Analyzing the Cauvery River Dispute Using a Systems of Systems Approach

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The Cauvery River conflict in southern India is a water-sharing dispute that has persisted for over a century. Over the last thirty years, the conflict has been exacerbated due to climate change, and population explosion. Addressing this long-standing conflict requires a comprehensive approach. This thesis employs a systems-of-systems (SoS) methodology to analyze the hydrological, socio-economic, and governance systems of the Cauvery River basin, aiming to provide a deeper understanding of this complex conflict. As the provinces of Karnataka and Tamil Nadu dominate the basin, their roles as primary decision-makers are central to resolving the dispute.

The thesis integrates systems-of-systems analysis, graph theory, document analysis, and hydrological modeling. Valuable insights are drawn from government reports and legal contexts, unveiling the historical priorities and biases of stakeholders. The Water Evaluation and Planning (WEAP) method is used to create a conceptual hydrological model of the Cauvery River basin. Cross-impact balance (CIB) analysis is employed to understand the complex socio-economic interactions in the basin and generate consistent scenarios. These consistent scenarios are useful in identifying descriptors or systems that are most influential in possibly resolving this conflict. Finally, a Decision Support System (DSS) called Graph Model for Conflict Resolution (GMCR) is developed that uses the outputs of CIB and demonstrates how a resolution may be achieved.

WEAP analysis provided the measure of unmet demand in the Cauvery River basin, and how it affects agricultural productivity. CIB analysis yielded many consistent scenarios, however, after further analysis, a few systems emerged that were more influential in the system than the others. Managing water demand in Karnataka and managing water supply in Tamil Nadu were among the most active descriptors in the analysis. Increasing governmental effectiveness, and reduction of corruption were the other important descriptors from the CIB analysis. GMCR proposes resolutions based on the decision-maker's options and preferences. Cooperative efforts and improved governmental effectiveness emerge as compelling solutions. The analysis identifies unmet basin demands critical for decision-making. The research emphasizes the importance of communication and governance improvements, highlighting the potential for a rapid and amicable resolution between Karnataka and Tamil Nadu.

The study underscores the effectiveness of systems-of-systems methodology in analyzing intricate issues. Future work could involve participatory approaches for judgment score calculations and expert elicitation

to enhance research outcomes. As climate change impacts intensify, such methodologies become increasingly vital for crafting sustainable solutions to global challenges.

In conclusion, this research showcases the significance of systems-of-systems analysis for understanding and resolving complex problems. The proposed standard operating procedures offer a valuable framework for researchers addressing intricate issues. As the urgency of climate change grows, the utilization of such methodologies becomes paramount for devising effective and sustainable global solutions.

Acknowledgments

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1. Introduction

1.1 Water Availability and Climate Change

Water is one of the most important resources in the world, as it ensures the survival of our species. The scarcity of water is one of the major global issues. The huge increase in global population has caused incredible stress on the availability of resources. Climate change has further exacerbated the conflicts arising from the sharing of crucial resources like water. There have been studies all around the world that discuss the effects of climate change on their local river basins. Piao et al. (2010) discussed how climate change has affected the ability to effectively feed the people of China. Twenty-two percent of the world's population lives in China; however, the country only has 7% of the world’s arable land. Stress on the available water resources greatly affects the ability to grow food. Abbaspour et al. (2009) discussed how climate change aggravated the availability of water resources and caused an increase in domestic water supply demand in Iran. Serrat-Capdevila et al. (2007) discussed the effects of climate change on the San Pedro River Basin in southeastern Arizona (USA) and northern Sonora (Mexico). J. Xu et al., (2009) discussed the effects of climate change on the water-rich Himalayan region. The Himalayan region is the source of at least ten key rivers in Asia. The cascading effects of climate change can cause loss of ice affecting the water availability in the region. The water shortage in the major continents was studied by McDonald et al. (2011). The increasing water demand due to the greatly increasing population would create water scarcity across the continents. The Intergovernmental Panel on Climate Change (IPCC) reported in 2007 that nearly all the regions of the world are expected to experience a net negative impact of climate change on water resources and freshwater ecosystems (IPCC, 2007). Therefore, water is an extremely important resource for survival.

The scarcity of water resources may cause conflict among water-sharing entities. There are many instances where a river basin is shared by two or more countries, and when the availability falters, the conflicts flare up. Some of these nations have had troubles, like India and Pakistan over the Indus River; Sudan, Egypt, and Ethiopia over the Nile; and Israel, Palestine, and Syria over the Jordan River (Wolf, 1998; Wolf et al., 2003). Therefore, the “Right to Watercourse” (Vinogradov et al., 2003) has been an issue of discontent among neighboring countries. Examples of points of contention include: Which country shall use what percentage of the water? Does the country of origin of the river have the complete right to upstream water? Should the downstream country have an uninterrupted flow of water? There has never been an easy or rule-of-thumb solution for these kinds of issues and arguments because every river basin is unique. Although we do not yet have a legal infrastructure for conflict resolution between provinces, there is a legal framework that is used between countries that we can draw from. The International Joint Commission (IJC) was established in 1909 between the countries of Canada and United States of America to prevent and resolve water conflicts (International Joint Commission, 2023). The United Nations (UN)'s International Court of Justice (previously called the Permanent Court for International Justice) passed resolutions to mitigate this problem. In 1997, the UN introduced the Convention on the Law of the Non-Navigational Uses of International Watercourses (Kahn, 1998). This was a landmark decision for the non-navigational uses of watercourses, and it laid down a major share of our understanding in terms of water sharing. The conflict discussed in this research is majorly based on the non-navigational utilization of the Cauvery River between the Indian states of Tamil Nadu and Karnataka.

The country of India is divided into states. The political authority and powers are divided between the Central government (or the Union government or the Federal government) and the individual state governments. There are two levels of government, the central government at the national level, and the individual state governments at the regional level. Each level of government has its own set of responsibilities and powers. The Constitution of India is supreme and delineates the powers and the responsibilities of the central governments through the constitution's Seventh schedule (Government of India, 1956a). The Seventh schedule (Article 246) provides three lists that divides the subjects that can be legislated by the union government (e.g., defense, foreign affairs, currency, etc.), the state government (e.g., police, public health, agriculture, water, etc.), and finally by both the governments (e.g., education, criminal law, marriage, etc.). Such a structure is required to govern a country that has such a vast cultural, linguistic, and geographical diversity (Huma, 2015).

It is important to note that this work uses state-space modeling and therefore, for clarification, the states in India are hereafter designated as "provinces". The states of Karnataka and Tamil Nadu will be called the provinces of Karnataka and Tamil Nadu throughout this work.

1.2 Cauvery River conflict

In the southern part of India, the Cauvery River basin has been involved in a conflict for more than a hundred years. Cauvery is the fourth largest river in southern India, with a length of 802 km (kilometers). It originates in the Indian province of Karnataka and discharges into the Bay of Bengal while flowing east through the more southern province of Tamil Nadu, providing hydropower and water for agriculture to significant regions of both provinces. The basin's location is circled in the map of India shown in Figure 1.

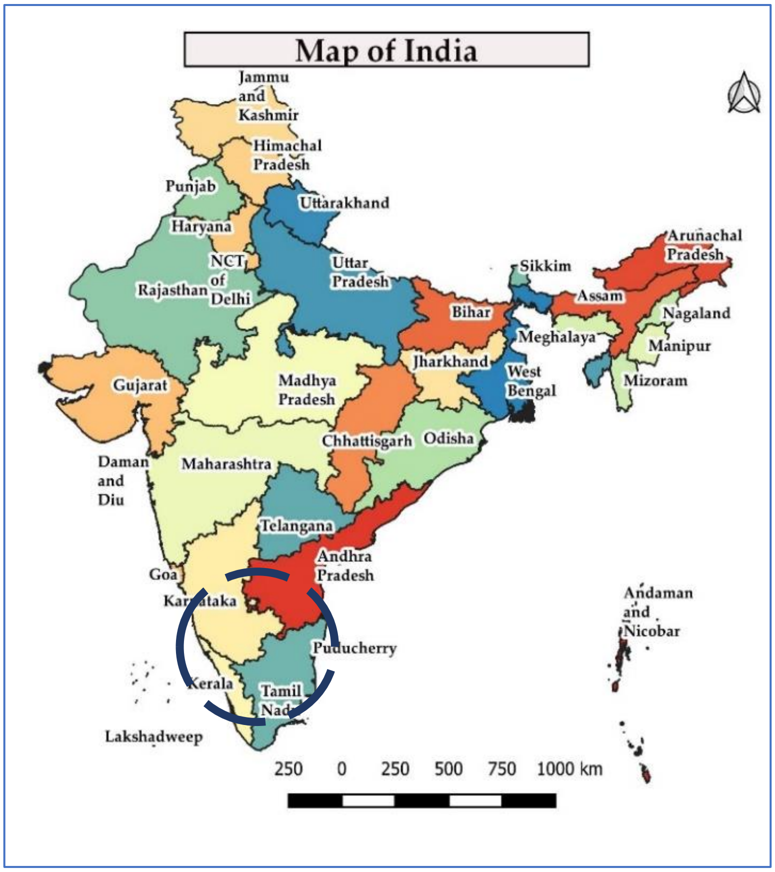


Figure 1 Map of India with the Cauvery Basin encircled. Created in QGIS using data from DIVA-GIS (Hijmans et al., 2012).

Figure 2 depicts the Cauvery River basin (encircled in Figure 1) and the districts within the two major provinces of Karnataka and Tamil Nadu. The Cauvery conflict is not limited to just water sharing, but rather the re-sharing of a very heavily utilized river (Iyer, 2003). The dispute exacerbated over the last thirty years as the population of the city of Bangalore (Bengaluru) in the province of Karnataka exploded (Sudhira et al., 2007). The water from the Cauvery River is used by Bangalore primarily, and the increasing population has greatly expanded the load on the natural resource—the population grew from 150,000 in 1950 to 11.5 million in 2018 (Figure 3). On the other hand, major quantities of water flowing toward the province of Tamil Nadu have been historically used for irrigation (Anand, 2007). Paddy (rice) has been grown in the region for a very long time and is, therefore, the principal crop in the basin. Paddy is grown in the basin in three seasons: winter, monsoon, and summer, which explains the huge water demand. Generally, paddy requires 2500 liters of water per kg of grain produced (B. Bouman, 2009).

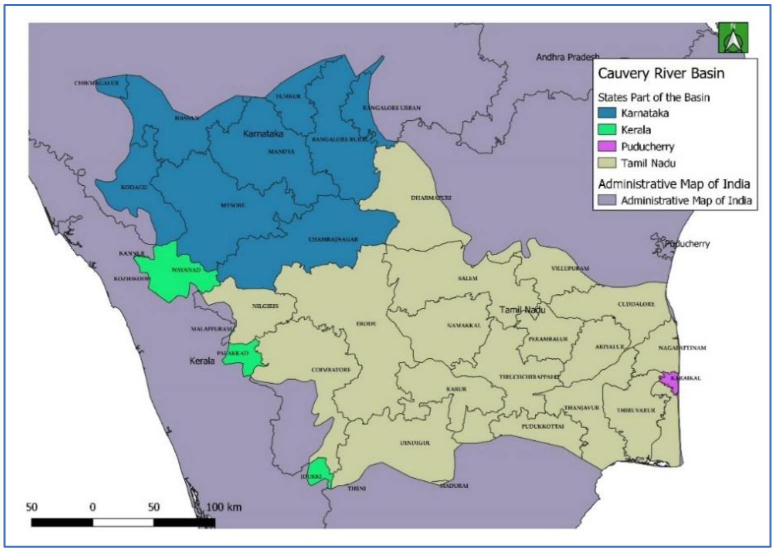


Figure 2 Cauvery River Basin Created in QGIS using data from DIVA-GIS (Hijmans et al., 2012)

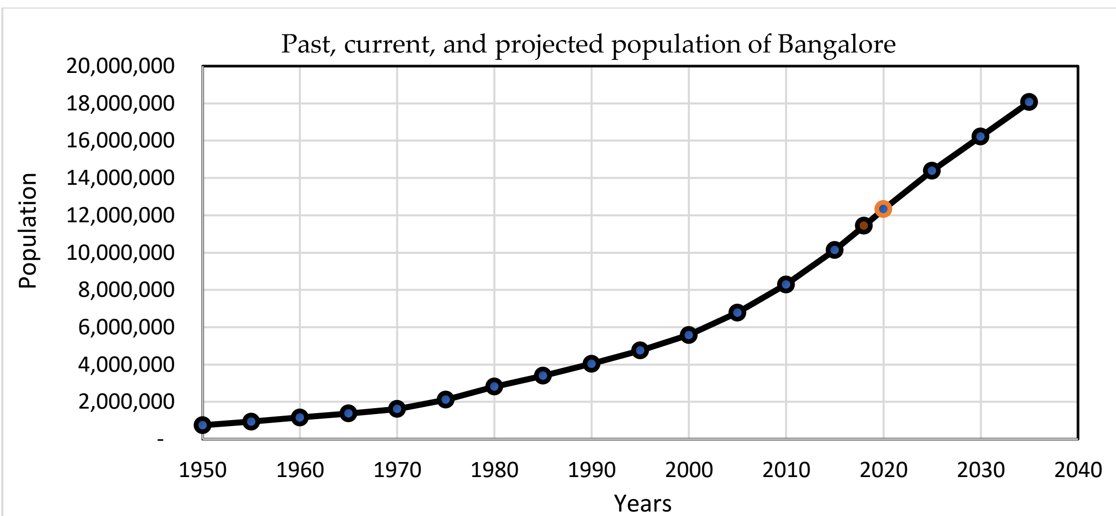


Figure 3 Population growth of Bangalore (Bengaluru), Karnataka (United Nations, 2018)

The heavy dependency of both provinces on the water flowing from the Cauvery River has prevented the conflict from being resolved. The Cauvery River conflict is not just limited to supply and demand of water. The societal and governance factors have further contributed to increasing the complexity of this dispute. The governments of both the provinces as well as the federal government have tried to resolve this conflict, however, they have failed to do so. The historical background information is provided in Chapter 2. The chapter chronicles the events of last one hundred years. There have been many legal decisions taken to resolve this issue, but as of 2023, none have been successful. One example of the conflict is from 2013 when the water share of Tamil Nadu was reduced from a previous ruling in 2007. Tamil Nadu wanted the previous ruling re-instated, as it claimed that it is a riparian state and should receive more water. Karnataka's share was increased in the 2013 decision, and it wants to keep it that way. A major drawback of these verdicts is that they are based on the current and historical seasons or years. Once passed, these verdicts and the share bestowed upon parties shall remain and in function in perpetuity or until a new legal action is taken. As established, the dispute is not limited to water allocation. Climate change, governmental effectiveness, politics, etc. all play intrinsic roles in exacerbating this conflict. Therefore, a proper analysis is required that encompasses the effects of various systems acting upon the region.

1.3 Previous work in the Cauvery River basin

Bhave et al. (2018) conducted a study in the province of Karnataka, focusing on Decision-making Under Uncertainty (DMUU) and its connection to the impacts of climate change on the province's socioeconomic system. They developed an iterative DMUU approach which included a combination of scenario generation, close interaction with stakeholders, and water resources modeling. They engaged with the stakeholders in the province and used qualitative data with quantitative data to create a comprehensive study about the issues of water scarcity (Dessai et al., 2018). The input in their water resources model came through a system of adaptation pathways, which were ascertained using Key Informant Interviews (KIIs). In the (Bhave et al., 2018) study, they used this method to gauge future projects in the agricultural and industrial sectors of Karnataka under climate change. The water resources model was calibrated and validated using the observed streamflow data. They used the Indian Summer monsoon and the water demand in the region to simulate the effect of scarcity of water (Bhave et al., 2018). The majority of the other current research on how to improve water sharing in the above region is focused on individual system interventions in fields such as economics (Ghosh & Bandyopadhyay, 2009), policy (Richards & Singh, 2002), social work (Anand, 2004), etc., separately. There are also huge gaps between water resources modeling and policy adoption. There is a lack of a systems of systems approach (H. Xu et al., 2018). A more holistic approach shall consider multiple relevant systems and when a systems-of-systems approach is not followed, analysts apply assumptions that oversimplify or ignore the influence of systems external to their expertise. This introduces analyst bias. A holistic approach taking into consideration as many systems as possible contributing to the function/operation in the region can help us carry out scenario analysis with reduced analyst bias and other assumptions in the system. Scenario analysis is a powerful technique where plausible alternative futures are inspected.

1.4 Research questions

The research questions that this research is attempting to answer are as follows,

1. Identify reasons for continued water-sharing conflict between the provinces of Karnataka and Tamil Nadu and recommend leverage points that the two provinces can employ to collaborate and potentially solve this conflict.
2. Identify how climate change and policies related to water resources under the changing climate have affected the provinces.

The current project builds upon the research carried out by Bhave et al. (2018), and Dessai et al. (2018) for the province of Karnataka and extends it to include the province of Tamil Nadu. The first step is to build a hydrological model to identify the water balance in the Cauvery River basin on an annual basis. The aim is to identify the current use of water resources in the basin. The hydrological model as explained in Chapter 4 of this work will also include six varying scenarios. Probable changes in precipitation and water demand in the region will be used to build scenarios. A series of area-specific methodologies are proposed to ensure a comprehensive, or systems of systems, analysis of the conflict. Multiple systems involved in the conflict are analyzed. The methodology is inspired by Bhave et al. (2018) and consists of four distinct stages which are explained in detail in Chapter 3. Table 1 enlists the differences between the current work and the previous work.

Table 1 The difference between the Bhave et al. (2018); Dessai et al. (2018) *work and the thesis*

Current Work	Methods Used	Previous Work	Novel to this work
Include stakeholders' opinions and expertise on the Cauvery conflict	Document Analysis	(Bhave et al., 2018) for Karnataka	For Karnataka and Tamil Nadu
Water Resources Modeling of the Cauvery River Basin	Water Evaluation and Planning (WEAP)	(Bhave et al., 2018) for Karnataka	For Karnataka and Tamil Nadu
Systems theoretical modeling necessary to prompt complex interactions in the Cauvery River Basin	Cross Impact Balances (CIB)	-	For Karnataka and Tamil Nadu
Decision Support System to analyze the options/preferences of the stakeholders and produce resolution(s)	Graph Method for Conflict Resolution (GMCR)	-	For Karnataka and Tamil Nadu

The first two stages mirror the study carried out by Bhave et al. (2018) for Karnataka and the latter two stages are novel to my research. The major differences between the existing literature and the contribution of this thesis are outlined in the table above. The Bhave et al. (2018) study carried out climate change research in the Cauvery River Basin and focused on the province of Karnataka. The proposed research is anticipated to reveal the complex interactions of the socio-economic, political, and hydrological systems affecting the Cauvery River basin conflict which includes both Karnataka and Tamil Nadu. These interactions will then point to the system interventions required to potentially solve the conflict. This research will also cover both the provinces of Tamil Nadu as well as Karnataka.

The major systems in the Cauvery River Basin are the hydrological system, socioeconomic system, and governance system. The systems and the subsystems are identified using the relevant reports published by the federal government and provincial governments. The published journal papers are also used for their unbiased technical opinions. The Cauvery Water Disputes Tribunal reports published since 1990 are examined for data. This document analysis is instrumental in constructing a causal loop diagram that further simplifies the complex systems of systems interactions. A Water Evaluation and Planning (WEAP) model is developed to understand the hydrological system (Bhave et al., 2018; Dessai et al., 2018; Stockholm Environment Institute, 2020). Cross Impact Balances (CIB) is an example of a systems science theoretical approach that can represent the complex nature of the factors because it models feedback. Consequently, the socioeconomic, and governance systems are researched using the Cross-Impact Balances (CIB) approach (Lloyd & Schweizer, 2014; Schweizer, 2020; Schweizer & Kriegler, 2012; Weimer-Jehle, 2006). And finally, a decision-making tool Graph Model for Conflict Resolution (GMCR) is used to explore negotiation strategies between the two provinces to reach a possible resolution (Fang et al., 1993; Kinsara, 2014; Kinsara et al., 2015; Sharma, Hipel, et al., 2020; H. Xu et al., 2018). Both CIB and GMCR are flexible models and can capture non-linear interactions. The methods are explained in detail in chapters 4, 5, and 6.

1.5 Summary and Flow of the Thesis

In summary, climate change is a major factor affecting the rainfall in the Cauvery River Basin. The reduction in rainfall has exacerbated the water-sharing conflict over the last thirty years. Therefore, the provinces must be properly prepared to understand and alleviate the issues caused by climate change. Climate change policies and institutional ineffectiveness in regulating the provinces have caused major path dependencies in the system (David, 2000; Pierson, 2004). The two provinces are currently in a game theory-like situation where they are blocking each other's potential moves just to cause harm to each other. The institutions find it easier to work around the established format of dispute resolution, with the same exercise being carried out every time there is a need to mediate. It has reached a stalemate situation, where the actual problem is not getting addressed. Also, policy interventions are required in the region to improve the use of water resources. These interventions or leverage points are placed within a complex system where a small shift in one area can produce big changes in everything. These leverage points need to be utilized at an appropriate level in the governance as well as at the relevant time. The Causal loop diagram (figure 8) presented in Chapter 3 points to the interactions of the various factors affecting the Cauvery River Basin. In this research, the complex nature of the conflict is analyzed in detail. Lastly, there is no conflict of interest in this study. The author does not come from the region he is researching. Also, he has immense respect for the cultural and social aspects of the southern part of India. It is important to note that the research is timely and needed.

Chapter 2 provides the historical background information of the Cauvery River conflict. Chapter 3 provides more information regarding the methods used in this work and how they combine. Chapter 4 presents the data required for building the Water Evaluation and Planning (WEAP) model and the results. Chapter 5 discusses the data acquired for building the Cross Impact Balances (CIB) and the results from the analysis. Chapter 6 discusses the decision support system GMCR. Chapter 7 provides a conclusion and recommendations.

2. History of the Conflict

2.1 Origins of conflict

The conflict goes back to the early 19th century when the parties in the dispute were the Madras Presidency (Tamil Nadu) and the princely state of Mysore (Karnataka). India was a British colony for centuries, and most of its provinces were under the direct control of the British. They controlled both Mysore (present-day Karnataka) and Madras (present-day Tamil Nadu) for a short period of time in the middle of the 19th century, as indicated in Figure 4. During the British regime, numerous plans were drawn up for the utilization of the Cauvery waters by both states. However, the drought and subsequent famine in the mid-1870s put a hold on the implementation of these plans.

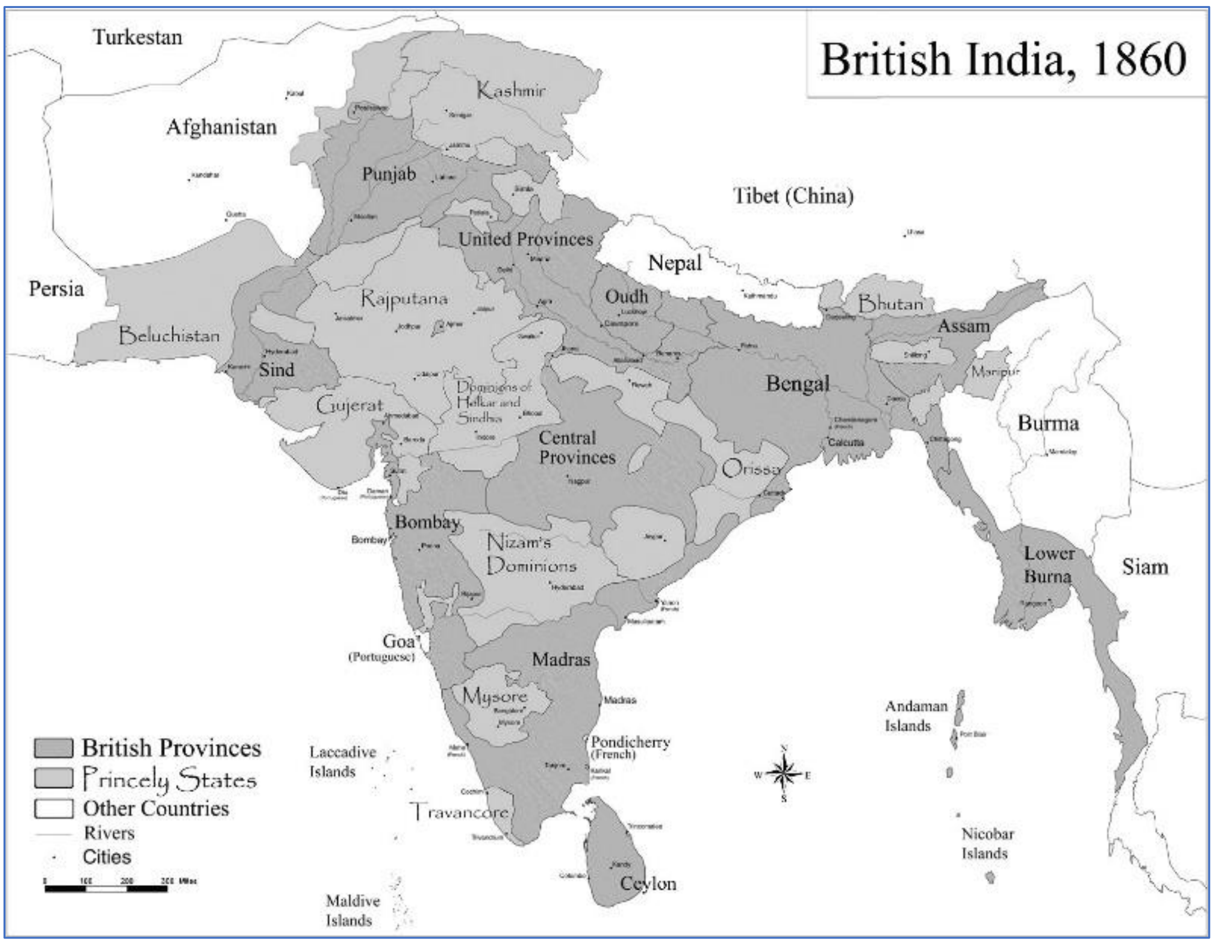


Figure 4 Pre-Independence Map of India © Kmusser / Wikimedia Commons / CC-B 3.0 / GFDL (Kmusser, 2006)

2.2 Pre-Independence (before 1947)

At the end of the 19th century, Mysore planned to revive various irrigation projects, but the Madras Presidency resisted any movement in that direction. However, the state of Mysore proposed to build a dam upstream, but the state of Madras did not agree, as it wanted to build a storage dam downstream. Mysore state approached the then British government, requesting them to intervene. As a result, a conference was held in 1890 to reach an agreement. The potential arrangement allowed Mysore to deal with irrigation works and gave Madras practical security against any mishaps. The agreement was signed on 18 February 1892 (D'Souza, 2005).

After the government intervenes in 1892, it was decided that the state of Mysore would build the dam under reduced storage. Nonetheless, during the construction phase, the groundwork was established for a dam with an increased capacity of 41.5 TMC (thousand million cubic feet), causing dissatisfaction within the Mysore state. The issue, as per the rules of the agreement of 1892, was sent for arbitration (Bosu, 1995). The arbitration started in 1913 and gave its verdict in favor of Mysore in 1914. However, Madras did not agree with the ruling and a new pact was signed in 1924 (D'Souza, 2005). This pact was to remain for 50 years and gave directives regarding the distribution and the use of the water. It did not consider the possibility of gentrification after independence, thereby causing some administrative issues which are discussed in the following sections. The timeline of the pre-independence era conflict is presented in Table 2.

Table 2 Pre-Independence era conflict timeline regarding the Cauvery River

Year	Major events
1890	• Mysore plans to revive various irrigation projects. Madras is against these plans, as the scale of the construction is unknown.
1892 – 1905	• Mysore tries to build a dam; however, Madras intervenes. • The Central Government directs Mysore to reduce the capacity of the dam. • Mysore, ignoring the directive, laid the foundation for handling the original capacity. • Madras approaches the central government again.
1905 – 1913	• The Central Government offers that the issue should be solved by arbitration.
1914	• Arbitration results in Mysore's favor; Madras refuses to accept.
1914 – 1924	• Negotiations were delayed due to the 1st World War.

	• A pact is signed between Madras and Mysore regarding water sharing, which shall remain active for the next 50 years.

After Indian independence in 1947, the state boundaries changed, which brought Kerala and Pondicherry (Puducherry) into this dispute. Nonetheless, Tamil Nadu and Karnataka remain the biggest parties in the dispute.

2.3 Post-Independence (after 1947)

As the pact of 1924 was about to expire, a Cauvery Fact-Finding Committee (CFFC) was constituted in 1970. The timeline of the post-independence era conflict is presented in Table 3.

Table 3 Post-Independence conflict timeline regarding the Cauvery River

Year	Major events
1970	• Cauvery Fact-Finding Committee (CFFC) is established.
1974	• CFFC under the Prime Minister of India proposes a new pact. • Tamil Nadu accepts but backs out later.
1976–1986	• Continuous meetings between state representatives bear no results.
1986	• A farmer's organization files an appeal to the court (*in Tanjavur*).
1991	• The Cauvery Water Disputes Tribunal (CWDT) is established, and an agreement is passed. • Karnataka passes an ordinance nullifying the CWDT agreement.
1995	• Tamil Nadu appeals to the Supreme Court, as Karnataka did not release the stipulated quantities of water.
1997	• The Cauvery River Authority (CRA) is established to enforce the Interim Order.
2000	• CRA is divided into the CRA and Cauvery Monitoring Committee (CMC).
2007	• CWDT in consultation with CRA and CMC gives the verdict.
2007–2013	• Negotiations between the states. (Karnataka approached CWDT as Tamil Nadu's share was larger.)
2013	• The 2007 CWDT verdict is changed, and Karnataka's share is increased.
2017	• The Supreme Court of India upholds its previous ruling.

2018	• A permanent committee is constituted called the Cauvery Water Management Board. • Presently, CWMA is the sole federal body tasked with implementing the CWDT orders

A series of inter-state (inter-provincial) meetings based on CFFC's reports was held during 1973 and 1974 under the chairmanship of successive union ministers (i.e., *Federal Ministers in India*) for irrigation. At the final meetings of this sequence held in November 1974 and February 1975, a draft agreement that would act as a replacement for the 1924 agreement was discussed, but not adopted. In August 1976, however, a draft agreement prepared by the Union was accepted by all the states, and this fact was announced in the Parliament by the Minister for Agriculture. However, in the next meeting of the Chief Ministers, Tamil Nadu backed out of the agreement and Karnataka followed suit (Bakshi, 2015).

Many inter-state meetings were called to amicably resolve the issue. However, these meetings, many being under the auspices of the Union Government, were in vain. Farmer groups were one of the most affected strata of society. Due to non-agreement between the states, the farmers from both the states suffered heavily. Due to a non-existent agreement after the 1924-agreement expired, there was no proper distribution of water supply, and the farmers did not have any governmental body to address their grievances. Therefore, when the above issue could not be resolved, in 1986, the Farmers' Association of *Tanjavur* approached the Supreme Court, seeking a direction to the Central Government to constitute a tribunal for adjudication of the disputes (Ministry of Law, 1956). The tribunal, if set up under the Interstate Water Dispute Act of 1956, would possess the powers to make decisions but would not be able to enforce them. During the pendency of this suit, negotiations continued for four more years fruitlessly. In the last inter-state (inter-provincial) meeting held in April 1990, the principal contestants, consisting of Tamil Nadu and Karnataka, agreed to disagree (CWDT, 2007a).

2.4 Cauvery Water Disputes Tribunal (1990)

A Cauvery tribunal was constituted in 1990 based on the directives of the Supreme Court of India to preside over such matters and handle them swiftly and efficiently. This tribunal gave its order in 1991, favoring Tamil Nadu and enjoining upon Karnataka to release waters to the *Mettur* Reservoir in Tamil Nadu following a stipulated release pattern. The allocation of water by Karnataka to Tamil Nadu was calculated based on the last ten years of flow at the Biligundulu station located on the border of the two provinces. The annual flow is shown in the graph below.

Figure 5 Data recorded by Karnataka at the Biligundulu station. (CWDT, 2007c)

The pattern is shown in the table below. In the 1991 verdict, the total allocation from Cauvery River was divided among the four riparian provinces of Tamil Nadu, Karnataka, Kerala, and Puducherry (Pondicherry). Tamil Nadu was adjudged an allocation of 391 TMC (thousand million cubic feet), and Karnataka was allocated 251 TMC of water (CWDT, 2007d, 2007c).

Table 4 The province of Karnataka shall regulate the release of water in the following manner. (BCM – Billion Cubic Meters)

Month	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April	May	Sum
TMC	10.16	42.76	54.72	29.36	30.17	16.05	10.37	2.51	2.17	2.40	2.32	2.01	**205**
BCM	0.29	1.21	1.55	0.83	0.85	0.45	0.29	0.07	0.06	0.07	0.07	0.06	**5.805**

Karnataka was also directed not to increase its area of irrigation utilizing Cauvery waters. Karnataka's reaction to this was extremely adverse. It passed an ordinance against this order, thereby prompting the Supreme Court to intervene. The court ruled in favor of Tamil Nadu, following which there were demonstrations in both states. From 1992 to early 1995, the Cauvery Basin was blessed with good monsoon rains, and tranquility prevailed in the region. By the middle of 1995, however, the basin faced a lean monsoon, and this paved the way for a further period of tension and anxiety. In December 1995, Tamil Nadu approached the Supreme Court, seeking an order for 30 TMC (thousand million cubic feet) to be released by Karnataka from its reservoirs. The court passed it on to the Tribunal for an appropriate decision, and the latter ordered 11 TMC to be released by Karnataka. The State of Karnataka pleaded helplessness, as its reservoirs were short of enough water to cater to the needs of its own farmers. Tamil Nadu again approached the Supreme Court, informing it of the seriousness of the situation (Bosu, 1995).

The Supreme Court, to expedite matters, thought that the Prime Minister should intervene and bring about a compromise (Bakshi, 2015).

Accordingly, a Conference of the Chief Ministers of all the party states and the Union Territory of Pondicherry (Puducherry), along with other political leaders, was convened by the Prime Minister on 30 December 1995. The Prime Minister took a keen interest in the matter and based on his meetings with the Chief Ministers of Tamil Nadu and Karnataka, gave an Interim Order that Karnataka should make an immediate release of 6 TMC to save the standing crops in Tamil Nadu. Karnataka abided by the Prime Minister's decision.

In 1997, the Government of India constituted the Cauvery River Authority (CRA) to implement the Interim Order. In this order, 11 TMC more water is supposed to be sent to Tamil Nadu, which is battling a drought. The CRA had an ambiguous amount of power, as it could take over the functioning of the dams if the Interim Order were not being honored. However, Karnataka opposed the establishment of CRA, as it felt that the Interim Order had no scientific basis and was internally flawed. The Federal Government, taking into consideration the state's objections, made several modifications to the powers of the CRA and came up with a new arrangement. Under this new arrangement, the Government established two new bodies: the Cauvery River Authority, and the Cauvery Monitoring Committee. The Cauvery River Authority would consist of the Prime Minister and include the Chief Ministers of the four states consisting of Karnataka, Tamil Nadu, Pondicherry (Puducherry), and Kerala. The Cauvery Monitoring Committee, on the other hand, was an expert body that consisted of engineers, technocrats, and other officers who would take stock of the 'ground realities and report to the government.

The period following the 2002 lean monsoon (Moorthy, 2002) was turbulent for both the states; it was almost a recap of the 1995 situation. However, at that time, the demonstrations were severe and there was even a temporary restriction on public transport between the two states. The animosity prevailed throughout the year. In the following years, there were sufficient rains and hence no major issue was reported (Iyer, 2002; Moorthy, 2002). After much deliberation, the CWDT delivered a verdict in 2007 over the sharing of water between the states tweaking the 1997 verdict, which was again disagreed upon by the states of Tamil Nadu and Karnataka. The matter was again placed under arbitration and the Supreme Court of India instructed the state of Karnataka to release the water, as instructed by the Supreme Court yearly thereafter. Droughts in 2012 did not help the cause of the then Prime Minister, whose request to Karnataka to release water for Tamil Nadu was rejected by the state. This prompted Tamil Nadu to act against Karnataka, i.e., take Karnataka to court because it was in contempt of the apex court's decision.

There were protests against the rulings in Tamil Nadu and Karnataka, which requested a quick verdict on the matter, which was left in limbo after the 2007 verdict (CWDT, 2007a, 2007b, 2007c, 2007d, 2007e).

2.5 Tribunal hearings and decisions after 2013

On February 20th, 2013, based on the directions of the Supreme Court, the Indian Government announced the final award/agreement of the Cauvery Water Disputes Tribunal (CWDT) on sharing the waters of the Cauvery system among the basin States of Karnataka, Tamil Nadu, Kerala, and the Union Territory of Pondicherry (Puducherry). In this award, the share for Tamil Nadu was reduced from the 2007 verdict (from 419 thousand million cubic feet (TMC) to 404 TMC), and that of Karnataka was increased (270 TMC to 285 TMC), as shown in the table below.

Table 5 The major decisions given by the Cauvery Water Disputes Tribunal (CWDT)

	1990	2007	2013 onwards
Tamil Nadu	390.85 TMC	419 TMC	404.25 TMC
Karnataka	250.62 TMC	270 TMC	284.75 TMC

This verdict has probably inflicted more damage on an already complicated conflict. In mid-2015, Tamil Nadu again accused Karnataka of not releasing the required quantity of water as was established by the tribunal (Press Trust of India, 2015). Therefore, to further increase the powers of the executive branch of the tribunal, on 10 May 2013, the Supreme Court issued an interim directive to the Government of India to establish a temporary Supervisory Committee to implement the CWDT order till the constitution of the "Cauvery Management Board".

In February 2018, the Supreme court of India passed another judgement in the Cauvery River dispute. The biggest departure from the earlier judgements was that the Supreme Court emphasized that the water from Cauvery River is a national asset and no one province can claim ownership. Within the laws of India, water is a provincial issue and therefore, the 2018 judgement was important (Ghosh et al., 2018; Supreme Court of India, 2018). This judgement, for the first time ever, recognised the multidimensionality, and diversity of water use. However, it still did not recognize the effects of the ecosystem on water systems (Waters & Ghosh, 2022).

In the February 2018 judgement, the Supreme Court of India directed the Government of India to set up the Cauvery Water Management Authority (CWMA), which was inline with the CWDT's final order. Therefore, in June 2018, a Cauvery Water Management Authority was constituted, which will be a permanent committee overseeing all the matters related to the Cauvery River dispute. In accordance with the direction from the Supreme Court of India, the fulltime chairman of the CWMA will have to be an irrigation engineer of the rank of Chief Engineer (from the prestigious Indian Engineering Services). The other two members have to be nominated by the Ministry of Water Resources, River Development and Ganga Rejuvenation, and the Ministry of Agriculture & Farmers' Welfare (Supreme Court of India, 2018; Waters & Ghosh, 2022).

It can be argued that that only including the experts from irrigation, and the agriculture background seems a little constricting. The Cauvery dispute requires inputs from experts of all fields. To understand and analyse the multidimensionality of the Cauvery River basin, an integrated water management methodology is required. The following chapter discusses the methods employed in this work.

3. Methods

The following section explains the methods that will be used in this thesis. Three methods shall be employed to reach the necessary conclusions. The inputs and the outputs of these methodologies will be used amongst them to populate their various data requirements.

The Cauvery River dispute essentially is a water-sharing conflict. However, multiple systems are affecting this conflict. A system has its objectives and expectations. A system operates to provide a unitary goal (Maier & Rechtin, 2002). The coal Industry is an example of a system whose operating boundaries are fixed, and the unitary goal is coal production. A system of systems consists of multiple systems acting together (Dersin & Komljenovic, 2014). For example, as shown in the figure 6 below, a societal system of systems consists of industries, agriculture, energy, and infrastructure systems. Furthermore, the systems of systems deal with the interaction of multiple system of systems.

This conflict is analyzed using the systems of systems (SoS) approach (H. Xu et al., 2018). The systems of systems approach in water resources management are a holistic approach that considers the entire water system as a complex network of interconnected systems. In the diagram below, it is noticeable that there are multiple systems within the societal and environmental systems of systems.

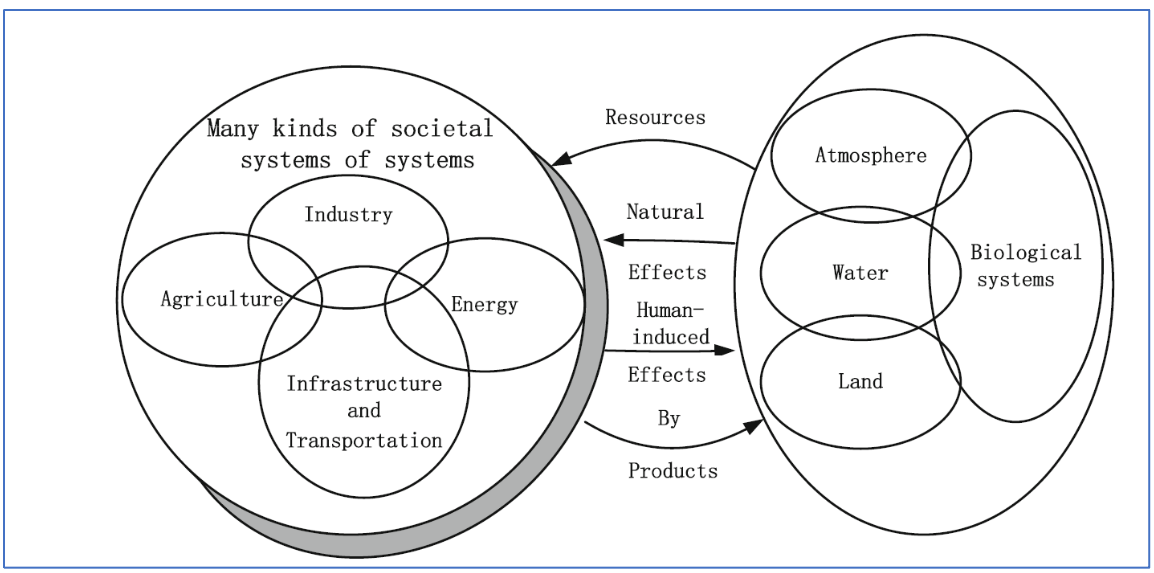


Figure 6 Societal and environmental systems of systems (Hipel et al., 2009)

On the right side, the environmental system of systems is comprised of intricate interconnected atmospheric, water, land, and biological systems. The arrow at the top signifies the connection between these two sets of systems, indicating that the societal system of systems extracts resources from the environmental system of systems for its functioning. For example, the steel industry relies on environmental resources like iron ore and energy sources to operate. Unfortunately, various activities within the societal system of systems result in the release of by-products into the environmental system of systems. For instance, steel plants emit carbon dioxide and other air pollutants through their smokestacks, contributing to global warming and climate change. Moreover, other pollutants are discharged into nearby bodies of water, leading to a decline in water quality. The middle arrows illustrate that humans can impact both environmental and societal system of systems, while the natural world has a direct influence on societal system of systems. Due to the extensive release of greenhouse gases by numerous societal systems and associated changes in land use, humans are responsible for causing climate change, which, in turn, negatively affects societal systems such as agriculture.

The systems of systems approach have been utilized in different fields, like environmental conservation (Albers et al., 2018), defense (Ministry of Defense, 2013), and infrastructure development (Eusgeld et al., 2011). Instead of focusing on individual components or systems in isolation, this approach aims to understand and manage interactions and interdependencies among these various elements. The International Council on Systems Engineering (INCOSE) defines this approach as a collection of independent systems, integrated into a larger system that delivers unique capabilities (International Council on Systems Engineering, 2018).

The system of systems approach recognizes the interrelated components like the physical system of systems, governance system of systems, and socio-economic system of systems in the Cauvery River basin. It is important to note that although the interaction arrows are going to and from the system of systems "bubbles", the interactions in the Cauvery River basin are across the system of systems boundaries. The bubbles here are only to demonstrate the virtual boundaries of the system of systems. The following figure depicts the systems acting on the Cauvery River basin.

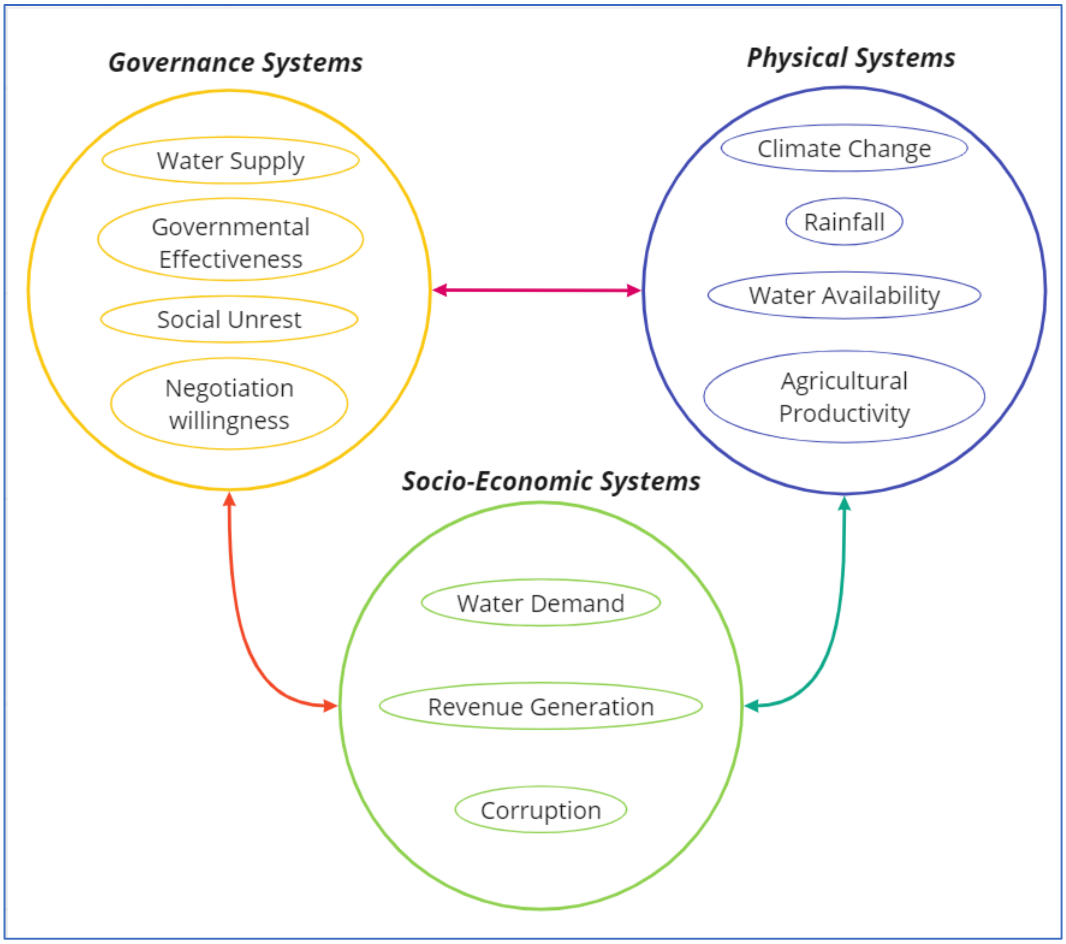


Figure 7 Systems of systems in Cauvery River basin

The physical system of systems consists of the precipitation (rainfall) system in the basin, evaporation from the basin, the climate change that affects the temperature in the basin, water availability in the basin, and the agricultural productivity from the soil in the basin.

The governance system of systems consists of the systems required in the administration of the natural resources in the basin. The water supply network, the effectiveness of the government in managing the resources, social unrest in the basin due to the unavailability of resources and developing policies for sharing natural resources with the neighboring provinces.

Finally, the socio-economic system of systems consists of the systems that provide feedback from the services provided by the government. The water demand by different economic sectors in the basin, the revenue generated from the goods and services provided by the government, and corruption in the basin.

The systems of systems approach acknowledges that the decisions made in one part of the Cauvery River basin can have cascading effects on other systems within the basin and effective management of the resources requires an inclusive understanding of the relationships. The various systems are analyzed using a causal loop diagram (CLD) as shown in Figure 8. It is important to note that the interactions within the causal loop diagram are among systems that belong to different system of systems. There are two types of feedback mentioned in the causal loop diagram, positive, shown with a '+' sign and a blue connecting line, and negative shown with a '- 'sign and a red connecting line. Positive feedback loops are self-reinforcing, and negative feedback loops are self-correcting. Causal loop diagrams play a key role in understanding complex systems because they help in transferring our thought processes (mental models) into transparent and visible cause-effect diagrams (Haraldsson, 2004). Monat & Gannon (2015) sifted through several pieces of literature on causal loop diagrams and found that it provides a great deal of power and value. Because it focuses on the relationships among system components, as well as the components themselves, it helps in solving complex problems that are difficult to solve using conventional reductionist thinking. Causal loop diagrams have been used to identify causes of obesity in rural Australian communities (Allender et al., 2015), causes of flooding in Pakistan (Rehman et al., 2019), causes of a high-speed train accidents in China (Fan et al., 2015), and more recently to analyze the challenges of food and biofuel markets amid the Ukraine-Russia war (Shams Esfandabadi et al., 2022).

The Cauvery River conflict is a dispute between two neighboring provinces of Karnataka (upstream), and Tamil Nadu (downstream) in southern India. The historical analysis of the conflict in the Cauvery River basin shows the most consequential system elements that have effects on the dispute. The causal loop diagram for this conflict identifies the relationships between the elements mentioned in the SoS diagram (Figure 7). These elements are in general similar for both provinces because of their proximity. The main nine elements/systems of the Cauvery River dispute are as follows,

1. **Climate Change**: An increase in ambient temperatures is one of the leading causes of erratic rainfall in the basin. The provincial governments have come up with action plans against climate change (Government of Karnataka, 2011; Government of Tamil Nadu, 2015).
2. **Rainfall**: Erratic rainfall, especially in the last three decades, is one of the main reasons for this conflict. The Cauvery Water Disputes Tribunal (CWDT) in its decisions has consistently tracked the average annual rainfall in both provinces and acknowledged the irregularity in rainfall as one of the major concerns (CWDT, 2007a, 2007b, 2007c, 2007d, 2007e).

3. **Water availability**: The water available in the Cauvery River is dependent on the rainfall of Karnataka. However, water availability in Tamil Nadu, other than being dependent on rainfall, is also dependent upon the water released by the province of Karnataka. Tamil Nadu has raised the issue of the non-release of water many times to the CWDT. The CWDT reports have documented every instance of this issue being raised (CWDT, 2007e).
4. **Water Demand**: The demand centers in both Karnataka and Tamil Nadu are highly dependent on the consistent availability of water. The Cauvery River is responsible for providing water resources to the most populated city of Karnataka, Bengaluru (BBC, 2016; Sudhira et al., 2007). In the last three decades, the population has exploded in Bengaluru due to the eruption of tech-based industries. In Tamil Nadu, the water from Cauvery has always been used for irrigation (Nagaraj et al., 2003).
5. **Water Supply**: The water supply pipelines are "metered" connections in Bengaluru. The increase in population has complicated the water supply networks. With increasing water demand, it's equally important to supply the water properly with minimizing wastage (Bangalore Water Supply and Sewerage Board, 2018; Buurman & Santhanakrishnan, 2017). In Tamil Nadu, groundwater is consistently used to offset the lack of water supply through canals for irrigation purposes. Over extraction of groundwater has put serious question marks over sustained water supply. Therefore, it is imperative to conserve the aquifers and find water supply solutions elsewhere (Ars & Sreenivas, 2016; Prayag et al., 2023; Srinivasan & Lele, 2017).
6. **Revenue Generation**: The revenue generated through metered connections in Bengaluru forms a substantial income stream for the Karnataka government. Leakages in the water supply reduce this revenue generation and lead to an increase in the non-revenue cost of water (Mukherjee et al., 2015). For Tamil Nadu, Rice (paddy) cultivation is a major contributor to its GDP. The government also makes substantial income from exporting rice to other states (Arthi T et al., 2018; Karthick et al., 2020; Mariappan & Das, 2017; Sivagnanam & Murugan, 2015).
7. **Governmental Effectiveness**: If either of the governments were effective in developing and implementing policies ethically, and morally, this conflict would have settled a long time ago. Both governments have engaged in futile "what-about" arguments consistently rather than managing their respective resources judiciously (Janakarajan, 2010, 2016; Pani, 2009).
8. **Corruption**: In the Cauvery River basin, there have been regular cases of mismanagement of money within the governments. Cases of bribery are rampant in the basin. However, they are hardly ever reported. Such fraudulent activities impede progress and hinder development in the

provinces (Bajpai & Myers, 2020; Consumer News and Business Channel, 2019; Dutta et al., 2013; Johnson, 2022; Kandukuri, 2015; Kozacek, 2016; Sohail & Cavill, 2008; Times News Network, 2021; Vijayalakshmi, 2008).

