ecosystem health serves as a comprehensive reflection of the physical, chemical, and biological integrity of river ecosystems (Chen et al., 2019; Aazami et al., 2015). Previous studies have investigated various factors to identify the key determinants of river ecological health, including benthic macroinvertebrates, river habitat conditions, and water quality parameters (Chen et al., 2019). However, when considering biological indicators, fish health becomes crucial as it directly links to the provisioning of services such as food and human health. Fish species richness refers to the number of different fish species present in a particular area or ecosystem. It is one of the indicators of biodiversity and represents the diversity of fish species within a given habitat or geographical region. Species richness is commonly used to assess the ecological health and complexity of aquatic ecosystems (Xu et al., 2021). Therefore, fish species richness is chosen as the indicator of river health, reflecting the overall health of the aquatic ecosystem. No particular specific fish species is targeted in this study. Fish migration patterns have not been included due to data limitations which includes tracking efficiency, sample bias, limited spatial coverage, as well as species-specific challenges (Planque et al., 2011; Elsdon et al., 2008).

Species-discharge models, based on mean river discharge, are often used to quantify the impact of anthropogenic modification of rivers on species richness (Xenopoulos and Lodge, 2006). However, the flow regime of a river is composed of several ecologically relevant flow characteristics such as magnitude, frequency, duration, timing, and rate of change of flow events that impact species richness. In other words, flow characteristics other than mean river discharge also play a vital role in sustaining aquatic ecosystems. Many Species Discharge Relationship (SDR) models have been derived based on data of large basins (>500 km^2) globally to explain long-run riverine fish species richness (FSR) as a function of discharge and other variables (Schipper and Barbarossa, 2022; Xenopoulos and Lodge, 2006; Iwasaki et al., 2012). In the present study, the basin is >10,000 km^2, at which scale discharge is a key variable explaining differences in species richness (Schipper and Barbarossa, 2022) . We adopted an empirical function (equation 4.5) by (Iwasaki et al., 2012) to quantify fish species richness. We use the equation to assess changes in fish species due to changes in flow characteristics for the same basin (keeping area and latitude constant to incorporate the fixed effect of the basin). This is very similar to the use of the Budyko curve derived from basin data sets across the globe in hydrology, e.g. space for time substitution to assess the impacts of changes in precipitation on rainfall partitioning in basins in the long run (Bouaziz et al., 2022). Indicators for flow characteristics, such as coefficient of variation of mean frequency of low flow in a year, coefficient of variation in the Julian date of annual minimum flow, and maximum proportion of the year in which floods have occurred, are also used. Here floods are defined as events when flows are greater than or equal to flows with a 60 per cent exceedance probability (Olden and Poff, 2003). This choice of a regression equation (equation 4.5) was suitable for our analysis since the underlying model does not consider water quality and other aspects.

Therefore, only the possible combinations in which the current four reservoirs can appear in the basin are considered as counterfactuals and it is assumed that these dominantly lead to changes in streamflows that in turn influence the variability of FSR based indicators of environmental quality. Further, the equation is not used for predicting FSR but for an index of environmental health in a two-dimensional tradeoff analysis of dominant ecosystem services that are affected by plausible reservoir scenarios dominantly affecting streamflow.

4

$$\mathbf{FSR} = \exp\left(\mathbf{3.95} - \mathbf{0.0342LAT} + \mathbf{0.273AREA} + \mathbf{0.373MAD} - \mathbf{1.57FL_2} + \mathbf{0.832TH_3} - \mathbf{0.116TL_2}\right) \quad (4.5)$$

where,
FSR = Fish Species Richness,
LAT = Absolute value of the latitude of the gauge station where flow is measured
$Area$ = $\log_{10}$ transformed basin area (km^2)
MAD = $\log_{10}$ transformed mean annual discharge ($m^3 s^{-1}$)
FL_2 = Coefficient of variation of mean frequency of low flow per year
TH_3= Maximum proportion of the year (number of days /365) during which floods have occurred
TL_2 = Coefficient of variation in the Julian date of the annual minimum flow.

The fish species richness index is then normalized into an index, called the *normalized fish diversity index* where $NFDI_i$, for any i^{th} scenario calculated as:

$$NFDI_i = \frac{FSR_i}{max_i(FSR_1,..,FSR_2,..,FSR_i)} \quad (4.6)$$

where,
$NFDI_i$ is the Normalized Fish Diversity Index for the i^{th} scenario
FSR_i is the Fish Species Richness for the i^{th} scenario
i = 16 is the number of scenarios of possible reservoir combinations (counterfactuals)

Utilizing the normalized fish diversity index in our analysis helps reduce dependence on absolute FSR numbers and their changes over different scenarios. Rather than focusing solely on numerical values, our methodology prioritizes the relative ranking within the tradeoff space. By incorporating proxies for environmental quality and agriculture, this normalization approach facilitates a nuanced assessment. It highlights the relative positions of various scenarios, providing insight into their impacts on both environmental quality and agricultural production.

Due to limitations on the years for which crop prices were available, we used 6 years of simulations 2011-2016 to estimate flow-related quantities needed in equation 4.5. Daily-scale simulations are used for calculating FSR parameters like TH_3, FL_2, and TL_2, along with mean annual flow calculations and evaporation deficit in yield estimations. Daily-scale modeling facilitates space-time substitution in SDR-based FSR, enabling assessment of agricultural production trade-offs with reservoir combinations. In these scenarios, other factors are assumed constant

4.3. RESULTS

TThe calibration and validation performance of the model developed for the study area as indicated in chapter 3. The model was calibrated using the NSGA II multi-objective optimization algorithm, and the Pareto front ranges for both -NSE (Nash Sutcliffe Efficiency) and MAE (Mean Absolute Error). The developed model is then used to simulate flow regimes for the 16 scenarios of different spatial configurations of existing reservoirs as shown in Table 4.1, and the degree of hydrological alterations is assessed. The production of considered ecosystem services is then quantified, and a production possibility frontier for the considered ecosystem services is derived and discussed.

4.3.1. IMPACT ON FLOW REGIMES GENERATED BY DIFFERENT SPATIAL CONFIGURATIONS OF RESERVOIRS

The flow regimes corresponding to different spatial configurations (also referred to as scenarios, see Table 4.1) of the existing reservoirs are analysed to understand the impact of the latter on the former, utilizing major hydrological indicators like mean annual flow and annual extreme flow conditions. Additionally, the analysis involves classifying the flow regimes based on the storage volumes of the reservoirs and its uses. All the hydrological indicators are calculated based on the discharges that are simulated at the most downstream (Kollegal) gauge station.

Flow regimes characterized by storage volume under different scenarios

The highest mean annual flow was estimated for S_0 (1,548 m^3s^{-1}) with no reservoir, followed by S_c (1,460 m^3s^{-1}) and Sb (1,377 m^3s^{-1}) containing only one reservoir in the scenarios (Figure 4.6). In terms of storage volume, KRS (D) is the biggest reservoir followed by Hemavathi reservoir (B) and Kabini reservoir (C). KRS (D) in combination with one another reservoir (S_{bd}, S_{cd}, S_{ad}) and two other reservoirs (S_{bcd}, S_{abd}, S_{acd}) yielded mean annual flows of less than 500 m^3s^{-1}. Figure 4.6 shows the mean monthly variation in the flow for all 16 combinations.

Figure 4.7 shows that the magnitude of annual extreme conditions, the 1-3-7-30-90 day minimum and maximum flows, were greatly affected by the construction of reservoirs having bigger storage volumes. However, in scenarios of configurations with three reservoirs, S_{abd} has less impact compared to S_{acd} despite Kabini (C) having less storage capacity compared to the Hemavathi reservoir (B).