9. **Social Unrest**: The citizens living in the basin have clashed with each other and burnt public properties as and when the government was unable to provide the stipulated quantities of water. In the last decade, the people have violently protested the government's policies in both of the provinces. One of the biggest incidences happened in 2016 when public property in high quantity was destroyed by demonstrators (Lodaya & Mukherjee, 2016; Pokharel, 2016).

The figure below shows the interactions between the systems in the Cauvery River basin.

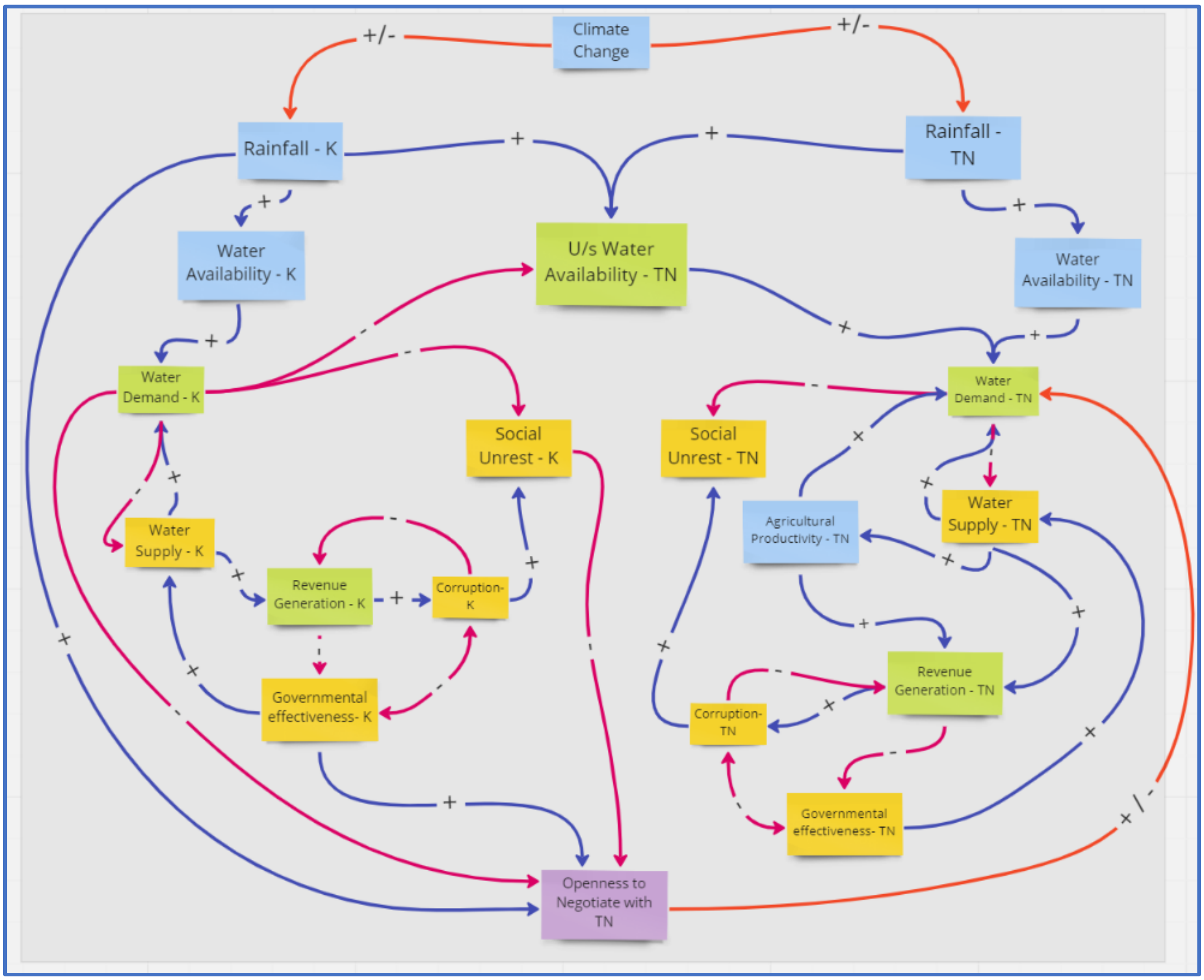


Figure 8 Causal loop diagram

The above elements/systems are depicted in the causal loop diagram (Figure 8) based on preliminary and historical data analysis. There is a need for a much more in-depth analysis of the interactions. The interactions here may seem linear, however, the system interactions in a wickedly complex system are generally non-linear. Also, these cascading interactions produce a further non-linearity in the systems of systems analysis.

The above causal loop diagram has elements/systems from both provinces. The elements with the suffix -TN are systems in the province of Tamil Nadu, and the elements with the suffix – K are systems in the province of Karnataka. The province of Karnataka is depicted generally on the left-hand side of the figure and Tamil Nadu on the right. Climate change is a major force affecting the rainfall in both of the provinces; hence it is situated at the center at the top. Climate change negatively affects the rainfall in both provinces, which in turn affects the water availability in both provinces. The element at the bottom of the figure above is "The openness to negotiate with Tamil Nadu". This study aims to find possible solutions for the Cauvery River conflict with Karnataka recognized as the party that currently has a more favourable position.

To analyze this systems of systems, first, the systems will be analyzed, then their interactions with other systems will be analyzed, and so forth. The following figure shows the modified version of the interactions between the systems of systems.

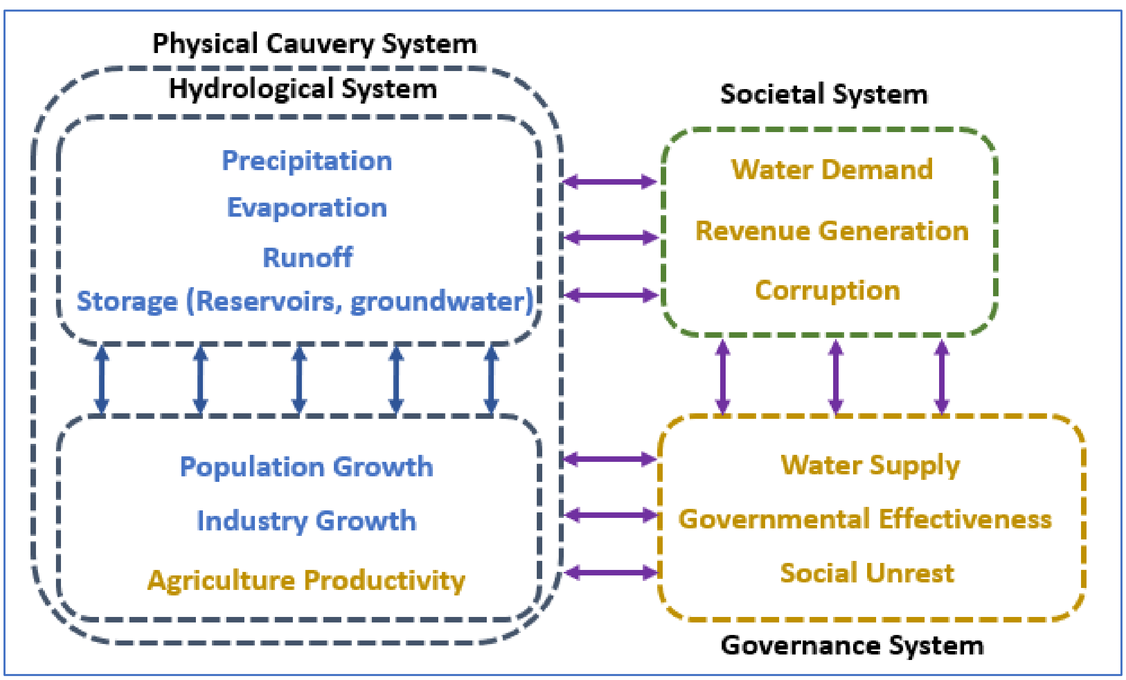


Figure 9 Cauvery conflict: modification of systems of systems

The base system in the Cauvery River basin is the hydrological system consisting of precipitation, evaporation, runoff, and storage. Population growth system, industrial growth system, and agricultural productivity are part of the physical system of systems. However, they have strong interactions with the societal system of systems. Water demand, revenue generation, and corruption is also part of the societal system of systems. The water supply system and effective governance system are part of the governance system of systems.

The systems of systems analysis are conducted in three steps. First, the hydrological system needs analysis of the precipitation, evaporation, runoff, and storage like groundwater flows and reservoirs. Since the basic conflict is based on water availability, the expectation from this systems analysis is the measurement and forecasting of differences in water supply and water demand in the basin. A hydrological model works on the conservation of mass principle. Two software packages were considered: HEC-HMS, and WEAP. HEC-HMS (Hydrologic Modeling System) is a modeling software developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) (US Army Corps of Engineers, 2023). Water Evaluation and Planning (WEAP) is a software package developed by the Stockholm Environment Institute (SEI) (Stockholm Environment Institute, 2020). Both of the software is widely used all over the world. However, WEAP is more suitable for developing countries. Also, this researcher had prior experience with WEAP. Therefore, WEAP is chosen for this work. Also, the software can handle scenario analysis. How this method is used for data analysis, the data used, the modeling, the results, and the discussions are explained in the WEAP chapter *(chapter 4)* of this thesis.

Second, for the analysis of socio-economic, and governance system of systems such a method is required that can handle multiple interactions and provide meaningful results. In social systems, theoretically, there are impacts to and from system elements. Such a method is required that can clearly define the system elements and can establish the varying relationships between the elements. Cross Impact Balances (CIB) is a method that is derived from systems analysis thinking. This method is capable of handling large numbers of system elements (Weimer-Jehle, 2006, 2023a). ScenarioWizard, a software package developed at the University of Stuttgart, uses the principles of cross-impact balances, and the input values from the researcher to produce meaningful results (Weimer-Jehle, 2018). The complete methodology with nomenclature and its working, the modeling, the results, interpretation of results is explained in the CIB chapter *(chapter 5)* of this thesis.

Finally, the conflict's resolution is obtained using Graph Model for Conflict Resolution (GMCR) (Kinsara, 2014; H. Xu et al., 2018). GMCR is a decision support system methodology derived from Game Theory. It utilizes the stakeholders' moves and countermoves to make informed decisions. This method is explained further in detail in the GMCR chapter *(chapter 6)* of this thesis.

The output from WEAP is used as input in CIB, and the output from CIB is used as input in GMCR. The following table explains the details of this process. The inputs required for the WEAP method are mentioned in green, the outputs from WEAP are shown in blue. Inputs in CIB from WEAP are shown in blue, and from document analysis are mentioned in black. The outputs from CIB are shown in brown. The inputs in GMCR from CIB are shown in brown colour. Finally, the outputs from GMCR are shown in purple colour. The inputs and the outputs here are mentioned in brief with complete detailed explanations in the subsequent chapters.

Table 6 Inputs and outputs from WEAP, CIB, and GMCR

	Inputs	**Outputs**
WEAP	• Climate data ○ Rainfall data (government reports) • Scenario data (Climate data from Princeton) ○ Evaporation Data (government reports) • Scenario data (Climate data from Princeton) • Demand site inflows (government reports, research papers) • Agriculture productivity (government data) • Revenue generation (government data) • Streamflow data (government data, research papers)	• Inflows and outflows to and from demand sites • Unmet demand • Crop production and market value
CIB	• Interaction values between descriptors • Inflows and outflows to and from demand sites (from WEAP) • Unmet demand (from WEAP) • Crop production and market value (from WEAP) • Governmental effectiveness, corruption, and social factors (government reports, research papers)	• Consistent scenarios • Active descriptors in the conflict
GMCR	• Consistent scenarios and active descriptors (option preference data (from CIB))	• Equilibria • Resolution(s)

Stakeholder contributions are important for work like this. A Key Informant Interviews (KII) study was created to elicit information from the subject matter experts who had knowledge about the Cauvery River basin. However, due to Covid-19 outbreak in early 2020 forced the study to become remote. The information about the study is presented in Appendix 9.2. Unfortunately, due to overwhelming situation in India, the number of experts who responded positively were too few to be included in this work. The lead researcher had fruitful discussions with four experts. The experts' ideas and suggestions have definitely increased the understanding of the conflict. The study further used federal and provincial government reports and data, research papers, historical governmental action reports, and media articles to inform the inputs throughout the work. The following figure shows the schematic of the process of this work.

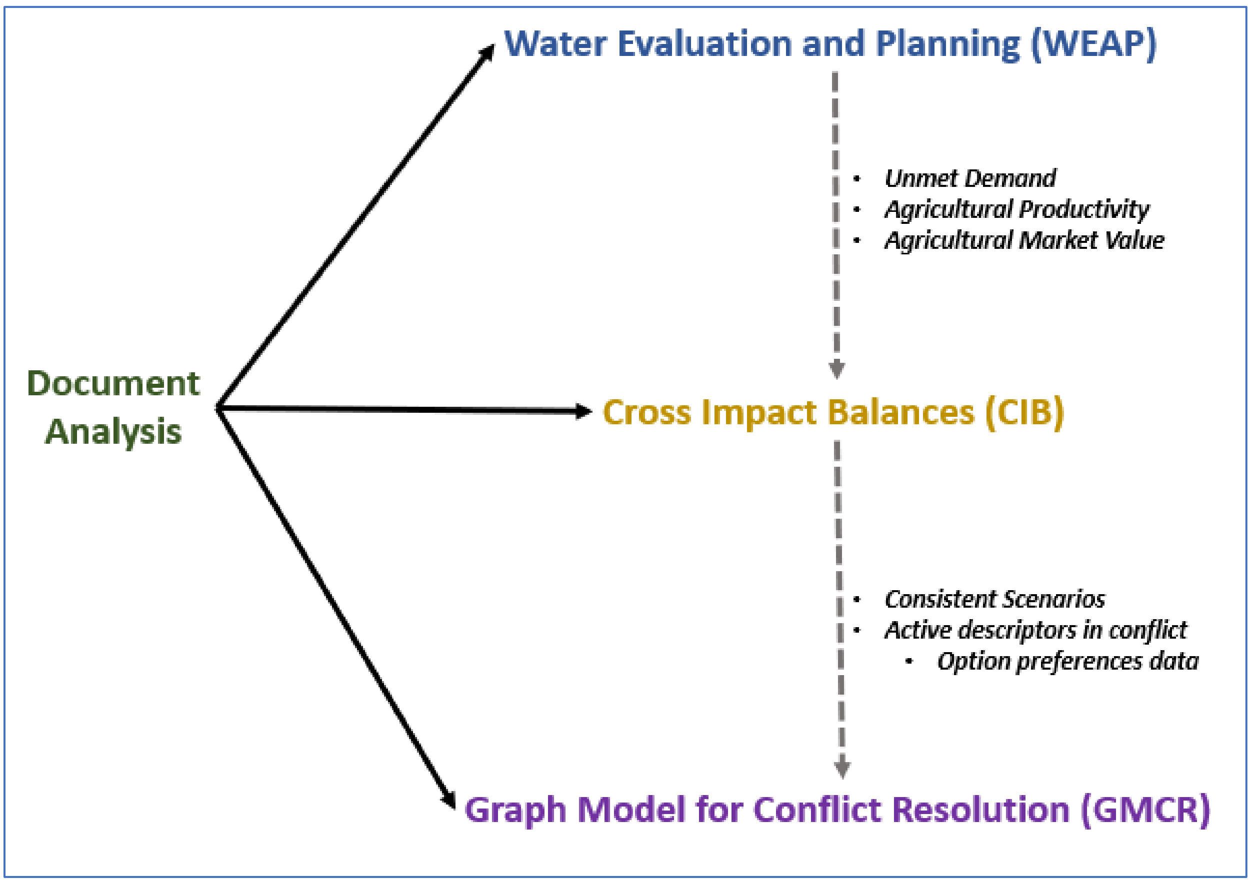


Figure 10 Schematic of the flow of this research

The document analysis informs the three methodologies. The various reports and scholarly work are cited regularly throughout the three methods chapters. The outputs are shown along the grey dotted line in the figure above. The outcome of the GMCR method is discussed in the GMCR chapter (chapter 6) and the conclusion chapter (chapter 7) of this thesis.

4. Water Evaluation and Planning (WEAP)

4.1 Introduction

The Water Evaluation and Planning (WEAP) system is a software tool that is used to model and analyze water resource systems. It is a decision-support tool that allows users to understand the trade-offs and impacts of different water management options, and to evaluate the sustainability of different water resource plans.

WEAP is designed to be a flexible and user-friendly tool that can be used by a wide range of stakeholders, including water resource managers, policymakers, and researchers. It can be used to model water supply, demand, and allocation for a variety of purposes, including irrigation, domestic use, and hydropower generation.

WEAP can be used to model water resource systems at a variety of scales, from local to regional and global. It includes a range of data inputs and modelling capabilities and can be used to explore the impacts of different scenarios and assumptions on water resource availability and use.

WEAP is a water assessment tool developed by the Stockholm Environment Institute (SEI) for integrated water resources planning (Stockholm Environment Institute, 2020). The tool works on a basic water balance system, considering various inflows, outflows, and storages in a water system. It can handle surface and groundwater fluxes, along with modelling the expected supply and demand of water resources in a water basin. The water demand of a city in a riparian zone, in general, increases due to an increase in population. Due to the software's versatility, it is widely used for developing climate change-based scenarios. WEAP has an intuitive, Geographic Information System (GIS) based graphical interface which provides a visual representation of the system.

Hydrological modelling is recreating the physical conditions using mathematical models and predicting the flow of water through the Earth's surface and subsurface. The hydrological models aim to understand and manage the water cycle, including precipitation, evaporation, transpiration, infiltration, runoff, and groundwater flow. There are different types of hydrological models and each of them is designed to simulate different levels and aspects of a water cycle. A model is a simplified representation of physical systems in the world (Loaiciga et al., 1996; Moradkhani & Sorooshian, 2009).

Interdisciplinary work in hydrology is required in some aspect or other. The precipitation that affects the water availability in the river basin, comes from the atmosphere. Meteorology covers the atmospheric moisture that regulates the precipitation. Also, the evaporation modelled is influenced by the water retained by plants, other open water sources, soil moisture, etc. Soil moisture is modelled under hydrogeology. The water extracted from a river basin is dependent upon irrigation, and industrial and domestic systems, which requires knowledge of socio-economic systems. Therefore, information and knowledge of different types of systems are required for hydrological modelling (Devia et al., 2015; Pandi et al., 2021; Sood & Smakhtin, 2015).

A hydrological model uses various parameters to mimic the system effectively. These parameters are then used to modify and tweak the system so that it can produce real-life results. In hydrology, the models can be lumped, distributed, semi-distributed, continuous, and event-based depending upon the distribution and availability of temporal and spatial data. A lumped conceptual model of a river basin, for example, considers individual sub-basins as a single unit and the characteristics used to identify the hydrologic system are averaged over simplified temporal scales (Savenije, 2022; Savenije & van der Zaag, 2000; Sivapalan et al., 2012; Yu, 2015).

WEAP incorporates the hydrological process with the water management model by introducing the concept of demand priorities and supply preferences (Yao et al., 2021). WEAP is essentially an integrated modelling software that models water supplies, demands, and environmental requirements as well as considers the effects of policies on water quantity, and quality. A range of water issues can be analyzed through a scenario-based approach (Agarwal et al., 2019).

WEAP has been used to model other rivers in India. Malla et al. (2014) used WEAP to assess the water demand and supply for the City of Srinagar, Jammu and Kashmir. Bharati et al. (2008) used WEAP to analyze the inter-basin water transfer of the Godavari and Krishna Rivers. The Cauvery River basin has been studied previously by many researchers from India and all over the world. Researchers have looked at the hydrology of the basin. Some of the researchers have divided the Cauvery River basin into upper, middle, and lower basins (Das, 2021; Horan et al., 2021; Imaran et al., 2022). Researchers from Leeds University (Bhave et al., 2013, 2014, 2018; Dessai et al., 2018) have carried out similar WEAP modelling for the province of Karnataka. The current research looks at the whole river basin.

The most common type of hydrological model is the rainfall-runoff model. The rainfall-runoff method is a simple method that computes runoff as the difference between precipitation and a plant's evapotranspiration (Khalil et al., 2018). A part of the precipitation can be set to bypass the evapotranspiration process and go straight into a runoff to ensure a base flow in a river basin (Allen et al., 1998; Liu, Yu, et al., 2018). The following figure shows the basic schematics of the methodology.

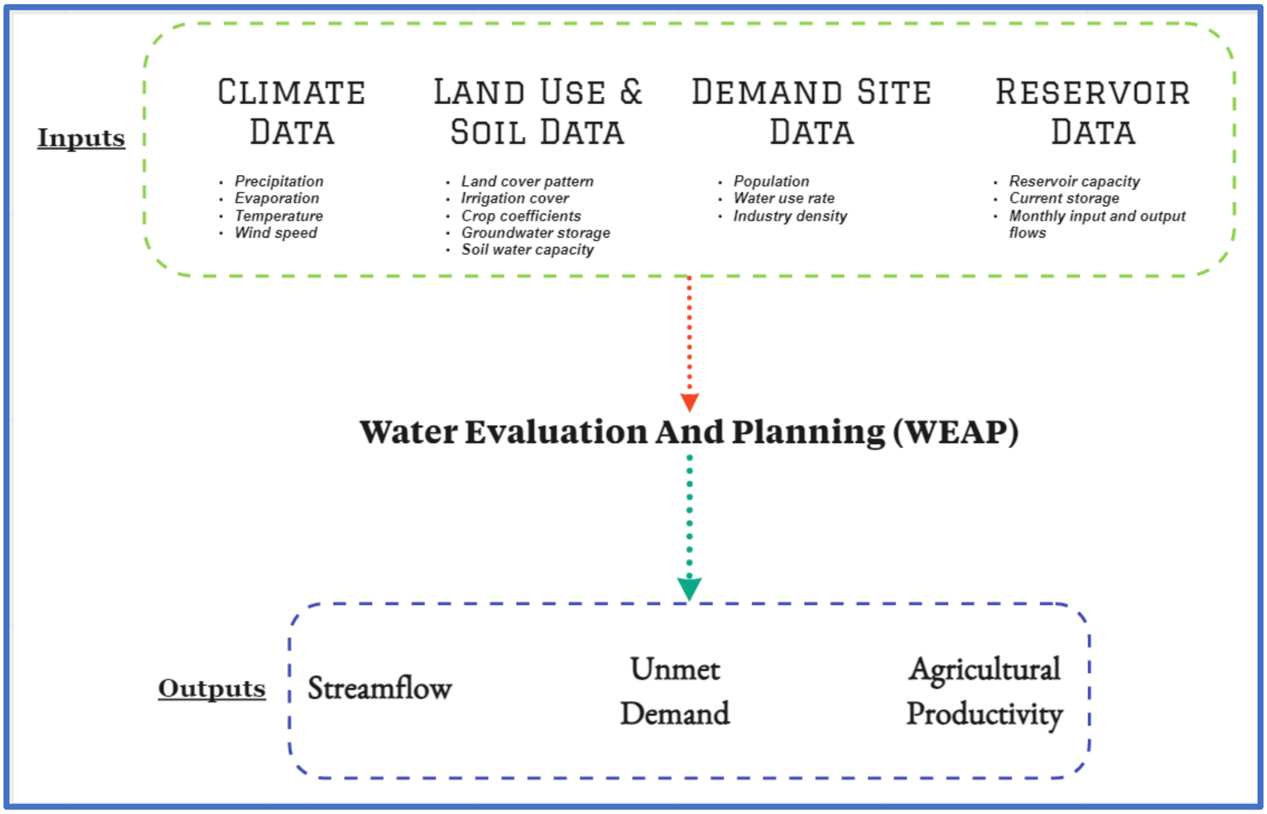


Figure 11 General WEAP schematic

The figure above explains the data required for the WEAP analysis and the outputs that will be used in this work (Stockholm Environment Institute, 2020). A step-by-step process for developing a WEAP model is described below.

1. The first step in developing a WEAP model is to set up the area of your analysis. An area in WEAP is a self-contained set of data and assumptions. It is typically the geographical extent of the river basin.
2. Add WEAP elements to the area. There are thirteen different types of elements and the ones that are used in this work are listed in section 4.2. Elements represent the physical system in WEAP. A demand site element node can represent a city or agriculture or industry. Other examples of nodes are a wastewater treatment plant, groundwater aquifer, reservoir, or a special location along a river. Links are another type of element. Links are used to connect different nodes. A transmission

link connecting a river and a demand node will represent the flow of water from the river to the demand site. The quantity of water flowing depends upon the annual activity level of the demand site.

3. Add data to the WEAP elements. A demand site like agriculture would require data like total irrigation area, type of crops, the annual water requirement, etc. An element like groundwater requires data like natural inflow, infiltration from the catchments, other demand nodes, and annual depletion levels.
4. All the data is added to the "current accounts". The base year data is entered in WEAP in current accounts. It also has the basic assumptions data like the percent annual increase in population, etc. which is used to calibrate the model.
5. The water balance calculations are carried out at every node. For this research, a simple rainfall-runoff model known as a simplified coefficient method is used. This method is further explained in section 4.2.10.
6. Hydrological flow patterns are modelled using the Water Year method. This method uses historical data to identify what a normal water year is. A non-normal water year type can be very dry, dry, wet, and very wet. For example, a wet year can have 25% more rainfall than a normal water year, and so on.
7. Further scenarios can be developed based on the requirements of the work. In this work, six scenarios are developed, and the features are further explained in section 4.3.

The following sections explain the study area, the data used in this work, the methodologies, the scenarios developed, and the results obtained from this work.

4.2 Study Area

4.2.1 Location, Latitude and Longitude

The Cauvery River basin in Southern India is 80,000 km^2 including eight tributaries. The basin spreads over the provinces of Tamil Nadu, Karnataka, and Kerala and the Union territory of Puducherry (Pondicherry). The Cauvery River is the third largest river, after the Godavari, and Krishna Rivers and it is the largest in the province of Tamil Nadu. The basin lies between 10° and 14° North latitudes and 76° and 80° East longitudes. In this study, the provinces of Tamil Nadu and Karnataka are the prime focus as they constitute close to 90% of the basin area.

4.2.2 Number of districts in the basin

The Tamil Nadu part of the basin has a total of 19,464 km^2 and the Karnataka part of the basin has a total of 20,706 km^2 (ESA, 2017). There are 15 districts in the province of Tamil Nadu and 8 districts in the province of Karnataka part of the basin (Aishwarya B et al., 2021).

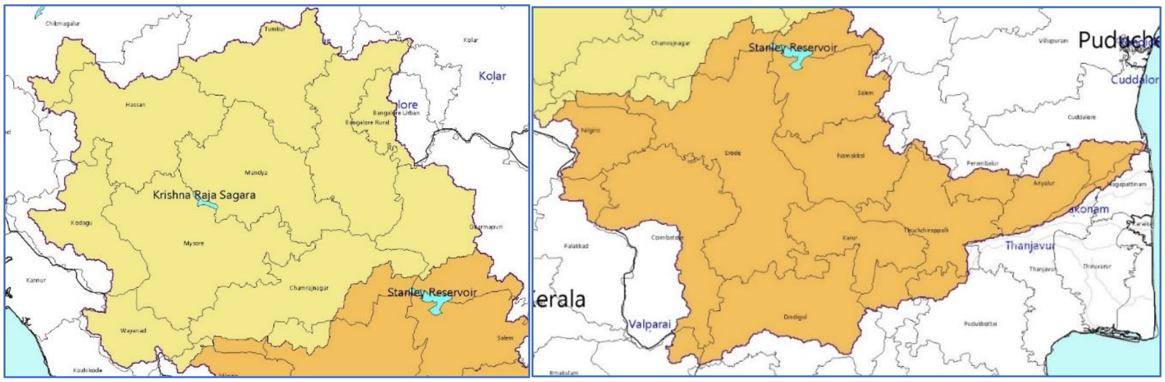


Figure 12 Karnataka - upstream (left), Tamil Nadu – downstream (right)

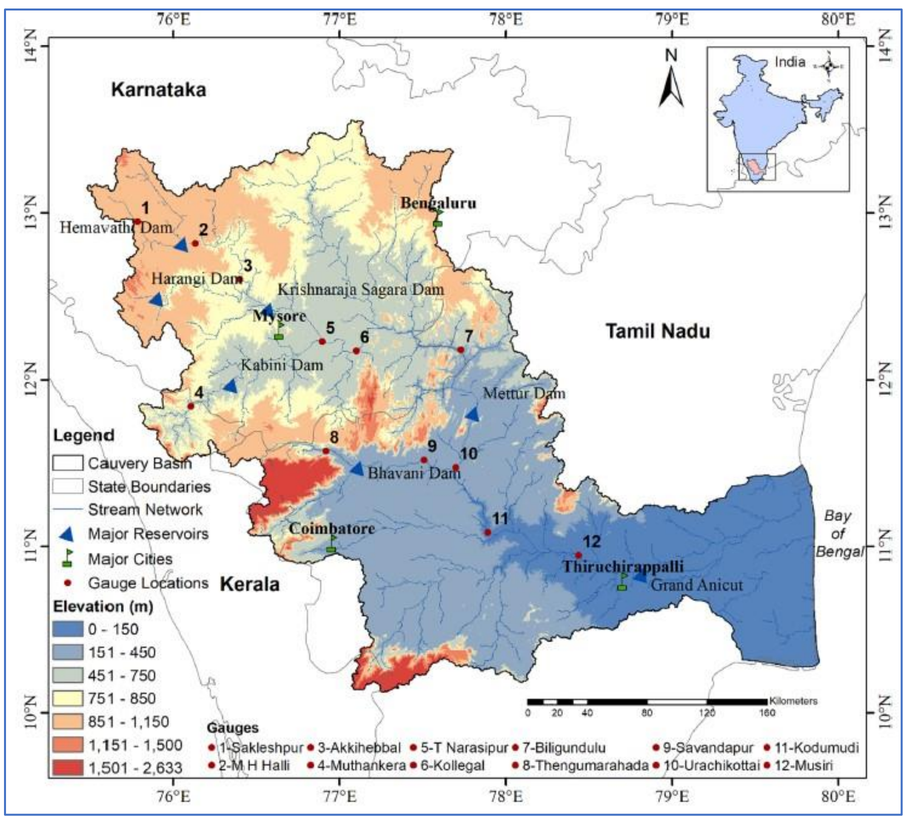


Figure 13 The digital elevation model (DEM) model for the Cauvery River basin (Gowri et al., 2021)

The land use types within the basin are unique. The Cauvery River flows from Karnataka in the west towards Tamil Nadu in the east. The elevation or height above mean sea level is visible in the figure above. Near 13 degrees north and 76 degrees east, the elevation is as high as 2000 metres above mean sea level. Therefore, the natural flow of the river is from the Northwest towards the Southeast.

The length of the Cauvery River is approximately 800 km. The total length in the province of Karnataka is 320 km, the length in the province of Tamil Nadu is 416 km and the remaining 64 km is part of the border between the two provinces (CWDT, 2007a, 2007b, 2007c).

4.2.3 Climate

The precipitation, evaporation, and temperature data are inbuilt and calculated in the Water Evaluation and Planning (WEAP) system as explained in the introduction. The following figure shows the precipitation data. The general weather and climatic conditions are well-modelled in the basin. All the climate data are cyclic after the 2010 annual data sets. The data used were refined by the Terrestrial Hydrology Group at Princeton University (Sheffield et al., 2006; Stockholm Environment Institute, 2020). The spatial resolution of the data is 0.25 degrees, i.e., one data point for a 28 square kilometre area.

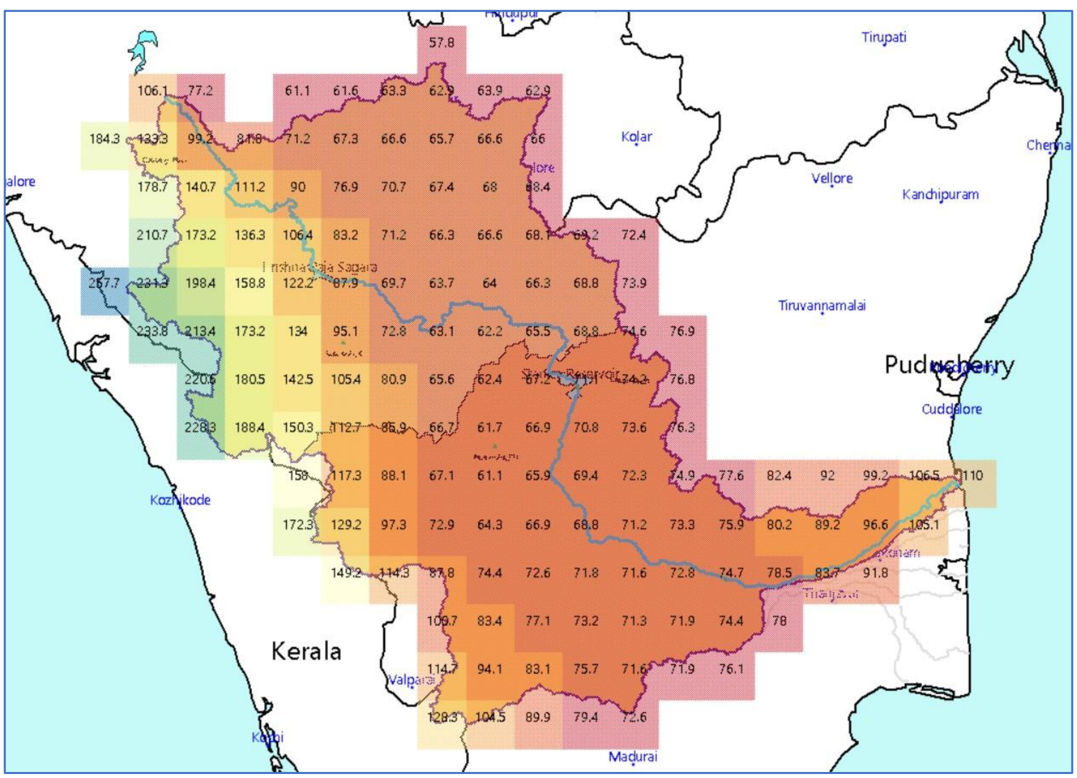


Figure 14 Precipitation data for the Cauvery River basin at 0.25-degree resolution plotted over the Cauvery River basin.

This data set uses a combination of reanalysis data and observation data. For this study, the data points from the years 1990 to 2010 were used. The figure below shows the average monthly precipitation in the basin.

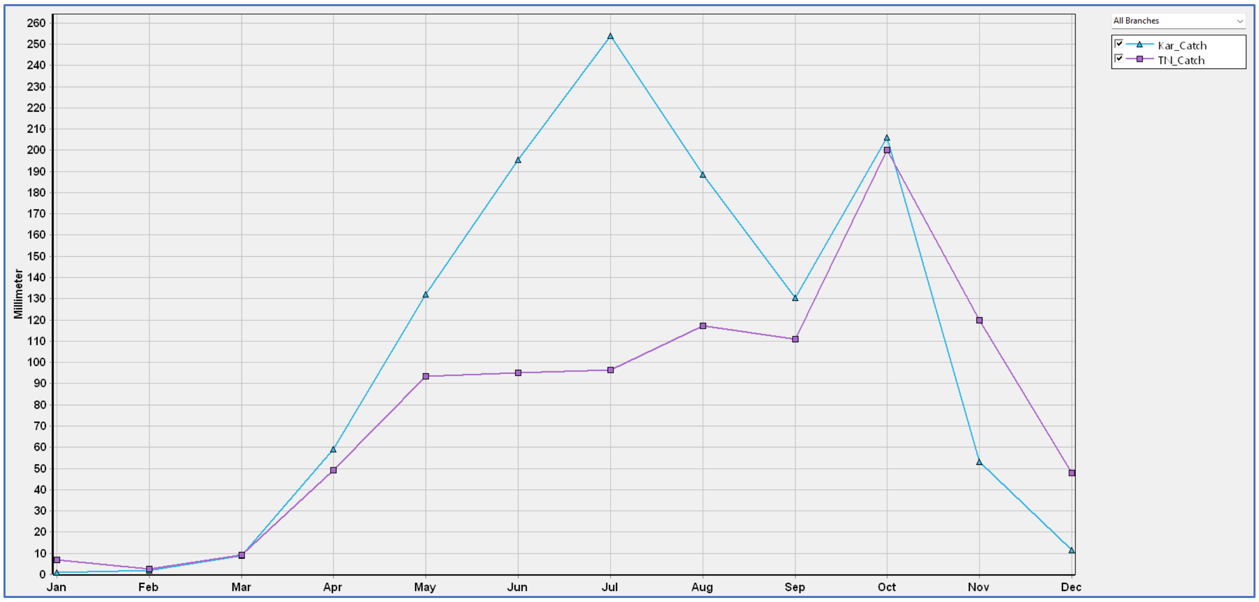


Figure 15 Average monthly precipitation data (1990-2020) of the two provinces in the Cauvery basin. Kar_Catch in Karnataka, and TN_Catch is Tamil Nadu.

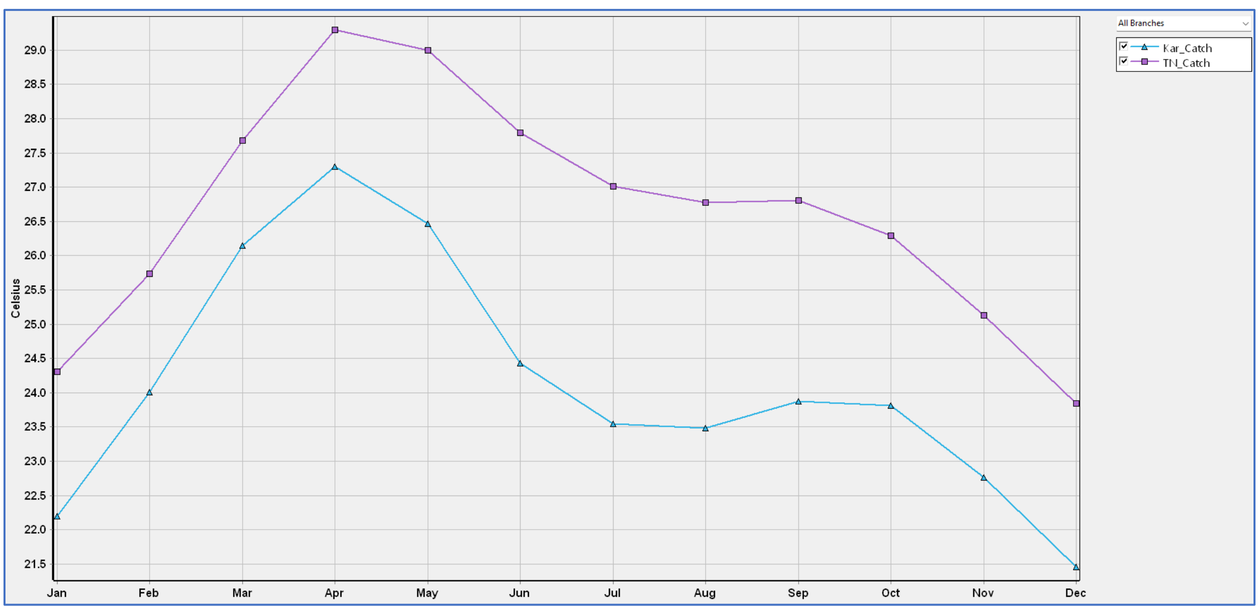


Figure 16 Average monthly temperature data (1990-2020) of the two provinces in the Cauvery basin. Kar_Catch is in Karnataka, and TN_Catch is in Tamil Nadu.

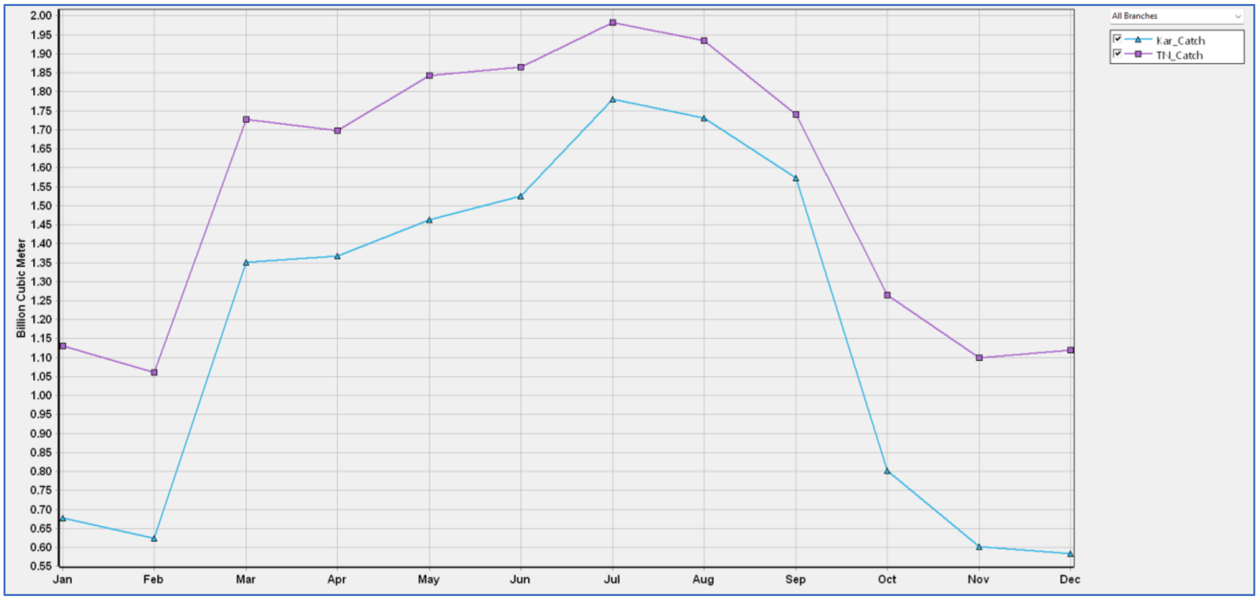


Figure 17 Average monthly evapotranspiration data (1990-2020) for Cauvery basin. Kar_Catch is in Karnataka, and TN_Catch is in Tamil Nadu.

Figures 15, 16, and 17 are the three main data sets extracted from the Princeton University database (Sheffield et al., 2006). The monthly values were used to calculate the annual data points. The analysis in this model is annual across the board.

4.2.4 Study Design and Data

A major component of this research is to approximate the effects of climate change on the existing water resources availability in the basin. Therefore, the base year for the research is 1990. It is well documented that the irregularity in rainfall was initiated in the mid-1990s. The increase in the population of the basin further exacerbated the availability of water in the Cauvery River. The climate data are available until the year 2010. The data were extracted using the Catchment delineation mode in the WEAP software (Stockholm Environment Institute, 2020). The scenarios are developed for the years ranging from 2020 to 2050.

The following subsections explain the process of creating a WEAP model from scratch. The section will discuss the general parameters required to build a model, the data required, and WEAP's design.

4.2.5 General WEAP parameters

The first step in this process is to create a blank space for the project and find the approximate location of the river basin. The approximate space is frame locked and further WEAP elements are added within that space. The time horizon is set up under the “years and time steps” of the general parameters list. The base year or current account year is 1990. The last year of scenarios is kept at 2050. The timesteps are shown in the figure below.

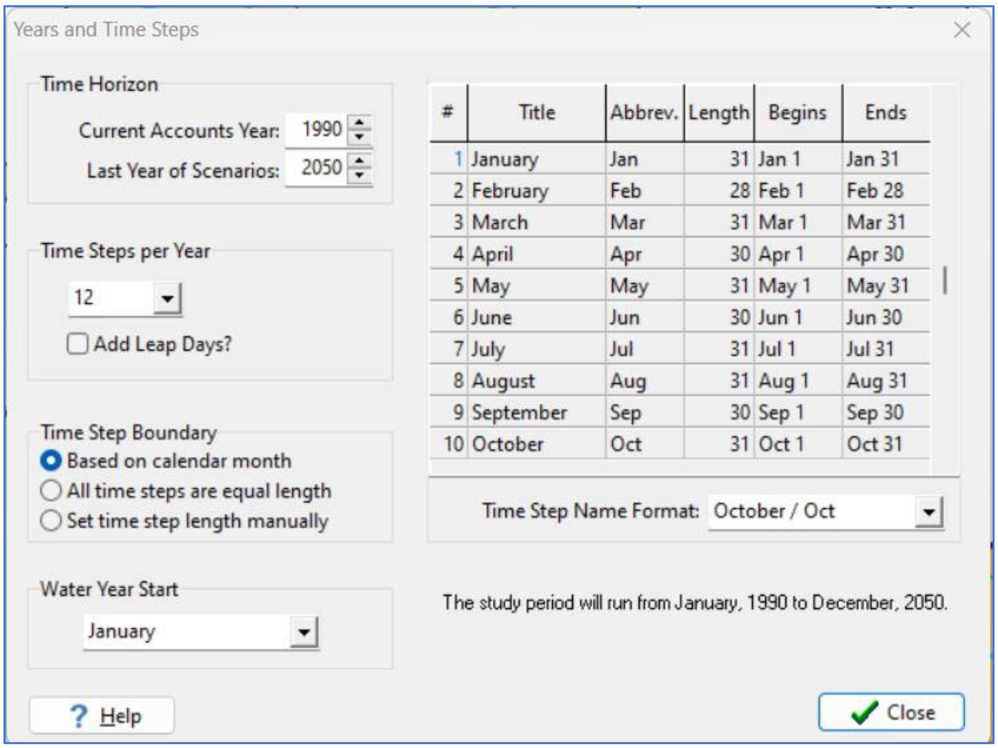


Figure 18 General parameters (years and time steps)

The WEAP features that are part of the model were selected carefully to mimic the existing sources and sinks in the basin. The Cauvery River basin WEAP model has 9 features selected from the existing list of possible WEAP objects. The WEAP objects are explained in the subsections below.

4.2.6 River

The general flow of the river is transcribed on the map by using the “river” WEAP element. The general location is added to the map and WEAP uses the flow line to add water activity levels. The river is divided into smaller sections called “reaches”. These reaches are on either side of a transmission link and the return flows. Both transmission links and return flows are explained in the sections below.

4.2.7 Reservoir

There are six major reservoirs in the Cauvery River basin. Three of them are in Karnataka, namely, the *Harangi* Reservoir, the *Hemvathy* Reservoir, and the *Krishnaraja Sagar* Reservoir. The other three are in Tamil Nadu, namely, the *Kabini* Reservoir, the lower *Bhawani / Bhavanisagar* Reservoir, and the Mettur Reservoir. The *Mettur* reservoir is near the basin's geographical boundary between the provinces of Karnataka and Tamil Nadu. The *Krishnaraja Sagar* and the *Mettur* reservoirs are shown in Figure 19. The average current storage is calculated from the data available at the India Water Resources Information System (INDIA - WRIS, 2015).

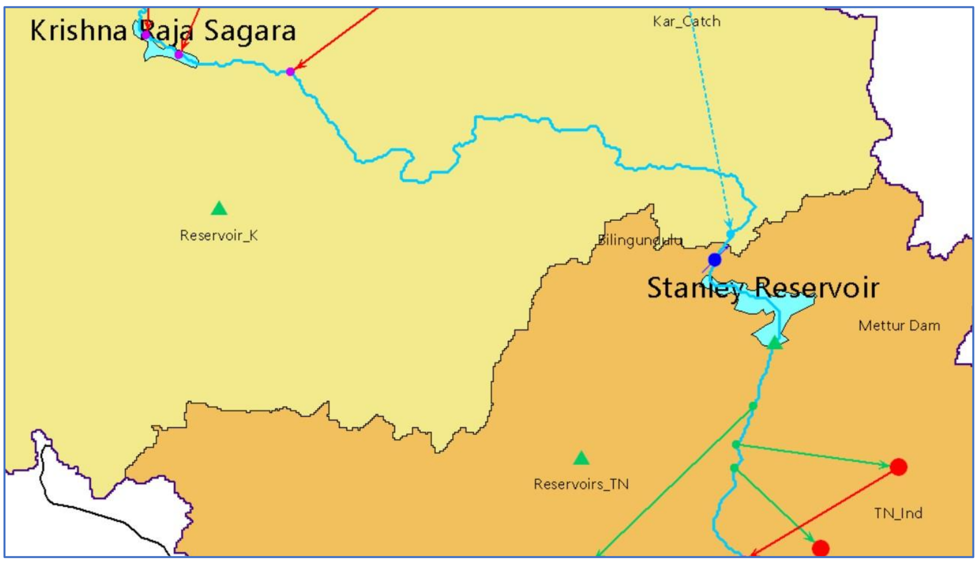


Figure 19 Reservoirs in the basin are shown here. Also, the representative reservoirs are shown as Reservoir_K and Reservoir_TN.

The reservoirs in Karnataka and Tamil Nadu are clubbed together into "*Reservoir_K*", and "*Reservoir_TN*", respectively. The reservoirs are depicted in the figure above. Mettur Reservoir is also known as Stanley Reservoir.

4.2.8 Groundwater

The groundwater is available in the basin is divided into two provinces. The total groundwater potential of Karnataka and Tamil Nadu is denoted as GW_K, and GW_TN, respectively. It is depicted as green squares on the schematic as shown in the figure below.

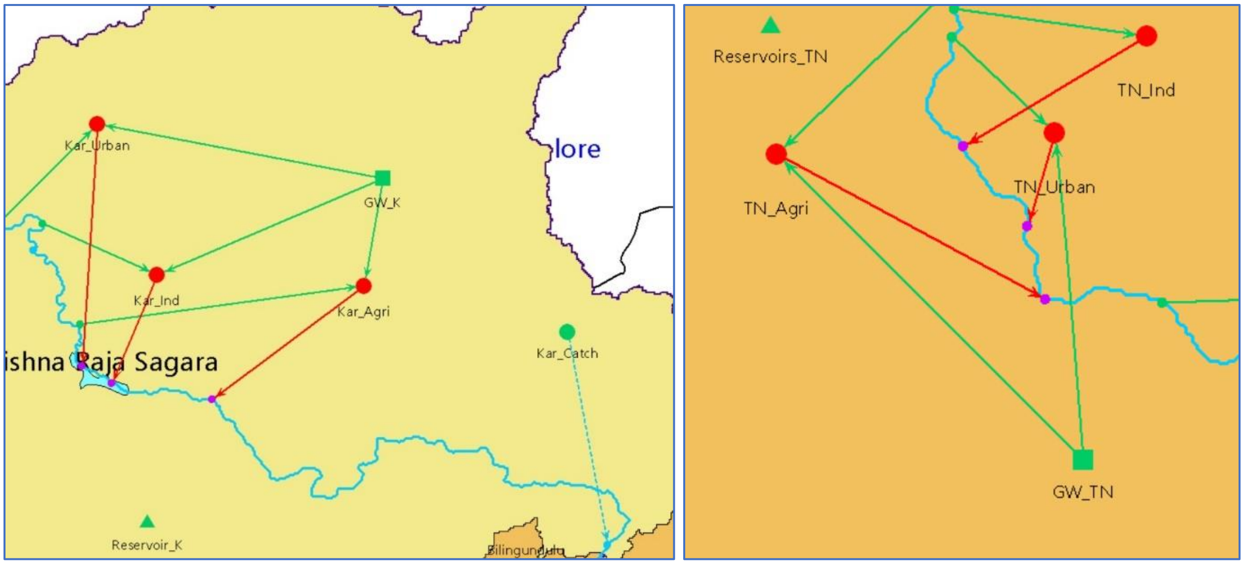


Figure 20 Groundwater representation: GW_K (Karnataka) (left), and GW_TN (Tamil Nadu) (right)

4.2.9 Demand Sites

Demand sites are the nodes that are placed in the respective basins to act as proxies for the agricultural, industrial, and domestic water demands. They are depicted in the figure 20 above as red dots, where Kar_Urban, Kar_Ind, and Kar_Agri are the domestic, industrial, and agricultural demand nodes for the province of Karnataka. Similarly, TN_Urban, TN_Ind, and TN_Agri are the domestic, industrial, and agricultural demand nodes for the province of Tamil Nadu. While adding these nodes, they are given demand priorities. Demand priority is set up for the allocation of a resource in case of limited availability. In the Tamil Nadu sub-basin, priority is given to the TN_Agri demand node and in the Karnataka, sub-basin priority is given to the K_Urban demand node.

4.2.10 Catchment, runoff/infiltration

A river basin is divided into smaller catchments of tributary rivers. For this research, a conceptual model of the whole river basin is divided into two main catchments. The river catchments are placed from upstream to downstream. The upstream catchment flows into the downstream catchment. The areas of the different types of land use types are added along with the crop coefficients. The climate data, irrigation data, soil water capacity, and flooding data are added at this node. More information about the data is presented in the subsequent sections.

The runoff/infiltration path is drawn automatically from the catchment delineation mode. The catchment delineation mode is used before any other WEAP elements are added. The area boundaries are set first which determines the extent of the study. The runoff and irrigation demands are determined using the Rainfall-Runoff (simplified coefficient method) (Khalil et al., 2018). The figure below shows the flow chart of the simplified coefficient method.

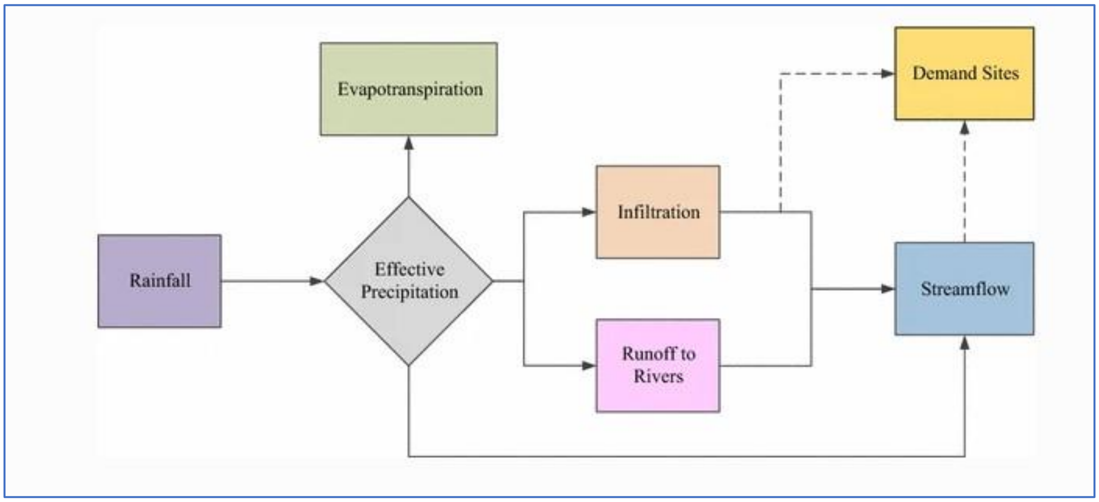


Figure 21 Rainfall-Runoff (Simplified Coefficient Method) (Khalil et al., 2018)

4.2.11 Transmission links and return flows

The transmission links are used to connect the supply sources to the demand nodes. In this work, the author has used 12 links. There are six links from the river to the six demand sites in both catchments. Also, there are links from the groundwater source in Karnataka to all three demand sites. Groundwater in the TN catchment is used by the agriculture demand node and the domestic demand node. Similarly, the return flows take the unused or wastewater back to the river. As a rule, the first return flow is added to the river below the last transmission link. The figure below shows the transmission links in green and the return flows in red.

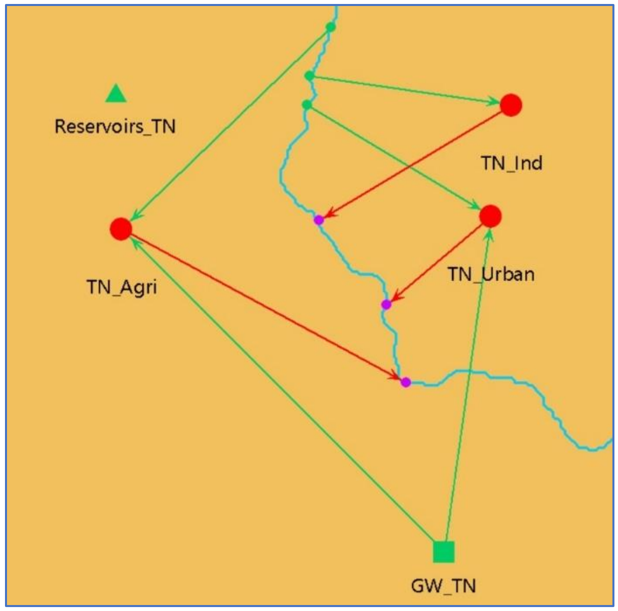


Figure 22 Transmission links (green), and the return flows (red)

4.2.12 Streamflow gauge

A streamflow gauge element is placed on the river element and is used in the calibration of the river flow data. It measures the modelled water flowing right before the streamflow gauge and compares it with the collected data. In this research, the author has added three streamflow gauge elements. The first and the most upstream stream flow gauge is placed at an approximate location of the Village *Kudige* in the province of Karnataka, the second streamflow gauge is located at the border of the two provinces, before the Mettur Dam in the approximate location of the Village Biligundulu in the province of Tamil Nadu, and the third and final streamflow gauge is placed at the downstream of all the demand sites, transmission links, and the return flows at the approximate location of the Village *Musiri* in the province of Tamil Nadu. The approximate schematic is shown in the figure below.

Figure 23 Simplified schematic of the Cauvery River basin model with WEAP elements.

4.2.13 Land Use Data

The land use data for the study area are calculated by WEAP from the inbuilt land use land change data source by ESA-CCI-LC (ESA, 2017). The land use type is ascertained using various land use global land change products, i.e., global LC maps at 300 m spatial resolution on an annual basis from 1992 to 2015, AVHRR HRPT 1 km surface reflectance 7-day composites from 1992 to 1999, etc. These products are then utilized against the remote sensing data. Since the data are obtained in pixels, the greater the resolution, the more information can be obtained from it (Mousivand & Arsanjani, 2019). There are many land use data products available (Arino et al., 2012; Friedl et al., 2002; Hansen et al., 2000; Liu, Li, et al., 2018; Liu, Yu, et al., 2018). The finest remote sensing data are obtained at 300m X 300m resolution. The land use type is ascertained by simple math; the higher the type of a "land use" feature in a finer pixel band, that pixel is deemed that of that specific land use type. For example, if a 1000 X 1000-pixel box has 100 smaller pixels within it. Furthermore, if the pixel distributions are 60 pixels of forest land use type, and the rest are any other pixel type, the big 1000 X 1000 pixel is deemed as forest land use type.

ESA-CCI-LC	Selected Categories
Rainfed Cropland	Agriculture
Irrigated Cropland	Agriculture
Mosaic: Mostly Cropland	Agriculture
Mosaic: Mostly Natural Vegetation	Agriculture
Tree Cover, Broadleaved, Evergreen	Forest
Tree Cover, Broadleaved, Deciduous	Forest
Tree Cover, Needleleaved, Evergreen	Forest
Tree Cover, Needleleaved, Deciduous	Forest
Tree Cover, Mixed Leaf Type	Forest
Mosaic: Mostly Tree and Shrub	Forest
Mosaic: Mostly Herbaceous	Grassland
Shrubland	Shrubland
Grassland	Grassland
Lichens and Mosses	Barren or Sparse Vegetation
Sparse Vegetation	Barren or Sparse Vegetation
Sparse Trees	Barren or Sparse Vegetation
Flooded, Tree Cover, Fresh or Brackish Water	Wetland
Flooded, Tree Cover, Saline Water	Wetland
Flooded, Shrub or Herbaceous Cover	Wetland
Urban	Urban
Bare	Urban
Open Water	Open Water
Snow and Ice	Open Water

Figure 24 Land use categories

The data in Figure 24 above was assigned using available data. In general, there are 23 land use types accepted and confirmed through remote sensing research (ESA, 2017; Platt & Goetz, 2004; Seto et al., 2010; Yuan et al., 2009). The land use data were further simplified based on the requirements of the analysis. The land use types are condensed from 23 to 9 based on the general land use observed in the basin. For example, any kind of tree cover was deemed as forest, etc. (Anbazhagan & Dash, 2003).

The land use distribution for the two provinces in the basin as of 1990 is shown in the Table 7 below. The distribution of the land cover type is determined within the WEAP software (Mousivand & Arsanjani, 2019).

Table 7 Land use distribution of the two provinces as calculated by WEAP

	Land Use type	**Karnataka (km2)**	**Tamil Nadu (km2)**
1	Agriculture	27441.01	30023.93
2	Forest	10693.7	7473.53
3	Grassland	146.03	108.52
4	Wetland	1.47	0.42
5	Urban	374.29	634.09
6	Shrubland	80.6	255.08
7	Barren or Sparse Vegetation	0	40.34
8	Open Water	757.74	511.42
9	Snow and Ice	0	0

The agricultural area in the above table is of great importance. This area will be used to calculate the irrigation water demand of the basin. Also, a distinction will be made between rainfed agriculture, and irrigated agriculture, based on the above agriculture data. The exact measurements and how they were utilized in the model are mentioned in the Irrigation data section.

4.2.14 Demographic data

The base year of our study is 1990. Hence, the official population census of 1991 of the two provinces was used. According to the Cauvery water disputes tribunal (page 200, volume 5), in the Cauvery River basin the population of the provinces of Karnataka, and Tamil Nadu were 11,556,000 and 16,850,000, respectively (CWDT, 2007e). The population growth is generally geometric. Therefore, the census data from the last 50 years were analyzed.

Table 8 The population data (Government of India, 2022)

States	Karnataka	Growth Rate, K	Tamil Nadu	Growth Rate, TN
1951	19,402,000		30,119,000	
1961	23,587,000	21.6%	33,687,000	11.8%
1971	29,299,000	24.2%	41,199,000	22.3%
1981	37,136,000	26.7%	48,408,000	17.5%
1991	44,977,000	21.1%	55,859,000	15.4%
2001	52,851,000	17.5%	62,406,000	11.7%
2011	61,130,704	15.7%	72,147,000	15.6%

The decadal population growth of Karnataka, and Tamil Nadu is 20.8% and 15.34%, respectively. These decadal values are used in the prediction of the annual population growth for the two provinces in the WEAP model. WEAP uses the annual activity levels for predicting the demands. The domestic water demand is calculated using these population values. The industrial demand is calculated by assuming the demand as one unit. The annual irrigation values are calculated in the next section.

4.2.15 Irrigation data

The total culturable area in the basin is approximately 53,680 km^2 in 1990 as shown in the 2007 the Cauvery Water Disputes Tribunal report (CWDT, 2007e). The culturable area in Karnataka is 24,770 km^2 and in Tamil Nadu is 28,910 km^2. However, the net sown area in Karnataka and Tamil Nadu are 16,840 km^2 and 20,590 km^2, respectively. The difference in the culturable areas and the net sown area is quite staggering between the two provinces. The net irrigated areas in Karnataka and Tamil Nadu are 3,550 km^2 and 6,980 km^2, respectively. In the WEAP model, the agricultural areas are replaced by these net irrigated areas because of the way the algorithm has been set up (Bosu, 1995; Stockholm Environment Institute, 2020).

The current irrigated areas of Karnataka and Tamil Nadu are extracted as 6,330 km^2 and 8,170 km^2, respectively (Aishwarya B et al., 2021). These values are input into the WEAP model using the interpolation function. The irrigated area in the basin can either be 0% or 100% in the WEAP environment. Therefore, for the modelling, the irrigation area is kept at 100% for the months from February to July, and the rest was kept at 0%. This was done because of the rainfall patterns and the cropping patterns.

Paddy (Rice) as a proxy in Tamil Nadu

In WEAP, the water/irrigation requirement is defined using the crop coefficient (K_c). The K_c coefficient incorporates the crop characteristics and averaged effects of evaporation from the soil (Allen et al., 1998). The Kc values also represent the changes in leaf area, crop planting date, degree of canopy cover, etc. (Pokorny, 2018). Each crop has different K_c values based on the time of the season, i.e., days or weeks after planting. An example of the calculations is shown in the figure below.

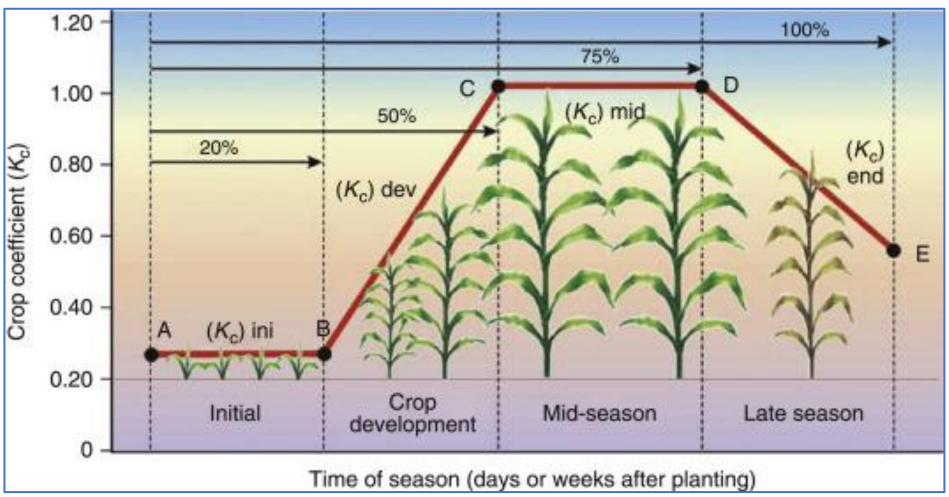


Figure 25 Crop coefficient (K_c) values over the cropping season (Pokorny, 2018)

The 15 districts of Tamil Nadu, which are part of the basin, grow crops like paddy (rice), sugarcane, banana, coffee, coconut, jowar, ragi, groundnut, and pepper. From the average agricultural data from 2000 to 2015, 68% of the area is utilized for paddy production. This totals almost 5,548 km^2. The following table shows the crop types and their average K_c values over the complete growing period. For modelling purposes, the weighted K_c value of paddy is used.

Table 9 K_c of the crops grown in the Tamil Nadu portion of the Cauvery River Basin

Proportion grown	Area (km2)	Crop type	Kc Values	Weighted Kc Values

67.91%	**5548.32**	**Paddy**	**1**	**0.679**
6.65%	543.06	Sugarcane	0.8	0.053
0.90%	73.60	Banana	0.98	0.009
0.93%	76.00	Coffee	0.93	0.009
10.12%	827.04	Coconut	0.65	0.066
7.32%	598.00	Jowar	0.4	0.029
1.66%	135.28	Ragi	0.4	0.007
3.85%	314.28	Groundnut	0.88	0.034
0.66%	54.10	Pepper	0.45	0.003
100%	**8169**			

Only using K_c of one of the crops has a possibility of overestimation of the crop water requirement. Paddy's weighted K_c value is applied to the whole culturable area. However, a conceptual model like this one should be able to provide sufficient insights.

The minimum depth of flooding is kept at 200 mm because paddy (rice) is used as a proxy for cultivation in Tamil Nadu. The maximum depth is kept at 3000 mm because the ponding of paddy can be anything between 1000 mm and 2500 mm (Surendran et al., 2021). The cultivation of paddy requires an average of 250 mm depth of water throughout the year. For this model, the ponding depth is fixed as shown in the table below.

Table 10 The average ponding depths for paddy cultivation in millimetres

Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July
225	225	225	250	250	250	350	350	350	325	325	325

The yield of paddy is added to the model to calculate the annual crop production. This yield will be used to ascertain the future production of paddy based on water availability. The potential yield of paddy is 317,500 kilograms per square kilometer (Arthi T et al., 2018; Khalil et al., 2018).

The cost of paddy (rice) in 1990 was 2.25 INR (Indian National Rupee) per kilogram. The data for the subsequent years were obtained from the Reserve Bank of India datasets (Reserve Bank of India, 2015).

Other proxies in Karnataka

The 8 districts of Karnataka, which are part of the basin, grow crops such as paddy (rice), sugarcane, banana, coffee, cotton, coconut, *jowar* (sorghum), *ragi* (millet), groundnut, and pepper. From the average agricultural data from 2000 to 2015, only 14% of the area is utilized for paddy production. In Karnataka, the majority portion of the area is used to cultivate coffee. The areas are mentioned in the table below. For modelling purposes, the weighted Kc value of coffee was used.

Table 11 Kc of the crops grown in the Karnataka portion of the Cauvery River Basin

Proportion grown	Area (km2)	Crop type	Kc Values	Weighted Kc Values
14.25%	902	Paddy	1	0.143
4.57%	289	Sugarcane	0.8	0.037
3.26%	206.3	Banana	0.98	0.032
35.72%	**2261.07**	**Coffee**	**0.93**	**0.332**
1.36%	85.78	Cotton	0.89	0.012
9.89%	625.75	Coconut	0.65	0.064
1.75%	110.74	*Jowar (sorghum)*	0.4	0.007
8.52%	539.2	*Ragi (millet)*	0.4	0.034
18.74%	1186	Groundnut	0.88	0.165
1.96%	123.8	Pepper	0.45	0.009
100%	**6330**			

Like the Tamil Nadu Kc calculations, this may lead to over-calculation of the water requirement. Water requirement in Karnataka is dominated by the urban and domestic supply of water, therefore, the irrigation water requirement will not play a bigger role in supply and demand calculations.

4.2.16 Reservoirs – Dams and Tanks

As shown in Figure 19, there are six major reservoirs in the Cauvery River basin. The *Harangi, Hemavathy, and Krishnaraja sagar* reservoirs in Karnataka and *Kabini*, lower *Bhawani / Bhavanisagar* reservoirs in Tamil Nadu. The sixth reservoir is the Mettur Dam which is used for irrigation water supply in Tamil Nadu. This dam is also used to produce hydroelectricity which is distributed to the state of Tamil Nadu.

The Tamil Nadu and Karnataka reservoirs are combined into two separate reservoirs for modelling purposes. The data of the reservoirs were collected from the Water Resources Information System databank curated and maintained by the Department of Jal Shakti, Government of India (INDIA - WRIS, 2015). The earliest reliable data available is from the year 2000. The annual average storage and the full capacity are measured in billion cubic meters (BCM). The total available storage would remain the same in the year 1990 as well. Therefore, the same data is used for modelling purposes.

Table 12 The reservoir data in the Cauvery River basin (INDIA - WRIS, 2015)

	2000	2001	2002	2003					
Reservoir	**Average Current Storage (BCM)**				**BCM (Mean)**	**MCM**	**Full Capacity (BCM)**	**MCM**	
Harangi Reservoir	0.08	0.07	0.07	0.07	0.0725	72.50	0.22	**220**	**2310**
Hemavathy Reservoir	0.42	0.30	0.11	0.15	0.2450	245.00	0.93	**930**	
Krishnaraja Sagar	0.56	0.43	0.20	0.28	0.3675	367.50	1.16	**1160**	
Kabini Reservoir	0.13	0.11	0.07	0.07	0.0950	95.00	0.44	**440**	**1370**
Lower Bhawani \ Bhavanisagar Reservoir	0.20	0.12	0.10	0.23	0.1625	162.50	0.93	**930**	

The full capacity of the Karnataka reservoirs is 2310 million cubic meters (MCM), and the Tamil Nadu reservoirs are 1370 million cubic meters (MCM) excluding the Mettur reservoir. The Mettur Dam was built in the year 1934 and has an effective storage of 93.5 TMC (thousand million cubic feet) or 2648 MCM (million cubic meters) (CWDT, 2007a). The figure below lists some of the dam's important information.

Figure 26 Mettur Dam specifications (CC BY-SA 3.0) (Kumar, 2011)

For the modelling simulation, 534 MCM, the storage of the dam in 1990 is taken as the initial storage value. The dam has a volume of 62 MCM which is not available for allocation called dead storage in Figure 26.

The volume elevation curve is calculated from the storage volume data and the total head (elevation) data. In WEAP, the volume elevation curve is used to model the surface for evaporation as well as to compute the head in the case of hydropower production simulation. For the calculations, the dam is assumed to be a cylinder where the height of the cylinder is the elevation, the volume of the cylinder is the volume of the storage, and the surface area of the cylinder is the area available for evaporation calculations (Sayl et al., 2017; Stockholm Environment Institute, 2020). The following figure depicts the volume elevation curve based on the flow data available through the Mettur Diary dataset (Mettur Diary, 2022).

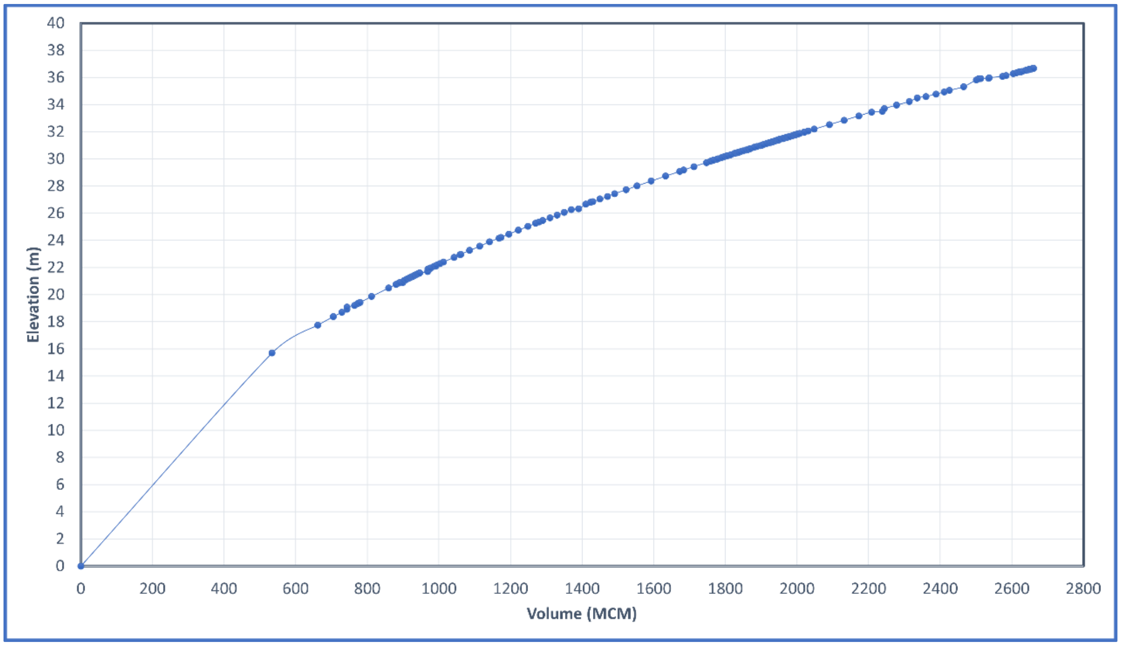


Figure 27 Volume elevation curve for the Mettur dam

The net evaporation data for the dam are gathered from a study carried out in 1985 (Vedula, 1985). The WEAP model presents the data in Table below. The data from 1985 are used as a proxy for the current data in 1990. This data is only active in current accounts. The climate data interaction produces the evaporation data for the basin together.

Table 13 The net evaporation data in millimetres

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evap (mm)	1070	1190	1470	1320	1380	1540	1390	1330	1370	1130	910	900

4.2.17 Streamflow gauges

There are three streamflow gauge datasets used in this study. The *Kudige* streamflow dataset is used as the head flow data for the Cauvery River because it is the most upstream gauge measurement available. The Biligundulu streamflow data set is used by the Cauvery Water Disputes Tribunal to ascertain the water available in the Cauvery River for allocation in Tamil Nadu (CWDT, 2007a, 2007c, 2007b, 2007d, 2007e). The *Musiri* streamflow data are used at the end of the river flow. The gauge data is obtained from the annual water yearbook published by the Central Water Commission (CWC). The datasets include the exact location, flow measurements, the water level, zero at the gauge, etc. (Central Water Commission, 2017). These data sets are used to calibrate the model. Since the data is taken from files in pdf format, the uncertainty needs to be noted.

4.2.18 Groundwater data

The groundwater availability is obtained from Central Water Commission (Water and Related Statistics CWC publication February 2000 - Page 107-108, Table 2.10) publication referenced in the 2007 tribunal result (CWDT, 2007c). The groundwater data within the Cauvery River basin is calculated from the India Water Resources Information System datasets (INDIA - WRIS, 2015). The reliable data sets available are from the years 2011, and 2017. For calculating the data for 1990, an inverse geometric regression was used based on the datasets from 2011 and 2017. This may lead to over estimation of the groundwater values; however, for the intention of this work, the values are good enough.

Two sets of data are used from the database, i.e., reduction in groundwater, and annual replenishment.

Table 14 The groundwater data of the districts of Karnataka within the Cauvery River basin (INDIA - WRIS, 2015)

Districts of Karnataka part of the Cauvery River basin			
		Reduction	**Annual Replenishment**
	Karnataka	**MCM**	**MCM**
1	*Mysore*	713.86	968.90
2	*Chamrajanagar*	423.87	577.53
3	*Mandya*	1162.16	1595.63
4	*Bengaluru*	406.68	532.02
5	*Tumkur*	968.52	1305.73
6	*Hassan*	908.86	1253.64
7	*Chikmagalur*	696.56	1048.98
8	*Kodagu*	338.89	494.12
	Total	**5619.39**	**7776.55**

The groundwater storage capacity is assumed to be infinite as per general practice. As shown in Table 14 above, the total annual quantities of groundwater reduced and replenished in the aquifer in Karnataka is 5,619.36 MCM, and 7,776.55 MCM, respectively.

Table 15 The groundwater data of the districts of Tamil Nadu within the Cauvery River basin (INDIA - WRIS, 2015)

Districts of Karnataka part of the Cauvery River basin			
		Reduction	**Annual Replenish**
	Tamil Nadu	**MCM**	**MCM**
1	*Thanjavur*	1495.88	1662.11
2	*Nagap*	301.74	335.25
3	*Tiru*	1375.60	1528.44
4	*cudd*	2345.26	2605.86
5	*erode*	1319.54	1466.14
6	*salem*	992.57	1102.87
7	*namakkal*	932.28	1035.81
8	*Dharmapuri*	712.52	791.69
9	*tiruppur*	840.32	933.68
10	*dindigul*	1017.21	1130.22
11	*coimbatore*	831.90	924.34
12	*theni*	677.14	752.37
13	*pudukottai*	2713.05	3014.50
14	*villupuram*	2840.45	3156.04
15	*the nilgiris*	225.49	250.55
	Total	**18620.93**	**20689.86**

As shown in Table 15 above, the total annual quantities of groundwater reduced and replenished in the aquifer in Tamil Nadu is 18,620.93 MCM, and 20,689.86 MCM, respectively.

4.2.19 Demand sites – Activity and water use rate

The annual level of activity drives the water demand in the river basin. In this model, the Kar_Agri, and the TN_Agri are the irrigated agricultural areas (measured in square kilometers) of the Cauvery River basins in the provinces of Karnataka, and Tamil Nadu, respectively. Similarly, the Kar_Ind and the TN_Ind are the industrial units that utilize water from the Cauvery River in the provinces of Karnataka, and Tamil

Nadu, respectively. Finally, the Kar_Urban and the TN_Urban are the population of people (measured in "capita") residing in the Cauvery River in the provinces of Karnataka and Tamil Nadu, respectively.

In the current accounts, the industrial activity level is assumed to be one unit because it is easier to define the water supply demand of the industries. The populations are defined in the population section and the agricultural areas are defined in the land use sections.

For scenario development, the general growth of the activity is considered. In the Cauvery River basin, the irrigated area in 1990 in Karnataka, and Tamil Nadu was 3,550 km^2, and 6,980 km^2, respectively. This area further increased to 6,330 km^2, and 8,170 km^2, by 2020 respectively. Therefore, in the model, the data are interpolated accordingly. The data is taken from multiple reports published by the CWDT. This data has not been subjected to any uncertainty analysis. The data is picked directly from the reports. Also, it is assumed that there is little to no increase in the agricultural area due to governmental intervention. However, the intensity of irrigation has constantly been increasing in the basin.

The population of the provinces of Karnataka, and Tamil Nadu within the basin has increased exponentially. The data points available are from the census data in 1991, 2001, 2011, and 2017, as listed in Table 16. The basin population was calculated from individual district population census. The districts falling within the Cauvery River basin were extracted and then their populations were added together. The 1991 dataset used a population of 1990 in the modelling exercise. The rest of the population census data were calibrated using another study done in the region (Aishwarya B et al., 2021).

Table 16 Population of the provinces within the Cauvery River basin

	Karnataka (cap)	**Tamil Nadu (cap)**
1991	11, 556, 000	16, 850, 000
2001	19, 244, 219	37, 361, 522
2011	23, 233, 302	42, 813, 997
2017	27, 439, 638	47, 542, 441

The exponential forecasting feature within the WEAP modelling environment was used to ascertain the population growth for future scenarios until the year 2050.

The agricultural water use rate was calculated using the allocated water in the first tribunal decision/order of 1990. As per the order, to be effective from 1st July 1991, Karnataka was directed to release at least 205

TMC (5.81 billion cubic meters) of water to the province of Tamil Nadu. As per the report, the measurement of the release is to be carried out at the Biligundulu streamflow gauge near the border of Karnataka and Tamil Nadu. The following table shows the monthly distribution of water (CWDT, 2007a).

Table 17 Monthly distribution of the 205 TMC water as stipulated by the Cauvery Water Disputes Tribunal

	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	April	May	Sum
TMC	10.16	42.76	54.72	29.36	30.17	16.05	10.37	2.51	2.17	2.40	2.32	2.01	**205**
BCM	0.29	1.21	1.55	0.83	0.85	0.45	0.29	0.07	0.06	0.07	0.07	0.06	**5.805**

Apart from the above 205 TMC, it was ascertained that an additional 25 TMC was being supplied to the province of Tamil Nadu from the sources upstream of Biligundulu and within the province. In the same report, the tribunal also acknowledged that the total volume of water required by the province of Tamil Nadu to satisfy its irrigation needs is 390.85 TMC (11.1 BCM), and similarly for the province of Karnataka, the water required is 250.62 TMC (7.1 BCM). This volume combines with the known agricultural/irrigation areas within the basin, and the water use rate was calculated in volume per unit area. The water use rate for Tamil Nadu used in the model is 1.401 million cubic meters (MCM) per square kilometer (km^2), and the water use rate for Karnataka is 1.274 million cubic meters per square kilometer.

The domestic water requirements are calculated by assuming a basic standard of hygiene and safety. The National Capital Region Planning Board (NCRPB), which is now under the Ministry of Housing and Urban Affairs, used to be called the Ministry of Urban Development. In May 1999, a recommendation which was given to be used in the development of a water supply project is shown in the table below.

Table 18 The recommendation from the NCRPB (National Capital Region Planning Board, 2009)

Recommended Per Capita Water Supply Levels for Designing Schemes

Sl. No.	Classification of towns/cities	Recommended Maximum Water Supply Levels (lpcd)
1.	Town provided with pipes water supply but without sewerage system	70
2.	Cities provided with piped water supply where sewerage system is existing / contemplated	135
3.	Metropolitan and Mega cities provided with piped water supply where sewerage system is existing contemplated	150

LPCD in the above table is liters per capita per day. Since the information about the population of the various cities and districts was not available, the tribunal estimated the domestic water demand by assuming that 25% of the urban population will receive water at the rate of 135 lpcd, and the remaining 75% of the population will receive water at the rate of 100 lpcd. The rural population was assumed to require 40 lpcd of water to carry out basic needs. In this model, the calculations are carried out using 100 lpcd, considering the demography of the river basin. This translates into 36.5 cubic meters of water per head annually.

The industrial water requirement is calculated based on the Cauvery Water Disputes Tribunal (CWDT). The industrial demand is satisfied using both the Cauvery River water and groundwater. The total industrial water requirement in Tamil Nadu is 2.2 TMC and at 2.5% consumptive use, it totals to 0.055 TMC. The Mettur dam also supplies 0.28 TMC of water to the industrial sector in Tamil Nadu (CWDT, 2007e). The total industrial water demand comes out to be 0.335 TMC (9.486 million cubic meters). The annual growth rate is 1.8% as per the tribunal. Similarly, the industrial water requirement of Karnataka is 0.04775 TMC (1.352 million cubic meters). The growth rate was ascertained to be 1.4% by the tribunal. The same values are used in the model. However, it is to be noted that the industrial water requirement was severely miscalculated by the tribunal as they did not anticipate the booming IT industry in Bangalore (Bengaluru). These calculations, although miscalculated, laid the foundation of public policy at that time. The miscalculation caused the lack of water infrastructure and the dwindling water supply infrastructure. Therefore, the same values are used for modelling purposes to mimic the system as closely as possible.

4.2.20 Other initial parameter values

Some of the initial parameters remain fixed for the current accounts as well as the scenarios. The values in the table below are utilized in the WEAP modelling.

Table 19 Default parameters used in WEAP

Parameter	Values
Soil Water capacity	1000 mm
Deep water capacity	1000 mm
Runoff resistance factor	2
Root zone conductivity (Agriculture)	90 mm/month
Deep conductivity	200 mm/month
Preferred flow direction	0.15
Z1 and Z2	30 percent

4.2.21 WEAP calculations background

The basic calculations are carried out within the WEAP modelling structure based on water balance equations. The water balance calculations are carried out at every node and link in the system and at each time step (Agarwal et al., 2019). As explained in the previous sections, a node is represented as a demand site, reservoirs, groundwater aquifers, etc. and lines between any two nodes are known as links. In this model the lines are usually river sections, transmission links, and/or pipelines. Each time period is independent of each other with notable exceptions in calculations of storage in the system, i.e., dams, aquifer, soil moisture, etc. Therefore, in each period of time, all the water entering in a system is either stored in one of the storage elements or it leaves at the end of the time period. The withdrawal of water at a demand site, usage, and return of the unused water to the river section can happen in the same time step (Stockholm Environment Institute, 2020). For this research, a yearly timestep is considered for the water balance calculations. However, the calculations of meteorological elements are carried out at a monthly time scale and then aggregated to a yearly timestep.

The following section discusses the different scenarios used in this study.

4.3 Scenarios

The current accounts are for the year 1990. The current account is the starting year for the modelling. The reference years are the time for which the data are available, i.e., 1991 to 2014. The scenario output is for the years from 2015 to 2050.

4.3.1 Scenarios explanations

The scenarios are based on two aspects; increase and decrease in precipitation and increase and decrease in water demand. The precipitation increased and decreased by 10 percent. This assumption is based on the general variability of the rainfall calculated in the region as well as the other studies carried out in the Cauvery River basin that accounted for climate change (Aishwarya B et al., 2021; Bhave et al., 2013, 2014, 2018; Mishra et al., 2017).

Table 20 Scenario information for rainfall

Scenario	Abbreviation	Precipitation
Scenario 1	HR, HW (High rainfall, high water demand)	10% increase from Business as usual
Scenario 2	HR, LW (High rainfall, low water demand)	10% increase from Business as usual
Scenario 3	BR, HW (BAU rainfall, high water demand)	Business as usual (BAU)
Scenario 4	BR, LW (BAU rainfall, low water demand)	Business as usual (BAU)
Scenario 5	LR, HW (Low rainfall, high water demand)	10% decrease from Business as usual
Scenario 6	LR, LW (Low rainfall, low water demand)	10% decrease from Business as usual

The increase and decrease in water demand are different for the two provinces. Table 21 explains the values. Scenarios 1, 3, and 5 are high water demand variants, and scenarios 2, 4, and 6 are low water demand variants. The high and low water demands are calculated based on the current accounts' water demand. The annual agricultural demand for the provinces of Karnataka and Tamil Nadu are 1.274, and 1.401 million cubic meters per square kilometer, respectively. For high water demand scenarios, the agricultural water demand is assumed to increase by 1% per year. This value is a higher approximation based on existing data. The water demand has steadily increased; however, the water availability is hindered by the tribunal’s verdicts in the years 1990, 2007, and 2018. The increase in an agricultural area is higher than the increase in water availability for irrigation in Tamil Nadu. By increasing the demand by 1% annually until 2050, the model should achieve a realistic outcome. Similarly, for the province of

Karnataka, the growth is also set at 1% annually. For low water demand scenarios, the agricultural water demand for both provinces were set to reduce by 1% annually. The values were kept at 1% to create symmetry with the high-water demand scenarios.

The urban/domestic water demand depends upon the increase in the population of the provinces. The annual domestic water demand in 1990 is set at 36.5 cubic meters per person annually. This was translated from the general guidelines of 100 liters per capita per day (lpcd) water requirement as per the governmental hygiene codes. With the projected increase in population in the basin, even with constant per capita water requirements, the water required at the domestic water demand node will increase. However, it can be argued that with an increase in the urbanity of the provinces, the per-head demand will increase. Therefore, for both the provinces and the high-demand scenarios, the domestic water demand was assumed to be 135 lpcd (43.80 cubic meters per person annually) in 2020, which is the urban water requirement for most of the bigger cities in the world. This value was projected using linear forecasting until the year 2050. However, for the low water demand scenarios, the domestic water demand was assumed to be 95 lpcd (34.67 cubic meters per person annually) in 2020. This value was used to linearly forecast the demand until the year 2050.

The industrial water demand depends on the increase in industrialization in the province. The industrial water demand was assumed to be growing in both provinces based on the data from CWDT verdicts. The increase in industrial water demand for Karnataka was calculated to be increasing at the rate of 1.4% every year with its value being 1.352 million cubic meters in 1990. Similarly, the increase in industrial water demand for Tamil Nadu was calculated to be increasing at the rate of 1.8% every year with its value being 9.486 million cubic meters in 1990. For high water demand scenarios, an annual 10% increase was assumed for both provinces, which is in line with the tribunal reports as well as some of the other similar studies in the Cauvery River basin (Bhave et al., 2013, 2014, 2018; CWDT, 2007e; Mishra et al., 2017). Similarly, for low water demand scenarios, an annual 10% decrease was assumed for both provinces. For Karnataka, the increase was changed from 1.4% to 1.54% (scenarios 1, 3, and 5) and decreased from 1.4% to 1.26% (scenarios 2, 4, and 6). For Tamil Nadu, the increase was changed from 1.8% to 1.98% (scenarios 1, 3, and 5) and decreased from 1.8% to 1.62% (scenarios 2, 4, and 6). The projected increase in water demand in the basin was validated using the provincial and city water authority's projections. For Tamil Nadu, the data was taken from the Chennai city (Government of Tamil Nadu, 2015) demand projections, and for Karnataka, the data was taken from Bengaluru city (Bangalore Water Supply and Sewerage Board, 2018) water demand projections.

Table 21 Scenario information for water demand

	Karnataka	Tamil Nadu
Scenario 1	Kar_Urban ((1990,36.5), (2020,43.80)) Kar_Ind (increase annually by 1.54%) Kar_Agri (increase annually by 1% after 2018)	TN_Urban ((1990,36.5), (2020,43.80)) TN_Ind (increase annually by 1.98%) TN_Agri (increase annually by 1% after 2018)
Scenario 2	Kar_Urban ((1990, 36.5), (2020,34.67)) Kar_Ind (increase annually by 1.26%) Kar_Agri (decrease annually by 1% after 2018)	TN_Urban ((1990, 36.5), (2020,34.67)) TN_Ind (increase annually by 1.62%) TN_Agri (decrease annually by 1% after 2018)
Scenario 3	Kar_Urban ((1990, 36.5), (2020,43.80)) Kar_Ind (increase annually by 1.54%) Kar_Agri (increase annually by 1% after 2018)	TN_Urban ((1990, 36.5), (2020,43.80)) TN_Ind (increase annually by 1.98%) TN_Agri (increase annually by 1% after 2018)
Scenario 4	Kar_Urban ((1990, 36.5), (2020,34.67)) Kar_Ind (increase annually by 1.26%) Kar_Agri (decrease annually by 1% after 2018)	TN_Urban ((1990, 36.5), (2020,34.67)) TN_Ind (increase annually by 1.62%) TN_Agri (decrease annually by 1% after 2018)
Scenario 5	Kar_Urban ((1990, 36.5), (2020,43.80)) Kar_Ind (increase annually by 1.54%) Kar_Agri (increase annually by 1% after 2018)	TN_Urban ((1990, 36.5), (2020,43.80)) TN_Ind (increase annually by 1.98%) TN_Agri (increase annually by 1% after 2018)
Scenario 6	Kar_Urban ((1990,36.5), (2020,34.67)) Kar_Ind (increase annually by 1.26%) Kar_Agri (decrease annually by 1% after 2018)	TN_Urban ((1990, 36.5), (2020,34.67)) TN_Ind (increase annually by 1.62%) TN_Agri (decrease annually by 1% after 2018)

The following section discusses the results from the different scenarios.

4.4 Results

The results are taken as screenshots from the results tab in the WEAP software. The unmet demand and the annual market value are two of the most important results taken from this analysis. The data is gathered to create a conceptual model of the basin. The total inflow and outflow from the basin are shown in the two figures below. It shows the quantities of water used and not used within the Cauvery River basin.

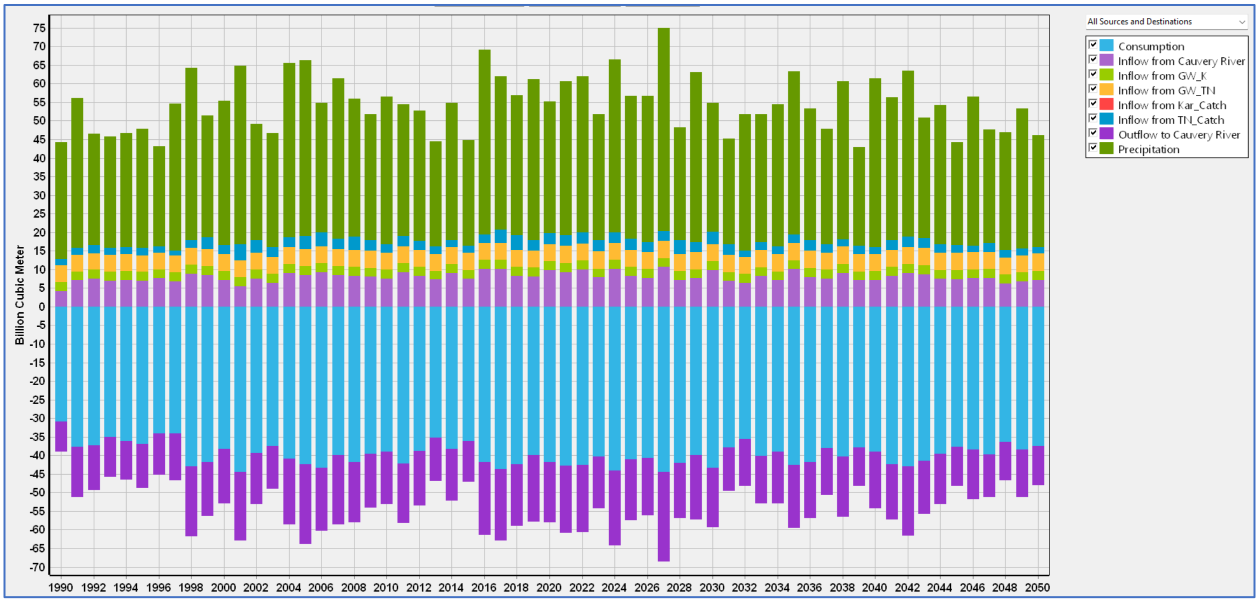


Figure 28 Annual average Demand site inflows and outflows in the Cauvery River basin (Reference scenario)

In the above figure, the annual average flows are shown for the reference scenario. It is important to note that there is no inflow or outflow from the demand node *Kar_Catch* because the inflow from the Cauvery River is considered as the total water originating and entering the province of Karnataka. The figure presents the inflows as positive numbers and the outflows and consumptions as negative numbers for ease of analysis. The sizeable green bars definitively show that most of the demand in the basin is covered by rainfall. The groundwater supply from both provinces is used for specific purposes, e.g., in Tamil Nadu, it is specifically used for domestic and agricultural purposes.

The following figure shows the average monthly inflows and outflows in the basin. The consumption is consistent with the general weather conditions in the basin, i.e., summer months are from April to September. The monthly rainfall in the basin is generally from May to August with the province of Tamil Nadu receiving a second wave of rainfall in October, November, and December. These are shown in the figure under precipitation. The consumption also varies from the summer months to the winter months, with specific irrigation demands as well as domestic demands.

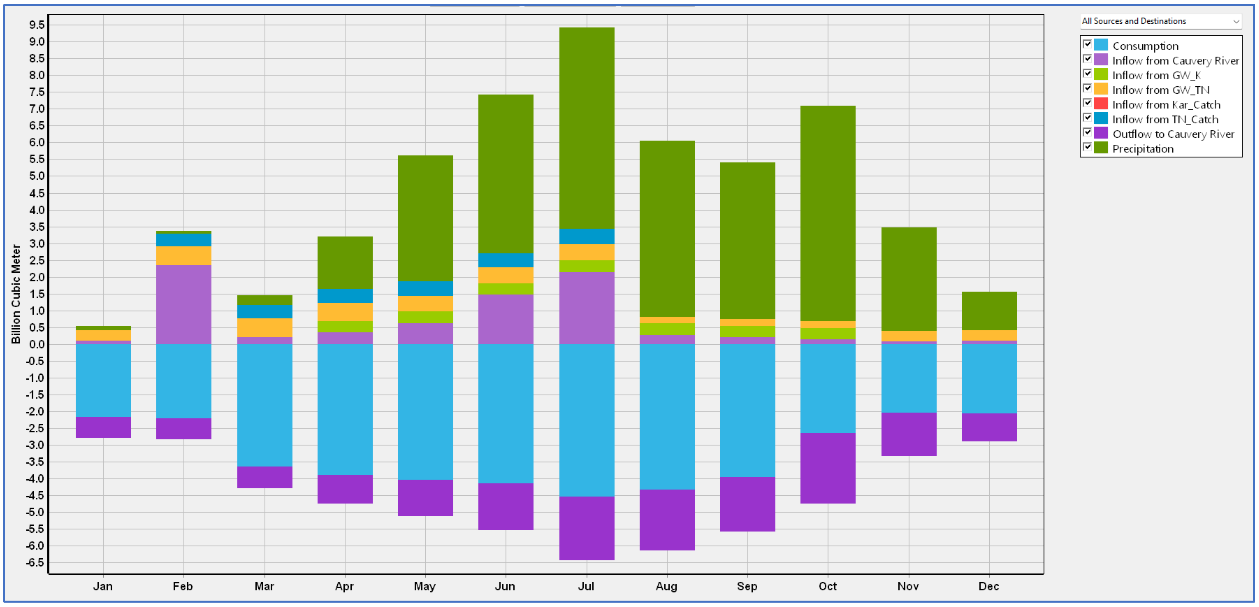


Figure 29 Average monthly Demand site inflows and outflows in the Cauvery River basin (Reference scenario).

The above figure also shows the inflow from *TN_Catch* completely nullifying in the months from August to January. This is consistent after the summer months as the aquifer would usually recharge and hence not provide any inflow to the basin. Also, the winter months do not have enough supply from the actual river upstream. It can be inferred that downstream flow towards the province of Tamil Nadu is highly restricted.

The main reservoir in the basin is the Mettur Dam/reservoir because of its location at the border of the two provinces. The storage volume in the dam is an interesting output of this study. The average monthly flow from the river at the Mettur Dam node and the average monthly storage at the dam is quite helpful. Figure 30 shows the modelled flow at the node before the Mettur Dam and figure 31 shows the storage at the Mettur dam. The average peak flow is regularly observed in July with a change in flow trend in October. The peak flow in July is consistent with the peak rainfall (as shown in the climate data section) in the Karnataka section of the Cauvery River basin and the change in trend flow in October is due to the rainfall expected in the Tamil Nadu section of the river basin.

Figure 31 shows the storage in the dam and the delay in the observation as compared to the nodal flow before the dam is clear from the modelling. As the rainfall increases in the monsoon seasons in the basin and upstream, the storage slowly increases in the dam.

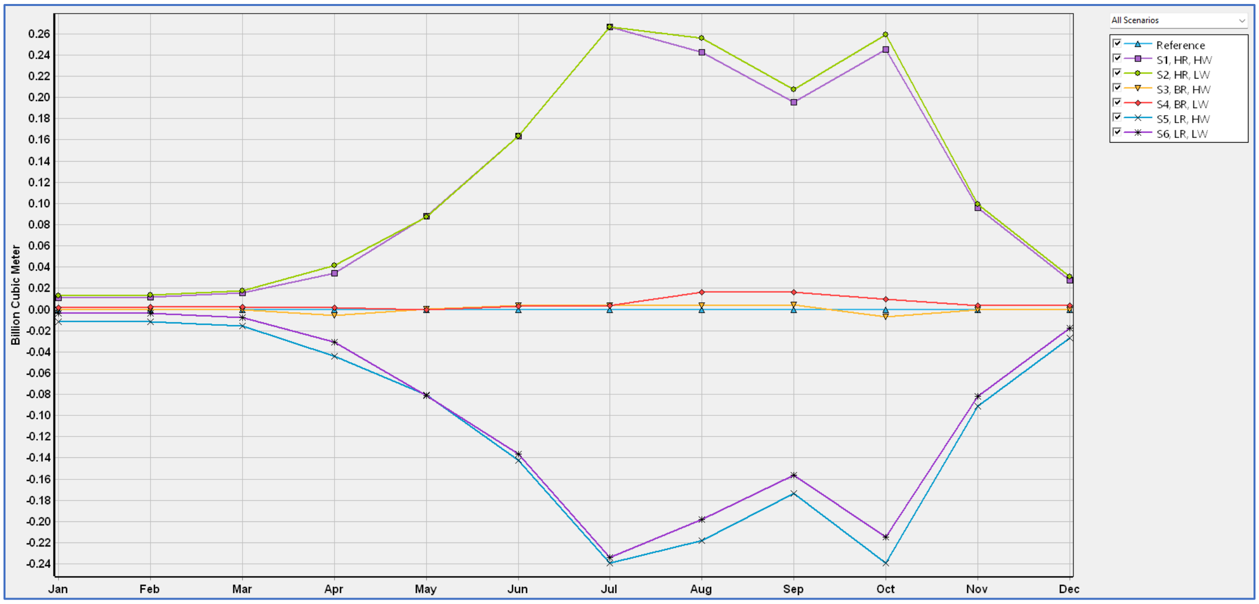


Figure 30 Average monthly node flow before Mettur dam node (all scenarios)

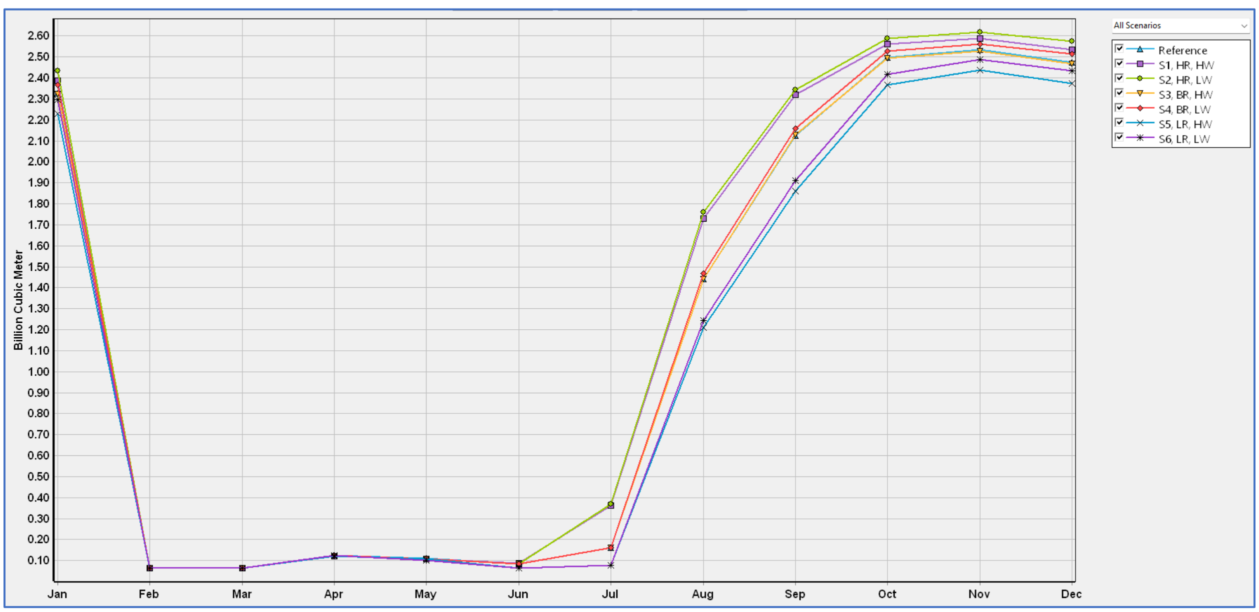


Figure 31 Average monthly reservoir storage in Mettur Dam (all scenarios)

The dam data are important for understanding the water flow within the provinces in the basin. The following sections discuss the gaps in water demand and supply under various scenarios. The scenario results are presented concerning the reference scenario, which is the business-as-usual scenario.

4.4.1 Unmet demand

The unmet demand is the difference in demand and supply calculated at the demand nodes in WEAP. The data is presented for the years 2020 to 2050. All the unmet demands are added together to represent the y-axis. The six scenarios' data are represented concerning the reference or the business-as-usual (BAU) datasets.