The extreme low peak flow for scenario S_d appears to be the lowest of the configurations with only one reservoir (Table 4.3) as KRS (D) reservoir has the largest storage capacity. Similarly, the KRS (D) generated flows with lowest values of extreme low peak conditions in spatial configurations with three (S_{bcd}, S_{abd}) and four (S_{abcd}) reservoirs. However, in scenarios involving one or two reservoirs despite having varying storage capacities, the extreme low peaks of flows generated by S_a, S_b, S_{ac}, and S_{bc} appear to be similar (Table 4.3).

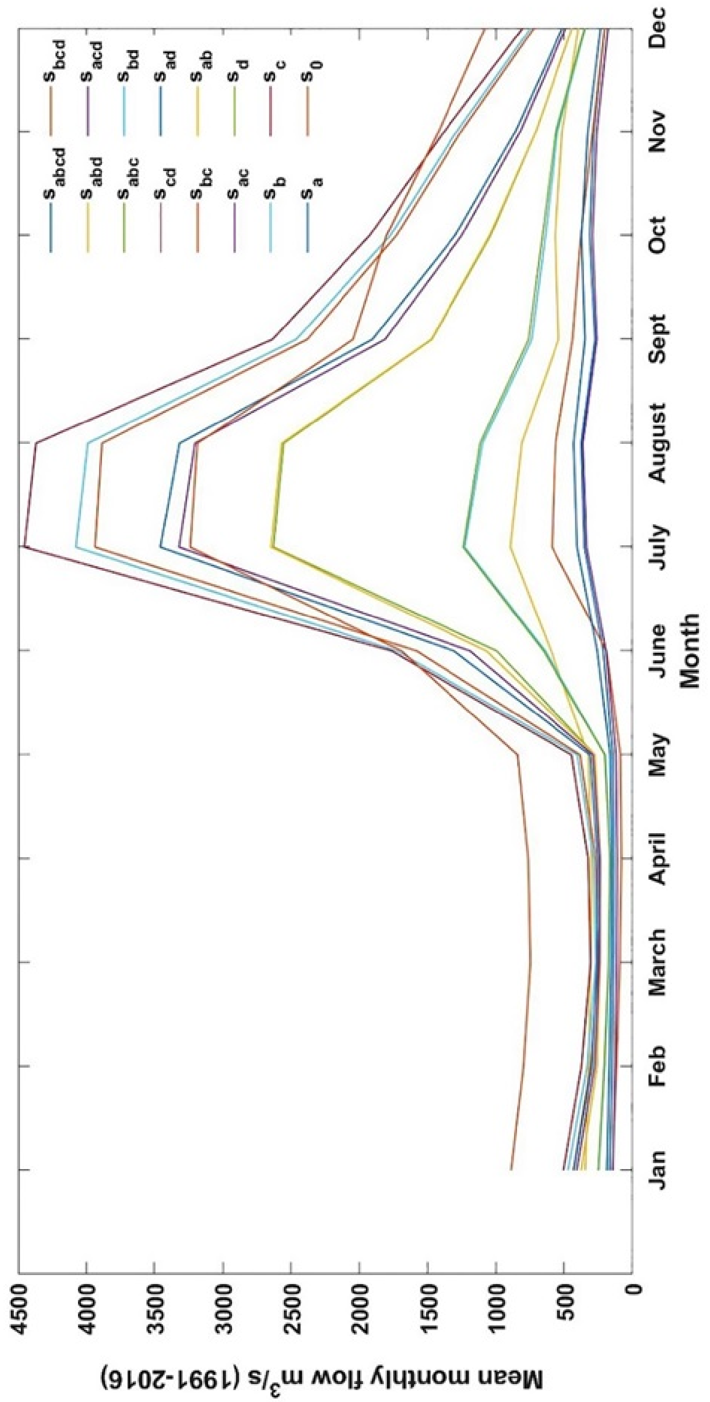
Flow regimes characterised by the use of reservoirs

Kabini (C) is the only reservoir used for hydropower. Scenario Sc generates a mean annual flow that is the second highest, after that of S0 with no reservoir in the basin (Figure 4.7). The mean annual flows of combined irrigation and hydropower reservoirs (Sac and Sbc) are observed to be higher (1,076-1,289 m^3s^{-1}) when compared with that of two irrigation reservoirs (S_{ab}). Similarly, the mean annual flow of scenario S_{abc} with 3 reservoirs is around 906 m^3s^{-1}, which is more than those of the scenarios S_{bd}, S_{cd}, S_{ad} but less than those of S_{bc}, S_{ab} and S_{ac} with two reservoirs. This is because Kabini (C) is a hydropower reservoir, which releases water frequently and ensures flows above a certain threshold resulting in a higher mean.

The comparison of a scenario with two irrigation reservoirs and one hydropower reservoir (S_{abc}) to a scenario with two irrigation reservoirs (S_{bd}) indicates that the former has less impact on mean annual extreme flow conditions such as 1, 2 and 7-day minimum than the latter. Comparing similar combinations of two reservoirs only for irrigation (S_{ad} and S_{bd}) versus those that contain the hydropower reservoir (S_{cd}) indicates that the hydropower reservoir decreases the low pulse count and low pulse duration compared to irrigation reservoirs.

Tabel 4.3: Overview of hydrological impact and environmental flow parameters of different scenarios

Scenarios	Hydrological impact					Environmental flow Parameters (m^3/s)	
	Mean annual flow (m^3/s)	Low pulse count (days)	High pulse count (days)	Low pulse duration (days)	High pulse duration (days)	Extreme low peak	Extreme low frequency
Scenario with four reservoirs Integrated							
S_{abcd}	265	2.2	3.4	52.5	-16.6	44.9	1.0
Scenario with three reservoirs integrated							
S_{bcd}	296	2.4	3.6	44.1	-73.3	44.9	0.9
S_{abd}	443	1.4	3.9	90.5	-16.8	66.9	0.9
S_{acd}	274	2.6	3.6	46.3	-29.1	44.9	1.0
S_{abc}	907	2.3	3.8	57.7	-17.1	117.0	1.4
Scenario with two reservoirs integrated							
S_{bd}	480	1.8	3.9	75.6	-88.3	61.0	0.6
S_{cd}	310	2.2	3.5	55.9	-79.7	48.7	1.1
S_{ad}	452	1.4	4.2	90.2	-89.8	67.1	1.0
S_{bc}	1289	2.6	3.8	46.4	-29.4	181.1	1.6
S_{ab}	995	1.6	3.1	86.9	-17.1	119.1	1.4
S_{ac}	1076	2.9	3.6	46.8	-29.9	181.0	1.7
Scenario with one reservoir Integrated							
S_d	488	1.9	4.0	74.2	-91.9	60.8	0.6
S_b	1377	2.6	3.6	42.5	-103.7	181.9	1.6
S_c	1460	2.4	3.5	42.0	-95.7	242.9	2.1
S_a	1164	2.6	3.4	48.0	-29.9	182.8	1.4
Scenario with no reservoir							
S_0	1548	2.4	4.0	45.0	-109.7	242.9	2.1



Figuur 4.6: The mean monthly flows resulting from different combinations of reservoirs