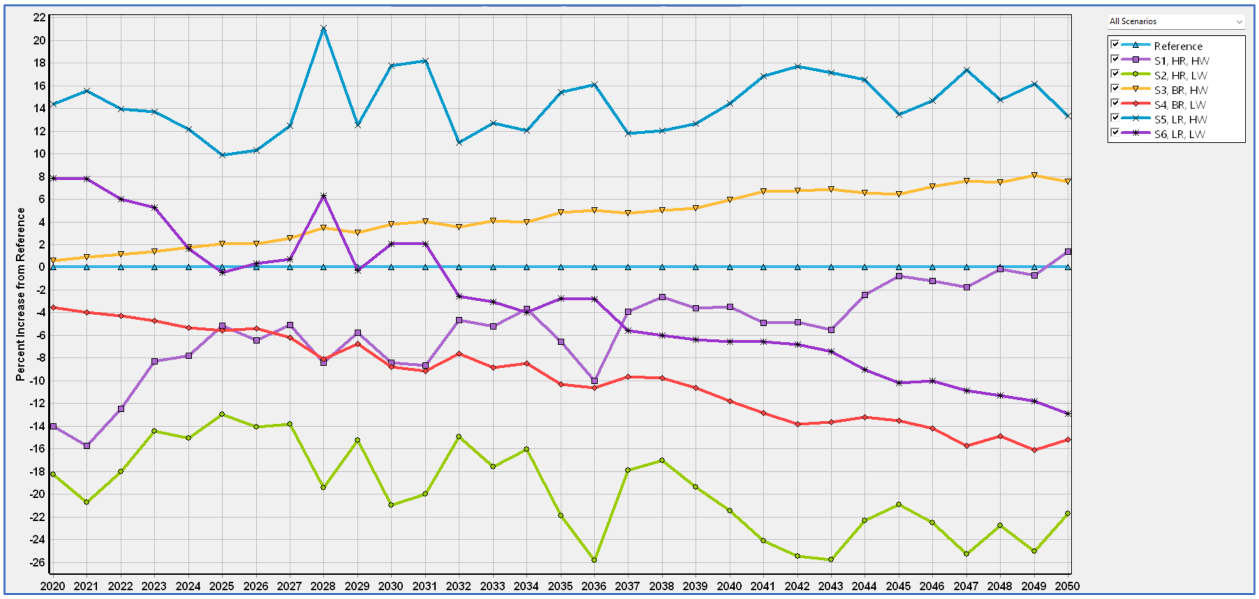


Figure 32 The unmet demand for the basin from years 2020 to 2050. The figure above is all six scenarios relative to the reference scenario.

Figure 32 shows that the scenarios which have higher water demand than the business as usual (BAU) consistently. Scenario 5, and scenario 3 are consistently above the reference scenario. Scenario 6 initially is above the reference line, however, from the years 2030 to 2050 it goes below. Scenario 6 is the low rainfall and low water demand setup. It can be inferred that eventually with lowering water demands in the basin, the unmet demand will be reduced from the BAU levels even with decreasing rainfall.

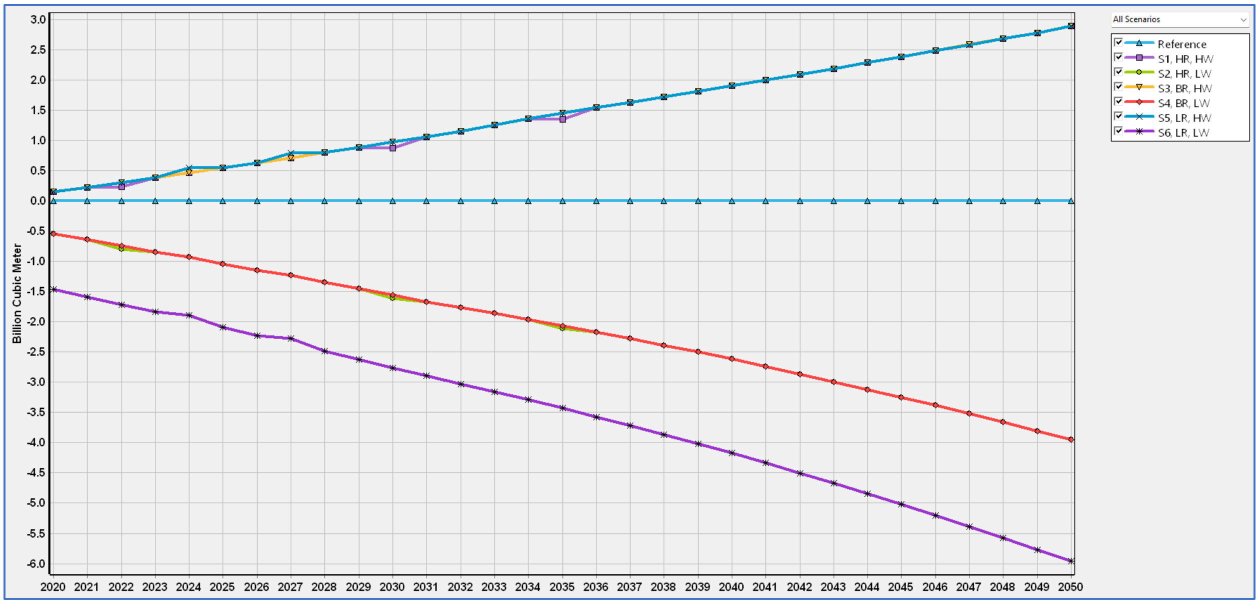


Figure 33 The unmet demand for the Karnataka demand sites for the years 2020 to 2050. The figure above is all six scenarios relative to the reference scenario.

Figure 33 displays the unmet demand for the Karnataka demand sites. The variation between the high-water demand and low-water demand is extremely prominent. The increasing industrialization and population growth in the Karnataka section of the basin have caused a constant increase in the unmet demand even under the increasing, decreasing or BAU scenarios for rainfall. The three almost coinciding lines in the upper section of the figure display scenarios 1, 3, and 5. With this model, it is predicted that the unmet demand can increase up to 30 percent of its reference value by the year 2050. This unmet demand cannot be served by the rainfall in the basin. Therefore, it can be concluded that this unmet demand will have to be supplied with more water resources either from the Cauvery River basin or other river basins within or around the province of Karnataka (Bangalore Water Supply and Sewerage Board, 2018, 2022; Joshi & ET Bureau, 2017).

The other scenarios are driven by lower demands. It is clear from scenarios S2, S4 and to some extent S6, that if the overall demand in the basin is reduced, the unmet demand can be reduced by 65 percent by the year 2050. This may still not be enough to bridge the absolute gap between supply and demand. However, other sources of water supply are required anyway. The water demand in the basin is controlled primarily by the supply requirements of the City of Bengaluru (formerly Bangalore) (Krishna, 2013; Sudhira et al., 2007). The Bangalore Water Supply and Sewerage Board (BWSSB) has tried multiple projects including and not limited to taking help from the Asian Development Bank (ADB) and the World Bank (WB) to bridge the gap between supply and demand (Asian Development Bank, 2018; World Bank Group, 2022).

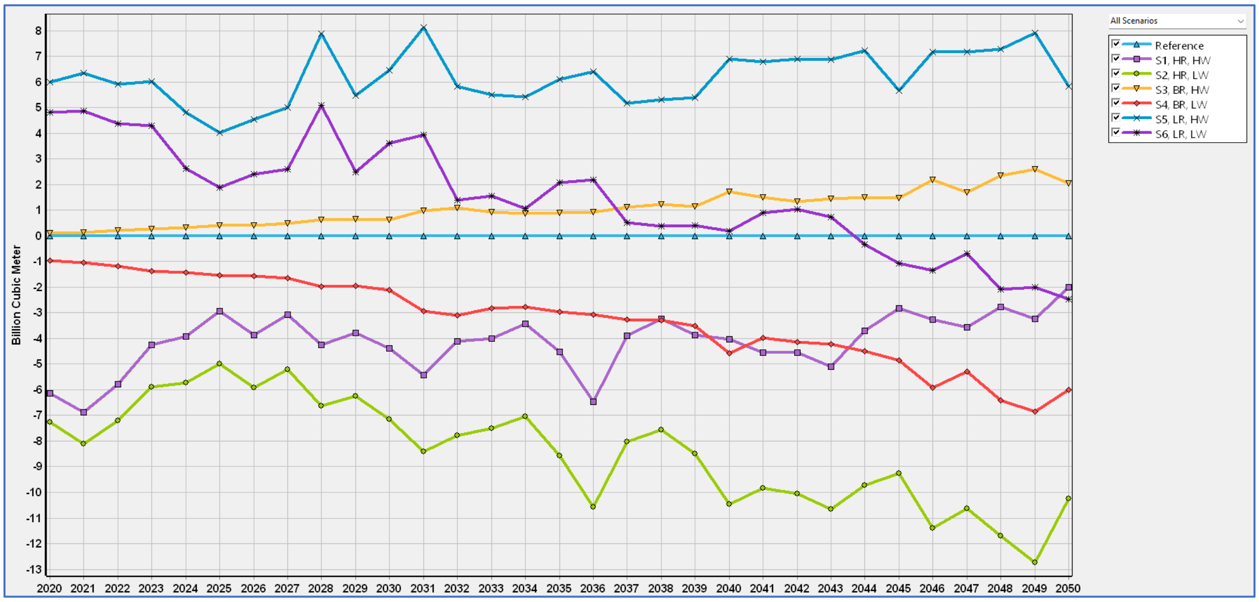


Figure 34 The unmet demand for the Tamil Nadu demand sites for the years 2020 to 2050. The figure above is all six scenarios relative to the reference scenario.

The unmet demand in the downstream province of Tamil Nadu is a little more nuanced compared to the upstream province of Karnataka. Scenario 5 is low rainfall and high-water demand and the unmet demand in this scenario is consistently higher than the reference scenario. Scenario 1 (high rainfall, high water demand), and scenario 6 (low rainfall, low water demand) are at two separate ends of the spectrum; however, they intersect by the year 2050. The water demand is still driving the unmet demand here and not the rainfall. Even with increasing rainfall, eventually, the high-water demand is going to create more unmet demand than the reference scenario. Also, if there is low water demand, either BAU rainfall or high rainfall would considerably aid in reducing the absolute unmet demand. However, interestingly, there is no clear trend when it comes to scenario 2, which is alarming. It can be inferred that the rainfall can only satisfy a smaller section of the unmet demand, and larger reservoirs or increased water from the Cauvery River or other rivers in the basin may be required to fulfil the demand. The government of the province of Tamil Nadu commissioned a report from the World Bank. According to this report published in the year 2019, there is a serious need to modernize the reservoirs, or tanks, as they are popularly called in Tamil Nadu (World Bank Group, 2019).

4.4.2 Annual Crop Production and Annual Market Value change

The annual crop production data here are presented for the downstream Tamil Nadu catchment. The irrigation proportion of Cauvery water used in both provinces favors Tamil Nadu greatly. The water is used from the river, as well as the reservoirs and the groundwater to fulfil the irrigation demands. The figures below show the annual paddy production under the six scenarios as well as the market value of the paddy in the province of Tamil Nadu.

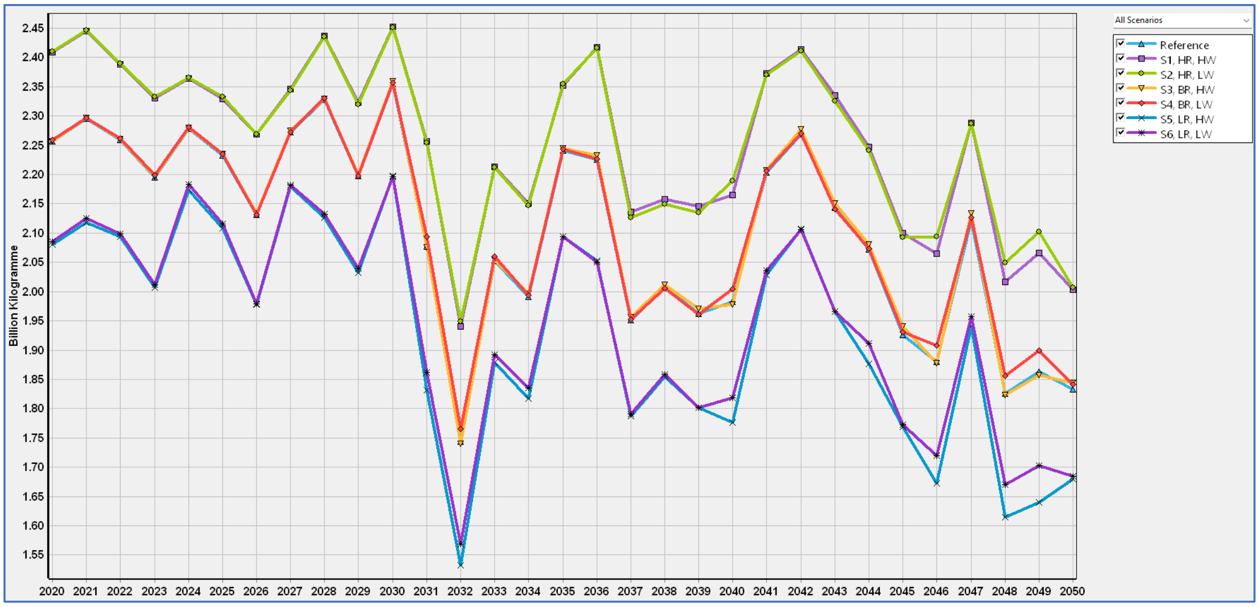


Figure 35 Annual crop production in billion kilograms (All six scenarios)

From figure 35 above, the trends are highly dependent on the water availability in Tamil Nadu. The observed trend shows that the annual production is generally in decline with a freak event in the year 2032. If the rainfall is high in Tamil Nadu, the production would be as high as 12 percent concerning the reference. Lower water demand (S2) but higher water availability would increase the annual production and similar trends are seen in the low water demand scenarios. The trend with the market value of paddy is in correlation with the production of paddy. The per kilogram value of paddy has constantly increased since 1990, the first year of our analysis. In 1990 the price of paddy was INR 225 per quintal (Department of Agriculture and Cooperation, 1991). By the year 2020, the price of paddy has increased to INR 1, 868 (USD 22.79) per quintal (1 quintal = 100 kilograms) (Reserve Bank of India, 2015). The model uses a linear forecast function with 20 data points to predict the price of paddy by the year 2050. The market value below is contingent upon this increase in the price of paddy. Hence, the figure below shows a constant increase in the market value of paddy in US Dollars.

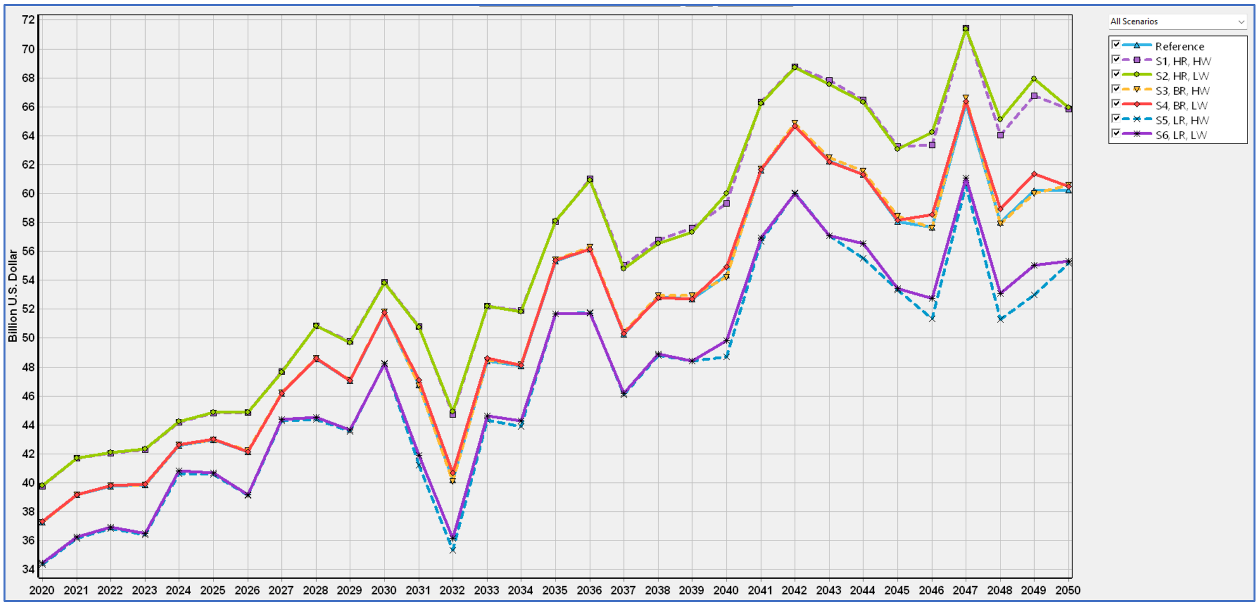


Figure 36 Annual market value of paddy in billion US dollars (All six scenarios)

The results are presented in the percentage format with respect to the reference scenario because the model is a conceptual representation of a lumped basin. The statistical analysis of the modelled data and the observed data shows good enough synergy.

The hydrological model developed here is a lumped model. A lumped model is generally applied in a region for the simulation of various hydrological processes (Darbandsari & Coulibaly, 2020). A lumped model employs parameters that depict the spatially averaged properties of a hydrologic system and, as a result, cannot be readily compared with on-site field measurements (Yu, 2015). The purpose of this modeling activity was to estimate the annual unmet demand in basin, as well as the annual agricultural yield in the basin. It is evident from the hydrological literature that a lumped model, modeled at annual scale can be difficult to validate (Ghimire et al., 2020; Harb et al., 2016; Srivastava et al., 2020). However, this study has calibrated the data using the best governmental data available. Also, the demand sites incorporated within the model are not exhaustive. Nevertheless, the documented climate change mitigation reports from the Karnataka (Government of Karnataka, 2011, 2023), and Tamil Nadu (Government of Tamil Nadu, 2013, 2015) provinces confirm the validity of the percentage increase in demand observed at the specific demand sites compared to the reference scenario. Other methods like Generalized Likelihood Uncertainty Estimation (GLUE) can also be used in future work to estimate the uncertainty in modelling (Meresa et al., 2022).

Although the WEAP modelling method is quite reliable, it does have a few limitations. The WEAP model is used here to simplify complex hydrological, environmental, and socio-economic systems, which can lead to inaccuracies in real-world modelling. For a data scarce region like the Cauvery River basin, the calibration process can be lengthy and time consuming. Uncertainties are inherent and require careful considerations of input data and assumptions. Nevertheless, WEAP is valuable for water resources planning. Also, the results generated are basin specific and therefore should be carefully interpreted.

4.5 Use of WEAP output in CIB

The three results mentioned in the previous section are used as inputs in the Cross Impact Balances (CIB) model. The figure below is reused from the Methods chapter and shows the inputs required for CIB.

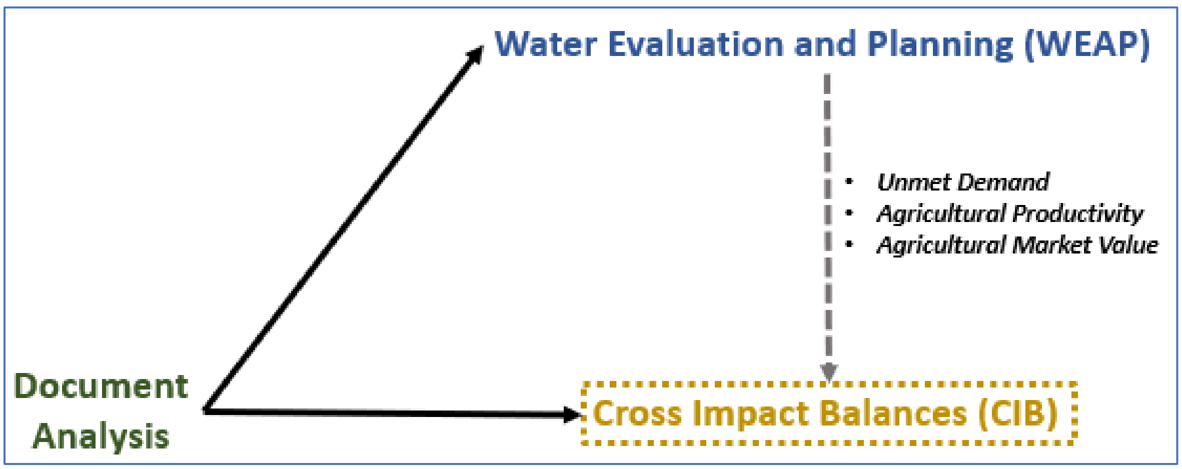


Figure 37 Partial schematic of the flow of this research

The future unmet demand data generated using WEAP is useful in providing insights into the water supply system in the basin. Also, the unmet demand plays an important role in determining the revenue generated from water supply metering in Karnataka, and from agricultural productivity in Tamil Nadu. Also, the agricultural productivity and the subsequent agricultural market value provides further insights about the effectiveness of the government, and possible corruption.

The next chapter introduces the CIB methodology. CIB utilizes the results from WEAP and the document analysis to develop a societal, and governmental systems interaction model for the Cauvery River basin. The chapter also explains the modeling interface, provides the results, and finally discusses the results.

5. Cross Impact Balances (CIB)

5.1 Introduction

Cross-impact balance (CIB) is a method used to help evaluate the potential impacts of different factors on each other. It is often used in the field of risk analysis and decision-making, where many different factors could potentially affect the outcome of a situation.

The CIB methodology is based on systems analysis (Weimer-Jehle, 2006, 2021, 2023a). Cross-impact balance analysis is one of the latest methods developed to analyze interdependencies in a multidisciplinary work that includes social systems (Weimer-Jehle, 2009). Generally, an exploratory evaluation is carried out to calculate the scenarios of a system's behaviour based on data collected from experts and other credible resources. However, as mentioned in the Methods chapter, the expert elicitation could not be conducted due to the global pandemic. Nevertheless, the key systems in this work were identified through a thorough examination of government reports, journal papers, and media articles.

It is important to emphasize that the Cauvery River basin is a highly complex eco-system and the conflict that originated as a water sharing dispute has, over the years, transformed into a complicated wicked problem. In the Cauvery River conflict, three system of systems are interacting with each other. The physical, the governance, and the socio-economic system of systems. This study is an example of a CIB application in studying a systems of systems.

Figure 38 below shows the high-level interactions between the system of systems; however, it is important to note that the actual interactions is between the systems and the bubbles are mere representations of virtual boundaries of the system of systems. These interactions are an attempt to understand a wickedly complex system.

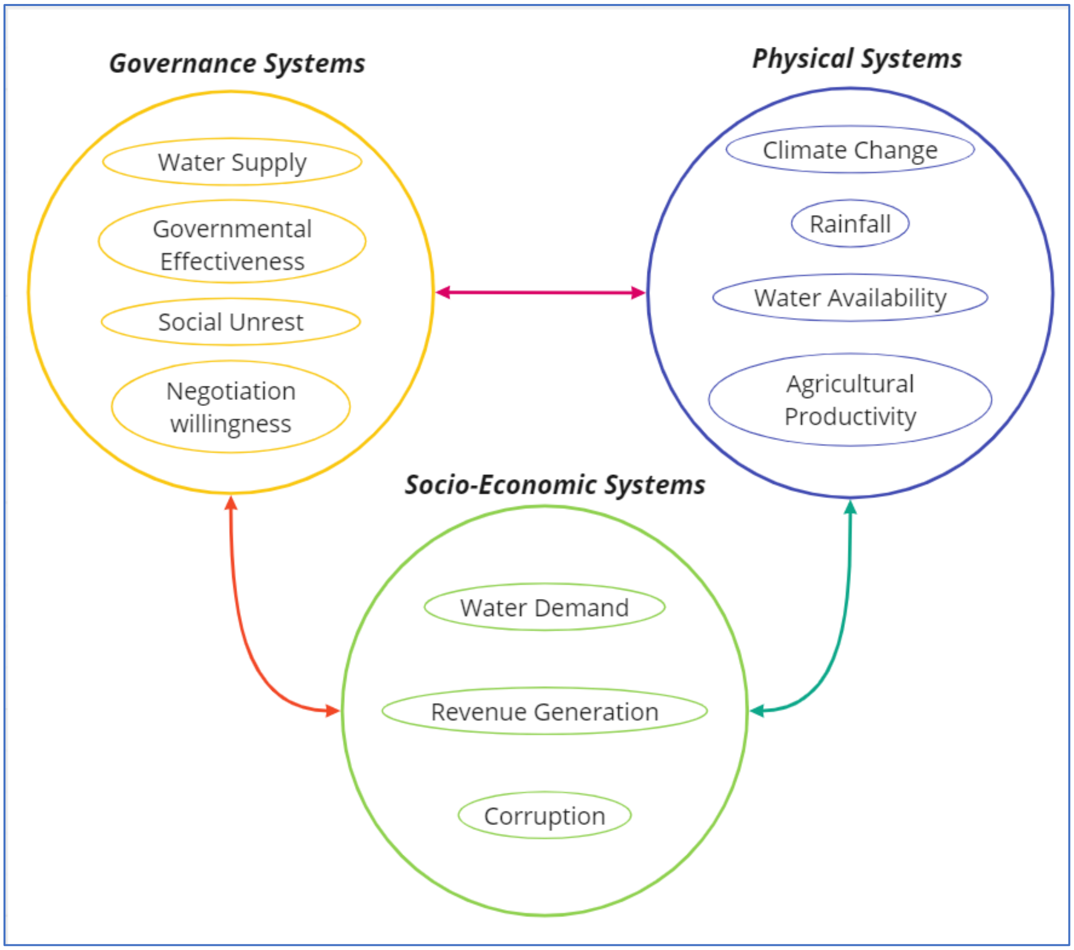


Figure 38 System of systems representation of the Cauvery River conflict

The systems of systems interactions are further simplified using a causal loop diagram. CIB analysis starts with identifying the most important factors that have a direct or indirect influence on the object of the examination. The causal loop diagram shows the impacts of and from the systems (descriptors) affecting the Cauvery River basin. Descriptors are the key factors driving and causing the conflict (Sharma et al., 2022). The four key steps in developing a CIB model are,

1. Identifying and defining the descriptors
2. Describing the variants and their boundary conditions.
3. Assessing the interrelations between each descriptor (CIB matrix)
4. Identifying the internally consistent scenarios

A CIB matrix of "*N*" descriptors is a *N* X *N* hypermatrix. An element of C_{ij} of the hypermatrix, also known as the judgement section, is a s_i x s_j matrix. S_i is the number of states of descriptor *i*. The following example shows the interactions between two descriptors from the Cauvery River conflict, descriptors "water supply in Tamil Nadu", and "agricultural productivity in Tamil Nadu". The water supply descriptor has high, moderate, and low variants. Agricultural productivity has high and low variants. The table is read from left to right, and the scores in the table are called judgment values.

Table 22 Cross Impact Balance analysis snippet

		Agricultural Productivity – TN *(j)*	
		High	*Low*
Water Supply – TN *(i)*	*High*	**3** *(1,1)*	**-3** *(1,2)*
	Moderate	**1** *(2,1)*	**-1** *(2,2)*
	Low	**-3** *(3,1)*	**3** *(3,2)*

The judgment values can be any whole number; however, generally and for this study, the range has been set from -3 to +3. Any negative judgment value means the relationship from the "impact of" (source) to "impact on" (sink) is restricting, and any positive judgment value means that the relationship is promoting. The complete list of the judgment values and their meaning is shown as follows:

-3: strongly restricting direct influence.

-2: restricting direct influence.

-1: weakly restricting direct influence.

0: no direct influence

1: weakly promoting direct influence.

2: promoting direct influence.

3: strongly promoting direct influence.

Table 22 is one of the submatrices C*(i,j),* part of the full Cauvery River conflict's CIB interaction matrix. The row*(i)* is the descriptor acting as an impact source, and the column*(j)* is the descriptor acting as an impact sink, i.e., *i* – impact from, *j* - impact towards. For example, $C_{1,1}$ (1,2) = -3 judgment value, i.e., high water supply in Tamil Nadu strongly restricts low agricultural productivity in Tamil Nadu. By analyzing a full CIB matrix, it is possible to identify which descriptors are most important and how they may affect each other. This can help decision-makers to make informed choices about which descriptors to prioritize and how to mitigate any negative system impacts.

One of the biggest advantages of using CIB is its ability to provide a storyline to explain complex problems somewhat easily. The software (ScenarioWizard)(Weimer-Jehle, 2023b) developed at the CIB lab, University of Stuttgart, to simplify the calculations of the judgment scores together, is easy to use. The CIB lab website has an easy-to-use layout with a step-by-step example explaining the various facets of the CIB method. Also, the methodology can handle quantitative as well as qualitative variants and provide meaningful realizations of wicked and complex problems. CIB (Weimer-Jehle, 2006a, 2018) is a flexible, exploratory scenario methodology and can model socio-economic system dynamics among many other possible applications.

Another benefit of CIB is that instead of a linear cause-and-effect model for socio-economic trends, CIB considers the many additional factors that may affect the decision-making context and presents how difficult or easy it will be to resolve the ongoing water sharing dispute (i.e., arrive at negotiated agreement). Also, as the cross-impacts are embedded into the scenarios, the underlying analyst bias shall be at the minimum. The judgement values in CIB are largely based on empirical evidence and data-based modelling. These judgement values and the interactions there-of are untouched by the analyst's worldviews. The CIB method supports minimizing the analyst's bias and the judgement scores ascertained by the analyst are always transparent and supported by evidence. CIB outputs consistent scenarios based on the most probable combination of the above-mentioned indicators. These consistent scenarios, which will be stakeholder specific, can serve as the preference statements for the decision-makers in the subsequent decision-making tool known as Graph Model for Conflict Resolution (GMCR) and provide context for the negotiation strategies. CIB's method of arriving at the preferences of the decision-makers is more organic compared to the method followed by Sharma et al. (2020), which was heavily based on fuzzy mathematics and less information.

A scenario in CIB is a random combination of variants selected from each of the descriptors. The judgment values of the selected variants, when summed (and by convention in ScenarioWizard software, displayed at the bottom of the CIB matrix), are called the impact score of that variant. A complete set of the "judgment scores" of one descriptor is called the impact balance of that descriptor. This impact balance represents the effect of each descriptor variant on the selected scenario. The scenario with the highest total impact score of all combinatorial scenarios is a consistent scenario. Additionally, within a regular symmetric CIB matrix, any scenario that is consistent will also be a local maximum in terms of total impact scores. A "consistent" scenario is selected among the list of scenarios by making sure that the impact score for each descriptor variant is positive.

CIB can include seemingly heterogeneous disciplines in decision-making. CIB's transparency and traceability are due to a matrix representation of inter-relating scenario factors and the simplicity of an algorithm that finds self-reinforcing circumstances (so-called "internally consistent" scenarios), which is simply repeated many times by the computer. The term "internal consistency" implies that a situation is coherent within itself, indicating its components support and complement each other. In other words, the elements of the scenario reinforce one another, resulting in self-consistency (Schweizer & Kurniawan, 2016). CIB is an easy-to-understand exploratory method whereas other mathematical approaches can be difficult for non-experts to understand. CIB will take in various indicators affecting a dispute/conflict, and it outputs consistent as well as inconsistent scenarios. CIB guides how scenarios can maintain consistency with a subset of basic scenario factors yet reflect the variety of local futures that are possible (Schweizer, 2020).

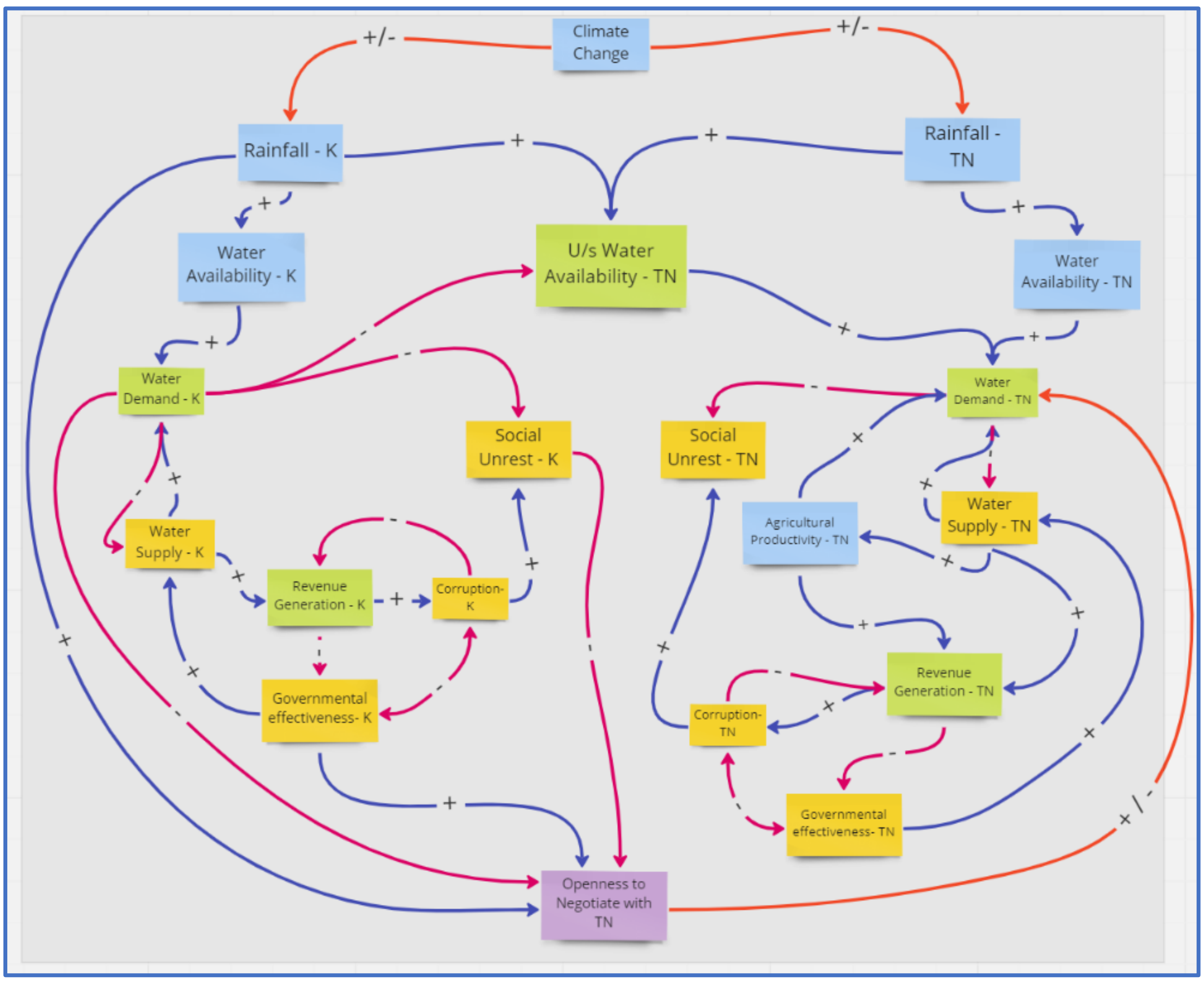


Figure 39 Causal loop diagram (same as Figure 8 of this thesis)

This work has identified a list of nineteen (19) descriptors and their interactions are shown in the causal loop diagram above. The definition of descriptors has been developed using a document analysis, and the results of WEAP simulations.

A causal loop diagram (CLD) shown above in Figure 39 is a tool used to illustrate the relationship between different indicators (variables) in a system (Bureš, 2017). Figure 39 is identical to Figure 8 shown on Page 22 of this document. It is a pictorial representation of the cause-and-effect relationships between the indicators, intending to understand how a system functions. A CLD uses arrows to show the direction of influence between the indicators. An arrow points from the impact source and towards the impact sink. A positive arrow is generally indicated by a small positive sign, or in this case, the arrows are also colour coded as blue. A positive arrow means that an increase in the impact source would lead to an increase in the impact sink. Therefore, a reduction in the impact source would also lead to a reduction in the impact sink. A negative arrow is generally indicated by a small negative sign, or in this case, the arrows are also colour coded as red. A negative arrow means that an increase in the impact source would lead to a decrease in the impact sink. The arrows colour coded as orange or with both the positive and negative signs mean that the effect is ambiguous (Bertalanffy, 2017; J. Kim, 1971).

In causal loop diagrams, feedback loops are an important feature. Feedback loops can either be self-reinforcing or self-correcting. A self-reinforcing loop keeps on adding on to itself and a self-correcting loop keeps on reducing itself. For example, it can be hypothesised from the CLD figure above that an increase in water supply causes an increase in the revenue generated in the subbasin, because the revenue generated depends upon the number of metered connections (Dick, 2015; Mallanna, 2018). This reduces the governmental effectiveness in the basin because it increases the instances of mismanagement in the government, and a reduction in governmental effectiveness reduces the water supply in the subbasin (Strategic Futures Group, 2020). This is an example of a self-correcting loop. These interactions are researched, examined, and presented with supporting arguments in the subsequent sections of this chapter. The CIB matrix is a state-specific adjacency matrix and is a network model therefore an appropriate way to model a causal loop diagram.

The following sections discuss at length the direct influences of descriptors on each other. There are a total of 39 interactions identified based on the causal loop diagram. Section 5.2 illustrates the definitions of the descriptors used in this work. Section 5.3 discusses the interactions in detail. Section 5.3.1 uses the results from the WEAP simulation to justify relevant judgement scores used for the CIB simulation. Section 5.3.2 uses various governmental reports, research papers, and newspaper articles to justify relevant judgement scores. Section 5.4 discusses the results from the CIB analysis. Finally, section 5.5 discusses how the CIB outputs inform the final steps of the research using GMCR.

5.2 Definitions of key drivers

There are nineteen key descriptors in this analysis. Table 23 shows the descriptors, the definition of the descriptors and the logic behind the different variants.

Table 23 The descriptors along with their descriptions and the variants

	Descriptors	Definitions		Variants
A	Rainfall - K	The rainfall in Karnataka is affected by climate change in the basin. The rainfall can either be high by ten percent, moderate or business as usual or low by ten percent. This range is extracted from the work done by Bhave et al. (2018) in the region. The annual moderate rainfall in Karnataka is 1400 mm.	A1	High Rainfall
			A2	Moderate Rainfall
			A3	Low Rainfall
B	Rainfall - TN	The rainfall in Tamil Nadu is affected by climate change in the basin. The rainfall can either be high by ten percent, moderate or business as usual or low by ten percent. This range is extracted from the work done by Bhave et al. (2018) in the region. The annual moderate rainfall in Tamil Nadu is 1400 mm.	B1	High Rainfall
			B2	Moderate Rainfall
			B3	Low Rainfall
C	Water Availability - K	Water is available for distribution in the Karnataka subbasin of the Cauvery River basin. The total water available from the upstream river reaches the groundwater, and the reservoir tanks in the subbasin. This water is supplied for agricultural, domestic, and industrial purposes (less than 3 BCM annually inflows from the river, groundwater, catchment - Scarce). This boundary condition was observed from the reference scenario in WEAP.	C1	Enough availability
			C2	Scarce availability
D	Water Availability - TN	Water is available for distribution in the Tamil Nadu subbasin of the Cauvery River basin. The total water available from the groundwater, the reservoirs like Mettur and other reservoir tanks in the subbasin. This	D1	Enough availability

		water is supplied for agricultural, domestic, and industrial purposes (less than 7 BCM annually inflows from the river, groundwater, catchment - Scarce). This boundary condition was observed from the reference scenario in WEAP.	D2	Scarce availability
E	U/s Water Availability - TN	Water flowing through the border of the two provinces is available for distribution in the Tamil Nadu subbasin of the Cauvery River basin. It is measured at the Mettur Dam as well as through streamflow calculations upstream of Mettur at Biligundulu (less than 6.5 BCM annually inflows from the river, groundwater, catchment - Scarce) as per the CWDT reports (CWDT, 2007c, 2007d, 2007e).	E1	Enough availability
			E2	Scarce availability
F	Water Demand - K	The demand in the basin increases due to an increase in the population of Bengaluru and an increase in industrial water demands. For example, the high-water demand is a ten percent increase from the BAU increase in water demand, and the low-water demand is a ten percent decrease from the BAU increase in water demand. (Values taken from the research carried out by Bhave et al. (2018) in the same region). The normal increase is 1.4% in the industrial demand. This is based on the CWDT reports.	F1	High water demand
			F2	Low water demand
G	Water Demand - TN	The demand in the basin increases due to an increase in the population, an increase in agricultural area, and an increase in industrial water demands. The sowing of paddy in Tamil Nadu requires extensive flooding and ponding of water. For example, the highwater demand is a ten percent increase from the BAU increase, and the low-water demand is a ten percent decrease from the BAU increase. (Values taken from the research carried out by Bhave et al. (2018) in the same region). The normal increase is 1.8% in the industrial demand. This is based on the CWDT reports.	G1	High water demand
			G2	Low water demand
H	Water Supply - K	The water supply to all the demand sites within the subbasin of Karnataka. The moderate water supply is	H1	High water supply

		2.95 BCM. Moderate water supply is the expected or targeted water supply to the demand sites based on the reference scenario created in WEAP, therefore, it is an exact value. Less than 2.95 BCM is a low water supply, and higher than 2.95 BCM is a highwater supply.	H2	Moderate water supply
			H3	Low water supply
I	Water Supply - TN	The water supply to all the demand sites within the subbasin of Tamil Nadu. The moderate water supply is 13 BCM. Moderate water supply is the expected or targeted water supply to the demand sites based on the reference scenario created in WEAP, therefore, it is an exact value. Less than 13 BCM is a low water supply, and higher than 13 BCM is a highwater supply.	I1	High water supply
			I2	Moderate water supply
			I3	Low water supply
J	Agricultural Productivity - TN	The annual production of paddy in Tamil Nadu is the driving factor of the GDP of the province. If the annual production of paddy is greater than 3.4 billion kilograms, then it is considered high productivity. 3.4 billion kgs is the annual average production for the last twenty years (Panneerselvam, 2021; Tamil Nadu Govt., 2021).	J1	High productivity
			J2	Low productivity
K	Revenue Generation - K	The revenue generated by the Bengaluru water supply board from the water supply services is the revenue generated here. It is a proportion of the GDP in the province. In Karnataka, the major proportion of the GDP is from services (Rajneesh, 2022). Their annual revenue generated is close to 0.8 billion dollars per year with a target of achieving 1.5 billion dollars per year by 2050. If we plot a trendline from 2020 to 2050, then any year the revenue generated is below that line is assumed to be having low revenue generated and higher on the trend line would have high revenue generated.	K1	High revenue generation
			K2	Low revenue generation
L	Revenue Generation - TN	The revenue generated from paddy production and sale is revenue generated here. The agriculture sector has the highest percentage of contribution in the province of Tamil Nadu. The current annual production value of	L1	High revenue generation

		paddy is 38 billion US dollars. With the increase in crop prices, the value is estimated to reach 60 billion US dollars by the year 2050. Therefore, any data point above this trend is considered high revenue generation, and any data point below the line is low revenue generated.	L2	Low revenue generation
M	Governmental effectiveness - K	An ineffective government is unable to perform its duties and at the same time fails to safeguard the rights of its citizens. In the Karnataka sub-basin, an effective government would be able to bridge the gap between supply and demand. Also, they would be effectively investing in better water supply infrastructure.	M1	Improving governmental effectiveness
			M2	Status quo or worsening governmental effectiveness
N	Governmental effectiveness - TN	An ineffective government is unable to perform its duties and at the same time fails to safeguard the rights of its citizens. In the Tamil Nadu sub-basin, an effective government would be able to guarantee a regular supply of water for irrigation at the same time investing in more efficient irrigation methods.	N1	Improving governmental effectiveness
			N2	Status quo or worsening governmental effectiveness
O	Corruption - K	Corruption within the Karnataka government prevents it from carrying out its duties and restricts citizen's rights. One of the major indictors is when there is evidence of misappropriation of funds as mentioned in Hart, (2019).	O1	Yes
			O2	No
P	Corruption - TN	Corruption within the Tamil Nadu government prevents it from carrying out its duties and restricts citizen's rights. One of the major indictors is when there is evidence of misappropriation of funds as mentioned in Hart, (2019).	P1	Yes
			P2	No
Q	Social Unrest - K	Social unrest is damage to public or private properties in Karnataka. Any amount of damage or threats within a system is considered social unrest.	Q1	Social unrest
			Q2	Status quo / No Social unrest

R	Social Unrest - TN	Social unrest is damage to public or private properties in Tamil Nadu. Any amount of damage or threats within a system is considered social unrest.	R1	Social unrest
			R2	Status quo / No Social unrest
S	Openness to Negotiate with TN	The openness or preparedness of Karnataka to negotiate with Tamil Nadu regarding the release of a stipulated quantity of water.	S1	Yes
			S2	No

The following sections provide justifications and discussions on the interaction between the descriptors.

5.3 Interactions in the model

As explained in the introduction section of this chapter, the judgement scores/values are whole numbers between -3 and +3. If there is no doubt about the interaction influence, a strong “3” score is ascertained. If the interaction influence is complicated/ambiguous, a weak “1” score is ascertained. If the influence is generally favouring an interaction, then a “2” score is ascertained. A “0” score is for interactions that probably do not exist. The rationale of the scores is explained in each of the descriptor relationships.

There are four major types of interactions within the causal loop diagram, i.e., WEAP interactions, document analysis interactions, WEAP–document analysis interactions, and GMCR interactions. They are combined into two sub-sections: WEAP and Document analysis.

5.3.1 WEAP

There are twelve (12) interactions observed from the hydrological modelling. The following section discusses the descriptor relationships and the rationale for the judgement scores.

5.3.1.1 Descriptor relationship: Direct influence of Rainfall (K) on Water availability (K)

The interaction was deduced from WEAP results. The more rainfall there is in the Karnataka sub-basin, the higher the water availability in the sub-basin. As per table 23 above, the variants of rainfall are high, moderate, and low, and the variants of water availability are enough, and scarce. The figure below shows the interaction.

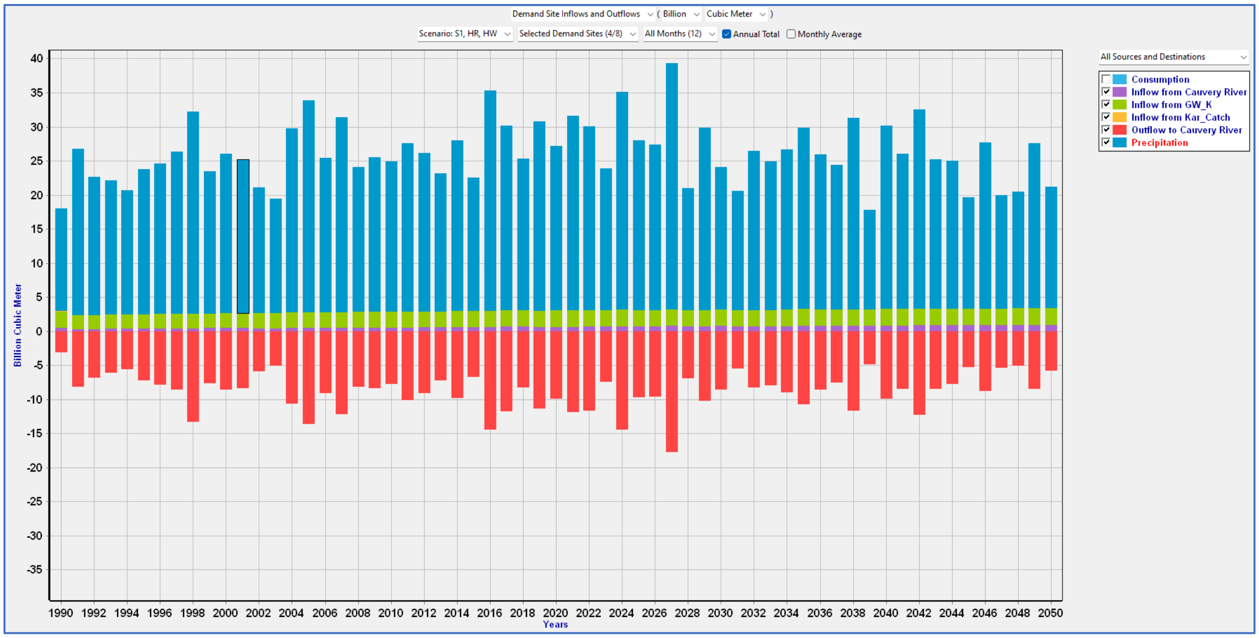


Figure 40 Rainfall-K and Water availability-K

Interpretation:

From the figure above, the rainfall and water availability are cross-checked. Every year's rainfall increases and decreases are corroborated by water availability. In the figure below, the row*(i)* is the descriptor acting as an impact source, and the column*(j)* is the descriptor acting as an impact sink, i.e., *i* – impact from, *j* - impact towards.

a. High rainfall (greater than 1400 mm per year) or 24 BCM from figure 40 promotes enough water availability. The water availability is calculated by adding the inflow from the river, and the inflow from the groundwater. From figure 40, it is clear that generally in the years the rainfall is greater than 24 BCM, the water availability is also greater than 3 BCM. This is why it has a judgement score of +2.
b. If a. is true, then High rainfall equally restricts scarce water availability. Therefore, this has a judgement score is -2.
c. Moderate rainfall weakly restricts enough water availability because business-as-usual rainfall does not fulfill the water availability. Over the last thirty years, the moderate rainfall (average 24 BCM annually) has rarely caused more than 3 BCM in water availability. Therefore, this judgement score is -1.
d. Moderate rainfall, therefore, weakly promotes scarce water availability. Therefore, this judgement score is 1.

e. From the figure above, the low rainfall (less than 1400 mm per year) strongly restricts enough water availability. The low rainfall events are quite prominently leading to a consistent less than 3 BCM water availability. Therefore, the judgement score is -3.

f. Low rainfall strongly promotes scarce water availability. Therefore, this judgement score is +3.

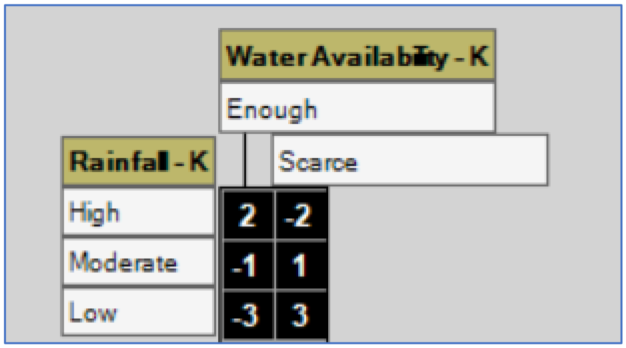


Figure 41 Interaction: Direct influence of Rainfall (K) on Water availability (K)

5.3.1.2 Descriptor relationship: Direct influence of Rainfall (TN) on Water availability (TN)

The interaction was deduced from WEAP results as well. The more rainfall there is in the Tamil Nadu sub-basin, the higher the water availability in the sub-basin. As per Table 23 above, the variants of rainfall are high, moderate, and low, and the variants of water availability are enough, and scarce. The figure below shows the interaction.

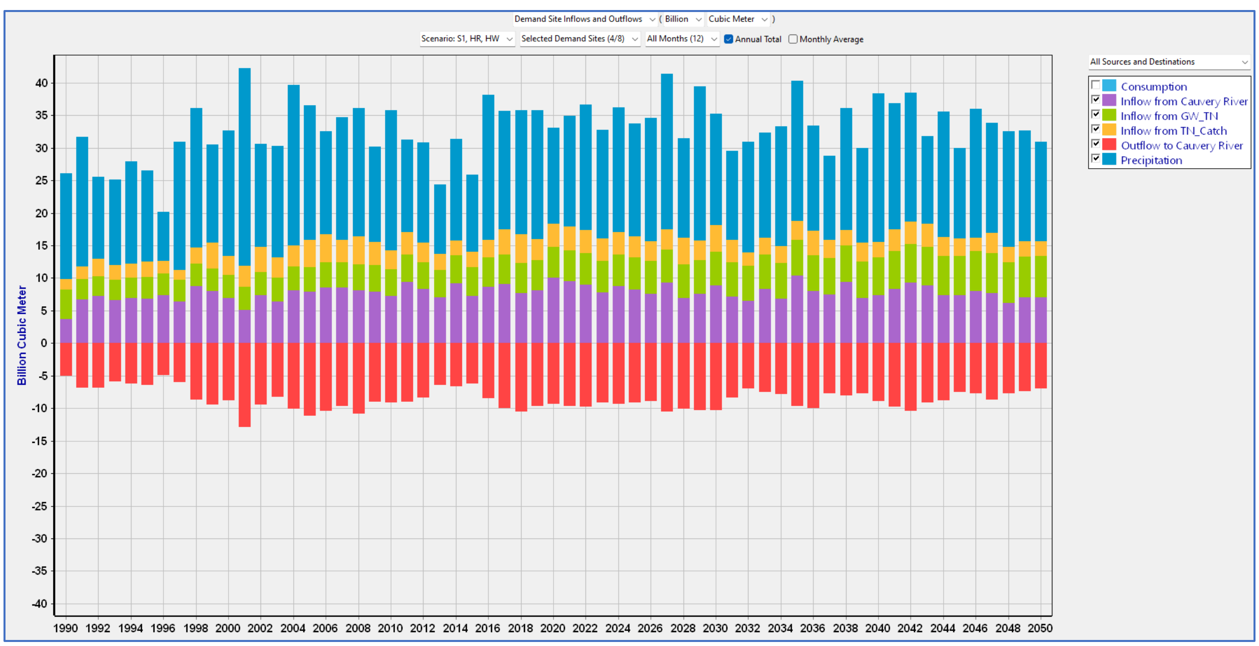


Figure 42 Rainfall – TN and Water Availability – TN

Interpretation:

From the figure above, the rainfall and water availability are cross-checked. Every year's rainfall increases and decreases are corroborated by water availability. The threshold for moderate rainfall is different for the Tamil Nadu sub-basin than that of the Karnataka sub-basin due to the difference in area between the two sub-basins and the distinct utilization of water.

a. High rainfall (greater than 1400 mm per year) or 32 BCM from Figure 42 promotes enough water availability. The water availability is calculated by adding the inflow from the river, and the inflow from the groundwater. From figure 42, it is clear that generally in the years the rainfall is greater than 32 BCM, the water availability is also greater than 7 BCM. This is why it has a judgement score of +2.
b. If a. is true, then High rainfall restricts scarce water availability. Therefore, this has a judgement score is -2.
c. Moderate rainfall weakly restricts enough water availability because business-as-usual rainfall does not fulfill the water availability. Over the last thirty years, the moderate rainfall (average 32 BCM annually) has rarely caused more than 7 BCM in water availability. Therefore, this judgement score is -1.
d. Moderate rainfall weakly promotes scarce water availability. Therefore, this judgement score is 1.
e. From the figure above, the low rainfall (less than 1400 mm per year) strongly restricts enough water availability. The low rainfall events are quite prominently leading to a consistent less than 7 BCM water availability. Therefore, the judgement score is -3.
f. Low rainfall strongly promotes scarce water availability. Therefore, this judgement score is +3.

The judgement scores for this interaction are identical to the interaction mentioned in subsection 5.3.1.1 because the effects of rainfall are similar on the water availability as they are part of the same Cauvery River basin.

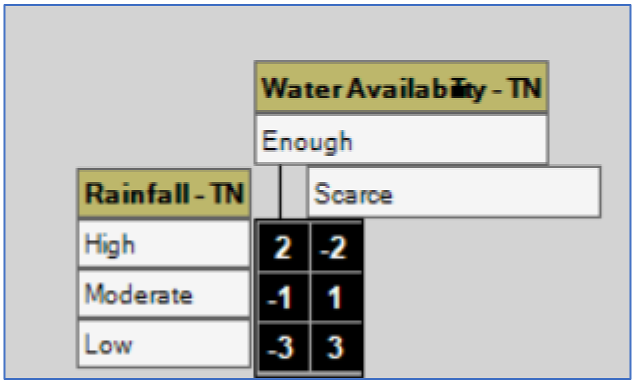


Figure 43 Interaction: Direct influence of Rainfall (TN) on Water availability (TN)

5.3.1.3 Descriptor relationship: Direct influence of Rainfall (TN) on upstream Water availability (TN)

The upstream water availability is the water flowing through the border of the two provinces as mentioned in the descriptor definition table. The volume of water required to flow through the borders is stipulated by the Cauvery water disputes tribunal. This volume is measured at the Biligundulu gauging station (in Tamil Nadu), which is approximately 40 kilometres downstream from the point where the Cauvery River enters the province of Tamil Nadu. The catchment of this small area does not influence the upstream water availability; however, a weak influence is considered.

a. High rainfall in Tamil Nadu weakly promotes enough upstream water availability in Tamil Nadu. An increase in the rainfall would increase the available water, however, the signal is weak. Therefore, this judgement score is +1.
b. Consequently, high rainfall in Tamil Nadu weakly restricts scarce upstream water availability in Tamil Nadu. Therefore, this judgement score is -1.
c. Moderate rainfall in Tamil Nadu does not influence enough upstream water availability in Tamil Nadu. The signal of moderate rainfall is non-existent and there was no evidence of any interaction. Therefore, this judgement score is 0.
d. Moderate rainfall in Tamil Nadu does not influence scarce upstream water availability in Tamil Nadu. Therefore, this judgement score is 0.
e. Low rainfall in Tamil Nadu weakly restricts enough upstream water availability in Tamil Nadu. The rainfall in Tamil Nadu does have a contribution to the water flowing in the Cauvery River that is measured at the Biligundulu station. Therefore, less rainfall would probably not lead to

enough water availability. This link/signal is quite weak as well. Therefore, this judgement score is -1.

f. Consequently, low rainfall in Tamil Nadu weakly promotes scarce upstream water availability in Tamil Nadu. Therefore, this judgement score is 1.

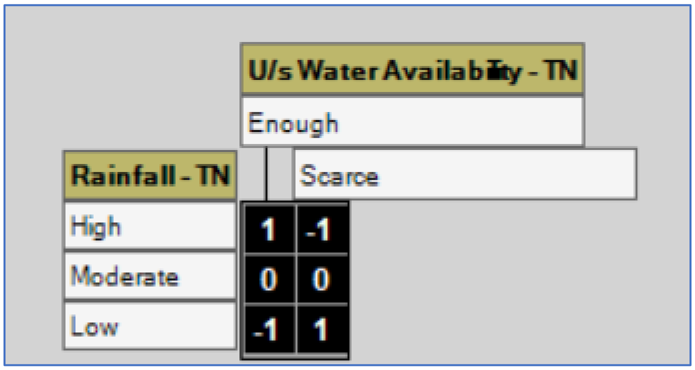


Figure 44 Interaction: Direct influence of Rainfall (TN) on upstream Water availability (TN)

5.3.1.4 Descriptor relationship: Direct influence of Rainfall (K) on upstream Water availability (TN)

The upstream water availability is the water flowing through the border of the two provinces as mentioned in the descriptor definition table. The volume of water required to flow through the borders is stipulated by the Cauvery Water Disputes Tribunal. Therefore, any year if the total flow of water is less than 6.5 BCM (which is approximately 250 TMC), it is considered as low water availability from upstream sources. More than 6.5 BCM is high water availability from downstream sources, as mentioned in Table 23. This bifurcation is measured at the Biligundulu gauging station, a little north of the Mettur Dam. As per the tribunal guidelines, the required water to be released was reduced from 212 TMC to 192 TMC in the latest result. However, for this work, the author is using the quantity stipulated in the 2013 result plus another 25 TMC contribution from the Tamil Nadu basin. The 2013 ruling was upheld in the final 2018 ruling. Therefore, the values stipulated in them are used.

The rainfall in the upstream province of Karnataka affects the water flowing through the border significantly. The interactions are quite strong here. The figure below includes the contributions from the various demand sites in the Karnataka sub-basin.

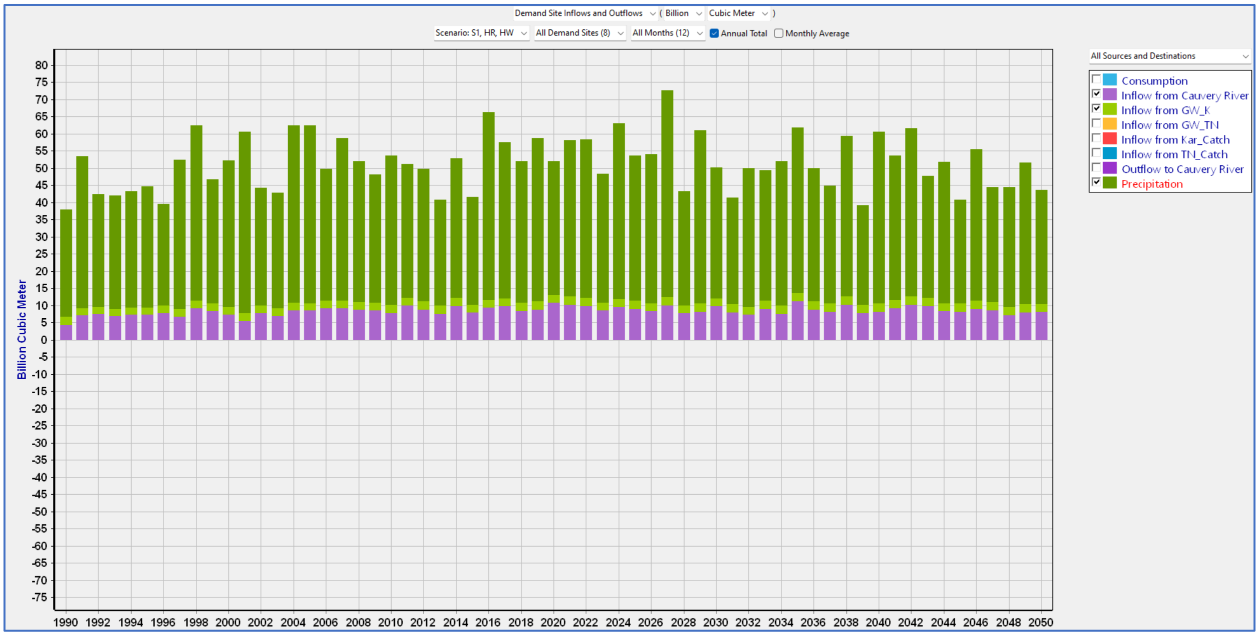


Figure 45 Contributions from Karnataka subbasin to the water availability in Tamil Nadu (the bottom half of the figure above is empty because the "consumption" tab is unchecked).

a. High rainfall in Karnataka strongly promotes enough upstream water availability in Tamil Nadu. An increase in the rainfall (greater than 24 BCM) has a strong positive signal towards the increase in the upstream water availability (greater than 6.5 BCM) at Biligundulu as shown in the figure above. Therefore, this judgement score is +3.

b. Consequently, high rainfall in Karnataka strongly restricts scarce upstream water availability in Tamil Nadu. Therefore, this judgement score is -3.

c. Moderate rainfall in Karnataka weakly restricts enough upstream water availability in Tamil Nadu. This is evident from the tribunal reports and the latest verdicts that moderate or business-as-usual rainfall is not able to guarantee the stipulated quantity of water. However, this has been the case in the last few years, the link is weak. Therefore, this judgement score is -1.

d. Consequently, moderate rainfall in Karnataka weakly promotes scarce upstream water availability in Tamil Nadu. Therefore, this judgement score is +1.

e. Low rainfall in Karnataka strongly restricts enough upstream water availability in Tamil Nadu. As mentioned in point 'a.' above, the rainfall in Karnataka has a major contribution to the water flowing in the Cauvery River that is measured at the Biligundulu station. Therefore, less rainfall would not lead to enough water availability based on the figure above. Therefore, this judgement score is -3.

f. Accordingly, low rainfall in Karnataka strongly promotes scarce upstream water availability in Tamil Nadu. Therefore, this judgement score is +3.

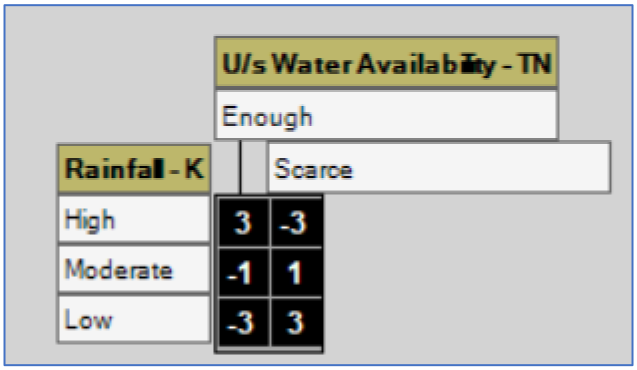


Figure 46 Interaction: Direct influence of Rainfall (K) on upstream Water availability (TN)

5.3.1.5 Descriptor relationship: Direct influence of Water availability (K) on Water demand (K)

Water availability has a distinct influence on water demand in Karnataka as demonstrated through WEAP. The water demand in the Karnataka sub-basin is shown in the figure below. The unmet demand, or the difference in supply and demand, is constantly increasing and may be affected by the rainfall in the region.

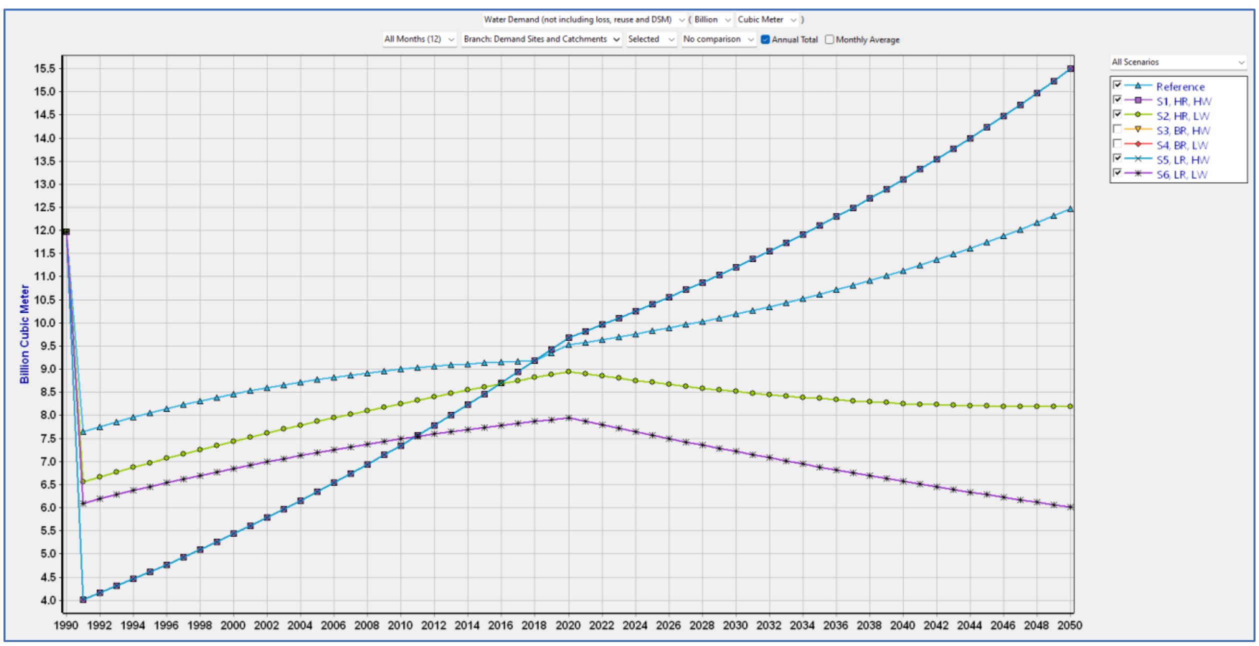


Figure 47 Water Demand in Karnataka

The constant increase in the demand until the last year of simulation is unaffected by the water availability, however, the low water demand scenarios provide more insight regarding the business-as-usual scenarios. This proves that water availability does not have a strong influence on water demand because the demand is driven by the increasing population in this sub-basin. However, scarce availability of water has a stronger influence on the water demand because that forces the municipalities to make rations and/or look for other sources of water.

a. Enough water availability in Karnataka weakly promotes high water demand in Karnataka. With increasing water availability in the Karnataka sub-basin, the demand is also increasing, hence the rise in the unmet demand. This proves a weak signal. Therefore, this judgement score is +1.
b. Therefore, enough water availability in Karnataka weakly restricts low water demand. Scenario six in the above figure demonstrates this. Therefore, this judgement score is -1.
c. On the other hand, scarce water availability promotes high-water demand in the Karnataka subbasin. This is visible from the figure above as well. The demand may not be entirely dependent upon the water availability. There are other factors like weather, and ambient temperatures. Therefore, this judgement score is +2.
d. Therefore, scarce water availability restricts low water demand. Therefore, this judgement score is -2.

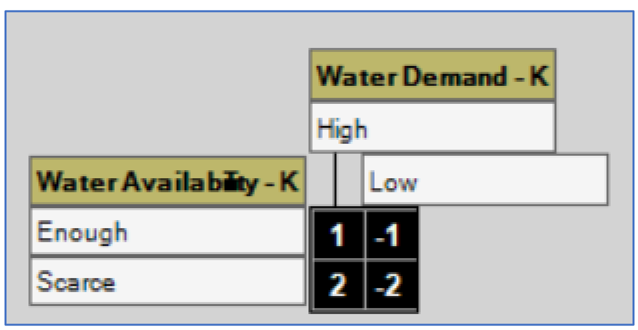


Figure 48 Interaction: Direct influence of Water availability (K) on Water demand (K)

5.3.1.6 Descriptor relationship: Direct influence of Water availability (TN) on Water demand (TN)

The influence of water availability is visible but not that significant on the water demand in the basin. The increase in water demand is influenced by the irrigation demand in the Tamil Nadu sub-basin. This demand doesn't strongly depend upon the available water from the Cauvery River because the irrigation demand is driven by the two rainfall seasons in Tamil Nadu. In the figure below, it is evident that the water demand is ever-increasing with increasing water availability.

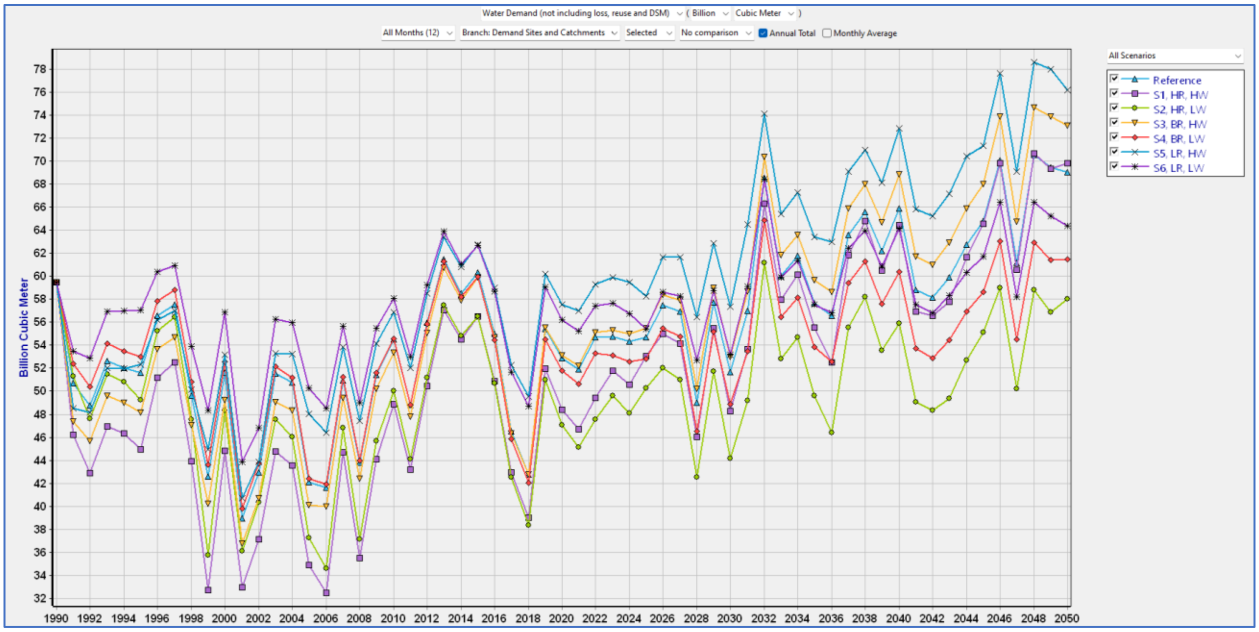


Figure 49 Water Demand in Tamil Nadu

a. Enough water availability in Tamil Nadu weakly promotes high water demand in Tamil Nadu. The water demand is increasing constantly in the basin due to the increasing population as well as the irrigation demands; however, the signal is weak. Therefore, this judgement score is +1.

b. Consequently, enough water availability in Tamil Nadu weakly restricts the high-water demand in Tamil Nadu. Therefore, this judgement score is -1.

c. Scarce water availability in TN also weakly promotes high water demand in TN. The pattern in the above figure is similar for high water demand as well as low water demand scenarios. Therefore, this judgement score is +1.

d. Consequently, scarce water availability in TN weakly restricts low water demand in TN. Therefore, this judgement score is -1.

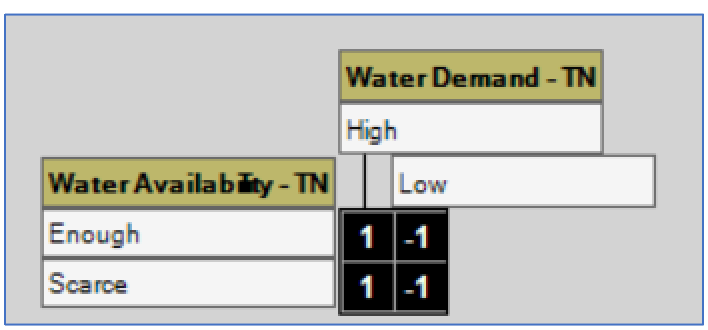


Figure 50 Interaction: Direct influence of Water availability (TN) on Water demand (TN)

5.3.1.7 Descriptor relationship: Direct influence of upstream Water availability (TN) on Water demand (TN)

The interaction from upstream water availability in TN to water demand in TN is like the interaction mentioned in the subsection 5.3.1.6 above. There is not much effect of upstream water availability in TN on the water demand in TN. The judgement scores are the same as that of interaction mentioned in subsection 5.3.1.6. The upstream water availability is measured at the Biligundulu station and does not affect the demands in the Tamil Nadu sub-basin.

a. Enough upstream water availability in TN weakly promotes high water demand in Tamil Nadu. The water demand is increasing constantly in the basin due to the increasing population as well as the irrigation demands. Therefore, this judgement score is +1.
b. Consequently, enough water availability in Tamil Nadu weakly restricts the high water demand in Tamil Nadu. Therefore, this judgement score is -1.
c. Scarce water availability in TN also weakly promotes high water demand in TN. Therefore, this judgement score is +1.
d. Consequently, scarce water availability in TN weakly restricts low water demand in TN. Therefore, this judgement score is -1.

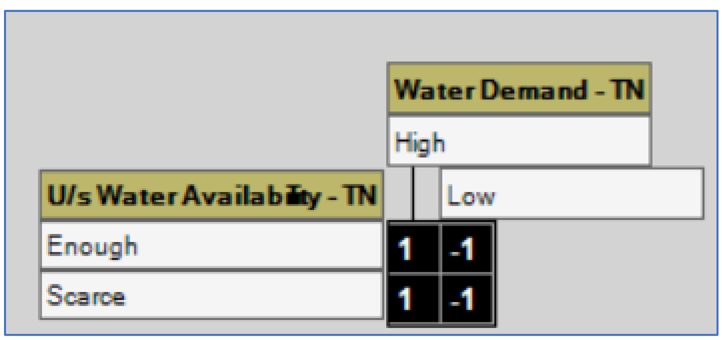


Figure 51 Interaction: Direct influence of upstream Water availability (TN) on Water demand (TN)

5.3.1.8 Descriptor relationship: Direct influence of Water Supply (TN) on Agricultural Productivity (TN).

The water supply delivered in the Tamil Nadu catchment is shown in Figure 52 below. The water supply delivered will continue to increase in future years in the Tamil Nadu catchment because it is dependent upon the water demand in the catchment. The figure shows the water supplied during high water demand scenarios.

Figure 52 Water supply delivered in Tamil Nadu catchment.

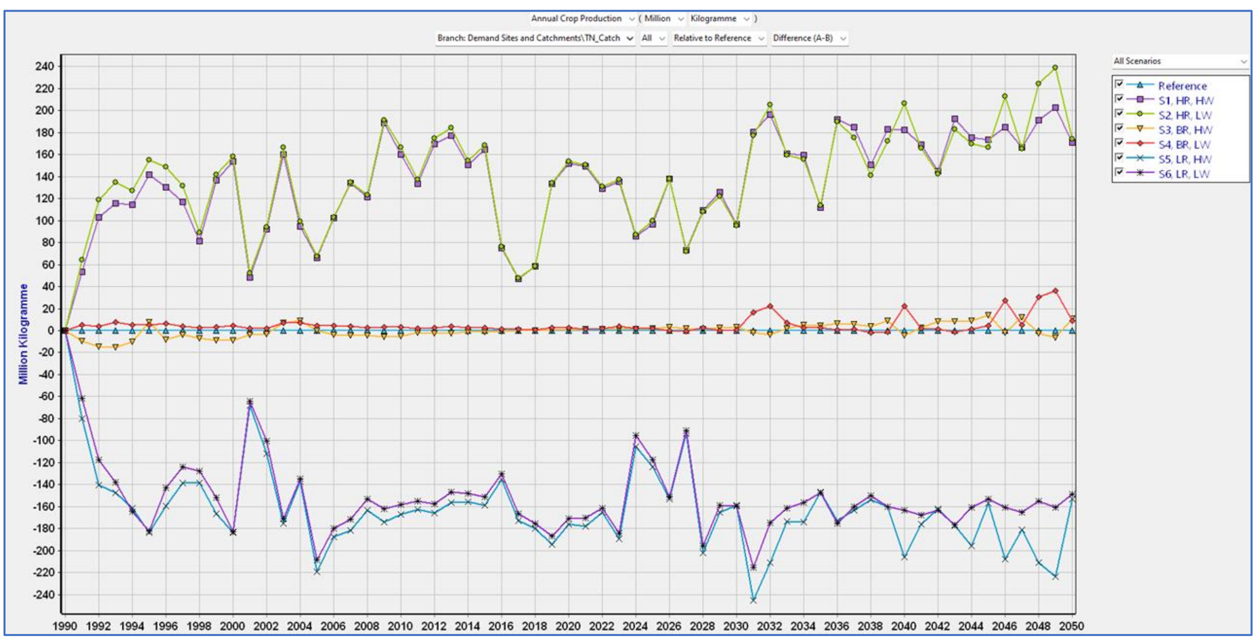
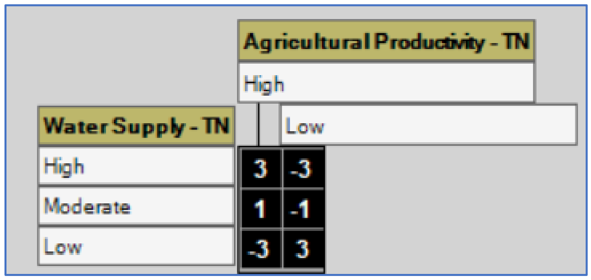


Figure 53 Agricultural productivity in Tamil Nadu

Figure 53 also depicts the productivity for scenarios where water demand is high. Agriculture productivity is high when the water supply is high, and productivity is low when the water supply is low. The scales are mentioned in Figure 53 above. The values shown are relative to business as usual. Therefore, the high water supply to Tamil Nadu leads to high agricultural productivity in Tamil Nadu. The judgement scores are therefore, ascertained accordingly and are mentioned in the figure below.



Water Supply - TN	Agricultural Productivity - TN: High	Agricultural Productivity - TN: Low
High	3	-3
Moderate	1	-1
Low	-3	3

Figure 54 Interaction: Direct influence of Water Supply (TN) on Agricultural Productivity (TN).

5.3.1.9 Descriptor relationship: Direct influence of Water Supply (TN) on Revenue Generation (TN)

The water supply to Tamil Nadu is mentioned in the preceding section. The relative revenue generated by Paddy is shown in Figure 55 below. High water supply in Tamil Nadu leads to higher revenue generated in the subbasin.

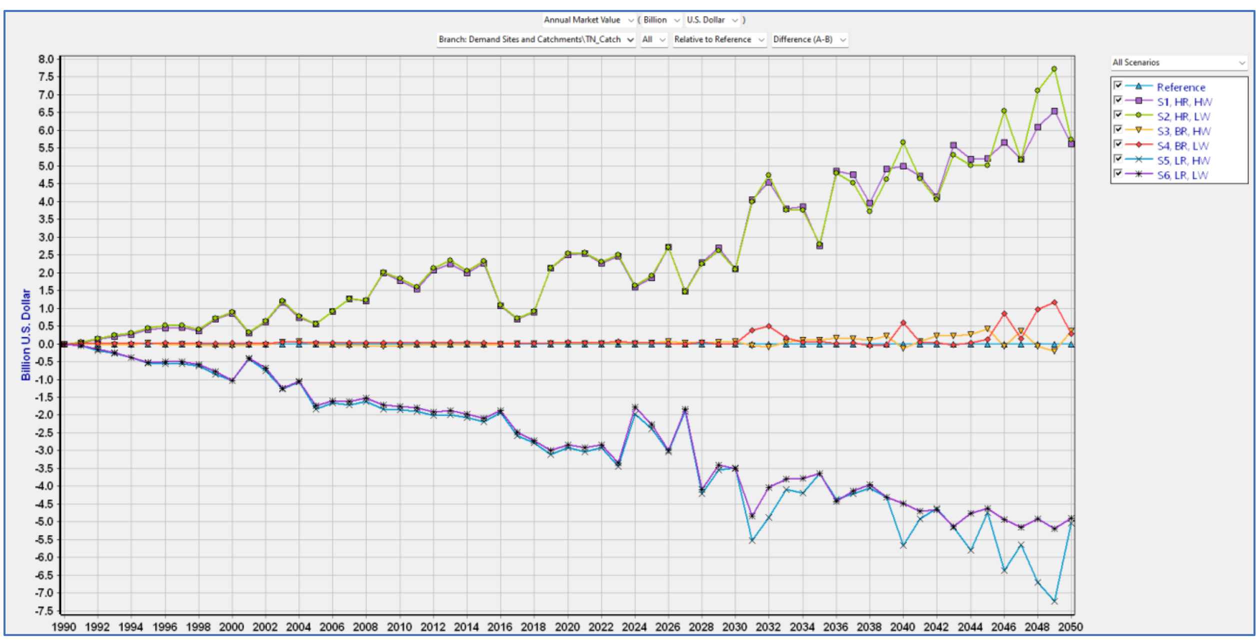


Figure 55 Annual market value of paddy

A low water supply would lead to low revenue generation as shown in the figure above. The moderate water supply is the business-as-usual case and leads to lower revenue generation in the province. The judgement scores are therefore, ascertained accordingly and are mentioned in the figure below.

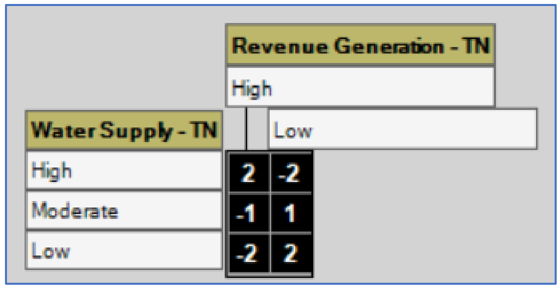
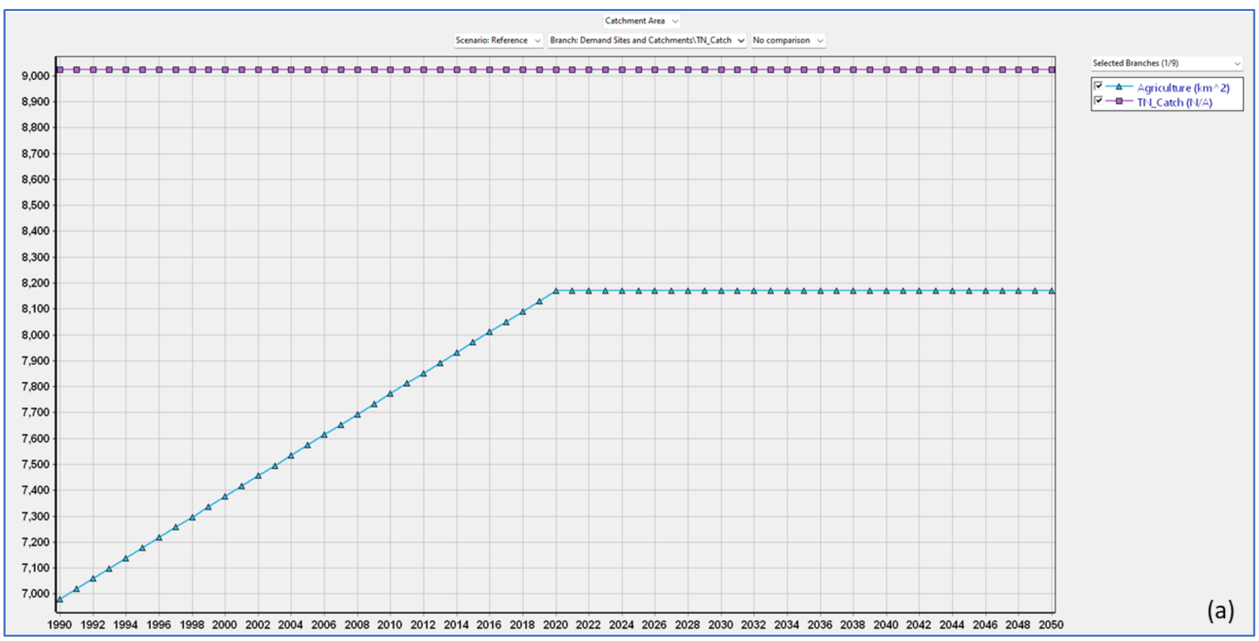


Figure 56 Interaction: Direct influence of Water Supply (TN) on Revenue Generation (TN)

5.3.1.10 Descriptor relationship: Direct influence of Agricultural productivity (TN) on Water demand (TN)

Agriculture production depends upon the area of agriculture and the subsequent irrigation in the area. Since the irrigation area is not increasing massively, the water demand is increasing slowly as well. Productivity is higher when the water availability is higher. Therefore, the direct influence of productivity on the water demand is strong. More productivity would mean more irrigation, hence more water demand.



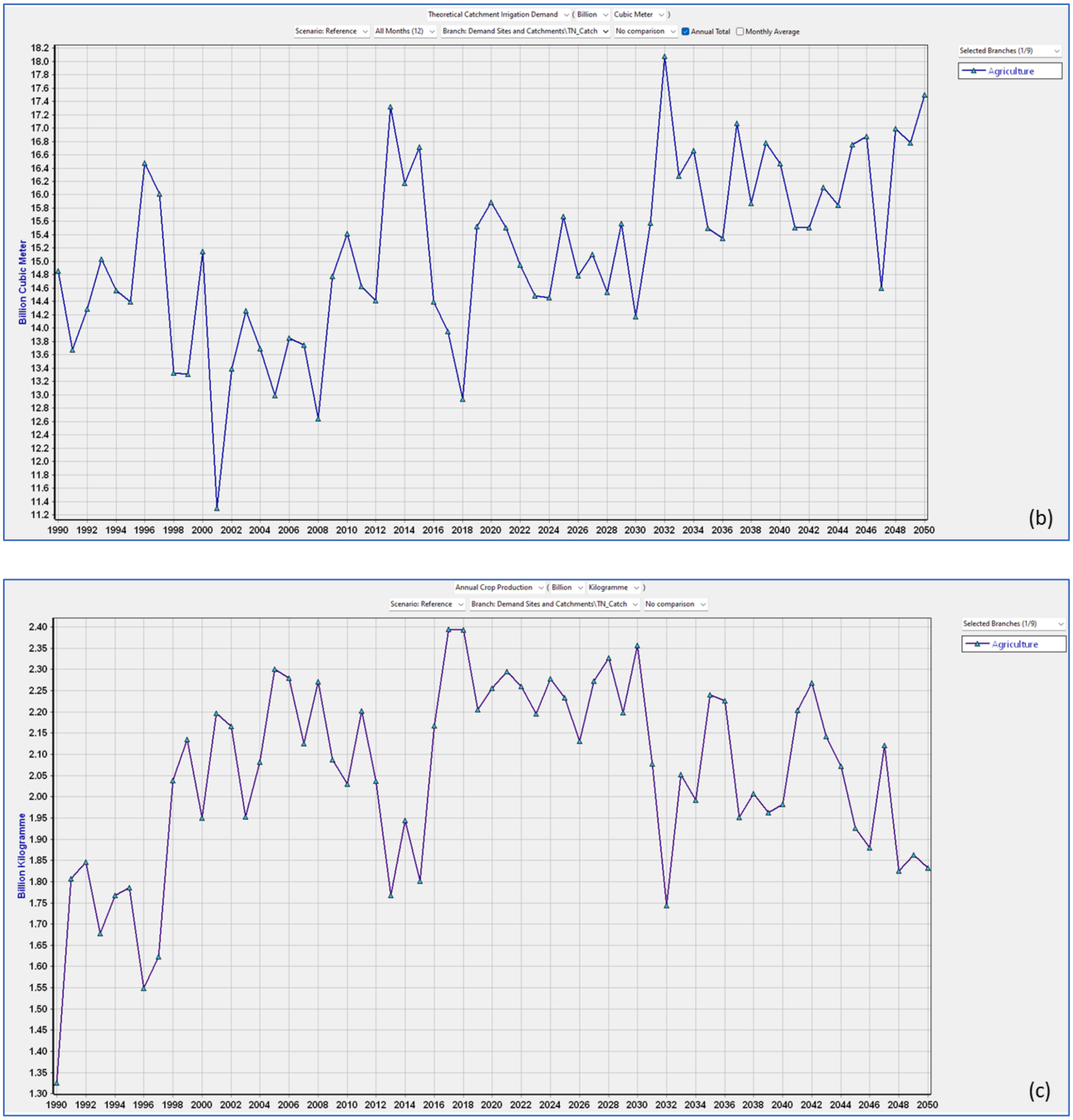


Figure 57 (a) Increase in agricultural area in Tamil Nadu catchment, (b) Theoretical irrigation demand in Tamil Nadu, and (c) Annual crop production in Tamil Nadu

Due to restrictions in the irrigated area (figure 57a), the increase in productivity is only possible if the theoretical irrigation demand is met. Figures 57b, and 57c need to be understood clearly. It can be seen from Figure 57b above that the irrigation demand is not steady and therefore not solely dependent over the agriculture area. Irrigation demand fluctuates with the fluctuations in the rainfall in the catchment. Since the water demand of the crops is not going to diminish, the theoretical irrigation demand will fluctuate based on the crop water requirements. The annual productivity of paddy would consistently require higher quantities of water. Not supplementing this demand is not an option, therefore, the higher the productivity, the higher the demand for the water used for irrigation.

a. High agricultural productivity in TN promotes high water demand in TN from the figures above. Therefore, this judgement score is +2.
b. Consequently, high agricultural productivity restricts low water demand in TN. Therefore, this judgement score is -2.
c. Also, low agricultural productivity in TN restricts high water demand in TN. Therefore, this judgement score is -2.
d. Consequently, low agricultural productivity in TN promotes low water demand in TN. Therefore, this judgement score is +2.

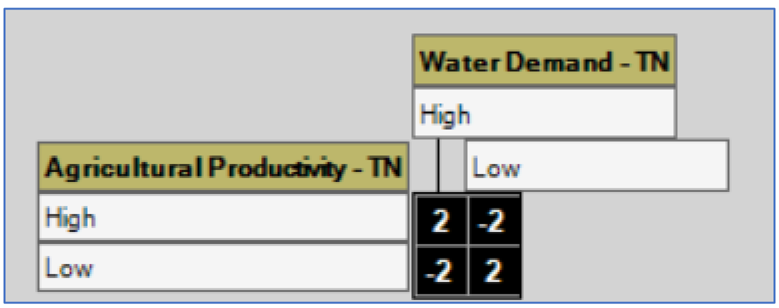
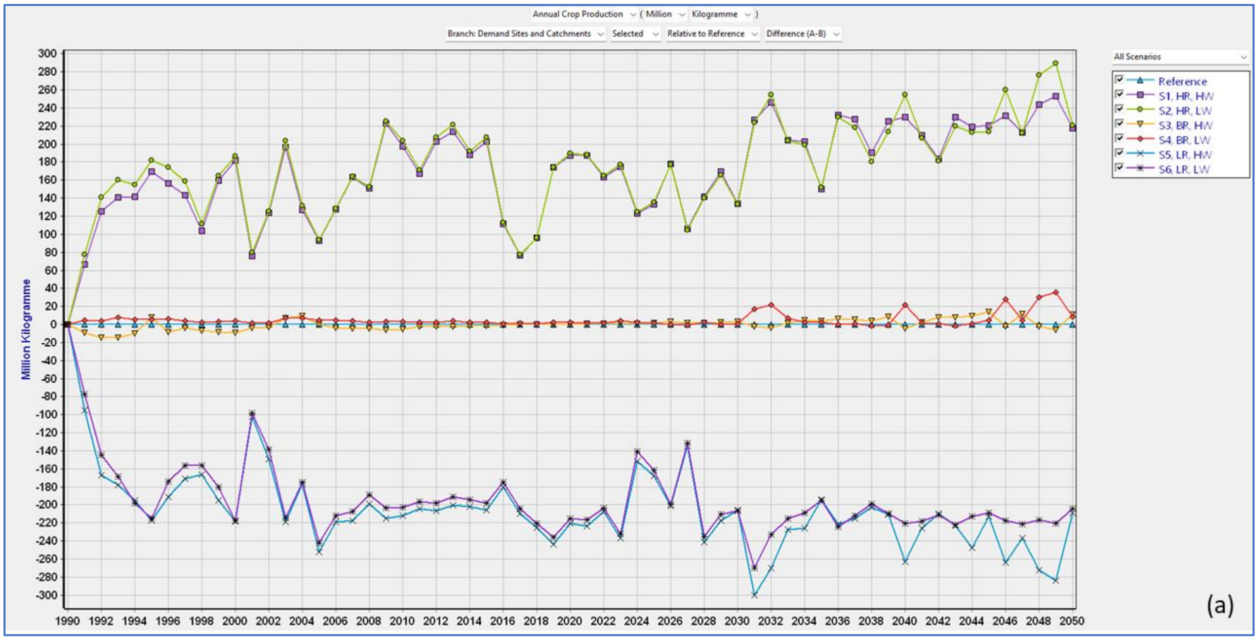


Figure 58 Interaction: Direct influence of Agricultural productivity (TN) on Water demand (TN)

5.3.1.11 Descriptor relationship: Direct influence of Agricultural productivity (TN) on revenue generation (TN)

This is a straightforward interaction. The annual prices of paddy are always increasing, therefore, the higher the agricultural productivity, the higher the revenue generation. Any increase in agricultural productivity leads to a direct increase in the revenue generation in paddy which is a proxy for revenue generation in Tamil Nadu. The signal is very strong; hence the judgment scores are at the end of the spectrum.



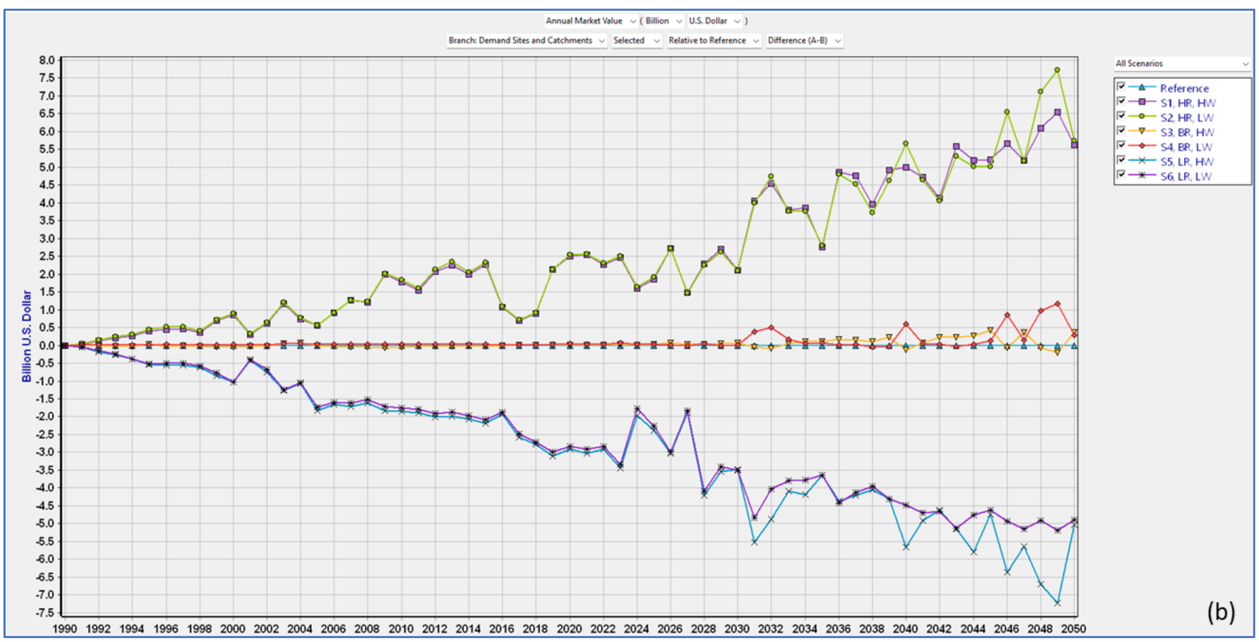


Figure 59 (a) Annual crop (paddy) production; (b) Annual market value

a. High agricultural productivity strongly promotes high revenue generated in Tamil Nadu for paddy. Therefore, this judgement score is +3.

b. Consequently, high agricultural productivity in TN strongly restricts low revenue generation in TN. Therefore, this judgement score is -3.

c. Also, low agricultural productivity in TN strongly restricts high revenue generation in TN. Therefore, this judgement score is -3.

d. Consequently, low agricultural productivity in TN strongly promotes low revenue generation in TN. Therefore, this judgement score is +3.

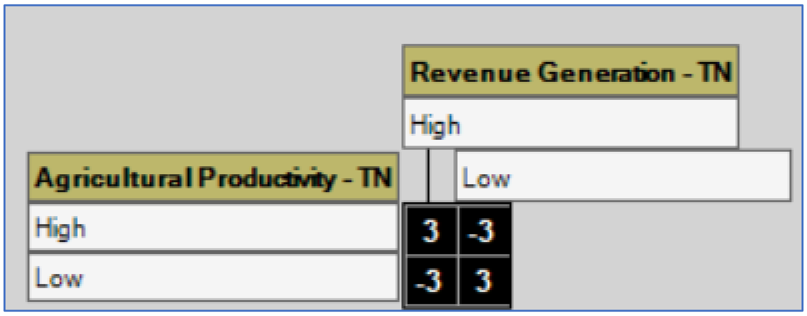


Figure 60 Interaction: Direct influence of Agricultural productivity (TN) on revenue generation (TN)

5.3.1.12 Descriptor relationship: Direct influence of Water demand (K) on upstream Water availability (TN)

Water demand in the Karnataka sub-basin affects the upstream water availability in Tamil Nadu faintly because higher water demand in Karnataka would mean less water available upstream in Tamil Nadu.

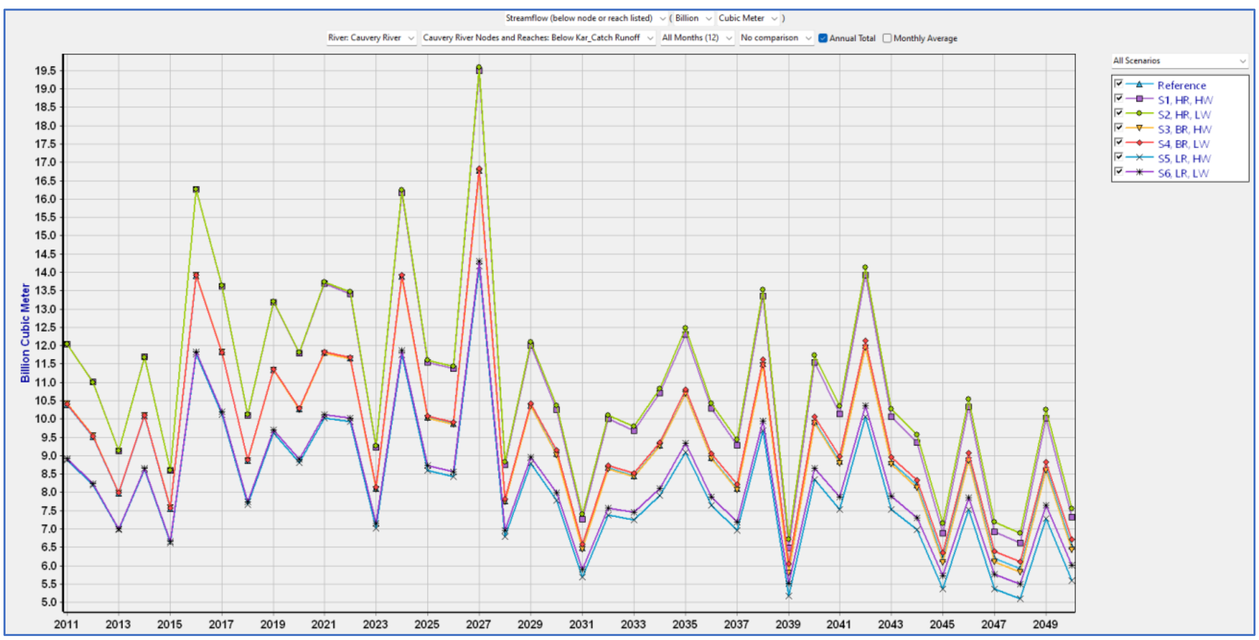


Figure 61 Stream flow from the Karnataka demand points

We measure the total simulated inflow into the Mettur Dam as a proxy for upstream water availability. The graph shown in the figure below is analyzed against the Karnataka catchment water demand. The high-water demand in Karnataka reduces the quantity of water flowing towards the Karnataka – Tamil Nadu border. The judgement scores are ascertained accordingly in the figure below.

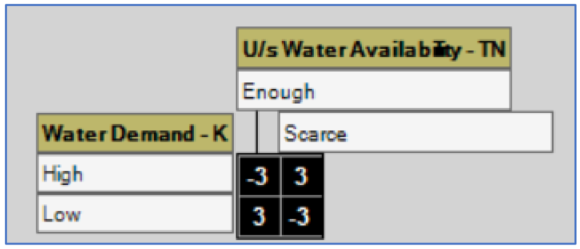


Figure 62 Interaction: Direct influence of Water demand (K) on upstream Water availability (TN)

5.3.2 Document analysis

Twenty-seven (27) interactions are coming from document analysis. Most of the data are taken from the Cauvery Water Disputes Tribunal rulings (CWDT, 2007e, 2007d, 2007c, 2007b, 2007a). The journal articles published by experts from the Cauvery River basin, and other relevant journals were also used to ascertain the judgment scores for this sub-section. Articles written in magazines and newspapers were also consulted to justify the judgment scores.

The judgement scores in this sub-section are generally determined using document analysis. For each type of interaction, there are a list of documents that the researcher went through. These documents were relevant to the provinces, and some discussed the interactions on a country level. As explained in the introduction section of this chapter, the judgement scores/values are whole numbers between -3 and +3. If all the documents confirmed the interaction influence, a strong "3" score is ascertained. If some of the documents do not confirm the interaction influence but more than half do, a score of "2" is ascertained. If less than half the documents confirm the interaction influence, a score of "1" is ascertained. Finally, if no interaction is found, a score of "0" is ascertained. This process of ascertaining the judgement scores is consistent throughout this sub-section, unless otherwise stated.

It is important to note that the literature on corruption in the Cauvery River basin related to water management is limited. The researcher has, therefore, used research articles talking about corruption in general in the provinces, and the country. The researcher has also cited multiple newspaper articles to support the arguments made. Increasing disagreement between facts and opinions have resulted in blurring of the lines between what is true and what is false. The articles with respect to "Corruption" are cited without any bias; however, journalistic predisposition may be kept in mind while reading the newspaper articles.

5.3.2.1 Descriptor relationship: Direct influence of Water Demand (K) on Water Supply (K)

The higher the water demand in Karnataka, the lower will be the possible water supply to the "demand sites". The supply-demand gap is ever-growing in the city of Bengaluru (Bangalore Water Supply and Sewerage Board, 2022; Raj, 2013).