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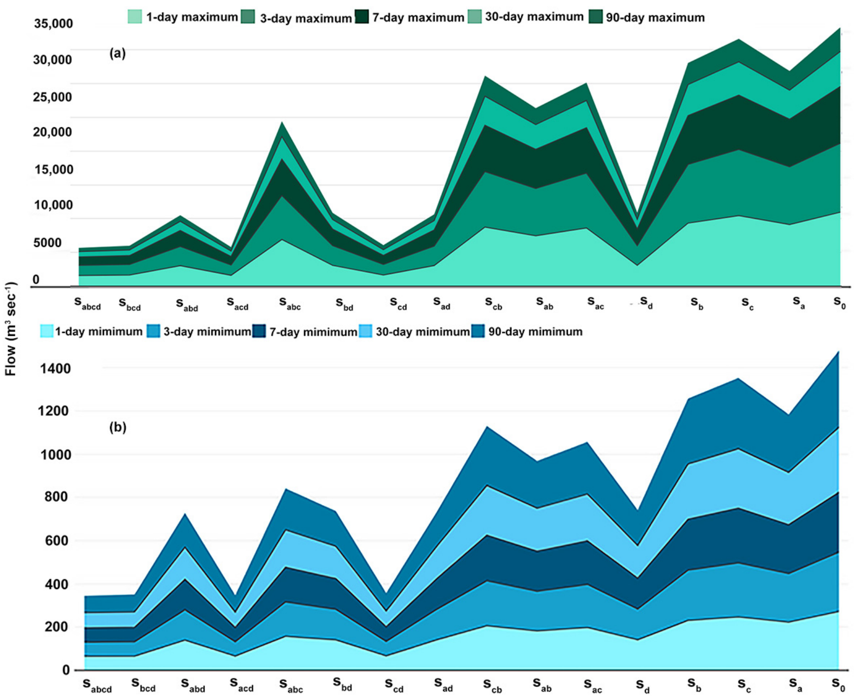


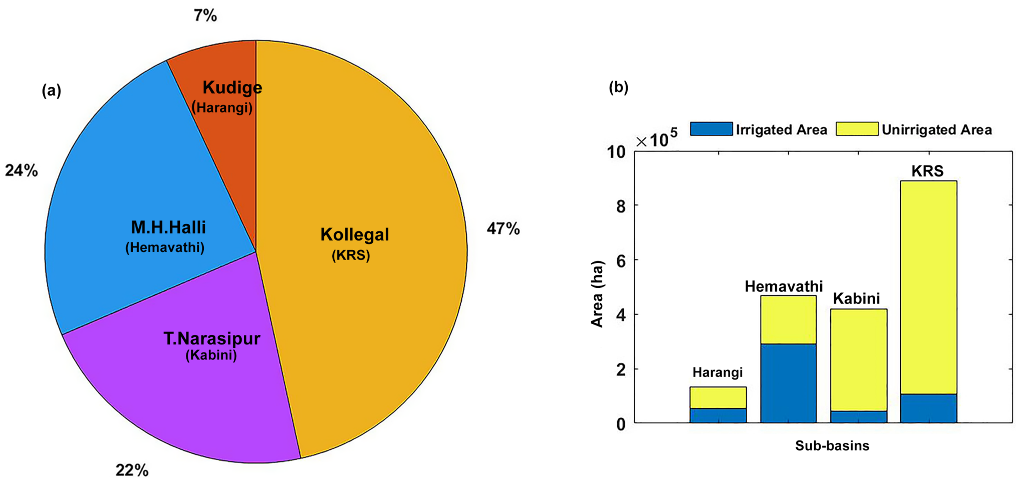
Figuur 4.7: The magnitude of annual extreme flow conditions of flow regimes generated by different combinations of reservoirs

Flow regimes characterised by varying the configuration of reservoirs
Harangi (A) and Hemavathi (B) reservoirs are located in the upstream area of the basin, on one of the tributaries of the Upper Cauvery. Harangi (A) reservoir is the smallest in terms of volume, followed by Kabini (C), Hemavathi (B), and KRS (D). When comparing the flow altered by configurations with only one reservoir, S_a produces regimes with lower mean annual flows than S_b. Generally, reservoirs with longer residence times tend to have a larger impact on the flow regimes compared to reservoirs with smaller residence times. However, S_a (with Harangi reservoir) has a higher impact on the flow regime than S_b (with Hemavathi reservoir). One reason could be that M.H. Halli sub-basin (with Hemavathi reservoir with a large residence time) receives the highest rainfall compared to other regions in the Upper Cauvery (Reddy et al., 2023) which contributes towards a lower impact of S_b compared to S_a.

Furthermore, in the absence of its reservoirs, the mean annual flow in M.H. Halli sub-basin is lower (75 m^3 s^{-1}) when compared to Kudige (139 m^3 s^{-1}), T. Narasipur (349m^3 s^{-1}) and Kollegal sub-basins (630 m^3 s^{-1}). This shows that M.H. Halli sub-basin contributes little to the overall flow. As a result, the S_a scenario generates a lower mean annual flow than the S_b scenario. Similarly, for two reservoirs configurations, the M.H. Halli sub-basin has a lower no-reservoir mean flow than the Kudige sub-basin. As a result, S_{ac} performs worse than S_{cb}. Among the configurations with three reservoirs, the mean annual flow and other indicators of hydrological alterations of the S_{bcd} and S_{acd} scenarios were as undesirable as the four-reservoir scenario. It is acknowledged that S_0, being the unregulated scenario without any reservoir, exhibits the highest flow due to the absence of flow regulation and water diversion. In contrast, S_c, which is a configuration with only a hydropower reservoir, needs to release water regularly for electricity generation purposes. As a result, S_0 is estimated to have the highest mean annual flow, followed by S_c and S_b.

Since the configuration S_{abd} has Hemavathi reservoir which falls in the M.H. Halli sub-basin that receives highest rainfall, thereby contributing significantly to the overall flow, S_{abd} has less impact on flow regime compared to S_{acd} despite Kabini (C) having less storage capacity compared to the Hemavathi reservoir (B).

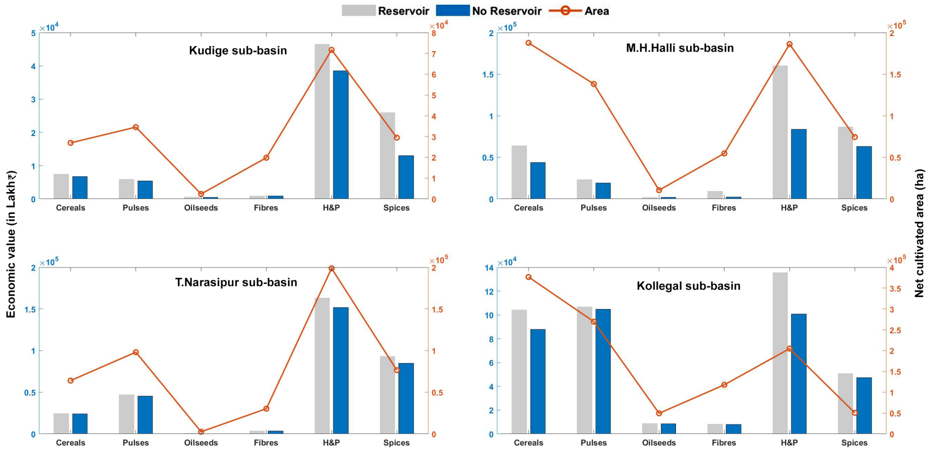
4.3.2. AGRICULTURAL PRODUCTION
The agricultural production in the sub-basins is calculated based on the assumption that irrigated area becomes unirrigated (i.e. rainfed) when the corresponding reservoir is removed in a spatial configuration scenario, without changing the crops that are being cultivated. The proportion of cultivated and irrigated land is given in Figure 4.8. Figure 4.9 shows the economic values of various crops grown in each of the four sub-basins, based on the flow regimes simulated by the integrated model with and without its respective reservoirs. In figure 4.9, each sub-basin is studied one at a time to demonstrate the economic value of irrigated crop cultivation.



Figuur 4.8: Overview of cultivated areas in different sub-basins. (a) represents the contribution of sub-basins to the total cultivated area of the Upper Cauvery basin, and (b) represents irrigated and unirrigated (or rainfed) areas in each sub-basin

Five categories of crops were distinguished, namely, cereals, pulses, oilseeds, horticultural plantation (HP) crops, and spices. Among horticultural plantation crops, coffee, coconut and cashew nut contributed 65 percent of the total HP cultivated area (Refer figure 4.9, author's estimation). According to current estimates, the contribution of plantation crops accounts for 58 percent of the economic value of the HP crops (see Figure 4.9, author's estimation).