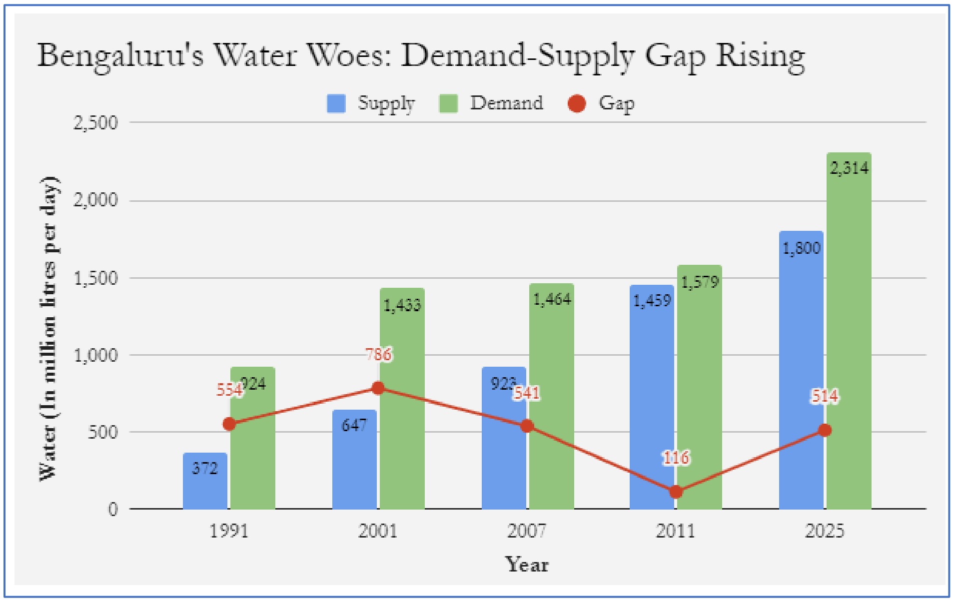


Figure 63 Observed demand and supply gap in Bengaluru (Chatterjee, 2018; Raj, 2013).

The figure above shows the demand, supply, and demand-supply gap values for the years 1991, 2001, 2007, 2011, and 2025 (projected).

Table 24 Demand supply gap in Bengaluru at different demand levels (Raj, 2015).

Year	Population (Lakhs)	Water Potential Available	Net Water Supply	UFW	Water Needs/Demand		Shortage	
					At 150 LPCD	At 200 LPCD	At 150 LPCD	At 200 LPCD
2000	57	705	433	218 (33)	862	1150	−157	−445
2001	62	705	458	220 (32)	934	1245	−229	−540
2002	64	995	462	250 (35)	966	1288	29	−293
2003	67	995	484	269 (36)	999	1333	−4	−338
2004	64	959	512	331 (39)	956	1275	3	−316
2005	65	959	542	340 (39)	981	1309	−22	−350
2006	67	959	531	372 (41)	1006	1342	−46	−383
2007	70	959	550	509 (48)	1032	1376	−73	−417

The table above shows the shortage in supply-demand at 150 and 200 LPCD (litres per capita per day). The consistent increase in water demand creates a strong signal towards decreasing water supply.

Consequently, the increasing demand for the province constantly restricts any possibility of increasing the water supply. Since the influence is strong, judgement scores of 3 and -3 are used. The low water demand does not have enough influence over the water supply; hence the judgement values are kept at zero.

a. High water demand in Karnataka strongly restricts high water supply in Karnataka.
b. High water demand in Karnataka weakly restricts moderate water supply in Karnataka. The influence of high water demand on the moderate or business-as-usual supply is still restricting as shown in Figure 47 Water Demand in Karnataka.
c. High water demand in Karnataka strongly promotes low water supply in Karnataka.
d. Low water demand in Karnataka does not influence the water supply in Karnataka.

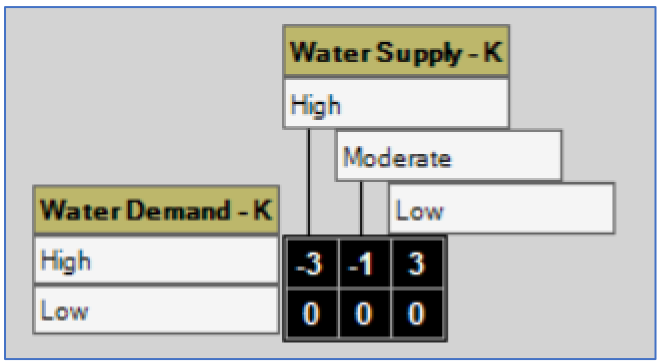


Figure 64 Interaction: Direct influence of Water Demand (K) on Water Supply (K)

5.3.2.2 Descriptor relationship: Direct influence of Water Demand (TN) on Water Supply (TN)

The higher the water demand, the lower will be the water supply. The influence of water demand in Tamil Nadu is like that of Karnataka. Most of the demand in Tamil Nadu is driven by irrigation. The Table 25 below shows the average annual water usage for rice showcasing the differences in the water demand for irrigation and the actual water supply. The scarcity and the average annual water use values are depicted for the three major paddy sowing seasons. *Samba* is generally in August to October, *Navarai* is generally December to January, and *Kuruvai* is generally from June to July (Ghosh & Bandyopadhyay, 2009; Government of Tamil Nadu, 2023).

Table 25 Scarcity value of water and water use for rice in the selected Cauvery Basin districts in Tamil Nadu (1987/88 to 2000/01) (Ghosh & Bandyopadhyay, 2009)

		Samba/Thaladi/Pishnam		Navarai/Kodai		Kar/Kuruvai/Sornavari	
Phase	Year	Scarcity value (kg m^{-3})	Average annual water use (in 10^9 m^3)	Scarcity value (kg m^3)	Average annual water use (in 10^9 m^3)	Scarcity value (kg m^{-3})	Average annual water use (in 10^9 m^3)
Late 1980s	1987/88 to 89/90	0.20889	11.49742	0.20746	0.57621	0.28021	0.65124
Early 1990s	1990/91 to 93/94	0.17163	11.25177	0.18930	0.96355	0.21309	1.57011
Mid-1990s	1994/95 to 96/97	0.14870	11.75764	0.19992	0.57099	0.21451	1.82149
Late 1990s to new millennium	1997/98 to 2000/01	0.17633	15.05974	0.22003	0.75109	0.22735	2.20993

When a resource is reduced in quantity or quality and the population grows, it further deteriorates the available resource and that creates unequal resource distribution (Homer-Dixon, 1994). The figure below shows the effect of the demand for a resource on the supply.

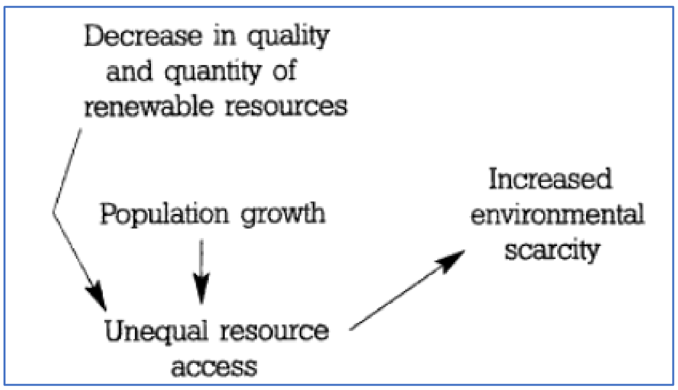


Figure 65 Resource depletion and population growth cause unequal resource access.

The steady increase in water demand over the years has a direct influence on the decrease in the water supply. The judgement scores are ascertained accordingly.

a. Based on the above information, high water demand in Tamil Nadu strongly restricts the high water supply in Tamil Nadu. Therefore, the judgement score is -3.
b. High water demand in Tamil Nadu weakly restricts moderate water supply in Tamil Nadu. The province has low water supply, most of the times hence the signal is weak. Therefore, the judgement score is -1.
c. Consequently, high water demand in Tamil Nadu strongly promotes low water supply in Tamil Nadu. Therefore, the judgement score is +3.

d. Low water demand in Tamil Nadu does not influence the water supply in Tamil Nadu. Therefore, the judgement scores are 0.

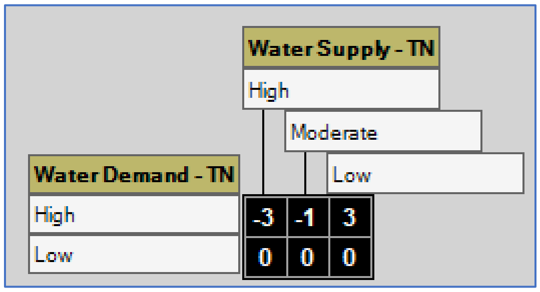


Figure 66 Interaction: Direct influence of Water Demand (TN) on Water Supply (TN)

5.3.2.3 Descriptor relationship: Direct influence of Water Demand (TN) on Social Unrest (TN)

The higher the water demand in Tamil Nadu, the higher will be the social unrest within the province. There is evidence throughout the last decade when the water demand has gone up, the social unrest in the basin has gone up as well. The people demanding the water supply would directly cause riots. The water from the Cauvery River is used in Tamil Nadu predominantly for agricultural purposes. The agricultural output from the basin, especially from paddy (rice), is responsible for the majority of GDP from the basin (B. Bouman, 2009; B. A. M. Bouman & Tuong, 2001; Chellaraj & Brorsen, 1988; The Better India, 2018). Therefore, if there is an instance where less water is available for irrigation, it is going to create unrest in the basin (Sivakumar, 2011).

Figure 67 Protests in Tamil Nadu after Karnataka refuses to share Cauvery Water. Source: (Madhav, 2016)

The figures above are from the 2016 agitation in the provinces. Since 1991, every time the tribunal has given out a result, it has resulted in riots and general social unrest in the basin (Chokkakula, 2014; Folke, 1998; Janakarajan, 2016).

Lobo, (2018c) reported that the high-water demand in the basin caused huge protests in the city of Chennai in Tamil Nadu because the government allowed the hosting of cricket matches for the Indian Premier League (IPL). Cricket games require large quantities of water for the maintenance of the grounds. There were widespread protests from all facets of society from politicians, movie stars, and farmers (Lobo, 2018a; The Hindu, 2018).

a. High water demand in Tamil Nadu promotes social unrest in Tamil Nadu. In the year 2018, social unrest in Tamil was one of the worst after a lean monsoon season (Express News Service, 2018). In more than half of the instances that high water demand has led to protests in Tamil Nadu. Therefore, the judgement score is +2.
b. Consequently, high water demand in Tamil Nadu restricts the status quo or no social unrest in Tamil Nadu. Therefore, the judgement score is -2.
c. Low water demand in Tamil Nadu restricts social unrest in Tamil Nadu. Lower water demand does not show any connection to social unrest. Therefore, the judgement score is -2.
d. Low water demand in Tamil Nadu promotes status quo or no social unrest in Tamil Nadu. If there is lower demand in the basin, then that will not cause any social unrest. Therefore, the judgement score is +2.

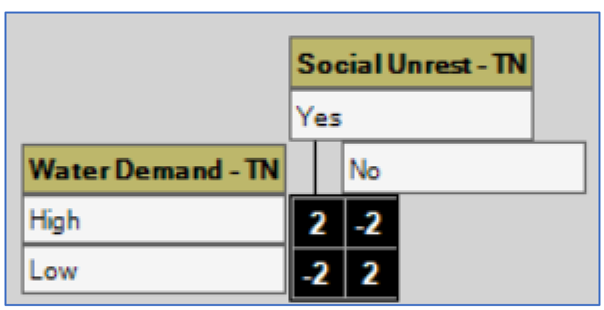


Figure 68 Interaction: Direct influence of Water Demand (TN) on Social Unrest (TN)

5.3.2.4 Descriptor relationship: Direct influence of Water Demand (K) on Social Unrest (K)

The higher the water demand in Karnataka, the higher will be the social unrest within the province. The influence is similar in Karnataka as it was in Tamil Nadu. However, the intensity of the riots is much more prominent. There is evidence of social unrest in the basin from 1991 up to 2018. In 1991, when the CWDT announced the first decision, there were many demonstrations throughout the basin in Karnataka (Folke, 1998). There has been similar unrest in Karnataka in the years 1995-96, 2002, 2007, and 2012 (Chokkakula, 2014; Janakarajan, 2016; Tiwari, 2016). Finally, in 2018, there was extensive property damage in the basin.

Figure 69 Unrest in Karnataka (Suri, 2018)

In the year 2002, a farmer killed himself by jumping into a reservoir to protest water deliveries to Tamil Nadu (Gleick & Heberger, 2014). Primarily, the unrest in the Karnataka subbasin was directed toward the people of Tamil Nadu origins. In 1991, twenty-three people were killed after the first CWDT decision was made. In 2012, many farmers in Karnataka tried to stop the flow of water to Tamil Nadu and many were injured in the process (Gleick & Heberger, 1998, 2014). Therefore, the judgement scores are ascertained accordingly.

a. High water demand in Karnataka promotes social unrest in Karnataka. Similar to the Tamil Nadu interactions, more than half the times in the last thirty years, an increased water demand has led to protests. Therefore, the judgement score is +2.
b. Consequently, high water demand in Karnataka restricts the status quo or no social unrest in Karnataka. Therefore, the judgement score is -2.
c. Low water demand in Karnataka restricts social unrest in Karnataka. Therefore, the judgement score is -2.
d. Low water demand in Karnataka promotes status quo or no social unrest in Karnataka. Therefore, the judgement score is +2.

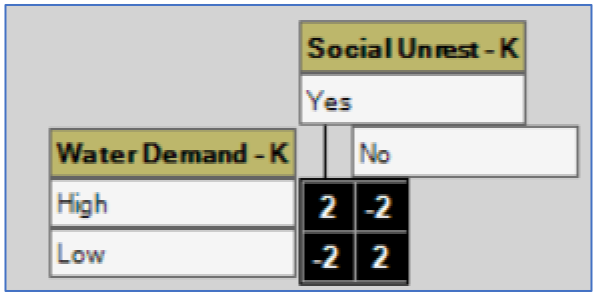


Figure 70 Interaction: Direct influence of Water Demand (K) on Social Unrest (K)

5.3.2.5 Descriptor relationship: Direct influence of Water Supply (K) on Water Demand (K)

This is an interesting interaction due to the Jevons Paradox. It is the idea that improvements in technology the increase the efficient use of a resource can paradoxically lead to an overall increase in consumption of that resource (Jevons, 1879; York, 2006). For example, in the field of agriculture, newer techniques like drip irrigation help in saving water. However, it may cause the farmers to employ this drip irrigation technique to expand the farming land, which will further increase overall water consumption (Sears et al., 2018).

In this case, the higher the water supply, the more users tend to use more water than moderate demand. Therefore, the judgement scores are ascertained accordingly.

a. High water supply in Karnataka promotes high water demand in Karnataka due to the reasons above. Therefore, the judgement score is +2.
b. Consequently, a high water supply in Karnataka restricts low water demand in Karnataka. Therefore, the judgement score is -2.
c. Moderate or business-as-usual water supply in Karnataka promotes high water demand in Karnataka. The moderate water supply is barely enough to offset the water demand in the basin (Dev, 2022; Karnataka Knowledge Commission, 2019; Press Trust of India, 2022b; Water Resources Group 2030, 2014). The city of Bengaluru (Bangalore) is estimated to become the next city to reach the Day Zero situation (World Bank Group, 2022). Therefore, the judgement score is +2.
d. Consequently, moderate, or business-as-usual water supply in Karnataka restricts low water demand in Karnataka. Therefore, the judgement score is -2.

e. However, in the case of low water supply, the water demand will be higher than it is in the case of moderate or business-as-usual water supply. Therefore, low water supply in Karnataka strongly promotes high water demand in Karnataka. Therefore, the judgement score is +3.

f. Consequently, the Low water supply in Karnataka strongly restricts low water demand in Karnataka. Therefore, the judgement score is -3.

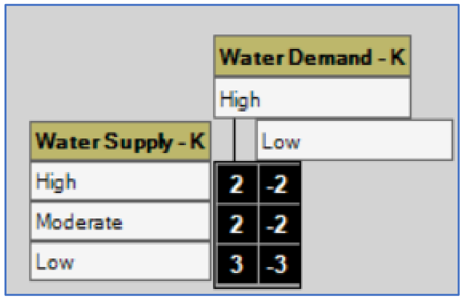


Figure 71 Interaction: Descriptor relationship: Direct influence of Water Supply (K) on Water Demand (K)

5.3.2.6 Descriptor relationship: Direct influence of Water Supply (K) on Revenue Generation (K).

The revenue is generated from the metered water lines to domestic users, industrial users, and agricultural users. If the water supplied to the end users is high, the revenue generated would be higher. The Bangalore Water Supply and Sewerage Board (BWSSB) maintains the data for the metered connections in the city of Bengaluru. As per the last data available, the BWSSB provides water to 12.9 million people in the city (Bangalore Water Supply and Sewerage Board, 2022).

The table below shows the relationship between the consumption of water and the domestic revenue generated by the municipality of Bengaluru (BWSSB). It provides a breakdown of the different aspects of water supply in the province.

Table 26 The consumption for 15 mm connections vs domestic tariff in rupees (₹) (Bangalore Water Supply and Sewerage Board, 2018)

Domestic Tariff for 15mm Connections					
Consumption	**Meter Service Charge**	**Water Amount**	**Sanitary Amount**	**Bill Amount (without borewell)**	**Bill Amount (with borewell ₹ 100)**
0	30	56	14	100	200
20000	50	188	47	285	385

40000	75	633	158	866	966
60000	150	1343	336	1829	1929
80000	150	2243	561	2954	3054
100000	150	3143	786	4079	4179

Table below shows the non-domestic tariff from the connections in Bengaluru. Increasing consumption increases the revenue generated here as well.

Table 27 The consumption for 15 mm connections vs non-domestic tariff in rupees (₹) (Bangalore Water Supply and Sewerage Board, 2018)

Non-Domestic Tariff for 15mm Connections					
Consumption	**Meter Service Charge**	**Water Amount**	**Sanitary Amount**	**Bill Amount (without borewell)**	**Bill Amount (with borewell ₹ 500 per HP)**
0	50	500	125	675	1175
20000	75	1070	268	1413	1913
40000	100	2330	583	3013	3513
60000	125	3740	935	4800	5300
80000	175	5315	1329	6819	7319
100000	175	7055	1764	8994	9494

It was reported by the Economic Times in 2017 that the Bengaluru development authority (BDA) and the BWSSB have consistently fallen short of their budgetary estimates (Joshi & ET Bureau, 2017). It was recently reported by The Hindu Bureau newspaper magazine that the BWSSB is trying to bridge the gap or the shortfall between the supply and the revenue generated (The Hindu Bureau, 2023). With the moderate or business-as-usual water supply, the revenue generation is low. The judgement scores are ascertained accordingly.

a. High water supply in Karnataka strongly promotes high revenue generation in Karnataka. Therefore, the judgement score is +3.
b. High water supply in Karnataka strongly restricts low revenue generation in Karnataka. Therefore, the judgement score is -3.

c. Moderate water supply in Karnataka weakly restricts high revenue generation in Karnataka. The business as usual or current water supply is generally less and that does not lead to high revenue generation. Therefore, the judgement score is -1.
d. Consequently, moderate water supply in Karnataka weakly promotes low revenue generation in Karnataka. Therefore, the judgement score is +1.
e. The low water supply in Karnataka strongly restricts high revenue generation in Karnataka. Therefore, the judgement score is -3.
f. Consequently, low water supply in Karnataka strongly promotes low revenue generation in Karnataka. Therefore, the judgement score is +3.

	Revenue Generation - K	
Water Supply - K	High	Low
High	3	-3
Moderate	-1	1
Low	-3	3

Figure 72 Interaction: Direct influence of Water Supply (K) on Revenue Generation (K)

5.3.2.7 Descriptor relationship: Direct influence of Water Supply (TN) on Water Demand (TN)

This interaction is somewhat like that of Karnataka. The province of Tamil Nadu is a water-scarce state with limited surface water resources and groundwater depletion due to over-extraction. Therefore, the supply-demand gap is growing (Ghosh & Bandyopadhyay, 2009). If there is a shortage of water supply, it can lead to an increase in water demand. The water demand in Tamil Nadu is driven by irrigation and domestic water needs (Venkatachalam, 2006).

The following table shows the estimated sectoral water demand until the year 2050. The demand is increasing constantly over the years.

Table 28 Estimates of sectoral water demand in Tamil Nadu (Suresh, 2021)

Category	2010	2020	2025	2030	2040	2050
	Volume in billion cubic meters (BCM)					
Irrigation	43.22	49.85	52.7	55.78	60.44	65.6
Domestic	1.0	1.2	1.5	2	3	4
Industry	1.5	1.7	2	2.5	3.5	4.5
Live stocks	0.8	0.9	1.015	1	0.97	0.94
Total	46.52	53.65	57.215	60.78	67.91	75.04

Jevon's paradox (Alcott, 2005; Jevons, 1879) still applies here for interactions 'a' and 'b' below. The interactions 'c', 'd', 'e', and 'f' are standard. The judgement scores are ascertained accordingly.

a. High water supply in Tamil Nadu promotes high water demand in Tamil Nadu. (+2)
b. High water supply in Tamil Nadu restricts low water demand in Tamil Nadu. (-2)
c. Moderate water supply in Tamil Nadu promotes high water demand in Tamil Nadu. (2)
d. Moderate water supply in Tamil Nadu restricts low water demand in Tamil Nadu. (-2)
e. Low water supply in Tamil Nadu strongly promotes high water demand in Tamil Nadu. (3)
f. Low water supply in Tamil Nadu strongly restricts low water demand in Tamil Nadu. (-3)

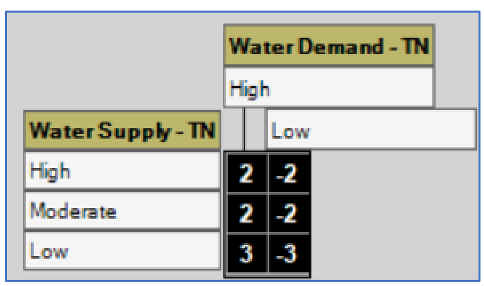


Figure 73 Interaction: Direct influence of Water Supply (TN) on Water Demand (TN)

5.3.2.8 Descriptor relationship: Direct influence of Revenue Generation (K) on Governmental Effectiveness (K)

The revenue generated in Karnataka sub-basin is predominantly from the metered connections in the city of Bengaluru. In the recently published Economic survey of Karnataka, presented by the provincial government, the percent composition of various sectors to the Gross Domestic Product (GDP) was noted.

The water supply services make up approximately 66% of the total GDP for the province of Karnataka (Rajneesh, 2022).

The following table is taken from the previously cited research, and it shows the percentage contributions from the three major sectors in Karnataka.

Table 29 Composition of Gross State Value Added (GSVA) of Karnataka state.

Product Sector	**%GSVA 2019-20**	**%GSVA 2020-21**	**%GSVA 2021-22**
Agriculture	12.3%	14.3%	14.1%
Industry	21.3%	19.4%	19.8%
Services	66.3%	66.3%	66.1%
GSVA	100%	100%	100%
Source: Directorate of Economics and Statistics, Government of Karnataka (2021-22)			

For the Karnataka sub-basin, which is part of the Cauvery River, the city of Bengaluru drives a majority of the revenue generated. If the revenue generated is higher, the government can become complacent and discontinue being effective. This is because when governments in developing countries have sufficient resources, they may feel less pressure to make changes or improvements in their policies or operations (Cottarelli, 2011). This interaction is shown in the first row of the figure 74 below.

Conversely, the revenue generated through the water supply connections in Bengaluru is not enough to improve worsening water supply infrastructure in the city (Bangalore Water Supply and Sewerage Board, 2022). This has caused the government of Karnataka to look for foreign investments in their infrastructure. The Asian Development Bank (2018) project is one example where the government is effectively trying to improve its infrastructure and in turn improve its effectiveness. However, the low revenue to governmental effectiveness interaction is weaker. Therefore, low revenue generation weakly promotes high government effectiveness, and weakly restricts low governmental effectiveness, respectively. Therefore, the judgement scores are ascertained accordingly in the figure below.

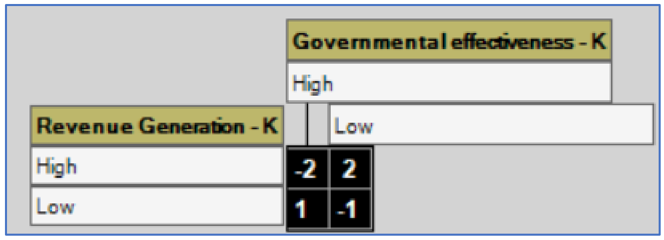


Figure 74 Interaction: Direct influence of Revenue Generation (K) on Governmental Effectiveness (K)

5.3.2.9 Descriptor relationship: Direct influence of Revenue Generation (TN) on Governmental Effectiveness (TN)

The Tamil Nadu subbasin of the Cauvery River basin utilizes its water for irrigation purposes. There is also evidence of use of groundwater use through the borewells. In this part of the subbasin, agriculture and agricultural activities make up a higher percentage of the state's Gross Domestic Product (GDP)(Tamil Nadu Government, 2020). Water from Cauvery is used in Tamil Nadu for various purposes. As shown in the table with estimates of sectoral water demands in Tamil Nadu (Table 28), a major portion of the water used is for irrigation purposes. Therefore, the agriculture productivity, and the revenue generated from paddy, is used as a proxy for the revenue generated for Tamil Nadu. As in the case of Karnataka, the higher the revenue generated through the sale of paddy, the lesser would be the effectiveness of the government because they would get complacent and stop investing in the improvement of the infrastructure.

Chennai, the capital city of Tamil Nadu, water supply and sanitation board in the year 2000 received 165 crores rupees (1 crore rupees is approximately 120, 880 USD) with a total of 656 crores for the water supply in the city. This money was received from financial institutions to offset the revenue gap generated against the services rendered (Ruet et al., 2002). The International Monetary Fund (IMF) report of the Tamil Nadu government's fiscal challenges published in the year 2020 detailed the consistent revenue deficits over the last ten years (Fisher et al., 2020). Tamil Nadu government has tried to provide irrigation facilities for the farmers in the basin. The government has consistently raised the issue of non-release of stipulated quantities of water by Karnataka in front of the federal government. However, this interaction is weak. Therefore, low revenue generation weakly promotes high government effectiveness, and weakly restricts low governmental effectiveness, respectively. The judgement scores are ascertained accordingly in the figure below.

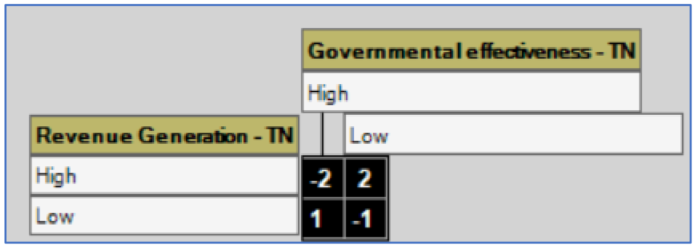


Figure 75 Interaction: Direct influence of Revenue Generation (TN) on Governmental Effectiveness (TN)

5.3.2.10 Descriptor relationship: Direct influence of Governmental Effectiveness (K) on Water Supply (K)

The water supply in Karnataka is affected by governmental effectiveness in Karnataka. The more effectively a government is run, the more attention can be laid on the water supply issues in the province. The government in Karnataka has generally not been able to bridge the gap between demand and supply (Buurman & Santhanakrishnan, 2017). The supply in the climate change-affected years has faltered. During these years, the government had to decide not to release the stipulated quantities of water to the downstream province of Tamil Nadu. In the year 2003, the Karnataka government carried out a pilot study in 28 cities to determine the possibility of providing a 24X7 water supply. The study was funded by the International Bank for Reconstruction and Development and the Government of Karnataka for a total of 52.7 million USD.

A study was published in 2010 summarising the findings of the pilot study. The study concluded that the 24X7 water supply in Karnataka is only possible with a long-term commitment from the donors and the government. The pilot projects were a success; however, the longevity and the quality of the water supply are going to be challenging (Franceys & Jalakam, 2010). The governmental effectiveness in the subbasin has been generally low when it comes to managing natural resources and water supply matters. Also, the water utilities systems rely heavily on human capacity for monitoring meters among other works. A province like Karnataka with strong ethnic divisions and an ineffective government can lead to further water supply scarcity issues (K. Kim & Swain, 2017). The low governmental effectiveness has led to a consistently low water supply in the Karnataka subbasin. This consistently lower effectiveness of government is synonymous with moderate and low water supply. That is what is shown in the interactions figure below with the judgement scores. Consequently, high governmental effectiveness would lead to a high water supply.

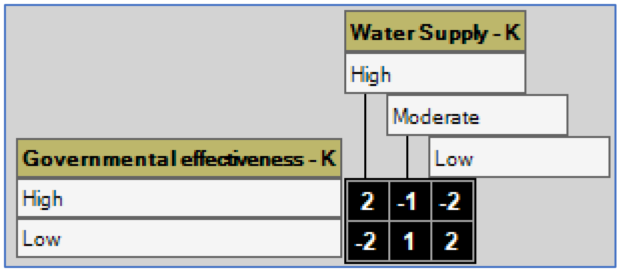


Figure 76 Interaction: Direct influence of Governmental Effectiveness (K) on Water Supply (K)

5.3.2.11 Descriptor relationship: Direct influence of Governmental Effectiveness (K) on Social Unrest (K)

Social unrest and or rioting is sometimes caused by a lack of governmental awareness and effectiveness. In Karnataka, the issue of the Cauvery River conflict has raised many challenges for the government. Sustaining the water supply in the river and protecting the water rights of the people living near the water source is one of the biggest challenges for the province. Therefore, whenever the government is unable or unwilling to protect its citizens, it can lead to unrest in the basin.

With a conflict like that of the Cauvery River, politics sometimes takes centre stage. The citizens of the province can be overly attached to their political leaders and even idolize them. Therefore, this can lead to people making sacrifices for their chosen leaders. When agitated, the people may riot to support or show loyalty to their leaders. Unfortunately, violent demonstrations and riots have occurred in the basin generally because of the Cauvery dispute (Sivakumar, 2011). In Bengaluru, the local citizens were agitated to cause rioting in September 2016. As per reports, the governments in the subbasin have not been able to control the extremists in its province. These people have created an agitation based on the distinct linguistic identities in the province. The government’s effectiveness needs to improve if it must solve the city's challenges (Tiwari, 2016).

Low governmental effectiveness promotes the possibility of social unrest. High governmental effectiveness will restrict social unrest. However, either high or low governmental effectiveness do not guarantee that there will be no social unrest. Therefore, the judgement scores in the second column in the figure below are 1 and -1, respectively. The judgement scores are ascertained accordingly.

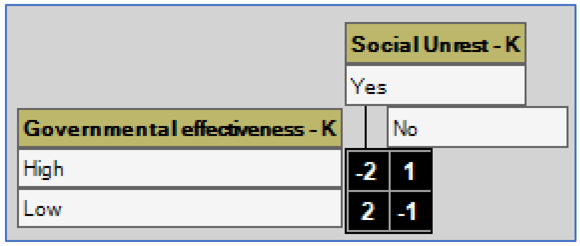


Figure 77 Interaction: Direct influence of Governmental Effectiveness (K) on Social Unrest (K)

5.3.2.12 Descriptor relationship: Direct influence of Governmental Effectiveness (K) on Openness to negotiate with TN.

Karnataka being the upstream province has an unfair advantage in the sharing of Cauvery River water. In the last thirty years, the province has refused to release the stipulated quantities of water in the years where they have felt short on water supply (Janakarajan, 2010). The government's effectiveness in making sure that ample water supply is available for its citizens is key to the openness to negotiate with Tamil Nadu. Karnataka has always maintained that back in the year 1924 when the first agreement on the sharing of the Cauvery River waters was passed, it was one-sided and against them. This grievance has pushed the province to have a general sense of dissatisfaction with any judicial agreements on this matter (Iyer, 2013). The Karnataka government's willingness to negotiate with the province of Tamil Nadu is affected by its effectiveness (Babu, 2008).

The possibility of a balanced negotiated agreement between the two provinces is required for an amicable resolution. However, there is still a considerable amount of animosity between the two states. As recently as 2022, the governments of both provinces were at loggerheads due to a project known as *Mekedatu* in the Cauvery River basin (Press Trust of India, 2022a). *Mekedatu* is a dam/reservoir construction project in the province of Karnataka. Tamil Nadu feels that when the dam is fully constructed, it is going to further restrict the flow of water from Cauvery (Cauvery Neeravari Nigam Limited, 2019; Press Trust of India, 2022a, 2023).

Therefore, the higher the governmental effectiveness, the more open Karnataka would be open to negotiating a fair agreement with the province of Tamil Nadu. And based on the current lower level of effectiveness in government, a willingness to negotiate with Tamil Nadu is not there. Therefore, the judgement scores are ascertained accordingly in the figure below.

Governmental effectiveness - K	Openness to Negotiate with TN: Yes	Openness to Negotiate with TN: No
High	2	-2
Low	-2	2

Figure 78 Interaction: Direct influence of Governmental Effectiveness (K) on Openness to negotiate with TN

5.3.2.13 Descriptor relationship: Direct influence of Governmental Effectiveness (TN) on Water Supply (TN)

The water supply in Tamil Nadu's irrigation sector is affected by how well the government is investing in the infrastructure. In a study carried out under the Negotiating peri-urban water conflicts (NEGOWAT) project (Ducrot, 2006), the researchers looked at some of the major water conflicts in the world. Water supply in the Cauvery River basin was one of the conflicts they looked at. Over thirty years, the government of Tamil Nadu had spent more than 30 billion INR (approximately 500 million USD) for augmenting the water supplies in the metropolitan city of Chennai; however, the problem persists. The average per capita water supply is one of the lowest in any city with that range of the population in India. It was reported that even during the good rainfall years, the water supply is extremely unreliable and sporadic with water supply for only three hours a day (Janakarajan, 2004). There is a need for an Integrated Water Resources Management (IWRM) approach in resolving the conflict otherwise the whole province would become dependent upon portable tankers and installed pumps (Bhatia et al., 2006; Raju et al., 2013; Ram & Irfan, 2021).

There have been consistent droughts and floodings in the Tamil Nadu subbasin. Within the last decade the city of Chennai has experienced some of the worst floods in 2015 and then immediately followed by the worst drought ever in the last thirty years. The Chennai Metropolitan Development Authority (CMDA) needs to take up more responsibility as the planning and regulatory body in ensuring better water governance (Roy & Ayyangar, 2022). The government's effectiveness in developing adaptive measures to ensure the water supply in the current situation and the future under exacerbated conditions is important (Govt of Tamil Nadu, 2018). Hence, reduced governmental efficiency would result in a moderate to low water supply, showing a diminishing range of variation.

Low governmental effectiveness weakly promotes moderate or business as usual water supply in the province. This is the status quo in the province right now. Consequently, high governmental effectiveness weakly restricts moderate water supply. The other judgement scores are standard. The judgement scores are ascertained accordingly in the figure below.

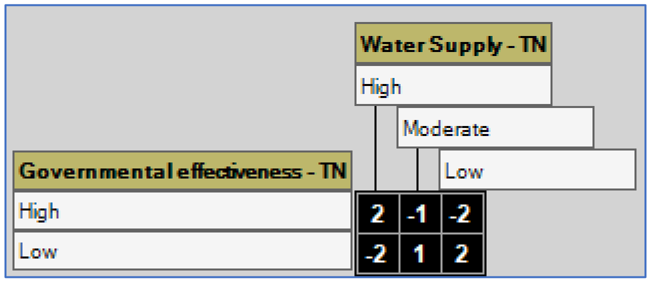


Figure 79 Interaction: Direct influence of Governmental Effectiveness (TN) on Water Supply (TN)

5.3.2.14 Descriptor relationship: Direct influence of Governmental Effectiveness (TN) on Social Unrest (TN)

The social unrest in Tamil Nadu has been in the news quite a lot lately. In the last three decades, there have been several times when people have taken to the streets and rioted for their demands. Several of the processions led by the people have become violent and it would require understanding on either side of the state border to resolve the conflict (Meenakshisundaram et al., 2010). The government in the province has tried to compensate the people who have lost personal artifacts in the riots since 1991. The riots in 2000, 2007, 2016, and 2018 have caused a lot of damage to people and property (Bangalore Mirror Bureau, 2016; Chokkakula, 2016; J. Gupta, 2016; Lobo, 2018b; Pavan, 2012; Willford, 2018).

The riots in the basin tend to proliferate across the borders. The Tamil language-speaking population living in Karnataka becomes an easy target when unrest breaks out. This does not bode well for the Tamil government (Willford, 2018). Governmental effectiveness in the basin has an extremely profound effect on the social unrest in the basin.

Low governmental effectiveness promotes the possibility of social unrest. High governmental effectiveness will restrict social unrest. However, either high or low governmental effectiveness do not guarantee that there will be no social unrest. Therefore, the judgement scores in the second column in the figure below are 1 and -1, respectively. The judgement scores are ascertained accordingly.

Governmental effectiveness - TN	Social Unrest - TN: Yes	Social Unrest - TN: No
High	-2	1
Low	2	-1

Figure 80 Interaction: Direct influence of Governmental Effectiveness (TN) on Social Unrest (TN)

5.3.2.15 Descriptor relationship: Direct influence of Social Unrest (K) on Openness to negotiate with TN.

The social unrest in the Karnataka subbasin affects its ability to negotiate a fair agreement with the province of Tamil Nadu. Sometimes, during the unrest, the people of Tamil origin were specifically targeted in Karnataka (Lodaya & Mukherjee, 2016; Safi & Doshi, 2016). Due to the proximity to the province as well as Bengaluru being the IT hub, a lot of people have migrated to this part of the province. If there are more such incidents in the basin, it is going to seriously impede any progress that can be made toward a fair agreement. Such unrest and riots in the Karnataka subbasin create a negative image of the province. They would want to resolve this as soon as possible and diplomatically. This is evident from the recent protests by farmers in India against the agricultural price raise by the federal government (Pradhan, 2021). Therefore, the higher the social unrest in Karnataka, the more they would want to negotiate with Tamil Nadu. Also, there is a weak chance that this social unrest can lead to no negotiations. The judgement scores are ascertained accordingly.

Social Unrest - K	Openness to Negotiate with TN: Yes	Openness to Negotiate with TN: No
Yes	3	-1
No	-1	3

Figure 81 Interaction: Direct influence of Social Unrest (K) on Openness to negotiate with TN

5.3.2.16 Descriptor relationship: Direct influence of Revenue Generation (K) on Corruption (K)

The revenue generated in the subbasin is from the money collected through the metered connections. The annual money generated, although not enough for offsetting the demand in the basin, is still quite a large number. The annual budget of the Bangalore Water Supply and Sewerage Board for the year 2020-

21 was 2,893,060,000,000 INR (approximately 35 billion USD) (Bangalore Water Supply and Sewerage Board, 2021). BWSSB is the wealthiest municipality in India as reported by the Business Standard newspaper in the year 2022 (Gera & Kumar, 2022). Wealth may support corruption. Corruption in the water and sanitation sector is a significant problem in countries in Southeast Asia and is driven by factors like weak governance, inadequate accountability mechanisms, and insufficient public participation (J. Davis, 2004). There are multiple examples of corruption from the last few years (ANI, 2022; Johnson, 2022). Therefore, it may be assumed that higher the revenue generated by the government in the subbasin, the higher would be the corruption in the basin. The judgement scores are ascertained accordingly.

The study conducted by Kandukuri (2015) detailed the monetary discrepancies in the province of Karnataka. There are other instances of corruption from lower levels of the government (Muniraju & S, 2018) to the highest levels (Bhende & Yatanoor, 2017; Fernandes & Shetty, 2016). It is assumed, that if the revenue generated is low, corruption would not happen, because the opportunity would cease to exist. The judgement scores are ascertained accordingly.

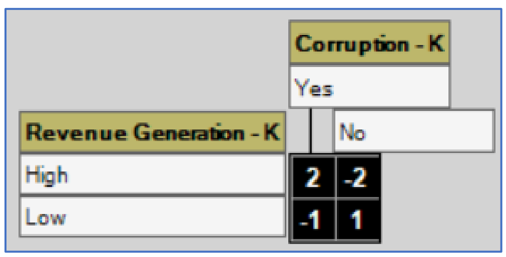


Figure 82 Interaction: Direct influence of Revenue Generation (K) on Corruption (K)

5.3.2.17 Descriptor relationship: Direct influence of Revenue Generation (TN) on Corruption (TN)

Chennai is the biggest metropolitan city in the Tamil Nadu sub-basin with a population of 10.97 million and annual budget of USD 16.30 Billion in the year 2019-20 (Tamil Nadu Government, 2020). In comparison, the population of Toronto is 2.79 million with an annual budget of USD 11.27 Billion for the year 2022 (Tory & Taylor, 2022). The corruption statistics state-wise are listed in the table below (Dutta et al., 2013). The provinces of Karnataka and Tamil Nadu are both in the top ten corrupt states in India based on this study. However, Tamil Nadu's ranking of 9 is bolstered almost entirely by corruption in the water supply sector (Dutta et al., 2013).

Table 30 Corruption in Indian provinces (Dutta et al., 2013)

States	Corruption (2004–05) [1]	Corruption (2007)
No change		
1. Bihar	695 (1)	Alarming
2. Jammu and Kashmir	655 (2)	Alarming
3. Madhya Pradesh	584 (3)	Alarming
4. Karnataka	576 (4)	Very high
5. Rajasthan	543 (5)	Very high
6. Assam	542 (6)	Very high
7. Tamil Nadu	509 (9)	Very high
8. Delhi	496 (10)	High

There are incentives for corruption if there is more than enough money coming into the state. Also, lack of accountability, and disproportionate distribution of power leads to corruption (Mistry, 2012). The growth of Paddy in the basin is responsible for at least 30 percent of the GDP of the whole state for the last few decades (Jayakumara & Pramod, 2012; Karthick et al., 2020; Kuppannan et al., 2017; Mariappan & Das, 2017). With the Cauvery River subbasin forming the majority of the portion of the state where paddy is grown, the percentage of paddy contributing to the GDP of the state is going to increase only. The province of Tamil Nadu is dependent on paddy and will persist until the year 2050. Even with decreasing yield, the prices will always go up. In the Tamil Nadu subbasin, all the districts have paddy as the most-grown crop. This translates directly into the annual revenue generated in the basin (Paramasivan & Pasupathi, 2016). The government of Tamil Nadu supports the agriculture industry by buying the products at ensured rates to safeguard the farmers from facing hardships due to fluctuations in the climate. However, recently, the government increased the price at which they buy paddy from the farmers by INR 1 per kilogram (MD, 2022). The farmers have protested this move by accusing the government of bottling the profits from Paddy and trying to cheat the farmers. The 2017 agreement between the government and the farmers, which was highlighted and commended by the World Bank also seemed to be overlooked while deciding to meagrely increase the buy price (World Bank, 2017). The government of India's Minimum Support Price (MSP) portal provides evidence. The MSP has only increased slowly in the province of Tamil Nadu, which is in contrast to the federal government's directives (Arthi T et al., 2018; Rajendran, 2021).

Therefore, the higher the revenue generated in the province, unfortunately, the greedier the people in charge become, and that ultimately leads to corruption. It is assumed, that if the revenue generated is low, corruption would not happen, because the opportunity would cease to exist. The judgement scores are ascertained accordingly.

Revenue Generation - TN	Corruption - TN: Yes	Corruption - TN: No
High	2	-2
Low	-1	1

Figure 83 Interaction: Direct influence of Revenue Generation (TN) on Corruption (TN)

5.3.2.18 Descriptor relationship: Direct influence of Governmental Effectiveness (K) on Corruption (K)

An effective government in any state works proactively to remove probable instances of corruption. An effective government is more careful with the taxpayer's money and invests the money in projects that are going to be useful for the citizens. However, an ineffective government would not be able to control the money going to corrupt causes. An effective government with a strong political will promotes the establishment of strong financial institutions that would help curb corruption (Gaspar et al., 2019). For example, statistical analysis referred to Mauro (1997) claims that government spending on education as a ratio to the GDP is negatively and significantly correlated with corruption, i.e., less spent on education, means more corruption. The judgement scores are ascertained accordingly.

In Karnataka, the Karnataka Urban Water Sector Improvement Project (KUWASIP) was tasked with demonstrating the possibility of a 24-hour water supply. The project was run from the year 2005 to 2011. With the kind of funds invested in the project, it could be demonstrated that only 30% of the households could be supplied with a round-the-clock water supply. The researchers at the time had concluded that the government would have to work more efficiently to make sure that the currently connected households receive the same quality of water. It was feared that an ineffective government may misappropriate the funds received and would not invest in projects that may help the people (Franceys & Jalakam, 2010). The government of the subbasin has a responsibility to safeguard the fundamental rights of its citizens. They also have an opportunity to affect positive social change by making sure that they invest in the people (Pani, 2009).

Therefore, high governmental effectiveness would promote no corruption in the basin. Consequently, low governmental effectiveness would lead to high levels of corruption in the basin. The judgement scores are ascertained accordingly.

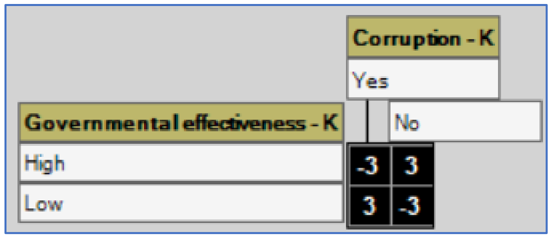


Figure 84 Interaction: Direct influence of Governmental Effectiveness (K) on Corruption (K)

5.3.2.19 Descriptor relationship: Direct influence of Governmental Effectiveness (TN) on Corruption (TN)

The influence of the effectiveness of governmental actions on corruption is like that in the province of Karnataka. If the governments can identify projects that will be less susceptible to corruption, it will lead to a positive scenario altogether for the citizens (Mauro, 1997). The disconnect between the government and the needs of its citizens can lead to corruption. Lewis (2017) explained how this disconnect perpetuates in society. The needs of a citizen are communicated to the local municipal authority. The local authority may or may not reciprocate the requirements to the provincial governments based on their vested interests. An effective governmental structure would recommend and practice honest and transparent communication negating the possibility of corruption (Lewis, 2017).

Naseer (2019) reported that the opposition accused the incumbent government of Tamil Nadu of not being able to handle the water crisis. They claimed that the policies of the government incentivized corruption and that caused the water crisis to boil over. In another case, the direct procurement centres for the sale of paddy, set up by the government of Tamil Nadu, had turned to the exploitation of the farmers due to ambiguous sale prices (Rajendran, 2021). Procurement pricing of paddy has been in contention for some time now in the state with the current government getting accused multiple times of nefarious policies (MD, 2022). It was also reported by CNBC News in India that a lack of vision from the government is causing Chennai's water supply crisis (Consumer News and Business Channel, 2019). There were reports in the year 2019 of residents in Chennai who have been trying to apply for a metered connection since 2011 and have not received proper support from the government for the last 8 years. The people told the reporters that the water authority officials often ask for bribes before submitting the applications. Based on these accusations, a First Information Report (FIR) was registered against the superintended engineer of the municipal corporation in Chennai (Prabhakar, 2019).

Therefore, a highly effective government would lead to no corruption and conversely, an ineffective government would lead to high corruption. The judgement scores are ascertained accordingly.

	Corruption - TN	
Governmental effectiveness - TN	Yes	No
High	-3	3
Low	3	-3

Figure 85 Interaction: Direct influence of Governmental Effectiveness (TN) on Corruption (TN)

5.3.2.20 Descriptor relationship: Direct influence of Corruption (K) on Revenue Generation (K)

The presence of corruption in the Karnataka sub-basin would mean fewer monetary resources available to be invested in infrastructure development. Lower quality and inefficient water supply systems would generate more distrust among the citizens, and they will be forced to investigate other methods of water supply, like water tankers, etc. (Reddy, 2020a). These tankers, although expensive, became more and more accessible. Ever since the local authorities failed to provide efficient water supply infrastructure to areas farther from the city centres, tankers have become an integral part of society (Reddy, 2020b). The judgement scores are ascertained accordingly.

Two independent studies were conducted by the International Monetary Fund (IMF) (A. Sen Gupta, 2007) and the Leibniz Information Centre for Economics (Bird et al., 2004) on the effects of corruption on revenue efforts in developing countries. They concluded that developing countries (they did not include India in the analysis) with corruption will lead to a reduction in revenue. The high-income developing countries, arguably like India, are more volatile due to high disparity in incomes (Ajaz & Ahmad, 2010; Bird et al., 2004).

Therefore, high corruption in Karnataka would lead to low generated revenue. Conversely, if there is no corruption it can be concluded that it may lead to high-generated revenue. The signal is weak here. The judgement scores are ascertained accordingly.

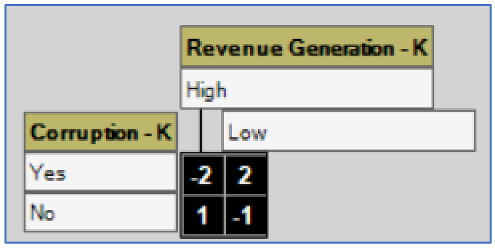


Figure 86 Interaction: Direct influence of Corruption (K) on Revenue Generation (K)

5.3.2.21 Descriptor relationship: Direct influence of Corruption (TN) on Revenue Generation (TN)

The corruption in the water sector in Tamil Nadu was evident during the summer of 2019 when the city of Chennai and the surrounding areas were battling a water crisis (Naseer, 2019). The situation in the Tamil Nadu subbasin is like that in Karnataka when it comes to corruption affecting the revenue generated in the basin. A study by a senior accountant from the Central Board of Direct Taxes (CBDT), India carried out the analysis of the corruption affecting the revenue generated in the Chennai district (Harriss & Wyatt, 2019). The paper discussed the various connections to corruption and its effects on the citizens and the economy. The paper defined a few types of corruption; with economic corruption is when acts of dishonesty affect the existing financial systems for personal gain. The magnitude of frauds that have occurred in the province has affected the available monetary resources (Harriss & Wyatt, 2019; Kozacek, 2016; MBAUniverse, 2023). The corruption in the basin has further affected any type of sustainable development growth in the basin due to a lack of funding (Consumer News and Business Channel, 2019; Kozacek, 2016; Times News Network, 2021).

Therefore, the higher the corruption in the basin, the lower will be the generated revenue. And consequently, if there is no corruption, the revenue generated can be higher. The judgement scores are ascertained accordingly.

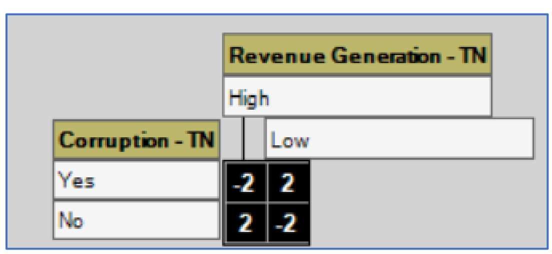


Figure 87 Interaction: Direct influence of Corruption (TN) on Revenue Generation (TN)

5.3.2.22 Descriptor relationship: Direct influence of Corruption (K) on Social Unrest (K)

As per Rodrik et al. (2004), corruption is a driver of political instability as it undermines the rule of law and faith in public institutions. Corruption exacerbates the political instability that may lead to social unrest. The current invasion of Russia in Ukraine exemplifies how a corrupt regime can threaten peace. In the last year, there have been many instances of social unrest and rioting in Russia (Kukutschka, 2023). Transparency International's Corruption Perception Index (CPI) deemed that any value below 40 out of 100 can cause a collapse of government institutions and a rise in internal violence (Dawson, 2015). Transparency International ranks the 180 countries in the world based on their corruption values. As per the 2022 rankings, India, unfortunately, scores exactly 40/100 with an overall rank of 85 (Transparency International, 2023). A study from the School of Advanced Study at the University of London, UK examined the key issues of state politics in India. The study discussed the simplicity and the complexity of social unrest in the states and how it is caused by corrupt politicians using the citizens' religious and belief systems (Manor, 2014). In the province of Karnataka, corruption among the different municipal corporations has led to rioting and protests over the last few decades and eventually affected the well-being of its citizens (IMF Blog, 2017; Kulkarni, 2020; Lodaya & Mukherjee, 2016; Pokharel, 2016).

Therefore, when corruption is high in the province, it will lead to more social unrest and rioting. Conversely, if corruption is eradicated in the province, we can hope to see no more protests and rioting. The judgement scores are ascertained accordingly.

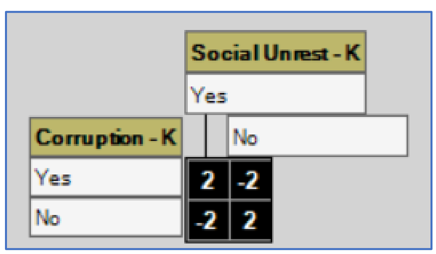


Figure 88 Interaction: Direct influence of Corruption (K) on Social Unrest (K)

5.3.2.23 Descriptor relationship: Direct influence of Corruption (TN) on Social Unrest (TN)

The situation in Tamil Nadu is pretty similar to that of Karnataka. The corruption in the municipal corporations and the political parties has led to constant protests in the subbasin. The frequency of occurrence of these protests, which ultimately lead to unrest and rioting, is higher in Tamil Nadu. Being the downstream province with the dependence of water supply on the upstream province, the shortcomings in water availability for everyday use are felt instantly (Anand, 2004). Over the years, the municipality of Chennai and the surrounding areas have been affected by corruption. Some of the social unrest events have been marked by multiple deaths and billions of dollars of property damage (Rao, 2017; Sattiraju, 2017; Tummala, 2006; Yeung & Gupta, 2019).

Therefore, the higher the corruption in Tamil Nadu, the more social unrest it will end up causing. Consequently, if there is no corruption it can lead to no social unrest. The judgement scores are ascertained accordingly.

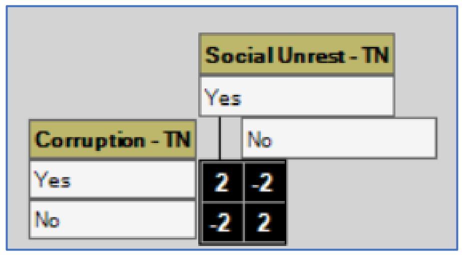


Figure 89 Interaction: Direct influence of Corruption (TN) on Social Unrest (TN)

5.3.2.24 Descriptor relationship: Direct influence of Corruption (K) on Governmental Effectiveness (K)

The high amount of corruption in the province strongly leads to low governmental effectiveness. Corruption impedes any semblance or possibility of a government working effectively. Corruption can tempt governmental officials to choose projects that increase the possibility of extorting bribes rather than helping the public. Corruption in large water infrastructure projects is rampant due to the large nature of the projects and the difficulty in tracking expenditures (Mauro, 1997). A study by Montes and Paschoal (2015) studied 130 countries, with 100 of them being developing countries, for the effects of corruption on governmental effectiveness. Their methodology was to find empirical proof through rigorous statistical analysis of the connections. They concluded that if a reduction in corruption is perceived then governmental effectiveness is also perceived. A study of the South Asian Association for Regional Cooperation (SAARC) countries explained the effects of corruption on political stability and governmental effectiveness (Awan et al., 2018). Also, Chen and Aklikokou (2021) found that the countries with high corruption tend to avoid or circumnavigate the use of anti-corruption measures such as e-governance, and vigilance commissions. Some of the water infrastructure projects in the basin are related to the health and sanitation of the citizens. The corruption that leads to these projects not being realized further affects the governmental effectiveness (Baillat, 2013; Office of the High Commissioner for Human Rights (OHCHR), n.d.).

Therefore, no corruption in the basin will lead to high governmental effectiveness. Reducing corruption is an important aspect in improving the governmental effectiveness. The judgement scores are ascertained accordingly.

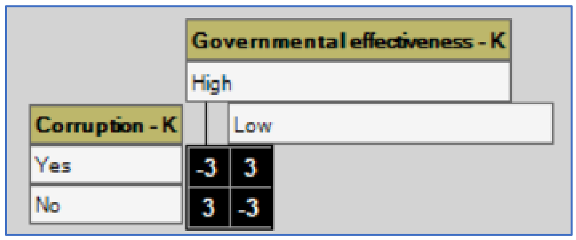


Figure 90 Interaction: Direct influence of Corruption (K) on Governmental Effectiveness (K)

5.3.2.25 Descriptor relationship: Direct influence of Corruption (TN) on Governmental Effectiveness (TN)

The relationship between corruption and governmental effectiveness in Tamil Nadu is like that in Karnataka. The higher the corruption in the province, the lower will be the governmental effectiveness. In the subbasin, there have been multiple instances of the "sand mafia" over mining the riverbanks, and riverbeds. This activity was linked to corruption in the province and the ineffective government. The sand mining issue has been prevalent in the basin since the early 1990s. The ineffective distribution of natural resources directly stems from the corruption in all the then political parties that have been in power over the last three decades (Jeyaranjan, 2019).

There have been many instances of corruption leading to governmental ineffectiveness reported in the last decade (Consumer News and Business Channel, 2019; Harriss & Wyatt, 2019; Roumeau et al., 2015; United Nations Development Programme, 2011). A global study of corruption in the water sector summarised the interactions of administrators.

The following table demonstrates how elected officials and leaders act ineffectively under a corrupt regime (J. Davis, 2004). It showcases how different levels of administrators conduct corrupt activities towards other members of the society.

Table 31 Corrupt Interactions in Water and Sanitation service provision (J. Davis, 2004)

	Customers	Professional engineering staff	Senior agency administrators	Elected and unelected leaders	Contractors
Low-skilled staff	Bribes to falsify meter readings, conceal illegal connections	–	–	–	–
Professional engineering staff	Speed money to expedite new applications, repairs	–	–	–	–
Senior agency administrators	–	Payments for favorable reviews, promotions, transfers	–	–	–
Elected and unelected leaders	Money for advocacy (e.g., preventing disconnection)	Payments, services for advocacy reposts and transfers	Services for advocacy reposts and transfers	–	–
Contractors	–	Contract kick-backs, concealment of substandard work	Tendering kickbacks	Tendering kickbacks	Collusion in contract bids

Higher corruption in the basin leads to low governmental effectiveness. Conversely, no corruption would drastically lead to an increasingly effective government. The judgement scores are ascertained accordingly.

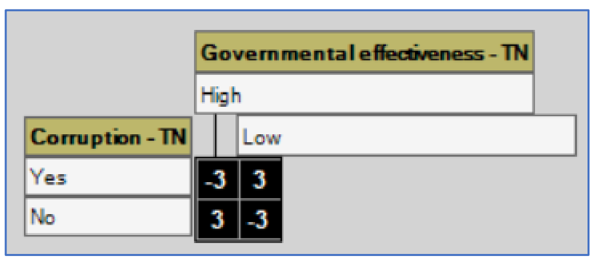


Figure 91 Interaction: Direct influence of Corruption (TN) on Governmental Effectiveness (TN)

5.3.2.26 Descriptor relationship: Direct influence of Rainfall (K) on Openness to negotiate with TN.

Rainfall in Karnataka subbasin influences the general acceptance of the citizens that a pact can be allowed with the downstream province. It is also to be noted that the government of Karnataka will begin negotiations with Tamil Nadu only if there are high quantities of rainfall consistently for at least a couple of years (CWDT, 2007d). Therefore, the impact of rainfall in Karnataka directly affects even the possibility of negotiation. From past experiences, it can be noted that during the years the rainfall has faltered, the government of Karnataka has not released the stipulated quantities of water to the downstream province (CWDT, 2007d, 2007c, 2007e). The moderate or business-as-usual rainfall, which is less than the required quantity for sustaining Karnataka's water demand, does not lead to a possibility of negotiation. The judgement scores are ascertained accordingly. And if the rainfall is low, the thought of negotiation is thrown out of the discourse.

Rainfall - K	Openness to Negotiate with TN: Yes	Openness to Negotiate with TN: No
High	2	-2
Moderate	-1	1
Low	-3	3

Figure 92 Interaction: Direct influence of Rainfall (K) on Openness to negotiate with TN

5.3.2.27 Descriptor relationship: Direct influence of Water Demand (K) on Openness to negotiate with TN.

The demand for water in the Karnataka subbasin affects the possibility of a negotiation with the province of Tamil Nadu. The high-water demand in the subbasin would never lead to a possibility of negotiation with Tamil Nadu. The city of Bengaluru's water demand is always increasing, and if they cannot find another source for their daily needs, the province of Karnataka would never negotiate for a lower proportion of Cauvery water than what they have now. Therefore, the higher the water demand in Karnataka, the lower the chances of negotiating with Tamil Nadu.

Water Demand - K	Openness to Negotiate with TN: Yes	Openness to Negotiate with TN: No
High	-3	3
Low	3	-3

Figure 93 Interaction: Direct influence of Water Demand (K) on Openness to negotiate with TN

The complete CIB matrix is available online. The matrix is available online because it is quite large and cannot be included within the dimensions of the page. Click here.

5.4 Results and Discussion

As explained in the introduction, CIB produces internally consistent scenarios which are useful in identifying the preferences of the province of Karnataka, and Tamil Nadu. In general, the output in the software is always presented by using strong consistency. Strong consistency is when the impact score of the dominant variant in a descriptor is used to ascertain which variant will show up within a consistent scenario. However, in a weak consistency, any impact score less than or equal to 0 for a variant may be interpreted as weakly consistent. The total impact score of a scenario is defined as the sum of all active descriptor variants. Therefore, the total impact scores greater or equal to zero are considered for analysis. Therefore, the number of consistent scenarios in a weak consistency is considerably larger than that in a strong consistency. The following paragraphs display the results for both strong and weak consistencies. It is interesting to look at all types of consistent scenarios because of the complex nature of this work. Also, it is important to examine every possibility.

5.4.1 Strong Consistency

There are 43 identified internally consistent scenarios with strong consistency with a good enough spread of the variants occurring further explained after Table 32. There are 42 possible variants from the 19 descriptors. The following table shows the variant statistics.

Table 32 Cross impact balances: Variant statistics in strong consistency

	Descriptor	Variants		
1	Rainfall - K	High	Moderate	Low
		33.3%	33.3%	33.3%
2	Rainfall - TN	High	Moderate	Low
		33.3%	33.3%	33.3%
3	Water Availability - K	Enough	Scarce	
		33.3%	67%	
4	Water Availability - TN	Enough	Scarce	
		33.3%	66.7%	

5	U/s Water Availability - TN	Enough	Scarce	
		19.4%	80.6%	
6	Water Demand - K	High	Low	
		100.0%	0.0%	
7	Water Demand - TN	High	Low	
		100.0%	0.0%	
8	Water Supply - K	High	Moderate	Low
		0.0%	0.0%	100.0%
9	Water Supply - TN	High	Moderate	Low
		0.0%	0.0%	100.0%
10	Agricultural Productivity - TN	High	Low	
		0.0%	100.0%	
11	Revenue Generation - K	High	Low	
		0.0%	100.0%	
12	Revenue Generation - TN	High	Low	
		0.0%	100.0%	
13	Governmental Effectiveness - K	High	Low	
		50.8%	49.2%	
14	Governmental Effectiveness - TN	High	Low	
		50.8%	49.2%	

15	Corruption - K	Yes	No
		49.2%	50.8%
16	Corruption - TN	Yes	No
		49.2%	50.8%
17	Social Unrest - K	Yes	No
		73.8%	26.2%
18	Social Unrest - TN	Yes	No
		49.2%	50.8%
19	Openness to Negotiate with TN	Yes	No
		9.0%	91.0%

In the consistent scenarios calculated by the ScenarioWizard (Weimer-Jehle, 2018, 2021) using strong consistency, 33 of these variants are present. Nine variants do not occur with strong consistency,

- Low Water demand – K,
- Low Water demand – TN,
- High Water supply – K,
- Moderate water supply – K,
- High water supply – TN,
- Moderate water supply – TN,
- High agricultural productivity – TN,
- High revenue generation – K, and
- High revenue generation – TN.

The study is designed to explore scenarios where low water demand in both provinces never occurs. Based on all the information from the official government reports, the provinces have always been water scarce. Karnataka's water supply efficiency is majorly influenced by the supply in the city of Bengaluru. In the literature section, it is explained how the city has less than adequate supply of water, therefore, moderate, and high-water supply variants do not occur, when a strong consistency analysis is carried out. Similarly, in the province of Tamil Nadu, the evidence shows that the water supply is generally low and is the cause of social unrest in the basin. Therefore, in scenarios with strong consistency, the high and moderate water supply variants do not occur. Water supply has a huge impact on agricultural productivity, and that in turn influences revenue generation in the province of Tamil Nadu. Therefore, if high, and moderate water supply variants do not occur then the high agricultural productivity, and the high revenue generation variants will also not occur. In the province of Karnataka, water supply influences revenue generation. Therefore, if the high, and moderate water supply variants do not occur, then the high revenue generation variant will also not occur.

From Table 32, the variant's spread statistics in general looks satisfactory with almost 80% coverage. In all the consistent scenarios, the positive willingness to negotiate variant occurs only 9% of the time. This is expected due to the complex nature of the problem we are trying to solve. The conflict has existed for over a hundred years, with the situation exacerbating rapidly over the last three decades. The governments of both provinces have settled their differences in such a way that an amicable negotiation is highly likely. Within the strong consistency outputs, there were a total of 43 internally consistent scenarios, and only 7 of them had a positive willingness to negotiate. These scenarios were filtered out of the software and are presented below.

Table 33 Seven selected internally consistent scenarios

	Scenario Number	**1**	**5**	**3**	**7**	**2**	**4**	**6**
1	Rainfall - K	high	high	high	high	moderate	moderate	moderate
2	Rainfall - TN	high	low	moderate	moderate	high	moderate	low
3	Water Availability - K	enough	enough	enough	enough	scarce	scarce	scarce
4	Water Availability - TN	enough	scarce	scarce	scarce	enough	scarce	scarce
5	U/s Water Availability - TN	enough	scarce	enough	scarce	scarce	scarce	scarce
6	Water Demand - K	high	high	high	high	high	high	high
7	Water Demand - TN	high	high	high	high	high	high	high
8	Water Supply - K	low	low	low	low	low	low	low
9	Water Supply - TN	low	low	low	low	low	low	low

10	Agricultural Productivity - TN	low	low	low	low	low	low	low
11	Revenue Generation - K	low	low	low	low	low	low	low
12	Revenue Generation - TN	low	low	low	low	low	low	low
13	Governmental Effectiveness - K	high	high	high	high	high	high	high
14	Governmental Effectiveness - TN	low	low	low	low	low	low	low
15	Corruption - K	no	no	no	no	no	no	no
16	Corruption - TN	yes	yes	yes	yes	yes	yes	yes
17	Social Unrest - K	yes	yes	yes	yes	yes	yes	yes
18	Social Unrest - TN	yes	yes	yes	yes	yes	yes	yes
19	Openness to Negotiate with TN	yes	yes	yes	yes	yes	yes	yes

In the seven scenarios shown above, the only variant change is occurring in the rainfall, and water availability descriptors. These consistent scenarios are supposed to provide more information to the provinces so that they can reach an amicably negotiated agreement. However, the rainfall descriptor can not be managed by either of the provinces and the water availability in both provinces is driven by the rainfall. The only variant that can be influenced by the government of Karnataka is the upstream water availability. Scenario 1 with an impact score of 54 creates a situation in which if both the province of Karnataka has high rainfall, enough availability, and enough water left to let it flow downstream to the province of Tamil Nadu, Karnataka will be willing to negotiate an agreement provided the corruption level is low in their subbasin. Karnataka’s willingness to negotiate with Tamil Nadu is strongly dependent upon having high governmental effectiveness, and no corruption. This is an acute departure from the status quo.

5.4.2 Weak Consistency

Another way of calculating the internally consistent scenarios is by assuming weak consistency. The software was run for the weak consistency setting as well. There are 165 identified internally consistent scenarios using weak consistency with a good spread of the variants occurring. There are 42 possible variants from the 19 descriptors. The following table shows the variants' statistics.

Table 34 Cross impact balances: Variant statistics in weak Consistency

	Descriptor	Variants		
1	Rainfall - K	High	Moderate	Low
		33.3%	33.3%	33.3%
2	Rainfall - TN	High	Moderate	Low
		33.3%	33.3%	33.3%
3	Water Availability - K	Enough	Scarce	
		33.3%	67%	
4	Water Availability - TN	Enough	Scarce	
		33.3%	66.7%	
5	U/s Water Availability - TN	Enough	Scarce	
		19.4%	80.6%	
6	Water Demand - K	High	Low	
		100.0%	0.0%	
7	Water Demand - TN	High	Low	
		100.0%	0.0%	
8	Water Supply - K	High	Moderate	Low
		0.0%	16.7%	83.3%
9	Water Supply - TN	High	Moderate	Low
		0.0%	16.7%	83.3%
10	Agricultural Productivity - TN	High	Low	

		16.7%	83.3%
11	Revenue Generation - K	High	Low
		0.0%	100.0%
12	Revenue Generation - TN	High	Low
		4.2%	95.8%
13	Governmental Effectiveness - K	High	Low
		50.0%	50.0%
14	Governmental Effectiveness - TN	High	Low
		50.0%	50.0%
15	Corruption - K	Yes	No
		50.0%	50.0%
16	Corruption - TN	Yes	No
		50.0%	50.0%
17	Social Unrest - K	Yes	No
		75.0%	25.0%
18	Social Unrest - TN	Yes	No
		50.0%	50.0%
19	Openness to Negotiate with TN	Yes	No
		24.5%	75.5%

In the consistent scenarios calculated by the ScenarioWizard using weak consistency, 37 of these variants are present. It means that the remaining five variants are never used or are never part of any consistent scenario, still having close to 86% coverage. This means that the probability of that variant happening is close to nil. These five variants are as follows,

- Low Water demand – K,
- Low Water demand – TN,
- High water supply – K,
- High water supply – TN, and
- High revenue generation – K.

The five variants here are a repeat of the strong consistency analysis. The judgment scores were ascertained by going through government reports, journal articles, as well as local magazine articles. It was evident that due to the socio-economic conditions in the Cauvery River basin, low demand for water will never occur. And this is partial because the basin can never supply high quantities of water. The revenue generated in Karnataka is dependent upon the water supply, hence high revenue generation variant never occurs in Karnataka. Revenue generated in Tamil Nadu is also dependent upon the water supply, therefore, high revenue generated in Tamil Nadu occurs in only 4.2 percent of the scenarios. There is a considerable increase in the positive willingness to negotiate the variant's presence in the list of consistent scenarios.

The goal of this work is to find the conditions in which a negotiated agreement can be reached between the two provinces. Therefore, the Yes variant of the Willingness to negotiate descriptor is filtered out of the 165 possible scenarios. This results in 57 scenarios where the province of Karnataka is willing to negotiate with the province of Tamil Nadu. Out of the 57, 5 scenarios are shown in the table below.

Table 35 Internally consistent scenarios

	Scenario Number	**54**	**56**	**55**	**29**	**25**
1	Rainfall - K	high	high	high	high	high
2	Rainfall - TN	high	low	moderate	low	high
3	Water Availability - K	enough	enough	enough	enough	enough
4	Water Availability - TN	enough	scarce	scarce	scarce	enough
5	U/s Water Availability - TN	enough	scarce	enough	scarce	enough

6	Water Demand - K	high	high	high	high	high
7	Water Demand - TN	high	high	high	high	high
8	Water Supply - K	low	low	low	low	low
9	Water Supply - TN	low	low	low	low	low
10	Agricultural Productivity - TN	low	low	low	low	low
11	Revenue Generation - K	low	low	low	low	low
12	Revenue Generation - TN	low	low	low	low	low
13	Governmental Effectiveness - K	high	high	high	high	high
14	Governmental Effectiveness - TN	high	high	high	low	low
15	Corruption - K	no	no	no	no	no
16	Corruption - TN	no	no	no	yes	yes
17	Social Unrest - K	no	no	no	yes	yes
18	Social Unrest - TN	no	no	no	yes	yes
19	Openness to Negotiate with TN	yes	Yes	yes	yes	yes

Scenario 54 here is like scenario 1 in strong consistency analysis. A negotiated agreement can be reached if the government of Karnataka is effective and there is no corruption. Scenario 29 is an interesting combination of variants because despite releasing less than stipulated quantities of water to Tamil Nadu and having social unrest in the province, Karnataka is willing to negotiate with Tamil Nadu. Low rainfall and low governmental effectiveness in Tamil Nadu can trigger a human rights protest in Tamil Nadu. This protest may reach the province of Karnataka due to the large, shared border and many ex-pats of Tamil Nadu origin living in Karnataka. This will force Karnataka to negotiate with the province of Tamil Nadu.

5.4.3 Discussions

For the purposes of this research, the results of a strong consistency are considered. The results from weak consistency have helped in analyzing the sensitivity of the descriptors and the judgement scores. The seven consistent scenarios from strong consistency analysis that have positive willingness to negotiate with Tamil Nadu are important to discuss here. One of the scenarios is explained below.

In scenario 1 as shown below, a negotiated agreement can be reached despite the corruption in the province of Tamil Nadu, and the governmental effectiveness also being low in Tamil Nadu. Also, both the provinces are dealing with social unrest, which would prompt the governments of both the provinces to try to reach an amicable resolution.

```
==========================================
Scenario No. 1
Weight            :  2304
Consistency value :  0
Total impact score:  56
------------------------------------------
Rainfall - K                     : Moderate
Rainfall - TN                    : Low
Water Availability - K           : Scarce
Water Availability - TN          : Scarce
U/s Water Availability - TN      : Scarce
Water Demand - K                 : High
Water Demand - TN                : High
Water Supply - K                 : Low
Water Supply - TN                : Low
Agricultural Productivity - TN   : Low
Revenue Generation - K           : Low
Revenue Generation - TN          : Low
Governmental effectiveness - K   : High
Governmental effectiveness - TN  : Low
Corruption - K                   : No
Corruption - TN                  : Yes
Social Unrest - K                : Yes
Social Unrest - TN               : Yes
Openness to Negotiate with TN    : Yes
==========================================
```

Figure 94 Scenario 1 variant lists

Also, in this scenario, the rainfall in Karnataka is moderate and the rainfall in Tamil Nadu is Low. This have caused the water availability to be scarce in the whole basin. The water demands are high, and the water supply are low. However, it can be inferred that it is only due to a high governmental effectiveness in Karnataka, the openness to negotiation is possible. The probability of this event happening is high due to its high impact scores. The different consistent scenarios provide the analyst with all possible outcomes and helps them explore the interdependencies of the descriptors that may not be visible normally.

The impact scores are calculated by adding the individual balance scores of each selected descriptors in a consistent scenario. For example, in the figure above, the impact score for scenario 1 is 56, and the consistency value is equal to 0. The consistency value of a scenario is calculated as the minimum value of all the individual descriptor consistencies. The individual consistencies are shown in the fourth column in the table below. For an internally consistent scenario, the consistency values have to be greater than or equal to 0. If the values are less than 0, the scenario is deemed as inconsistent. The table 36 below shows scenario 1 in more detail. The first column indicates the selected variant. The second column is the descriptor, the third column is the variant, and the fourth column is the impact balance or consistency values of that descriptor for the model. The fifth and final column indicates the balance of the selected variant for scenario 1.

Table 36 Scenario 1 with each descriptor's variant selected.

Selection	Descriptor	Variant	Balance	
	Rainfall - K	H	0	
x	Rainfall - K	BAU	0	0
	Rainfall - K	L	0	
	Rainfall - TN	H	0	
	Rainfall - TN	BAU	0	
x	Rainfall - TN	L	0	0
	Water Availability - K	Enuf	-1	
x	Water Availability - K	Scar	1	1
	Water Availability- TN	Enuf	-3	
x	Water Availability - TN	Scar	3	3
	U/s Water Availability - TN	Enuf	-5	
x	U/s Water Availability - TN	Scar	5	5
x	Water Demand - K	H	5	5
	Water Demand - K	L	-5	
x	Water Demand - TN	H	4	4
	Water Demand - TN	L	-4	
	Water Supply - K	H	-1	
	Water Supply - K	Mod	-2	
x	Water Supply - K	L	1	1
	Water Supply - TN	H	-5	
	Water Supply - TN	Mod	0	
x	Water Supply - TN	L	5	5
	Agricultural Productivity - TN	H	-3	
x	Agricultural Productivity - TN	L	3	3

	Revenue Generation - K	H	-1	
x	Revenue Generation - K	L	1	1
	Revenue Generation - TN	H	-7	
x	Revenue Generation - TN	L	7	7
x	Governmental Effectiveness - K	H	4	4
	Governmental Effectiveness - K	L	-4	
	Governmental Effectiveness - TN	H	-2	
x	Governmental Effectiveness - TN	L	2	2
	Corruption - K	Y	-4	
x	Corruption - K	N	4	4
x	Corruption - TN	Y	2	2
	Corruption - TN	N	-2	
x	Social Unrest - K	Y	2	2
	Social Unrest - K	N	-2	
x	Social Unrest - TN	Y	6	6
	Social Unrest - TN	N	-5	
x	Openness to Negotiate with TN	Y	1	1
	Openness to Negotiate with TN	N	1	
			Impact Score	**56**

By adding the selected impact balances, the impact score is calculated. Each consistent scenario has a different impact score based on the variant of the descriptor selected. The impact scores are helpful in testing the stability of the model.

By using the internally consistent scenarios the influence of each of the descriptors is also ascertained. The influence of the descriptors over each other is by plotting the active vs passive graph available in the analysis section of the software. The graph plots the descriptors based on the level of influence they have on the system and how much they get influenced. The x-axis is the passive sum, and the y-axis is the active sum. If the graph is divided into four quadrants, then the top left quadrant with descriptors like water supply – TN, water demand – K, and corruption – K, TN has a high influence on the other descriptors in the system. The descriptors in the bottom right quadrant of the graph like social unrest – TN, K, revenue generation – TN, upstream water availability – TN, and willingness to negotiate are influenced by the other descriptors in the system. The graph is shown below.

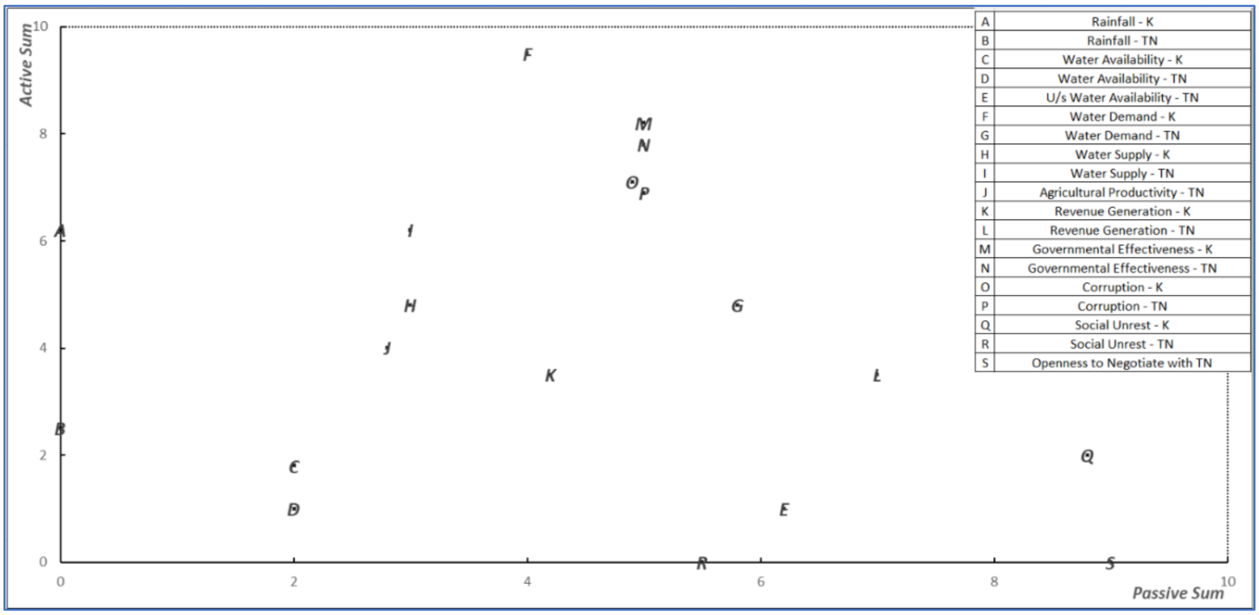


Figure 95 Active (y-axis) vs Passive (x-axis) descriptors spread.

It is important to remember that the Cauvery River conflict is not limited to sharing of water in the basin, there are other complex factors that influence the decision making.

The scenarios with positive “willingness to negotiate” inform the provinces of the options they have. This whole exercise was to improve upon the decision-making that can be carried out by the decision-makers. This work has developed a method that analyses the descriptors influencing each other within a systems of systems realm. The descriptors that have the most influence on the system are required to be prioritized by the decision-makers if they want to reach a meaningful resolution. The descriptors in the top left quadrant of Figure 95 are the most active descriptors. For example, descriptor Water Demand-K (F) is an active descriptor, meaning that managing water demand in the Karnataka sub-basin can lead to positive changes in the system. Similarly, Water Supply-TN (I) is an active descriptor and managing water supply in Tamil Nadu can yield positive results for the system. These active descriptors can translate directly into options that the two provinces may have.

The province of Karnataka has the following options,

1. Reducing water demand (F)
2. Increasing governmental effectiveness (M)
3. Reducing corruption (O)
4. Negotiate an agreement with Tamil Nadu.

The province of Tamil Nadu has the following options,

1. Increase water supply. (I)
2. Increase governmental effectiveness. (N)
3. Reduce Corruption (P)
4. Negotiate an agreement with Karnataka.

In conclusion, the CIB analysis adds more contextual information about the negotiation between the provinces. Karnataka is a more powerful negotiator due to being upstream. On the other hand, unfortunately for Tamil Nadu, the system appears to be highly deterministic. There are no descriptor outcomes that appear to be emergent, which may be the function of the current structure of the CIB matrix. This outcome, although anti-climactic, is not surprising. Many governments, federal and provincial, have tried to resolve this conflict for decades, and they seemed to be in this recurring trap where they keep making new administrative authorities, committees, etc. These new entities continue doing the same work all over again, rendering the conflict dormant for a small period of time before it gets reinvigorated due to some issue in the basin. A stronger and more robust resolution is required to resolve this conflict.

The scenarios discussed under strong consistencies in the previous section are some of the possible pathways that the Cauvery River conflict can end up in. The various complex combinations of socio-economic descriptors showcase possible futures. To further understand these scenarios, they can be compared to the scenarios in the Shared Socioeconomic Pathways (SSPs) developed for scientific assessment by the Intergovernmental Panel on Climate Change (IPCC). SSPs are a set of scenarios developed to explore different trajectories of global socioeconomic development and their implications for greenhouse gas emissions and climate change (Kriegler et al., 2012; O'Neill et al., 2014; van Ruijven et al., 2014). They are helpful to the policymakers and researchers in understanding how various systems such as population growth, technological advancements, and economic trends can influence climate change and adaptation efforts. There are five scenarios in the SSPs, and they are plotted on a graph with socioeconomic challenges for mitigation on the y-axis and socioeconomic challenges for adaptation on the x-axis. They are shown in the figure below.

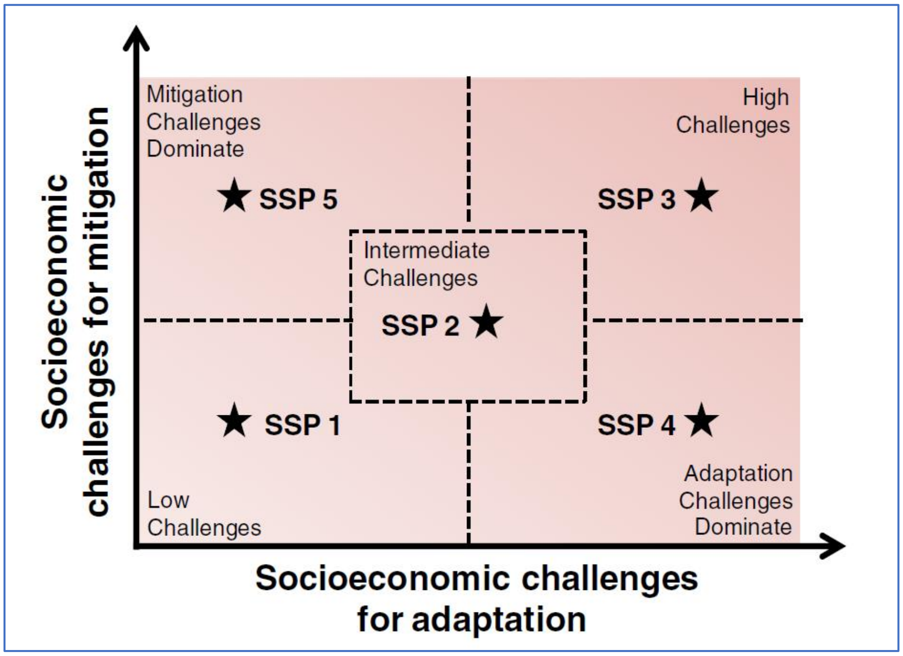


Figure 96 The five Shared Socioeconomic Pathways (SSPs) (Kriegler et al., 2012; O'Neill et al., 2014)

SSP1 has low challenges and therefore the sustainable development proceeds at a reasonable pace. In this pathway there is strong global co-operation, sustainable resources management which causes a more friendly and equitable future. SSP3 has high challenge for adaptation and mitigation. The emissions are high due to moderate economic growth, and a rapidly growing population. There is a regional rivalry for resources leading to conflicts. This leads to increased challenges in addressing climate change and achieving sustainable development. SSP2 is somewhere between SSP1 and SSP3 in terms of the challenges. Here the challenges and the opportunities are balanced however they may lead to uneven progress and regional disparity. SSP4 has high challenges for adaptation and low challenges for mitigation. In this pathway there is a global inequality. The technological advancements and economic development are high, and less focus is put on environmental concerns. This pathway leads parts of the world to be vulnerable towards climate change. SSP5 is fossil-fuel development focused. There are little to no climate change mitigation policies. The economic development is rapid and fueled by fossil fuels due to no investment in alternative energy resources. This pathway would lead to high green house gas emissions.

The scenarios from the CIB analysis demonstrates that the situation in the Cauvery River basin is similar to that described under SSP2. SSP2 has intermediate challenges towards both mitigation and adaptation.

The spread statistics of the variants within the consistent scenarios also points to the same conclusion. The climate change mitigation and adaptation policies are limited in the basin. There is economic disparity within the river basin as well. The effectiveness of government is also limited. The water resources supply and demand are limited in the basin and that leads to consistent conflict in the basin. This situation is dangerous and seems to be oscillating between SSP3 and SSP5 scenarios.

SSP3: there is an increasing fear of the natural resources' depletion, leading to large number of people succumbing to the climate crisis. Also, the investment in human capital is low, and growing population would hinder any possibility of mitigation.

SSP5: there is an absence of any climate policies. Due to rapid technological advances fueled by fossil fuels and not renewable sources, the possibility of mitigation is low. However, the economic development on the basin is increasing with IT industries and agriculture.

The CIB analysis along with SSPs help in identifying where this conflict is currently, and it also elucidates where it can end up at. Therefore, the decision makers need to reach a resolution expeditiously.

5.5 Use of CIB output in GMCR

The options extracted from the active descriptors within the consistent scenarios will be used as inputs in the decision support system based on the graph model for conflict resolution methodology. The schematic is as shown in the figure below.

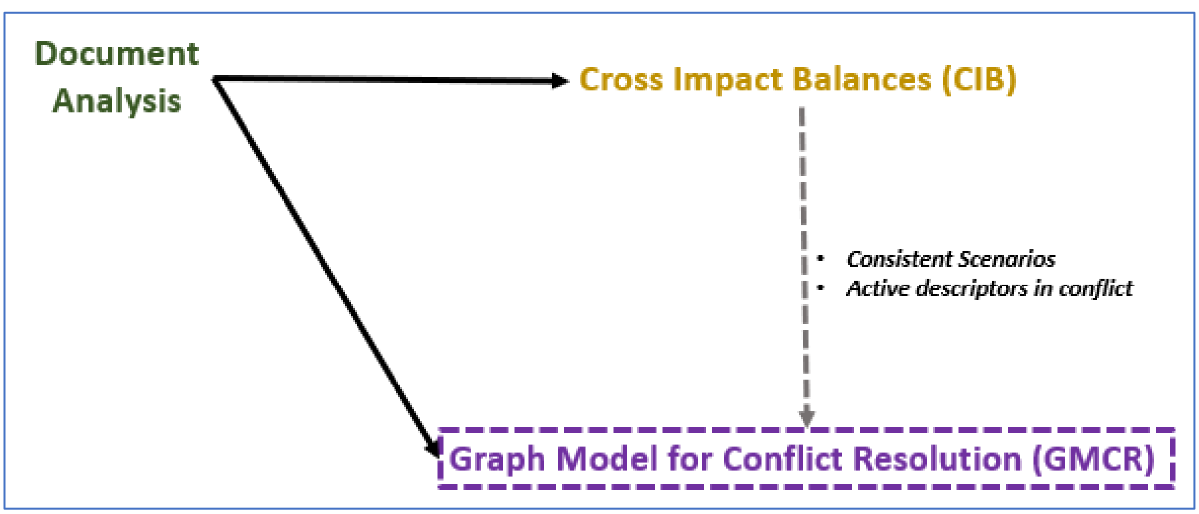


Figure 97 Part schematic for the Cauvery River conflict

The next chapter introduces the GMCR methodology, explains how the options from CIB are used to determine the preferences for the provinces, and finally discuss the resolutions.

6. Graph Model for Conflict Resolution (GMCR)

Resolving a complex water management problem is critical and necessary. The Cauvery River conflict is one such wicked complex problem. The conflict has two main decision-makers (DMs); Karnataka, and Tamil Nadu. In the previous sections, the various systems interacting in the Cauvery River basin were modeled and examined closely. The cross-impact balances (CIB) analysis generated a list of consistent scenarios and listed the indicators that have the most influence on the system. These indicators will help in ascertaining the options that the decision-makers have and how they can be prioritized. Section 6.1 explains the graph model, section 6.2 discusses the preliminary applications of GMCR, section 6.3 discusses the current GMCR application, section 6.4 discusses the results, and section 6.5 provides conclusions.

6.1 Graph Model

Global diplomacy to negotiation and decision-making are fundamentally human activities. As the demand for these skills rises, particularly in the fields of engineering and project management, there are numerous computerized decision analysis systems (Hipel et al., 1997) available on the market (Kassab et al., 2006). There are many formal multiple-participant decision-making models for conflict resolution. The genealogy tree is shown in the figure below.

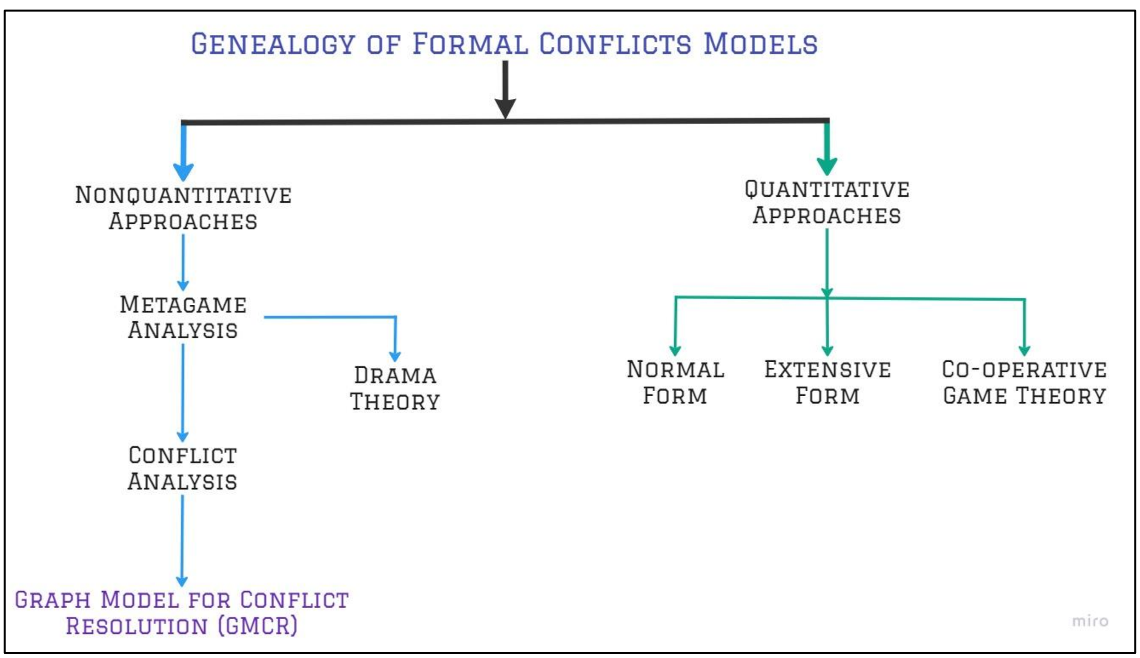


Figure 98 Genealogy of formal multiple participant decision-making models

The analysis is generally divided into two sections, i.e., quantitative, and non-quantitative approaches. Quantitative approaches commonly represent the preferences of decision-makers (DMs) as cardinal utilities, reflecting their underlying value systems. In these models, preferences are quantified using actual numerical values, with higher numbers indicating stronger preferences. The utilization of cardinal preference information characterizes these models as quantitative models. Classical game theory techniques, such as extensive form, normal form, and cooperative game theory, rely on such cardinal preference information (Hipel & Fang, 2020). The Graph Model for Conflict Resolution (GMCR) is categorized as a nonquantitative approach, which classifies preferences in terms of relative or qualitative aspects. In this classification, one only needs to ascertain whether a decision-maker (DM) prefers one state over another or considers them equally preferred (Fang et al., 1993; He, 2019; Hipel et al., 1993, 1997; Kilgour et al., 1996; Kinsara et al., 2015; Sharma, Hipel, et al., 2020).

The graph model is based on tracking feasible movements among decision-makers in the conflict. The Graph Model for Conflict Resolution (GMCR) uses mathematical knowledge and set theory to describe conflict situations in a graphical form. As shown in Figure 98, the basis of the graph model is founded in classical game theory, metagame analysis, and conflict analysis (Von Neumann & Morgenstern, 1953). The graph model for conflict resolution involves decision-makers (DMs), the options they have, and their preferences, as shown in the figure below.

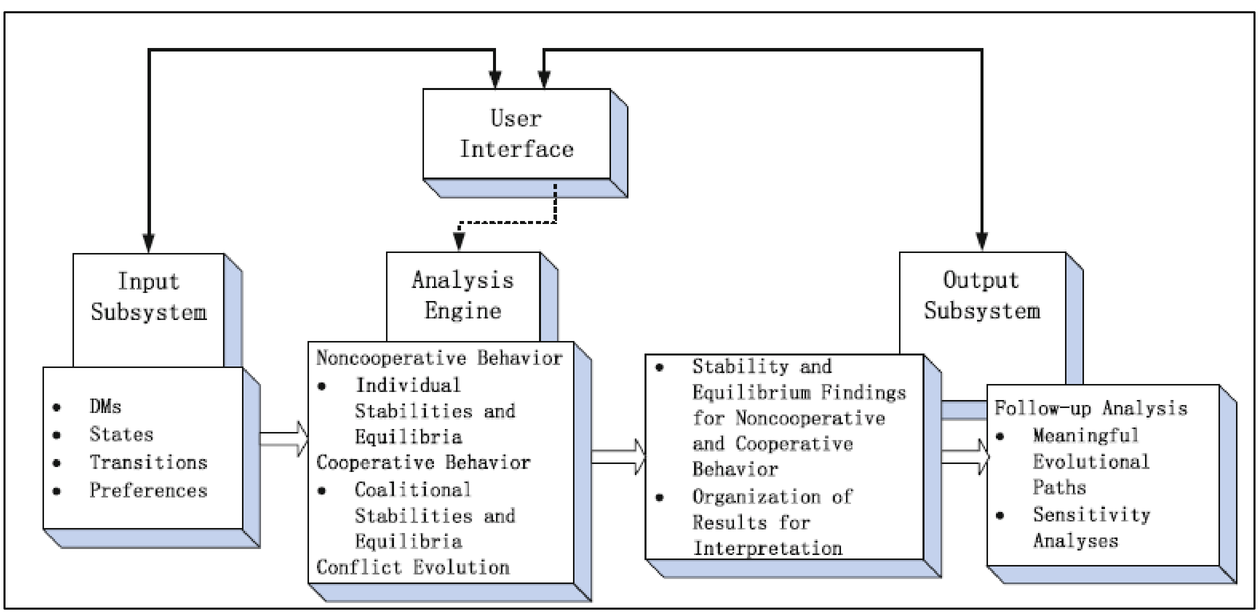


Figure 99 The overall structure of a graph model-based Decision Support System (DSS) (H. Xu et al., 2018)

6.1.1 GMCR Example

The GMCR is explained using the prisoner's dilemma because it is well-known (Barough et al., 2012; Han et al., 2013). It is a departure from the water management discussions in this work, however, it is a generic conflict that describes the basic situation in which one person must decide whether or not to cooperate with another. The prisoner's dilemma is similar to the "tragedy of commons". The tragedy of commons discuses the disputes in a shared resource setting, like water. The prisoner's dilemma conflict provides a framework upon which details about a specific dispute can be systematically discussed and better understood to reach an informed decision. In "Prisoner's Dilemma", there are two people suspected of a crime or robbery. They are arrested and kept in separate prison cells so that they cannot communicate directly with each other. The prisoners (decision-makers) can either cooperate or not cooperate (Kato, 2023). Co-operate means they do not confess the crime to the police, i.e., the prisoners cooperate.

The conflict is represented in the Normal Form in the table below. The Normal Form is similar to a matrix in which decision-maker 1 (DM1) is represented in a row, and decision-maker 2 (DM2) is represented in a column. The rows of the matrix represent the available strategies of DM1. The columns of the matrix are the strategies of DM2. Each cell in the matrix indices indicates one of the four possible States. States are the pseudo-physical spaces in which the decision-makers can move within a conflict.

Table 37 Prisoner's Dilemma in Normal Form in GMCR

		Second Prisoner	
		Co-operate (C)	Don't Co-operate (D)
First Prisoner	Co-operate (C)	***State 1*** (C, C)	***State 2*** (C, D)
	Don't Co-operate (D)	***State 3*** (D, C)	***State 4*** (D, D)

In Prisoner's Dilemma, the police ask the prisoners to confess. If prisoner 1 cooperates with prisoner 2 (does not confess to the crime), but prisoner 2 does not co-operate with prisoner 1 (confesses to the crime), then prisoner 1 will receive a 10-year sentence and prisoner 2 will go free. If both the prisoners do not cooperate, i.e., they both confess to the crime, then both receive a reduced sentence of 5 years.

Finally, if both the prisoners cooperate and don't confess, they only receive a one-year sentence. These possibilities are presented in the table above. Each of the prisoners has four separate preference rankings. The consequences are presented in the table below.

Table 38 Consequences of the Prisoner's Dilemma

	Consequences			
	State 1 (C, C)	***State 2*** (C, D)	***State 3*** (D, C)	***State 4*** (D, D)
Prisoner 1	1 Year	10 Years	Free	5 Years
Prisoner 2	1 Year	Free	10 Years	5 Years

For prisoner 1, the most preferred State would be State 3, and the least preferred State would be State 2. Similarly, for prisoner 2, the most preferred State would be State 2, and the least preferred State would be State 3. The preference ranking of prisoner 1 is State3 > State1 > State4 > State2, and the preference ranking of prisoner 2 is State2 > State1 > State4 > State3. The preferences list is the final step required before a GMCR model can be created, i.e., the decision-makers are defined, the options are explained, and the preferences are set.

The movement of the decision-makers within the State space can be visualized if the same conflict is displayed in the graph form. The graph form depicts how the conflict could move from one State to another. A node represents a State and the arc connecting the nodes represents the movement. The figure below depicts the graph form for the Prisoner's Dilemma.

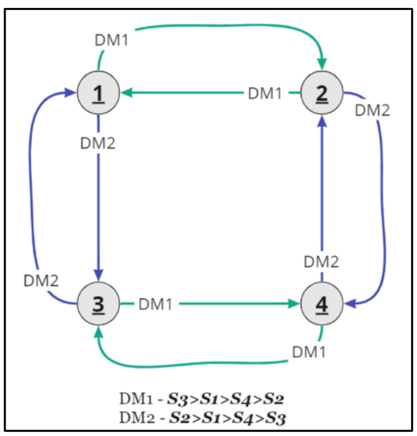


Figure 100 Graph form representation of Prisoner's Dilemma. The green horizontal lines are the moves controlled by prisoner 1, and the blue vertical lines are the moves controlled by prisoner 2. The preference rankings are mentioned at the bottom of the figure.

Prisoner 1 can only move between States 1 and 2 without changing its option, i.e., the option of prisoner 1 is fixed at co-operate. Also, prisoner 1 can only move between States 3 and 4 without changing its other option, i.e., don't cooperate. On the other hand, prisoner 2 can only move between States 1 and 3 without changing their co-operate option. Also, prisoner 2 can only move between States 2 and 4 without changing its other option, i.e., don't cooperate. These movements in a game are known as Unilateral Moves (UM). In GMCR, these moves are used to determine how a decision-maker moves within the game. In addition, the preference rankings are used to determine which moves would be useful for the respective decision-makers. In the above example, prisoner 1 can move between States 1 and 2. Based on the preference rankings, State 1 is more preferred than State 2. Therefore, if the conflict is in State 2, it is beneficial for Prisoner 1 to move from State 2 to State 1. The move that benefits a decision maker is known as a Unilateral Improvement (UI) for that decision maker. Generally, in a game, the number of unilateral moves will be more than the unilateral improvements. Similarly, the move from State 4 to State 3 is a unilateral improvement for prisoner 1. On the other hand, for prisoner 2, movements from State 3 to State 1, and movements from State 4 to State 2 are unilateral improvements. These concepts are important to clarify before the analysis is carried out.

The solution concepts mentioned in the following table are defined using graph notifications. The definitions are provided for two-player (decision-maker) conflicts. Let, N = {1, 2,…,n} denote the set of decision-makers. U = {1, 2,…,n} denotes the set of States. For each player $i \in N$, the set S_i is a finite nonempty set called *i*'s strategy set. The set of States or possible scenarios in the game are represented by the Cartesian product $S_1 X S_2 X \ldots X S_n$. The conflict is analyzed by determining the stabilities of each of the decision-makers for each of the States. Stability is determined using one of the five majorly used concepts, called Nash Stability, Sequential Stability, General Metarationality, Symmetric Metarationality, and Simultaneous Sanctioning[1]. Simultaneous sanctioning (SIM) is explained in the foot note. The solution concepts relevant to this study are shown in Table 39.

Table 39 Solution Concepts Used in Graph Model for Conflict Resolution

Solution Concepts	**Descriptions**
Nash Stability (*R*)	There are no unilateral improvements (UIs). It is rational for the DM to not move.

[1] After the above four stability checks, if a State is found to be unstable for all the decision-makers, a SIM stability check is carried out. When both the focal DM and the other DM move together from the same unstable State, at the same time, reaching a State which is preferred by both the DMs, the current State is not simultaneously sanctioned for both the DMs. This stability check is generally used in non-cooperative games. However, will not be used in this research.

Sequential Stability (*SEQ*)	The focal DM takes a UI and brings the conflict from a State "*i*" to State "*j*", which triggers the other DM to counteract and take a UI as well bringing the conflict to a new State "*k*". If the payoff value of State "*k*" is less than that of State "*i*", then the focal DM does not have any incentive to take the first UI. Therefore, State "*i*" will be SEQ stable for the focal DM.
General Metarationality (*GMR*)	The focal DM takes a UI and brings the conflict from a State "*i*" to State "*j*", which triggers the other DM to counteract and make a unilateral movement bringing the conflict to a new State "*k*". If the payoff value of State "*k*" is less than that of State "*i*", then the focal DM does not have any incentive to take the first UI. Therefore, State "*i*" will be GMR stable for the focal DM.
Symmetric Metarationality (*SMR*)	The focal DM takes a UI and brings the conflict from a State "*i*" to State "*j*", which triggers the other DM to counteract and make a unilateral movement bringing the conflict to a new State "*k*". The focal DM now can respond again by making a unilateral move to a new State "*m*". If the payoff value of State "*k*" and State "*m*" is less than that of State "*i*", then the focal DM does not have any incentive to take the first UI. Therefore, State *"i"* will be SMR stable for the focal DM.

The stabilities mentioned above are interconnected. The following figure depicts the individual decision-maker's stability in a conflict.

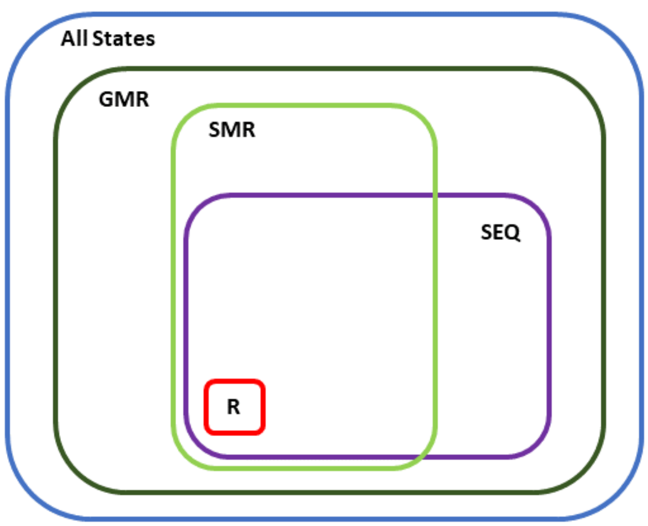


Figure 101 Individual decision-maker stability in a conflict expressed as a Venn diagram.