Figure 4.9 shows that the horticultural crops and spices contributed most to the economic value in all sub-basins. In M.H. Halli and Kollegal sub-basins, where the area under cereals is high, the economic value of cereal production is low compared to that of the horticultural crops and spices

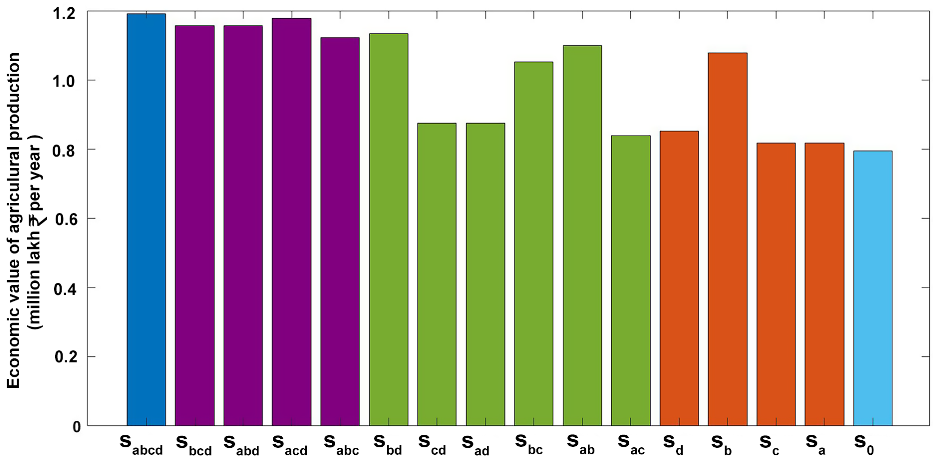


Figuur 4.9: The economic value (Lakh ₹per year) of different crop groups of individual sub-basins with and without reservoirs

When comparing the economic value of crops within a sub-basin with and without its reservoir, not much difference was observed in the economic values of pulses, oilseeds, and fibres in all the sub-basins. The differences in economic values with and without its reservoir are significant among horticultural crops and spices in three sub-basins, i.e. Kudige (Harangi), M.H. Halli (Hemavathi) and T. Narasipur (Kabini) sub-basins. In Kollegal (KRS) sub-basin, the majority of crops are rainfed and only 10 percent is irrigated, which explains the small difference in the economic value with and without its reservoir.

The values generated by alternative dam planning and design scenarios in comparison to the existing reservoirs as the baseline can be studied by varying the spatial configurations of the reservoirs (Figure 4.10). It demonstrates how economic value from agricultural production varies across the various scenarios of reservoir configurations. In general, increasing the number of dams does raise the economic value of agricultural production as compared to scenario S_0 (without any dams). The presence of all four dams in the basin generates the highest economic value from the agricultural production. Note that the agricultural value of S_0(no dams and therefore also no irrigation) is approximately 67 percent of the present situation, S_{abcd}, with irrigation in command areas of the four reservoirs.

The scenario of four dams S_{abcd} does not show a dramatic increase in value as compared to the scenarios of the configurations with three dams. Among the scenarios with two dams, there are three configurations, i.e. S_{bd}, S_{bc}, and S_{ab}, that show much higher value generation than other scenarios of configurations with two dams and are comparable to the scenarios with three and four dams. In the case of scenarios with one dam, scenario S_b shows a much higher economic value generation. This is because the Hemavathi reservoir (B) has a well-developed command area growing mainly horticultural



Figuur 4.10: The economic value of agricultural production under different scenarios of reservoirs

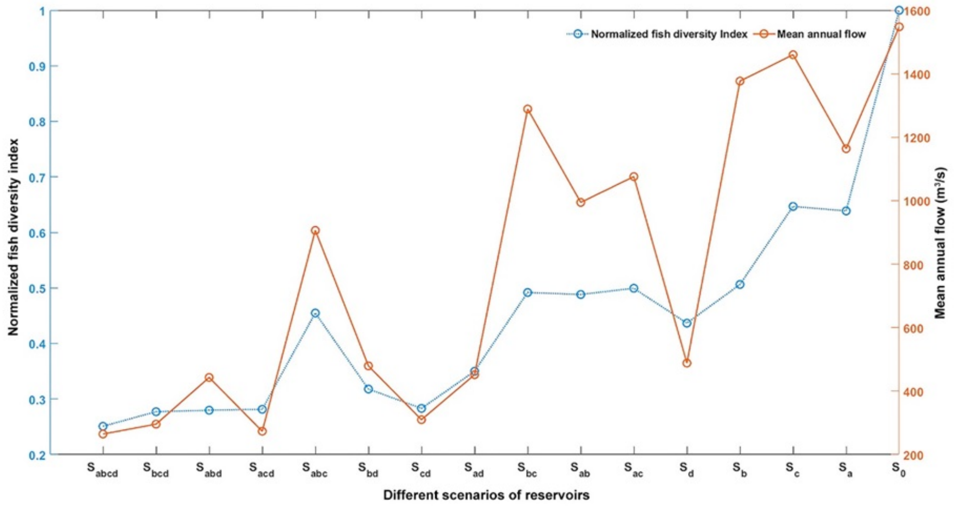
crops that fetch high prices.

However, the value contribution of alternative dam planning and design scenarios differs. For example, the scenario of 4 dams does not show a dramatic value increase as compared to the scenarios of 3 dams. Among the scenarios of 2 dams, there are 3 scenarios, i.e S_{bd}, S_{bc}, and S_{ab}, that show much higher-value generation than other scenarios and that are comparable to scenarios of 3 and 4 dams. In the case of 1 dam, scenario S_b shows a much higher economic value generation. This is because the Hemavathi reservoir (B) has a well-developed command area growing mainly horticultural crops that fetch high prices in the market thereby increasing the economic value.

4.3.3. THE NORMALIZED FISH DIVERSITY INDEX ACROSS SUB-BASINS

The Fish Species Richness (FSR) value is derived based on a global statistical model developed by (Iwasaki et al., 2012)), which is then converted into a normalized fish diversity index (NFDI). The results of normalized fish diversity index (NFDI) calculations for different spatial configurations of the reservoirs are shown in Figure 4.11, which ranges from 0.25 to 1.00 The values obtained by (Iwasaki et al., 2012)) are in the range of 20 to 250 species (0.8 to 1.00 based on the normalized index). Other field studies have confirmed that the FSR in the Cauvery River Basin tends to be around 146 species (Koushlesh et al., 2021). Figure 4.11 also shows the mean annual flows for the various configurations.

The NFDI is greatly impacted by the configurations that contain a large reservoir (such as KRS) due to significant decrease in mean annual flow and in the coefficient of variations of low flow frequencies. This can be seen in the configurations containing one (S_d), two (S_{bd}, S_{cd}, S_{ad}) and three (S_{bcd} , S_{abd} ,S_{acd}) reservoirs where lower NFDI values are observed. Among the scenarios of configurations with two reservoirs, S_{ad} has



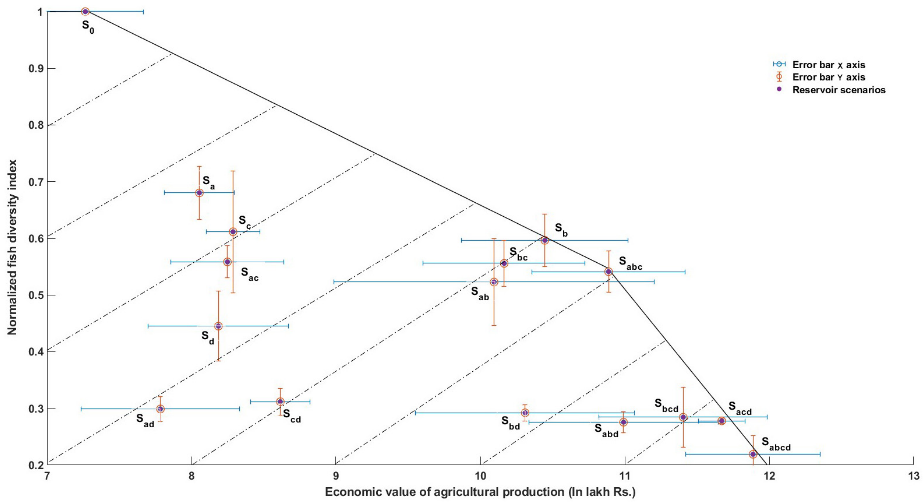
Figuur 4.11: The fish species richness (FSR-IHA) of the different combinations of reservoirs was calculated based on mean discharge and flow regime characteristics

better NFDI than S_{bd} despite having lower mean annual discharge, demonstrating the effect of other hydrological flow regime parameters on NFDI. Among the configurations containing three reservoirs, not much difference in NFDI values are observed except in S_{abc}, which scores higher than other configurations containing three reservoirs (S_{bcd}, S_{sbd} and S_{acd}). These latter configurations contain KRS, which is the most downstream and the largest reservoir and include two smaller reservoirs out of three in various spatial configurations upstream of the KRS reservoir. This shows that a very large reservoir can dominate the effect of reservoirs on the flow regime characteristics and consequently on NFDI.

4.3.4. THE PRODUCTION POSSIBILITY FRONTIER (PPF)

The agricultural production and the normalized fish diversity index (NFDI) for different spatial configurations of the reservoirs define the convex hull of the production set. (Figure 4.12). The Production Possibility Frontier (PPF) is then defined as the outward boundary of the production set. The points and the corresponding configurations lying on this boundary are deemed to be more desirable than the points lying inside because the ecosystem services linked to agricultural production and NFDI are provided less efficiently by the bioeconomy of the basin in the case of the latter than the former.

The findings show that the scenario without any reservoir (S_0) is advantageous for the fish species through the lens of the normalized fish diversity index (NFDI) used in this study. Due to lower values from agricultural production, scenarios of configurations with one reservoir (S_d, S_a and S_c) and two reservoirs (S_{cd}, S_{ad}, and S_{ac}) perform poorly with respect to the frontier. However, due to lower values of NFDI, scenarios of configu-



Figuur 4.12: Illustration of production set and production possibility frontier (PPF). The PPF is the outer edge of the set, between the value of agricultural production and normalized fish diversity index. The error bars represent the variability associated with agricultural production and NFDI for different years

rations with four reservoirs (S_{abcd}), three reservoirs (S_{bcd}, S_{abd}, S_{acd}) and two reservoirs (S_{bd} and S_{bc}) are also considered inferior with respect to the frontier. The scenario S_{bc} is however slightly worse off in terms of NFDI and agricultural production, relative to the PPF.

Five scenarios of configurations S_0, S_b, S_{abc}, S_{acd}, and S_{abcd} define the frontier. The scenario of the configuration with all reservoirs (S_{abcd}) produces the highest value of agricultural output but has the lowest NFDI. The scenario S_b is the only one with a single reservoir (Hemavathi reservoir B) that serves irrigated crops with a relatively good NFDI. Scenarios S, and S_{abc} do not include the KRS (D) reservoir with the largest storage capacity, and thus the flow regime was not significantly altered as compared to the cases of S_{abcd} and S_{acd}. This resulted in better NFDI for fish species and a better 'balance' between agricultural production value and NFDI. Finally, both S_{abc} and S_{acd} are on the frontier because the KRS (D) reservoir in the scenario S_{acd} adversely altered the flow regime by diverting more water for agriculture, thereby boosting agricultural production but simultaneously limiting the NFDI for fish species.

4.4. DISCUSSION

4.4.1. HYDROLOGICAL IMPACTS OF RESERVOIRS ON FLOW REGIME

The analysis of different combinations of reservoirs shows that the storage volumes of reservoirs have a significant impact on mean annual flows. For instance, a configuration adding a reservoir with high storage capacity and a large command area for irrigated crops, such as KRS, leads to a notable decline in mean annual flow. Comparing scenarios with different combinations of irrigation and hydropower reservoirs it is observed that including a hydropower reservoir can mitigate mean annual extreme flow conditions by maintaining higher minimum flow levels during critical periods. However,it also highlights that the presence of a hydropower reservoir situated upstream of an irrigation reservoir may impact the frequency and duration of low flow pulses more than scenarios without hydropower reservoirs. These findings emphasize the importance of considering the specific characteristics and objectives of different types of reservoirs when evaluating their impacts on the flow dynamics. The findings are consistent with a study conducted in the Lancang river in China where dams with storage capacities greater than 100 million m^3 had stronger impacts on streamflow regimes than smaller ones (Han et al., 2019).

Previous studies have indicated that hydropower dams cause monthly mean water levels to rise during the dry season and fall during the wet season (e.g., (Hecht et al., 2019). Even though the dry and wet seasons were not compared in the current study, we find that combining irrigation reservoirs with a hydropower dam has less impact on river flow regimes compared to combining reservoirs for irrigation purposes only. This is due to the regular water releases for energy production that maintain river flows year-round. The study also highlights that the reservoir-induced flow alterations can be compensated by tributary flow regimes. For example, the flow regime of a tributary can offset the low flow impact caused by a reservoir, resulting in a lower overall impact on the flow regime downstream. Similar findings have been observed in other studies, where tributaries significantly contributed to controlling flooding in downstream areas (Pattison et al., 2014).

4.4.2. SOCIAL AND ECOLOGICAL IMPACTS

In the present study, the average contribution of a reservoir to agriculture production was estimated to be ₹0.40 billion per year ($ 0.005 billion per year). It not only supports food security but also contributes to economic development and growth. Most of the horticultural crops and spices that are grown in the Upper Cauvery basin are exported to earn foreign currencies. Fishing is another important ecosystem service supported by the river flow. The economic value of both commercial and subsistence fishing of the Cauvery River is estimated to be ₹35.93 billion per year ($ 0.44 billion per year) (Pownkumar et al., 2022). While direct economic contribution of fisheries to human wellbeing is significantly lower than that of crop production, fish populations and species richness have a significant role in sustaining the river environment such as population dynamics down the food web (Carpenter et al., 1985). But the ecological importance of fisheries in maintaining ecosystem services and functioning, which is indirectly supported by fish species richness, is often ignored in river basin management decisions.

The primary objective of using normalized fish diversity index (NFDI) is therefore not to predict values for fish species richness, but rather to demonstrate how different configurations of existing reservoirs can lead to different (fish) biodiversity conditions in the long run (since we are using averages of these two variables over 16 years). By assessing these relationships, it becomes possible to identify the potential impacts of reservoir configurations on the long-run biodiversity and ecological stability of the river systems. The scenarios containing the largest reservoir (KRS; D) had significant negative impacts on FSR due to declines in mean annual flows and the coefficient of variation of the low flow frequencies. When comparing scenarios that contained the hydropower reservoir with scenarios containing only irrigation reservoirs, the NFDI values were higher in the former indicating that irrigation reservoirs more adversely alter the flow regimes with respect to NFDI. Further, in contrast to configurations with two reservoirs, there was a significant difference in the NFDI values amongst the scenarios of configurations containing three reservoirs due to greater alterations in flow characteristics.

In contrast, no significant difference in the economic value of agricultural production for different scenarios of configurations were observed based on storage volumes, the purpose of the reservoirs, and the orders of the streams on which the reservoirs are constructed. The economic value of agricultural production appears to be largely influenced by the area irrigated per unit volume of stored water in the reservoir. This means that if water is being stored for irrigation, then it should be used as efficiently as possible, i.e., by producing high value agricultural products, to maximize value.

4.4.3. THE ROLE OF PPFS IN DECISION MAKING

The production set in figure 4.12 shows the different configurations of two ecosystem services that can be produced using available water resources. The levels of ecosystem services that lie on the production possibility frontier (the outward boundary of the production set) represent the desirable production levels of the services. We limited our analysis to the existing set of reservoirs and did not synthetically include new reservoirs and the production set is defined as the convex hull of the 16 points. The construction of the convex hull is due to the discrete but realistic nature of the problem. There may be a continuum of production possibilities, but this continuum is neither real (because we only have the mentioned four reservoirs in the basin and therefore only 16 possible combinations of alternate realities depending on how these existing reservoirs could be removed in the future) nor within the scope of the current study. Given only a finite number of points, creating a convex hull to represent a convex production set, makes minimal assumptions and is consistent with the economics literature (see e.g., (Ginsburgh and Keyzer, 2002). The latter (i.e., the inclusion of new reservoirs) might have provided us with a more exhaustive set of points, but this would have been impossible to validate.

The analysis based on the configurations lying on the PPF revealed that large dams that do not maximize the value of water stored, *i.e.*, by growing low value crops in smaller command areas, affect both NFDI and the economic value of agricultural production adversely. Such reservoirs are least favourable, as they are Pareto inferior to other configurations. In contrast, smaller reservoirs on tributaries (away from the main river stem) that grow high-value crops and maximize the value of water stored are Pareto superior and most preferred. Small reservoirs then significantly increase the value of the water while have a lower detrimental effect on areas upstream and downstream (van der

Zaag and Gupta, 2008). For decision-making, this means that large reservoirs that do not maximize the value of water stored should be discouraged and smaller more effective reservoirs should be encouraged if faced with a choice between the two types of reservoirs. However, larger reservoirs are substantially less expensive (per m^3 of water storage capacity) than smaller reservoirs due to economies of scale, and as a result, the ecological costs must be included during the cost-benefit analysis (van der Zaag and Gupta, 2008)

4.4.4. ECOSYSTEM SERVICE PERSPECTIVE ON PPF AND FUTURE CHALLENGES

Understanding ecosystem service (ES) interactions was achieved through the interpretation of the production possibility frontier. However, the complexity of the interactions may prevent the translation of ES knowledge into decision-making processes (Vallet et al., 2018; Hegwood et al., 2022). In the present study, the scenario without reservoirs (S0) was hydrologically a superior choice in terms of fish species richness. However, it had the lowest agricultural output, which would negatively affect employment generation and economic growth. Similar to this, the integration of all four reservoirs S_{abcd} would boost agriculture production by increasing the area of land irrigated but at the expense of lower fish species richness that would be detrimental to riverine ecology. The combination S_b b and S_{abc}, which can enhance both ecosystem services, yield more balanced results.

However, intangible services were not analysed in this study. For example, humans directly consume or use both agriculture and fisheries products for food, nourishment, and employment, and to support their way of living. Both agroecosystems and fisheries provide regulating and supporting services that are crucial for ecosystem functioning and resilience. However, the human-driven ecosystem dis-service from agricultural activities can reduce ecosystem resilience and decrease service generation that are necessary for human survival. Therefore, the non-tangible ES and dis-services should also be taken into consideration using appropriate economic valuation tools in a tradeoff analysis. Further, there is a need to determine which efficient ES combinations would be preferred by stakeholders by assessing indifference curves that describe human preferences for different ecosystem services including regulating and supporting services (Cavender-Bares et al., 2015; King et al., 2015).

4.5. LIMITATIONS OF THE STUDY

The limitations of the presented work and areas of further research are now briefly discussed.

4.5.1. MODEL ASSUMPTIONS AND UNCERTAINTY

We acknowledge that no model is perfect. In the present study, the reservoirs operations at a daily scale are based on trigonometric functions that only incorporate water demand by various command areas as the dominant driver of reservoir releases. Accommodating dam-specific water releases might improve the simulation of intra-monthly variability in streamflow (see its discussion in (Ekka et al., 2022). Therefore, enhancing the model calibration process may involve incorporating operating rule curves that also consider specific reservoir functions and flow requirements. Whether this leads to changes in the conclusions drawn based on the possibility frontier shown in Figure 12 is beyond the current scope. However, even if we assume log effects of mean annual flow on NFDI, changes in flows of one or two orders in log scale would not affect the conclusions drawn (since NFDI is a function of log of mean flows and other streamflow characteristics). Hence, a reservoir configuration leading to substantial alterations in streamflow characteristics — deviating not just marginally but significantly from mean flows — would profoundly impact the NFDI. It must demonstrate a substantial increase in economic value to remain a Pareto superior choice. Reservoirs that significantly alter flow regimes but do not add significant value should therefore be discouraged since it would be a Pareto inferior choice.

Further, although it is acknowledged that the current analysis does not directly provide a practical solution, it highlights an important consideration for reservoir planning and management. The paper presents a proof of concept of the trade-off between the economic benefits of existing reservoirs for agricultural production and the potential negative impacts on fish diversity. While using the normalized fish diversity index as an indicator, the study provides an assessment of change in some aspects of freshwater habitat integrity. We have applied the equation developed by (Iwasaki et al., 2012) and (Yoshikawa et al., 2014) to the Upper Cauvery basin and have extended the application of space and time substitution based on the equation (by time here we mean the occurrence of different scenarios). The central idea is to assess how environmental quality varies with different reservoir configurations and how it trades off with agricultural production. We acknowledge the limitation of equation 5 that in explaining the variability in normalized fish diversity index it does not consider other chemical and biological factors since it is solely based on the assessment of changes in water quantity and not quality, nor of impacts of non-dam related interventions. The same holds for our model. If the impact of unaccounted variability, e.g. of water quality and non-dam related interventions, on fish species richness (FSR) exceeds the recognized reservoir-induced streamflow variability, the reliability of changes in FSR values based on Equation 5 may be compromised. Unconsidered unknown variables like human footprint and fragmentation can introduce bias (Schipper and Barbarossa, 2022).

We cannot verify what NFDI values are for the hypothetical scenarios since there are no counterfactuals. However, the 'observed' NFDI around the gauge station where equation 5 is being used to assess the environmental quality of various scenarios via NFDI is around 0.20, which is close to the estimated value of 0.24 by equation 5 (for the current state as the scenario with all reservoirs in place - the only scenario that is factual). By using the normalized fish diversity index, our analysis also desensitizes the use of absolute numbers of FSR (and absolute changes) and thus focuses more on the relative rankings in the tradeoff space in terms of proxies of environmental quality and agriculture production. Therefore, the innovation indeed lies not in applying the same equation but in building on (Iwasaki et al., 2012) and (Yoshikawa et al., 2014) to apply their equation for various configurations of existing dams and how that is used in the tradeoff analysis. Also, (Yoshikawa et al., 2014) provided a sensitivity analysis based on reducing flows of a certain basin by a certain percentage, and suggested consideration of sensitivity analysis in future studies. The construction of our production possibility frontier in this regard can be seen as a sensitivity analysis where various combinations lead to scenarios of streamflow alterations due to dam regulation, irrigation, and other uses and how FSR based on equation 5 is sensitive to it. To keep the index of environmental quality (NFDI) comparable between the scenarios (where reservoirs are placed or removed in combinations upstream), we only applied the equation at the most downstream gauge. The use of NFDI is more of a means to assess the capacities to have certain levels of fish diversities in various reservoir scenarios, assuming streamflow changes are the dominant effects – in the case of damming this means loss of diversity (see e.g. (Zarfl et al., 2019; Ganassin et al., 2021);, while the case of less dams leads to higher capacity and species recovery (see e.g. (Bednarek, 2001; Hansen and Hayes, 2012).

It is acknowledged that creating a basin-specific equation, tailored to the unique conditions and characteristics of the study area, could yield more precise results. This method would offer a more accurate prediction of how hydrological changes affect fish species richness and ecosystem health, improving the overall accuracy and relevance of the analysis. Apart from flow characteristics, factors such as pollution, over-fishing, and river fragmentation significantly contribute to declines in fish diversity. Additionally, habitat degradation caused by riverbank modifications, deforestation, and contamination further disrupts fish populations and ecosystems (Pelicice et al., 2017).

However, to address the limitations of the approach more effectively, further investigation and field information are required. To determine an appropriate threshold level of fish reduction, a comprehensive assessment of specific requirements of fish habitats, their migration patterns, and population dynamics in the presence of reservoirs is needed. This involves studying factors such as water temperature, dissolved oxygen levels, substrate composition, and availability of food sources. Additionally, assessing the migration patterns of fish can help identify potential barriers created by reservoirs and develop mitigation measures to facilitate their movement. Furthermore, studying population dynamics will provide insights into how the presence of reservoirs affects fish reproduction, growth, and overall population size.

4.5.2. ON DOMINANT ECOSYSTEM SERVICES IN THE CONSTRUCTION OF PPF

The current analysis of the Production Possibility Frontier (PPF) does not include the consideration of riverine and culture fisheries in reservoirs. These fisheries are estimated to have an economic value of approximately 0.59 $ million per year, representing around 12 percent of the economic value of agricultural production ($5 million per year). Also, the economic value generated by hydropower was not considered because only one of the four existing reservoirs supported it. Moreover, the study assumed that when an irrigated area is associated with a reservoir that is withdrawn, it becomes unirrigated (rainfed). This assumption may have influenced the economic value of different scenarios, as farmers might adjust their production practices in response to the change in irrigation. Future research can also consider synthetic reservoirs to more exhaustively explore alternative production sets and include values generated from multiple uses and changing cropping patterns.

While calculating the economic value of crops, the size of the cropped area is kept constant to isolate and analyze the impact of various reservoir combinations on economic outcomes. This approach simplifies the modeling process and helps in understanding the relationships and interactions between varying reservoir combinations, and crop production, without the added complexity introduced by varying land sizes. This simplification, however, comes with limitations. For example, in the face of varying water allocations, farmers can adopt various strategies related to changing crops, for example changing to rain-fed agriculture or shifting towards less water-intensive irrigated crops ((Graveline, 2016).

Another limitation of this study is the utilization of constant prices, a factor that may pose challenges in assessing the impact of droughts and reduced water allocations on crop yields. If the basin is large enough and dominates the domestic market in terms of production of certain crops, then droughts and reduced water allocations will reduce crop yields, which will constrain supply and can therefore significantly affect prices. Since agricultural demand is highly inelastic, significant changes in supply may lead to abrupt changes in prices (Haqiqi et al., 2023; Parrado et al., 2019). As agricultural markets are well-developed in the basin and well-connected to other domestic and international markets outside the basin, production changes in the basin, could be compensated by production in neighboring places unless there is a significant supply shock.

4.6. Conclusion

The main objective of this research component was to evaluate the hydrologic, ecological, and economic impacts of multiple existing dams in the Upper Cauvery River basin, India. To do so, a novel approach was presented that estimated the production of river ecosystem services using a landscape based hydrological model integrated with the modelling of the operations of multiple existing reservoirs at daily scale. The high resolution and robust simulation of pre-dam flow regimes offered the unique opportunity to assess the effects that cascades of existing reservoirs have on the river flow regimes downstream in a virtual experiment setting. Such a study has been conducted for the first time, especially for the case of Indian river basins where pre-dam data is unavailable but there are increasing calls for environmental impact assessment of large multiple dams (Erlewein, 2013; Lele, 2023).

The hydrological impacts of different configurations of reservoirs were assessed using Indicators of Hydrological Alterations. The biophysical quantification of major ecosystem services, indicated by the economic value of crop production and fish species richness, supported by the river were estimated and a production possibility frontier, representing the tradeoff between the two, was quantified. The main findings that can enhance our understanding of the effects of multiple existing dams on the provision of dominant ecosystem services and help optimize river management plans are summarized below.

- The mean annual flow and annual extreme conditions of minimum and maximum flows are adversely affected by the largest dam in terms of storage. In comparison to reservoirs used just for irrigation, scenarios of reservoirs used for hydropower and irrigation have less impact on low flow pulses and low flow duration.
- The large dam in the sample did not maximize the value of water stored. We found that low value irrigated crops were cultivated, which adversely affected both FSR and the economic value from agricultural production. Such a reservoir is the least favourable and should be discouraged by policy makers
- Growing high value irrigated crops with a highly established command area served by small and medium reservoirs can strike a favourable balance between agricultural production and fish species diversity
- Heavily altering the river landscape with reservoirs (e.g., by maximizing the number of reservoirs) provides a superior result in the sense that it maximizes agricultural income. However, it may not be preferred by diverse stakeholders such as fishers and environmentalists due to dismal biodiversity that it leads to, as indicated by fish species richness (FSR). Such an option produces lowest FSR. This perhaps should be favoured less than a configuration of reservoirs that strikes a favourable balance between agricultural production and fish species diversity while still efficiently producing both. This goal could also be achieved by prioritizing the enhancement of rainfed agricultural production. By doing so, we can potentially minimize the tradeoffs with other critical ecological services compared to irrigated agricultural production. By reducing the tradeoffs with other ecological services and enhancing water management practices, we can strive for a more sustainable and balanced approach to water resource management in the basin

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CONCLUSIONS

The conclusion is not just an end to a tale
But a starting point for a new journey to set sail
So let us raise a toast to the conclusion we've found
Expanding knowledge all around

Parts of this chapter are based on:

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5.1. INTRODUCTION

Human activities in river basins are visibly altering landscapes, posing challenges to the ecological and social health of rivers. There is a critical need for a more comprehensive approach to studying river landscapes in ecosystem service research, which is currently constrained by a limited understanding of ecosystem structure, function, and their connection to the ecological, economic, and socio-cultural values. This thesis argues for a holistic landscape perspective in ecosystem service research, emphasizing the interconnectedness of ecosystems and the influence of various factors such as land use, climate, and human activities on ecosystem services.

In this thesis, I have addressed the four research questions (see section 1.4) in Chapters 2, 3, and 4, by providing a comprehensive analysis of the complex dynamics between river flow regimes and the provision of ecosystem services.

The specific contribution of the present flow regime to social, ecological, and economic services in a river ecosystem can be understood through its multifaceted interactions and impacts on various components of the riverine environment and therefore to answer the first research question, a literature review was conducted to highlight that the quality and quantity of ecosystem services are closely linked to the effective functioning of biophysical processes, which in turn are influenced by the geomorphological, ecological, and hydrological characteristics of the river basins. By considering ecosystem services at the landscape scale, researchers can gain a better understanding of the trade-offs and synergies between different services, which can lead to more sustainable development strategies that balance human needs with environmental conservation.

The second research question, '*How do modifications of the river landscape affect the river flow regime?*' is answered by analyzing the impact of the dam on the river flow regime using a landscape-based hydrological model with a reservoir operations model, developed to support hydro-economic analysis at the basin scale. The study focused on the Upper Cauvery river basin of India, where the effects of dams on river flow regimes are studied under data-scarce conditions using the FLEX-Topo hydrological model and Indicators of Hydrologic Alterations (IHA).

The study finds that reservoir operations and water abstraction significantly influence the average monthly flow in the Upper Cauvery basin, leading to a decrease in flow across all sub-basins throughout the year compared to natural flow regimes. The study distinguishes between the hydrological impacts of reservoirs for irrigation and those for hydropower, highlighting the need for tailored management strategies.

The third and fourth research questions, '*What are the tradeoffs among economic, social and ecological services of rivers?*' and '*How can economic and social welfare be maximized while maintaining the ecological health and function of rivers?*' are answered by estimating the production of two key ecosystem services i.e. fish species richness, and agricultural production, dependent on flow regimes, and develops a production possibility frontier for these services for all cascading reservoirs in the basin.

The findings suggest that smaller reservoirs on lower-order streams that maximize the economic value of stored water, are more beneficial for both the basin economy and the environment compared to larger reservoirs. Furthermore, growing high-value crops in a command area can maximize the value of stored water and generate similar economic value with lower storage capacity, reducing hydrological alterations.

However, the social aspect of ecosystem services necessary for social welfare is not analyzed in this thesis and is left for future work. Addressing this gap in future research is crucial for developing comprehensive strategies that not only optimize economic and ecological outcomes but also ensure the well-being and welfare of communities dependent on river ecosystems.

In conclusion, this thesis highlights the importance of adopting a holistic landscape perspective in ecosystem service research for river basins. Such an approach can lead to a better understanding of the complex interactions between ecosystems and human activities, facilitating more informed decision-making for the sustainable development of river basins.

5.2. LIMITATIONS OF THE STUDY

It is important to acknowledge the limitations of this study, including the assumptions and uncertainties associated with the models used and the complexities of incorporating all relevant factors into the analysis as discussed below.

- This study focuses on the use of robust landscape-based hydrological models to analyze the impact of reservoir operations on ecosystem services, specifically in relation to fish diversity and agricultural production. The study acknowledges the limitations of the models used, particularly in capturing dam-specific water discharges and the intra-monthly variability in streamflow.

- The analysis highlights the trade-offs between economic benefits from reservoirs for agriculture and potential negative impacts on fish diversity. Flow regimes in sub-basins were found to be altered following reservoir impoundments, with most sub-basins experiencing a reduction in median, minimum and maximum flows due to regulated reservoir operations and water diversions for irrigation. However, the study does not account for the return flows from irrigation, which may impact the accuracy of the analysis.

- The study emphasizes the need for further investigation and field data to improve model accuracy, particularly in assessing specific requirements of fish habitats, migration patterns, and population dynamics in the presence of reservoirs. It suggests that a comprehensive assessment of these factors is necessary to determine a critical threshold level of fish reduction and to develop mitigation measures to facilitate fish movement.

- The economic value of riverine and culture fisheries in reservoirs, as well as the economic value generated by hydropower, was not considered in the analysis. Additionally, the study assumes that when an irrigated area associated with a reservoir is withdrawn, it becomes unirrigated (rain-fed), potentially influencing the economic value of different scenarios. Future research could consider synthetic reservoirs and varying crop production strategies to assess the economic impacts of different reservoir configurations more accurately.

- The study also acknowledges limitations in the calculation of economic values, particularly in using constant prices, which may not accurately reflect the impact of droughts and reduced water allocations on crop yields. It suggests that changes in supply could be compensated by production in neighbouring places unless there is a significant supply shock, highlighting the complex nature of agricultural markets inside and outside the basin.

Overall, the study provides valuable insights into the trade-offs and challenges associated with reservoir planning and management, emphasizing the importance of considering ecosystem services and the need for more comprehensive and accurate modeling approaches to inform decision-making.

5.3. WAYS FORWARD: CHALLENGES AND STRATEGIES FOR FUTURE RESEARCH

It is essential to acknowledge the intricate relationship between humans and rivers. Researchers and water managers need to focus on determining the flow regime necessary to sustain ecosystem health while meeting human water needs. With the current challenges posed by climate change, sustainable water resource management has become increasingly important. The following points need to be considered for future research on the sustainable management of river resources.

- ***Revise reservoir operation rule curve to balance environmental flows*** Reservoir operation rule curves are commonly used to determine how much water should be released from a reservoir to meet a variety of water demands, such as irrigation, domestic use, and hydroelectric power generation. However, these rule curves can also be used to help balance environmental flows, which are flow regimes required to maintain the ecological health of the river landscape. To balance environmental flows using a reservoir operation rule curve, research should be carried out to first determine the minimum flow requirements for the river system that needs to be managed. This may include consulting with ecologists, hydrologists, and other experts to determine what flows are required to keep the river healthy, such as maintaining fish populations, supporting riparian vegetation, and ensuring water quality. Therefore, adjusting the rule curve is crucial to ensure that the minimum flows are being met while meeting other water demands.

- ***Analyze the full value of ecosystem services in dam-related cost-benefit and tradeoff analysis*** In dam-related projects, it is critical to consider the full value of ecosystem services to ensure that decisions are made that balance the needs of various stakeholders while also protecting the ecosystem's long-term health. It is critical to identify all relevant ecosystem services when conducting a tradeoff analysis, which can be accomplished by consulting with stakeholders and experts to ensure that all important services are considered. Furthermore, to better understand the relationship between ecosystem services and the river ecosystem, the underlying ecological processes that support these services must be studied. For example, understanding the nutrient cycling processes that support fish production, can aid in the development of strategies for maintaining healthy fish populations. To provide the full value of ecosystem services, appropriate valuation techniques must be used while considering the spatial and temporal heterogeneity of the river landscapes. It is also critical to consider the cultural value of ecosystem services and ensure that they are incorporated into decision-making to balance the needs of various stakeholders while protecting the sustainability of the river ecosystem.

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List of Publications

Research Papers

1. **Ekka A.**, Pande S., Jiang, Y., and van der Zaag P.(2020). *Anthropogenic modifications and river ecosystem services: A landscape perspective* Water 2020, 12(10), 2706

2. **Ekka A.**, Keshav S., Pande, S., van der Zaag, P., Jiang, Y (2022). *Dam-induced hydrological alterations in the upper Cauvery river basin, India* Journal of Hydrology: Regional Studies,44,101231.

3. Pownkumar, V., Ananthan, P.S., **Ekka ,A.**, Qureshi, N. W., Thangavel, V. (2022).*Fisheries as ecosystem services: A case study of the Cauvery river basin, India.* Frontiers in Environmental Science, 10, [892012].

4. **Ekka A.**, Jiang, Y., Pande, S., van der Zaag, P., (2023). *How economically and environmentally viable are multiple dams? A hydro-economic analysis using a landscape-based hydrological model at the basin scale.* Hydrology and Earth System Sciences, 28 (14),3219-3241.

Abstracts and conference presentations

5. **Ekka A.**, Pande S., Jiang, Y., and van der Zaag P.(2019).*Understanding the impact of anthropogenic activities on river ecosystem services in India: A hydro-economic approach. In* Geophysical Research Abstracts (Vol. 21).

6. **Ekka A.**, Kesav, S., Pande S., van der Zaag P. Jiang, Y., (2020).*Integrating reservoirs in a landscape-based hydrological model to understand the impact of the reservoir on flow regime in the Cauvery river basin, India* In EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-16784,.

7. **Ekka A.**, Jiang, Y., Pande S., van der Zaag P.(2021). *Impact of Anthropogenic modifications on river ecosystem services in India* In 1st International Conference on River Corridor Research and Management, 25–27, February, 2021

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9. **Ekka A.**,Kesav, S., Pande S., van der Zaag P., Jiang, Y., (2021).*Understanding the impact of dam-induced hydrological alterations on river flow regime: A case study of upper Cauvery River basin, India.* In Delft International conference on Socio-hydrology, Online, 6–8 September, 2021