If a State is Nash or R stable for a decision-maker, it will be GMR, SMR, and SEQ stable as well. If a State is SEQ or SMR stable, then it will be GMR stable as well. Overall, a stability analysis is the systematic study of potential moves and countermoves by the decision-makers as they jostle for more preferred positions during the evolution of the conflict and the determination of the most likely resolution. This resolution is also known as equilibrium**.**

6.2 Earlier application of GMCR on the Cauvery River Basin

GMCR has been used in the past for water-related conflicts, like the Jordan River conflict, and general environmental conflicts (Hipel et al., 1993; Madani & Hipel, 2007). (Sharma et al., 2020) provided some preliminary results on the Cauvery River conflict using fuzzy methods. The method and some of its results are summarised in this subsection.

In the preliminary study of this research, the decision-makers in the conflict were assumed to be the provinces of Karnataka, Tamil Nadu, and finally the Supreme Court of India. The complete background history of the conflict was then analyzed. Since "water" is a provincial issue and the federal government can only make suggestions to the provinces, it was concluded that the federal government and by extension the supreme court of India did not have any executive powers. Therefore, the provinces of Karnataka, and Tamil Nadu were the only two decision-makers in the conflict. The decision-makers and the options are presented in the following table. Note that this table is similar to Table 37 in the previous section as it discusses the options available to the decision makers.

Table 40 Decision makers and their options (Sharma, Hipel, et al., 2020)

Decision Makers (DM)	Options
Tamil Nadu (DM1)	1. Reinstate the previous (the year 2007) ruling. 2. Request to modify and accept a crop-diversification clause. 3. Ask to modify and accept the pricing of the water clause.
Karnataka (DM2)	4. Push to enforce the current (year 2013) ruling. 5. Agree to the pricing of the water clause.
Supreme Court, CRA, CMC (SC) (DM3)	6. Support the current (the year 2013) ruling. 7. Modify to include crop diversification clause. 8. Alter to include pricing of water.

The conflict analyzed in (Sharma, Hipel, et al., 2020) focused on the Cauvery Water Disputes Tribunal (CWDT)'s verdicts from 2007, and 2013 (CWDT, 2007a, 2007b, 2007c, 2007d, 2007e). The 2007 verdict of the CWDT ascertained 419 TMC (thousand million cubic feet) of the total Cauvery River for Tamil Nadu, and 270 TMC for Karnataka. The province of Karnataka disputed this verdict, and after much deliberation, CWDT updated the allocation with Tamil Nadu's share being reduced to 404 TMC, and Karnataka's share being increased to 285 TMC. The methods, results, conclusions, and the calculations from the (Sharma, Hipel, et al., 2020) paper are demonstrated in Appendix 9.3.

The analysis was focused on the tussle between the two provinces trying to increase their respective share of water from Cauvery until the final order in 2018 was passed. One of the major drawbacks of the published study was that it only focused on the verdicts and not on the underlying factors affecting the conflict. The published work has helped lay the foundation of the current work. Also, there was a general lack of information and data on the conflict which prevented the researchers from carrying out the analysis using the regular stability calculations. Therefore, a fuzzy preferences approach was utilized. In regular GMCR, or crisp GMCR, the preferences only have ordinal preferences, i.e., a State is either more or less preferred than other States for a decision-maker. There are no cardinal preferences. In fuzzy GMCR, probabilities are assigned to the preferences of each decision-maker at the preference optimization stage of the analysis before the stabilities are calculated. This resulted in a very possible equilibrium scenario, i.e., water pricing. The water pricing option, which demands the cooperation of both decision-makers, has emerged as the most favorable option. In (Sharma et al., 2020) it was concluded that to potentially resolve this conflict, high political will was required. Water pricing can only be successful in a case of mutual agreement between Tamil Nadu and Karnataka. This option shall ensure that Tamil Nadu receives sufficient water every year, and in turn, Karnataka will receive a compensatory sum of money which it will invest in its infrastructure development. This may also prevent the State of Karnataka from taking a loan from the Asian Development Bank (ADB) and completing the project in-house. This option also utilizes Ostrom's idea, where the two States can become dependent on each other and don't require intervention from the regulatory bodies (Ostrom, 1990).

The stabilities and the ensuing equilibria are formed at "a" point in time of the conflict. The conflict is analyzed until a specific point in time. The above conflict was analyzed until the 2018 decision was passed by the Cauvery Monitoring Authority. This conflict has long been central in the politics of the region. State politicians have exploited the cultural, ideological, and linguistic differences between the people living in the Cauvery River Basin. The GMCR analysis in this chapter builds upon the work done by Sharma et al.

(2020). It is to be noted that the options mentioned in the previous GMCR study are no longer being recommended. One of the biggest drawback of the previous study was that it needed to be devoid of the analyst bias as much as possible. In the current study, with the introduction of WEAP and CIB analysis, the analyst bias is as low as possible. Also, the previous study recommended a holistic or a systems of systems analysis for better understanding the complex nature of the conflict. Therefore, the options from the previous study, although important for the preliminary design of this work, are not being used for analysis or recommended anymore.

6.3 Current GMCR

The current GMCR work uses the results from the system of system analysis assisted by the CIB method. Therefore, this conflict will be analyzed for any hypothetical time after August 2023. All the information available and the research analysis carried out using the document analysis, WEAP analysis, and CIB analysis will be used to inform the decision-making in the conflict. The preference rankings of the options available to the decision-makers are based on the active descriptors from the CIB analysis. From this analysis, the options available to the province of Karnataka are to reduce water demand, increase governmental effectiveness, reduce corruption, and negotiate an agreement with the province of Tamil Nadu. On the other hand, the options available to the province of Tamil Nadu are to increase water supply, increase governmental effectiveness, and reduce corruption.

Table 41 Results from the Cross Impact Balance analysis.

	Karnataka		Tamil Nadu
1	Reducing water demand.	1	Increase Water supply.
2	Increasing governmental effectiveness.	2	Increasing governmental effectiveness.
3	Reducing corruption.	3	Reducing corruption.
4	Negotiate an agreement with Tamil Nadu.	4	Negotiate an agreement with Karnataka.

For the GMCR analysis, these active descriptors from the CIB analysis are translated into present policy options over which the two provinces can negotiate. The options of the two decision-makers are as follows,

Table 42 Decision makers and their options

Decision Makers	Options
Karnataka	1. Accept Mekedatu Dam
	2. Reject River Linkage
	3. IWRM (Managing water demand)
Tamil Nadu	1. Reject Mekedatu Dam
	2. Accept River Linkage
	3. Aquifer Management (Managing water supply)

The water demand management in Karnataka and Tamil Nadu can be improved by the introduction of Integrated Water Resources Management (IWRM). IWRM is used as a proxy for the water management practices options for both the decision-makers. Researchers like Ghosh et al. (2018) and Ghosh & Modak, (2021), concur that the current water management techniques do not translate into resolving actual complex problem. Marini et al. (2020) talked about how essential the IWRM approaches are in resolving complex water management challenges.

Increasing water demand in the Karnataka sub-basin of the Cauvery River is a challenge for which this project is trying to find solutions. The Karnataka Integrated and Sustainable Water Resources Management Investment Program (KISWRMIP) is one of the schemes developed by the Water Resources Department (WRD) of the Government of Karnataka, which aims at Integrated Water Resources Management (IWRM) (Government of Karnataka, 2023). The total cost of the project is USD 225 million. USD 150 million was approved in the year 2011 by the Asian Development Bank (ADB) and the Government of Karnataka added a further USD 75 million to the project. The project in its current form focuses on strengthening the institutional capacities of the WRD, improving the water resources information system, and modernizing the irrigation system infrastructure including installation of telemetry for canal flow measurement (Government of Karnataka, 2023; Matsunaga et al., 2020; Raju et al., 2013). This project in Karnataka, currently in its second phase, is working on modernizing the irrigation systems. This current project is focused on the northern parts of the province. Based on the progress reports and other project documents, the work seems satisfactory (Shivashankar & Durugappa, 2022). The same approach can be applied to the water supply systems in the southern parts of the province, especially to the water supply infrastructure that supplies water to the city of Bengaluru. Due to the satisfactory progress of the KISWRMIP project, there is an existent built capacity in the province. This experience should be utilized and transferred to other projects in the province. This forms the third option available to the decision-maker Karnataka in the present conflict.

For Tamil Nadu, the water supply in the basin is driven by the irrigation water demand. The majority of the farmers, when not consuming the rainwater, use borewells to extract groundwater. Groundwater in Tamil Nadu has been depleting rapidly for the last two decades (Ars & Sreenivas, 2016). There is a constant battle between the rate of groundwater recharge (1 – 19.81 cubic kilometers per year) and the rate at which the groundwater is being extracted (2.3 – 21.4 cubic kilometers per year) in the province (Kitterød, 2022). There is a need to raise awareness regarding the depleting groundwater levels and aid the recovery of water levels in the aquifer (Prayag et al., 2023).

The decrease in the available surface storage can be used as a proxy for the deviation in the water availability in the basin. The WEAP analysis also shows the decreasing trend in the available water supply over the next thirty years. The following figure shows the trend over four scenarios, high rainfall - high water demand, high rainfall – low water demand, low rainfall – high water demand, and low rainfall – low water demand.

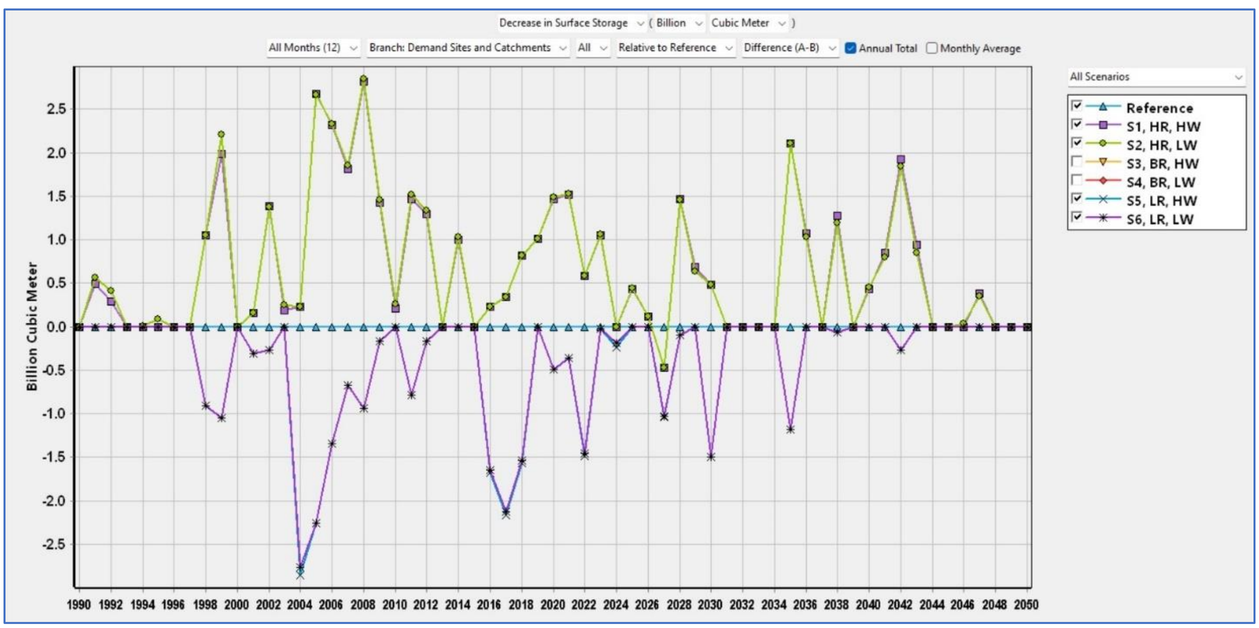


Figure 102 Decrease in Surface storage in Tamil Nadu Catchment

Over a period of time, the groundwater replenishment will decrease as the quantity of rainfall dwindles. Therefore, aquifer management is an extremely important policy point for the province of Tamil Nadu and one that needs more exposure from the federal government. By focusing the IWRM practices in Tamil

Nadu on groundwater replenishing, the water supply in the sub-basin can be sustained. Therefore, this forms the third option that the province of Tamil Nadu should have in the negotiations.

The negotiations in realizing the Mekedatu dam project as well as the river linking projects is used as a proxy for showcasing governmental effectiveness for both the decision-makers. The following sections discuss the various policy points that the provinces can take, the infeasible States within the game, how options available to the decision-makers are prioritized, the preference rankings of States of the decision-makers, and finally the equilibrium or the resolution.

6.3.1 Discussion of the options

The following section discusses the options available to the decision-makers and how and why they are on opposing sides of the same?

6.3.1.1 Mekedatu Dam project

Apart from the introduction of IWRM, the two provinces have a long history of non-cooperation. To reduce the water demand in Karnataka, the province has introduced the *Mekedatu* Dam project (Government of Karnataka, 2023). The Mekedatu balancing reservoir and drinking water project is a multipurpose project. The research aims at providing drinking water facilities to the city of Bengaluru and the surrounding areas. The research is planned to rectify the water supply problems of the exponentially increasing population of Bengaluru (Cauvery Neeravari Nigam Limited, 2019). The province of Karnataka has not obtained permission from the downstream province of Tamil Nadu before going ahead with the project. The situation is ironic because the conflict researched here began in the year 1890 due to a similar dam project development.

6.3.1.2 River Linking project

The government of India reintroduced the inter-State linking of rivers project. The project was first introduced as a probable future project under the National Perspective Plan (NPP) in the 1980s (Ministry of Jal Shakti, 2021). NPP was developed by the then Ministry of Irrigation in India (now Ministry of Jal Shakti) for water resources development through the cross-basin transfer of water. This transfer would take place from a water surplus basin to a water deficit basin (Ministry of Jal Shakti, 2022). The Cauvery River is one such water deficit river. The province of Tamil Nadu is in favor of the linking project. However, Karnataka has apprehensions about it. The federal government has finished preparing the detailed progress report (DPR) for the project. The province of Karnataka is against the linking project because there is a lack of clarity on the quantity of allocation of water after the linking is finished. Also, the linking of the rivers Cauvery with Pennar River will occur outside the provincial boundaries, hence Karnataka will not have any control over the outcome. The province feels that it will not benefit at all (Shankar, 2022).

6.3.2 Infeasible States

The two decision-makers have six options in total. Each of the States can either be accepted or rejected, therefore, the total number of States possible are $2^6 = 64$. There are 64 unique combinations of the States available (H. Xu et al., 2018). To simplify the analysis, some of these States are removed as they are either logically infeasible or preferentially infeasible. In GMCR, when an option is taken it is denoted by either a "Y" or "1" for yes, and a "N" or "0" for no. There are four types (Fang et al., 1993; Fraser & Hipel, 1984; Hipel, 2018; Kassab et al., 2006) of infeasibilities. They are explained below. The GMCRplus (Kinsara, 2014) software is used for the analysis.

6.3.2.1 Type 1: Logically infeasible for a decision-maker.

For example, Karnataka will have to choose at least one option. A State where none of the options are chosen would be deemed infeasible for Karnataka.

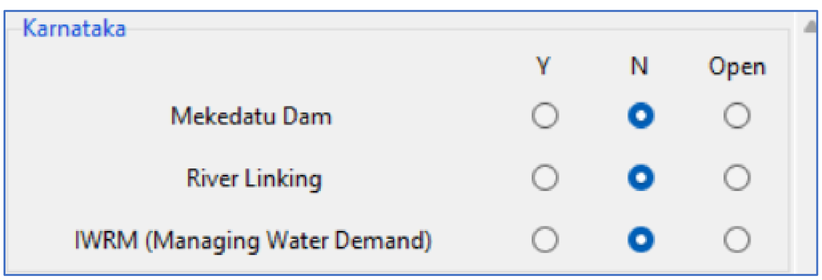


Figure 103 Type 1 infeasibility

6.3.2.2 Type 2: Preferentially infeasible for a decision-maker.

Since Karnataka wants to make the Mekedatu project happen, an option where they are against it will become preferentially infeasible. There are other instances of Type 2 infeasible States as well. They are shown in the Appendix A.

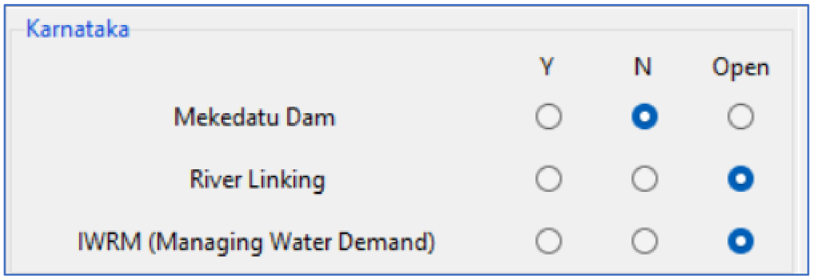


Figure 104 Type 2 infeasibility

6.3.2.3 Type 3: Logically infeasible for a group of decision-makers.

The decision maker Karnataka is in favor of the Mekedatu project, and the decision-maker Tamil Nadu is against the Mekedatu project. A State where Karnataka is against, and Tamil Nadu is for the project is logically infeasible.

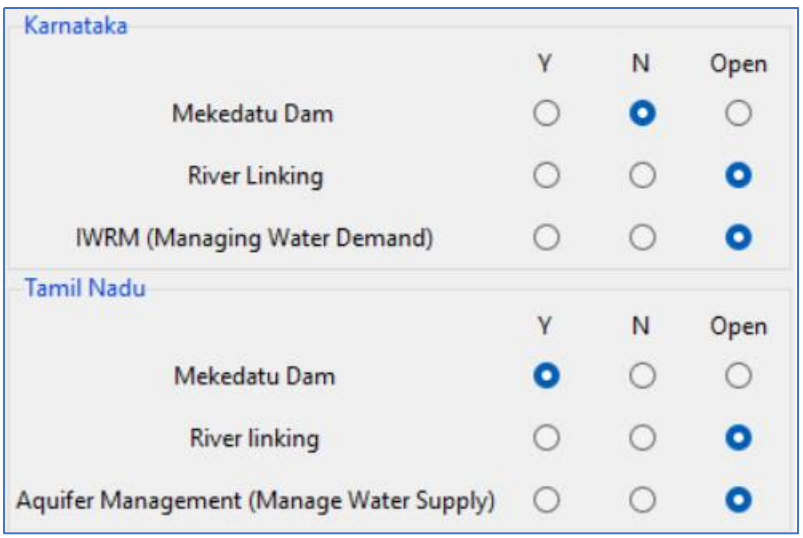


Figure 105 Type 3 infeasibility

6.3.2.4 Type 4: Preferentially infeasible for a group of decision-makers.

IWRM inclusion in some form is an important policy consideration for these two decision-makers. Therefore, a State where neither of the two decision-makers opts for the IWRM option would become preferentially infeasible.

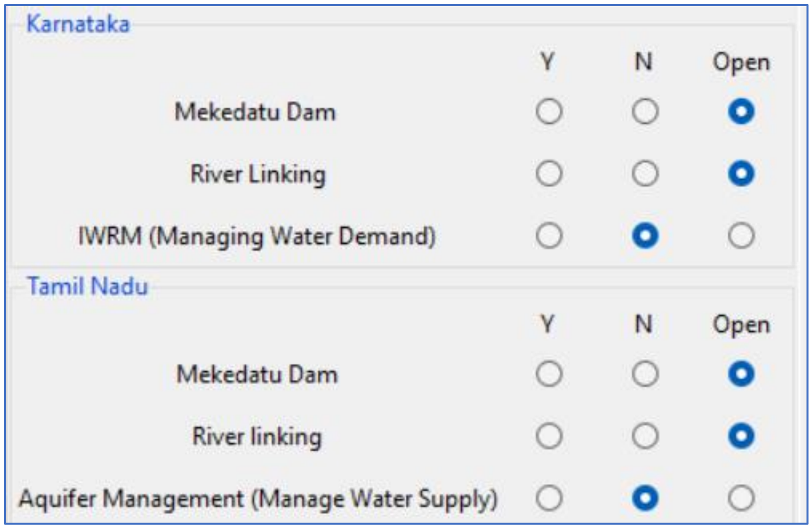


Figure 106 Type 4 infeasibility

After the four types of infeasibilities are removed from the conflict, 12 feasible States remain out of the total of 64 States. The 12 States that remain are shown below,

	Ordered	1	2	3	4	5	6	7	8	9	10	11	12
	Decimal	21	23	29	31	49	51	53	55	57	59	61	63
Karnataka	Mekedatu Dam	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	River Linking	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y
	IWRM (Managing Water	Y	Y	Y	Y	N	N	Y	Y	N	N	Y	Y
Tamil Nadu	Mekedatu Dam	N	N	Y	Y	N	N	N	N	Y	Y	Y	Y
	River linking	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Aquifer Management (	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y

Figure 107 The twelve feasible States

The decimal number of a State is calculated using the binary to number calculations. For example, State 1 is made up of Y, N, Y, N, Y, N combination of options. Assuming, Y = 1, and N = 0, then the decimal State number is calculated as follows,

Decimal State $= 1 \text{ (Y) X } 2^0 + 0 \text{ (N) X } 2^1 + 1 \text{ (Y) X } 2^2 + 0 \text{ (N) X } 2^3 + 1 \text{ (Y) X } 2^4 + 0 \text{ (N) X } 2^5$

$= 1 + 0 + 4 + 0 + 16 + 0$

$= 21$

The State Number mentioned from here on in the text will be the ordered number of the States.

6.3.3 Option Prioritisation

Option prioritization is the process of determining the options or combinations of options that help identify the preference rankings among the feasible States (Fraser & Hipel, 1984; Hipel et al., 1993; H. Xu et al., 2018). Each decision-maker in a conflict will have a preference ranking of the States from most preferred to least preferred.

For Karnataka, managing the water demand should be the most preferred option and not the construction of Mekedatu Dam because the project is opposed by Tamil Nadu. The project may lead to further animosity between the two decision-makers. Therefore, the States where IWRM is "Y" are the most preferred States for Karnataka. The second most preferred option combination is when IWRM is "Y" for Karnataka, and Aquifer management is "Y" for Tamil Nadu. A basin-wide water management plan is highly important for the future of the river basin. The third most preferred option for Karnataka should be a "Y" for the dam project, and a "Y" in IWRM. The province of Karnataka should want to include the dam project as part of the larger water management project. The next preferred option is a "N" to the river linking project as it does not provide any benefit to the province; however, there is a possibility that the current stipulated quantity of water coming from the Cauvery River basin may be hampered.

Similarly for Tamil Nadu, managing its aquifer or groundwater management is extremely important to ensure water supply in the future in case of faltering rainfall. Therefore, the option with a "Y" in Aquifer management is the most preferred. Opposing the Mekedatu Dam is not the most preferred option because that would lead to further conflict with Karnataka. The next preferred combination of options is when both provinces move forward together by choosing to opt for an integrated water management methodology. The next preferred option is when Tamil Nadu includes the river linking project into the IWRM-based methodology. The final preferred option is when the other decision-maker does not opt for the dam project. This option is logically infeasible for Karnataka and is therefore least preferred by Tamil Nadu. It is only included here to complete the option prioritisation for Tamil Nadu. The dam may cause a reduction in the quantity of water flowing towards Tamil Nadu.

6.3.4 Preference Rankings

The preference ranking of the decision-maker in Karnataka is as follows,

Table 43 Karnataka preference rankings with Ordered State Number

Decision Makers	Options	Ordered State Number											
		11	7	12	4	3	10	9	2	1	8	5	6
Karnataka (DM1)	*Option 1 (Accept Mekedatu Dam)*	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Option 2 (Accept River Linking)	N	N	Y	Y	N	Y	N	Y	N	Y	N	Y
	Option 3 (Adopt IWRM)	Y	Y	Y	Y	Y	N	N	Y	Y	Y	N	N
Tamil Nadu (DM2)	*Option 4 (Accept Mekedatu Dam)*	Y	N	Y	Y	Y	Y	Y	N	N	N	N	N
	Option 5 (Accept River Linking)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Option 6 (Adopt Aquifer Management)	Y	Y	Y	N	N	Y	Y	N	N	Y	Y	Y

For Karnataka, the most preferred State is where the province is pushing for the Mekedatu Dam project to be completed, and the province of Tamil Nadu agrees (Chidambaram et al., 2018; Prajwal, 2020; Press Trust of India, 2022a; Roshith et al., 2022). State 7 is the status quo at the moment except for the IWRM and Aquifer management options added to the game. State 12 is an ideal situation for the Cauvery River basin and therefore, preferred by the province. In general, any State in which Tamil Nadu opposes the Mekedatu Dam is less preferred by the province of Karnataka.

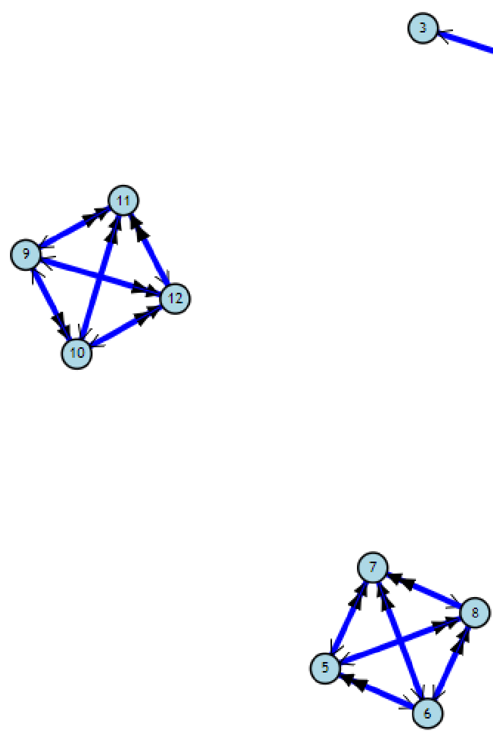


Figure 108 Karnataka unilateral improvements and movements in the conflict

The following figure shows the moves available to Karnataka in the Cauvery River conflict in graph form. The numbers subscribed within the circle are the State numbers. The blue arrows represent the movements within the States. Double arrows represent the direction of a unilateral improvement. The unilateral improvements are important to take note of because they help determine the progression of the game in the conflict. In the above figure, Karnataka has a UI from 3 to 4 as depicted using the double arrows pointing from State 3 to State 4. Similarly, it has UIs from 9 to 11, 9 to 10, 9 to 12, 10 to 11, 12 to 11, and so on.

On the other hand, the preference ranking of the other decision maker Tamil Nadu is as follows,

Table 44 Tamil Nadu preference rankings

Decision Makers	***Options***	***Ordered State Number***											
		8	**7**	**12**	**6**	**10**	**2**	**4**	**11**	**1**	**3**	**5**	**9**
Karnataka (DM1)	*Option 1 (Accept Mekedatu Dam)*	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Option 2 (Accept River Linking)	Y	N	Y	Y	Y	Y	Y	N	N	N	N	N
	Option 3 (Adopt IWRM)	Y	Y	Y	N	N	Y	Y	Y	Y	Y	N	N
Tamil Nadu (DM2)	*Option 4 (Accept Mekedatu Dam)*	N	N	Y	N	Y	N	Y	Y	N	Y	N	Y
	Option 5 (Accept River Linking)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Option 6 (Adopt Aquifer Management)	Y	Y	Y	Y	Y	N	N	Y	N	N	Y	Y

For Tamil Nadu, the most preferred State is one where it is refusing to accept the Mekedatu Dam project, pushing for the river-linking project, and Karnataka is also agreeing to the river-linking project (Ghosh et al., 2018; Lobo, 2018c). The Mekedatu dam issue has been raised multiple times now in the parliament and as recently as May of 2023 (Press Trust of India, 2023). Tamil Nadu continues to raise its concern over the built capacity of the dam project and wants the project to be shut down until its inputs are considered.

State 7 is the current status quo, and State 12 is an ideal situation and therefore preferred by the decision-maker. For Tamil Nadu, all the States in which the river linking project is not accepted by Karnataka are less preferred.

The following figure shows the moves available to Tamil Nadu in the Cauvery River conflict in graph form. The numbers subscribed within the circle are the State numbers. The green arrows represent the movements within the States. Double arrows represent the direction of a unilateral improvement.

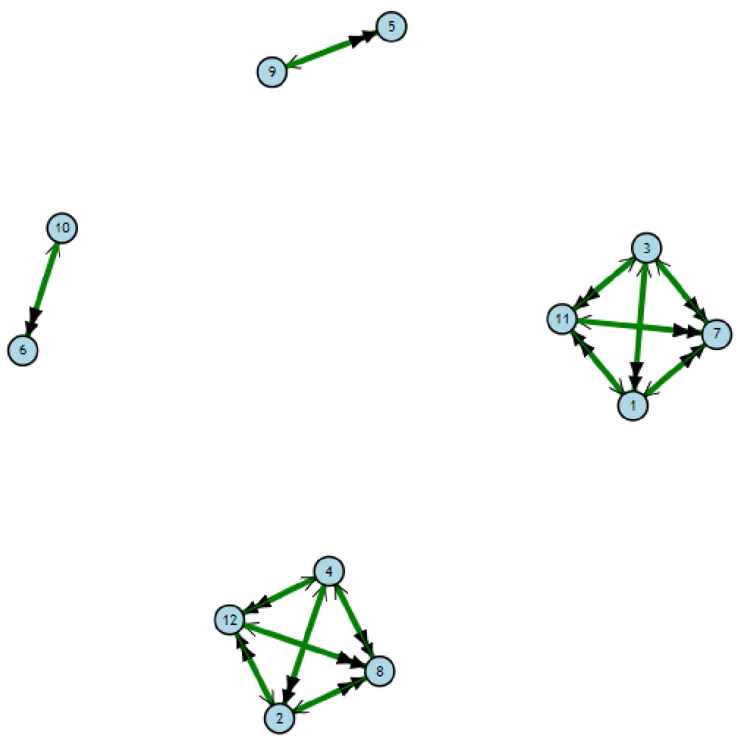


Figure 109 Tamil Nadu unilateral improvements and movements in the conflict

The decision-maker in Tamil Nadu has a unilateral improvement from State 10 to 6, from State 9 to 5, etc. The stabilities are calculated using unilateral improvements and improvements. The GMCRplus software (Kinsara, 2014) uses this information along with the definitions of different stabilities to calculate the results for each State in the conflict. As explained in the previous section, each State is checked for a unilateral improvement first, and then its unilateral movements are identified. Based on these moves, the stabilities of Nash, General Metarational (GMR), Symmetric Meta rational (SMR), and Sequential stable (SEQ) are determined for every state and decision-makers.

6.3.5 Equilibrium

A State in the conflict achieves or reaches equilibrium when that State is stable for all the decision-makers. The following table shows the output from the GMCRplus software.

Table 45 Equilibria results for the Cauvery River conflict.

	Ordered		1	2	3	4	5	6	7	8	9	10	11	12
	Decimal	Filter	21	23	29	31	49	51	53	55	57	59	61	63
1 - Karnataka	Mekedatu Dam	-	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	River Linking	-	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y
	IWRM (Managing Water	-	Y	Y	Y	Y	N	N	Y	Y	N	N	Y	Y
2 - Tamil Nadu	Mekedatu Dam	-	N	N	Y	Y	N	N	N	N	Y	Y	Y	Y
	River linking	-	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	Aquifer Management (	-	N	N	N	N	Y	Y	Y	Y	Y	Y	Y	Y
Payoff For:	Karnataka	-	4	5	8	9	2	1	11	3	6	7	12	10
Payoff For:	Tamil Nadu	-	4	7	3	6	2	9	11	12	1	8	5	10
	Nash	-							Y					
	GMR	-	Y	Y		Y			Y			Y	Y	Y
	SEQ	-							Y					
	SIM	-							Y					
	SEQ & SIM	-							Y					
	SMR	-		Y					Y			Y	Y	Y

The above table displays two States that have equilibrium. State 7 is stable because the State is Nash stable for both of the decision-makers. As per the stability's definitions, if a State is Nash stable it automatically becomes stable through other types of stabilities. States 2, 10, 11, and 12 are SMR stable, hence it automatically becomes GMR stable as well. States 1, and 4 are GMR stable as well.

6.3.5.1 State 7

State 7 represents Karnataka continuing to expect completion of the Mekedatu Dam, rejecting the river linking project, and agreeing to an Integrated Water Resources Management (IWRM) based water demand management plan. State 7 also has Tamil Nadu rejecting the Mekedatu Dam, expecting to go ahead with the river linking project, and agreeing to Aquifer management for managing water supply. This situation is as close to the status quo without the addition of water management options added on. This is an ideal equilibrium and resolution for the conflict. The most preferred options of both the decision-makers are taken as it is.

6.3.5.2 State 2

For Karnataka there is no UI from State 2. Hence the State is Nash stable for them. Tamil Nadu, on the other hand, has UIs from State 2 to State 8, and State 12. For stability calculations, both these unilateral improvements are checked. If Tamil Nadu takes the UI to State 8, the game is now in State 8. The next move is controlled by Karnataka. Karnataka can make a unilateral move to State 5. Now State 5 is less preferred than State 2, the initial State, for Tamil Nadu. Therefore, this move is blocked. If Tamil Nadu takes the other UI, i.e., to State 12, then Karnataka can make a unilateral move to State 9. State 9 is also less preferred than State 2 for Tamil Nadu, therefore, this move is also blocked. There are no credible countermoves left. Therefore, State 2 is SMR stable for decision maker Tamil Nadu.

6.3.5.3 State 10

For Karnataka, there are two UIs from State 10: State 11, and State 12. If Karnataka moves to State 11, then Tamil Nadu has the option to take the game to State 1. State 1 is less preferred than State 10 and therefore, the move is blocked. If Karnataka takes the other UI to State 12, then Tamil Nadu has the option of taking the game to State 2. State 2 is also less preferred than State 10 for Karnataka, therefore the move is still blocked. There are no credible countermoves left. Hence, State 10 is SMR stable for Karnataka.

For Tamil Nadu, there is one UI to State 6. If Tamil Nadu moves to State 6, then Karnataka can take the game to State 5. State 5 is less preferred than State 10 for Tamil Nadu, hence this move is blocked. There are no credible countermoves left. Therefore, State 10 is also SMR stable for Tamil Nadu.

6.3.5.4 State 11

For Karnataka, there are no UIs from State 11, therefore, State 11 is Nash stable for them. For Tamil Nadu, there is one UI to State 7. If Tamil Nadu moves to State 7, then Karnataka can take the game to State 5. State 5 is less preferred than State 11 for Tamil Nadu, hence this move is blocked. There are no credible countermoves left. Therefore, State 11 is SMR stable for Tamil Nadu.

6.3.5.5 State 12

For Karnataka, there is one UI from State 12 to State 11. If Karnataka moves to State 11, then Tamil Nadu has the option to take the game to State 1. State 1 is less preferred than State 12 and therefore, the move is blocked. There are no credible countermoves left. Hence, State 12 is SMR stable for Karnataka.

For Tamil Nadu, there is one UI to State 8. If Tamil Nadu moves to State 8, then Karnataka can take the game to State 5. State 5 is less preferred than State 12 for Tamil Nadu, hence this move is blocked. There are no credible countermoves left. Therefore, State 12 is also SMR stable for Tamil Nadu.

6.3.5.6 State 1

For Karnataka, there is one UI from State 1 to State 2. If Karnataka moves to State 2, then Tamil Nadu has the option to take the game to State 8. State 8 is less preferred than State 1 and therefore, the move is blocked. Hence, State 1 is GMR stable for Karnataka.

For Tamil Nadu, there are two UIs from State 1: State 7, and State 11. For stability calculations, both these unilateral improvements are checked. If Tamil Nadu moves to State 7, then Karnataka can take the game to State 5. State 5 is less preferred than State 1 for Tamil Nadu, hence this move is blocked. If Tamil Nadu takes another UI to State 11, then Karnataka can take the game to State 9. State 9 is less preferred than State 1 for Tamil Nadu, hence this move is blocked. Therefore, State 11 is also GMR stable for Tamil Nadu.

6.3.5.7 State 4

For Karnataka, there are no UIs from State 4, therefore, State 4 is Nash stable for them. For Tamil Nadu, there are three UIs from State 4: State 2, State 8, and State 12. For stability calculations, all of the unilateral improvements are checked. If Tamil Nadu moves to State 2, then Karnataka can take the game to State 1. State 2 is less preferred than State 4 for Tamil Nadu. Hence this move is blocked. If Tamil Nadu takes a UI to State 8, then Karnataka can take the game to State 5. State 5 is less preferred than State 4 for Tamil Nadu, hence this move is blocked. If Tamil Nadu takes UI to State 12, then Karnataka can take the game to State 9. State 9 is less preferred than State 4 for Tamil Nadu. Hence this move is blocked. Therefore, State 4 is also GMR stable for Tamil Nadu.

6.4 Discussion of the results

The GMCR methodology has provided seven stable states that are likely outcomes of the current version of the conflict modeled. Apart from the status quo of State 7, six viable possibilities can occur in this conflict. These stable states can be used in negotiation (Kilgour et al., 1995).

6.4.1 State 2

In this resolution, the province of Karnataka accepts the river-linking proposal as pushed by the province of Tamil Nadu. Also, the province of Tamil Nadu does not consent to the Mekedatu dam project. However, Karnataka goes ahead with the construction of the dam. This can be a resolution because Karnataka has also agreed to an IWRM-based water demand method. The hypothesis is that this is an indication from Karnataka to Tamil Nadu that they are serious and taking concrete steps toward managing the available resource. This resolution is not ideal but encouraging.

Decision-Makers	***Options***	**2**
Karnataka (DM1)	*Option 1 (Accept Mekedatu Dam)*	Y
	Option 2 (Accept River Linking)	Y
	Option 3 (Adopt IWRM)	Y
Tamil Nadu (DM2)	*Option 4 (Accept Mekedatu Dam)*	N
	Option 5 (Accept River Linking)	Y
	Option 6 (Adopt Aquifer Management)	N

Figure 110 State 2

6.4.2 State 10

In this resolution, Karnataka agrees to the river linking project proposed by Tamil Nadu, and Tamil Nadu agrees to the Mekedatu dam project proposed by Karnataka. Also, Tamil Nadu accepts the aquifer management methods for controlling the water supply in the sub-basin. However, Karnataka has rejected the plans for an IWRM-based water demand management in the basin.

Decision-Makers	***Options***	**10**
Karnataka (DM1)	*Option 1 (Accept Mekedatu Dam)*	Y
	Option 2 (Accept River Linking)	Y
	Option 3 (Adopt IWRM)	N
Tamil Nadu (DM2)	*Option 4 (Accept Mekedatu Dam)*	Y
	Option 5 (Accept River Linking)	Y
	Option 6 (Adopt Aquifer Management)	Y

Figure 111 State 10

The hypothesis is that since both the provinces were able to negotiate the river-linking and Mekedatu dam projects successfully, and the province of Tamil Nadu is going to manage its water demand through Aquifer management, the province of Karnataka can defer its plans to invest in the IWRM methods. The province of Karnataka should be able to provide a consistent water supply to the sub-basin through the Mekedatu dam reducing its dependency on the water supply from the Cauvery River. This resolution can be used as a policy discussion point to resolve this conflict.

6.4.3 State 11

State 11 is State 2 flipped where Karnataka refuses to accept the river linking project, and Tamil Nadu accepts the Mekedatu dam project. However, in this resolution, both provinces have accepted to employ water management methods in their respective subbasins. The hypothesis is that both provinces are moving forward with well-thought-out policy measures that can help sustain the water resources in the Cauvery River basin. Tamil Nadu should be fine with the river linking project not working as long as it can find a more sustainable way to increase the replenishing of its aquifers. This resolution is also a critical policy measure that needs to be used to resolve this conflict.

Decision-Makers	***Options***	**11**
Karnataka (DM1)	*Option 1 (Accept Mekedatu Dam)*	Y
	Option 2 (Accept River Linking)	N
	Option 3 (Adopt IWRM)	Y
Tamil Nadu (DM2)	*Option 4 (Accept Mekedatu Dam)*	Y
	Option 5 (Accept River Linking)	Y
	Option 6 (Adopt Aquifer Management)	Y

Figure 112 State 11

6.4.4 State 12

State 12 is the ideal situation where all the options are accepted and there is no requirement for any discourse. Based on past experiences, it is highly unlikely that the two provinces would accept each other's demands easily. This State can be removed from the conflict as a logically infeasible condition (Type 4); however, it was kept in the game for posterity.

Decision-Makers	***Options***	**12**
Karnataka (DM1)	*Option 1 (Accept Mekedatu Dam)*	Y
	Option 2 (Accept River Linking)	Y
	Option 3 (Adopt IWRM)	Y
Tamil Nadu (DM2)	*Option 4 (Accept Mekedatu Dam)*	Y
	Option 5 (Accept River Linking)	Y
	Option 6 (Adopt Aquifer Management)	Y

Figure 113 State 12

6.4.5 State 1

State 1 is where Karnataka rejects the river linking project, and Tamil Nadu rejects the Mekedatu dam project. Instead, the province of Karnataka invests in the IWRM methods. Tamil Nadu does not invest in the aquifer management plans. The hypothesis is that the province of Tamil Nadu feels that the replenishing of its aquifers can occur due to the river-linking project. This resolution is undesirable because it removes the possibility of discourse between the provinces and sets them up for further future conflicts.

Decision-Makers	***Options***	**1**
Karnataka (DM1)	*Option 1 (Accept Mekedatu Dam)*	Y
	Option 2 (Accept River Linking)	N
	Option 3 (Adopt IWRM)	Y
Tamil Nadu (DM2)	*Option 4 (Accept Mekedatu Dam)*	N
	Option 5 (Accept River Linking)	Y
	Option 6 (Adopt Aquifer Management)	N

Figure 114 State 1

6.4.6 State 4

State 4 resolution is State 10 resolution flipped for Tamil Nadu. Here both provinces have accepted each other's projects. Karnataka is investing in the IWRM methods. However, Tamil Nadu is not going ahead with aquifer management projects. The hypothesis is that due to the IWRM projects in Karnataka, they will not require as much water and with river linking in Tamil Nadu, the aquifers can be easily replenished. This resolution is less desirable because it puts more power in the hands of the upstream province. It is evident from historical events that in times of crisis, the upstream province will break treaties.

Decision-Makers	*Options*	4
Karnataka (DM1)	*Option 1 (Accept Mekedatu Dam)*	Y
	Option 2 (Accept River Linking)	Y
	Option 3 (Adopt IWRM)	Y
Tamil Nadu (DM2)	*Option 4 (Accept Mekedatu Dam)*	Y
	Option 5 (Accept River Linking)	Y
	Option 6 (Adopt Aquifer Management)	N

Figure 115 State 4

6.5 Conclusion

In this analysis, policy points like the Mekedatu dam projects, river linking projects, and IWRM best practices were chosen. There is a requirement to increase institutional effectiveness, reduce corruption, and manage the water resources to sustain the natural resources available in the basin. This follows from the recommendations of the CIB analysis. The outputs from the CIB analysis discussed the active descriptors that can affect positive change in the system. The policy points above are direct proxies for the recommendations of CIB. By using the policy points in the GMCR analysis, this thesis has demonstrated that resolutions are possible even for such complex water-sharing problems.

This methodology has helped the researcher to visualize the possible progressions of the conflict. The knowledge of the moves and the counter moves that the decision makers can take are invaluable to this research. In this conflict, three types of options are utilized to reach possible resolutions. These options may be changed based on the requirements of the policymakers at the time. As long as the intentions of the decision-makers remain the same, the general output should remain similar as well.

A preliminary analysis of this conflict using GMCR alone was published in the year 2020 (Sharma, Hipel, et al., 2020), and it was well received by the community. Also, a methods paper was published in IEEE's Explore journal (Sharma et al., 2020). This paper was used by Motschmann et al. (2022) to analyze the current and future water availability in the Santa River basin in Peru. They used the WEAP and CIB methods in their work and generated promising results. In 2022, a conference proceedings paper was published by the research team that discussed systems interventions and leverage points (Sharma et al., 2022). This paper discussed the lack of governmental awareness of climate change measures in the basin. This conclusion is also valid in the current research project. The effects of climate change are visible in the country. The nation has observed record-breaking high temperatures, droughts, and precipitation. An effective government needs to include climate change mitigation measures. There is a need to increase awareness and a need to invest in projects that can safeguard its citizens from adverse climate change-caused events.

Increasing governmental effectiveness is complex and requires transparency and accountability to mitigate issues related to corruption and inefficiency. Furthermore, there is a need for improved coordination between the federal (central) governments, and the provincial governments. There is also a need for investments in increasing the administrative capacity. For example, there are several administrative positions that have remained vacant in the country (Jagannathan, 2018). Also, India has a multi-political party system and different parties may control the federal and the provincial governments. This can also hinder effective policy formulation and implementation. These are some of the barriers that may cause hindrance to the improvement of governmental effectiveness. However, if it can be improved, then this research has demonstrated that a resolution is possible.

The current research can demonstrate that institutions that are involved in decision making like the provincial governments, judiciary, water resources department, etc. need to be changed. The path dependencies in the Cauvery River system have prevented the dispute from being resolved for a very long time. Understanding and resolving path dependency is crucial because it highlights the importance of historical context, institutional design, and the challenges of institutional change. To potentially break the feedback loops, major interventions in institutions and thought processes are required. In a complex system like the Cauvery River basin, we can find “places” and or “points” where a small modification can produce a big change in the outcome. These are called leverage points. The higher the place to intervene in a system, the more difficult it is to affect any real change. The 1999 paper by Donella Meadows (Meadows, 1999) listed twelve generalized places to intervene in a system as shown in the table below.

Table 46 Places to intervene in a system (modified from (Meadows, 1999))

	Places to Intervene in a System *(in increasing order of effectiveness)*
12	Constants, parameters, numbers *(such as subsidies, taxes, standards)*
11	The sizes of buffers and other stabilizing stocks, relative to their flows.
10	The structure of material stocks and flows *(such as transport networks, population age structures)*
9	The lengths of delays, relative to the rate of system change
8	The strength of negative feedback loops, relative to the impacts they are trying to correct against
7	The gain around driving positive feedback loops
6	The structure of information flows *(who does and does not have access to what kinds of information)*
5	The rules of the system *(such as incentives, punishments, constraints)*
4	The power to add, change, evolve, or self-organize system structure
3	The goals of the system
2	The mindset or paradigm out of which the system — its goals, structure, rules, delays, parameters— arises
1	The power to transcend paradigms

In the case of the Cauvery River basin, leverage point number 2 would be the most effective. The institutional paradigms have developed the structure, rules, and parameters of the governance system in the basin. From using archaic laws from 1956 (Government of India, 1956b; Ministry of Law, 1956), to "water" being deemed a provincial issue (Cullet & Gupta, 2009; Richards & Singh, 2002; Srikanth, 2009), to consistent administrative delays in providing a decision on the quantities of water sharing, the bureaucratic obstacles and challenges have halted any consistent progress in the basin.

In the recommendation section of this work, the principles of water governance developed by the Organisation for Economic Cooperation and Development (OECD) (Organisation for Economic Cooperation and Development, 2016, 2018) will be referred to illustrate further policy interventions required.

7. Conclusions and Recommendations

This project aimed to find a possible resolution for the Cauvery River conflict. The project took five years and went through several updates and upgrades. The research is timely because the whole world is going through weather extremes causing human suffering and near civilization collapse in some regions. The global pandemic in the year 2020 affected every aspect of everyone's life on Earth. Over the last few years, we have seen extreme temperatures and droughts leading to an increase in the frequency of high rainfall events. Climate change activists are consistently using social media to raise awareness among the people and demand that world leaders act. The Sustainable Development Goals (SDGs), Paris Agreement, net-zero coalitions, climate adaptation strategies, etc. will only work if the action is taken now. Effective, moral, and ethical decision-making is required to develop policies that will help in controlling the global rising temperatures. Effective governments, taking effective decisions, also play a huge role in resolving disputes. Like conflicts in personal life tend to stop us from living out our complete potential, conflicts among systems/entities in a democracy hinder any possible promising progress. Therefore, a methodology is required that can analyze and understand the intricacies of how a system works and how it interacts with other systems. The current project has provided a possible solution to this systems of systems problem.

As discussed in detail in this work, the Cauvery River conflict has been going on for over a hundred years now. The Cauvery River conflict is not limited to sharing of water between the provinces of Karnataka and Tamil Nadu, but it involves complex interactions of various systems acting upon it. There have been many studies carried out on the Cauvery River basin analyzing different systems, however, in isolation. The majority of these types of work, ignore other systems and stop short of providing any useful resolutions. The current work, however, provides an in-depth analysis of the hydrological systems, socio-economic systems, and governance systems. This work also explores an in-depth interaction between these systems as depicted in the causal loop diagram in figures 8, and 39.

In the current work, the important requirements were the approximation of unmet demand in the basin, and WEAP was able to manage that precisely. The major limitation of WEAP is that it is not built for detailed design. Also, the data required for analysis has to be imported into the system. More independent coding languages like Python (Sharma, 2015) and R can handle any kind of data; however, for the kind of outputs required in this work, WEAP has done a great job. The continuous increase in unmet demand due to the increase in population, and its interaction with higher and lower than business-as-usual rainfall was interesting to observe. The timeline analysis of this unmet demand and its impacts on agricultural productivity proved immensely useful in the cross-impact balances analysis. The advantage of conducting cross-impact balance analysis lies in its ability to comprehensively examine all possible system states through enumeration, ensuring they do not contradict one another (i.e., they are consistent) and thereby aiding in establishing a clear understanding of the system. It is a powerful tool for understanding complex systems, making informed decisions, and exploring the potential consequences of different scenarios, leading to more effective problem-solving, and planning processes.

In the current work, CIB was able to generate many useful consistent scenarios that helped in identifying the active variables in the system. These variables are most likely to affect all the other variables in the system. Therefore, by managing these active variables, the system can be modified into a more desirable system. The active descriptors like managing Water Demand in Karnataka and managing Water Supply in Tamil Nadu from the current CIB work formed the inputs for the decision support system GMCR. The active descriptors are the systems that have the most effect on the system. Prioritizing the management of these descriptors may lead to positive change in the system.

The analysis from the causal loop diagram, WEAP, and CIB resulted in identification of the most important descriptors or systems within the Cauvery River basin that can affect positive change in the system. The systems of systems analysis concluded with a list of preferred policy options for the decision makers in the Cauvery River basin conflict. In conflict resolution, the options, and preferences of decision-makers in a conflict are used to determine how they would move and countermove while negotiating. The outputs from CIB helped in forming these options, and the document analysis helped in forming the preferences of the decision-makers. The GMCR analysis provided a few possible resolutions; however, the most convincing ones have the two decision-makers working together and helping each other achieve their respective goals. In the CIB analysis, it was evident that the system was rigid, and not prone to sudden changes. However, reducing water demand in Karnataka, increasing the water supply in Tamil Nadu, and increasing the effectiveness of the governments in both provinces are the best possible ways to resolve this conflict. Increasing governmental effectiveness for both provinces translate directly from the CIB analysis because they were key active descriptors. Also, managing the water demand and the water supply, and also reducing corruption should indirectly lead an increased governmental effectiveness. The GMCR method provided a few contextual options and scenarios in which such a situation is possible. From this work, it can be demonstrated, that if the two provinces can find a way to improve their administrative effectiveness and communicate better with each other, this water-sharing conflict can be resolved. This creates a novel study where the learnings from systems of systems analysis, hydrological modeling, socio-economic modeling, and graph model theory supported by document analysis creates a new and effective methodology to understand system dynamics. This new methodology also creates a better probability of resolving any wickedly complex conflicts.

The current work has provided insights with evidence on how the systems of systems methodology can be used to analyze wicked complex systems. The Causal Loop Diagram is one of the most important contributions of this work. This work identified nineteen systems that are interacting with each other to create a complex network of systems of systems. The various systems acting on the basin have settled in a robust rhythm, also known as path dependency. This path dependency has prevented the decision-makers from resolving the conflict. One of the other important contributions of this work is identification of the descriptors or systems that are highly likely to affect change in this system, known as active descriptors. The identification of active descriptors like Governmental Effectiveness, Corruption, Water supply, and Water demand is a direct contribution from the CIB method. Additional important contributions of this work were the improvement in the preference ranking information for the decision makers, which follows from the application of the GMCR method. In negotiations, understanding how the opposite player is going to make decisions is invaluable. The Sharma et. al (2020) paper lacked reliable information behind the decision-making process. This work, after conducting the systems of systems analysis, is able to reliably provide preferences of the decision makers for this complex conflict. In this work, many possible resolutions are proposed. However, a resolution that is beneficial for the river basin needs to be adopted as soon as possible.

The methods adopted in this research can be applied to other river basins in transboundary disputes. The methods employed here have helped in understanding the conflict, identifying the key descriptors or systems affecting the conflict, and identifying the possible path forward for the decision makers in order to resolve the conflict. The methods here in part were successfully used by Motschmann et al. (2022). That is a positive indication that this work is reproducible. However, it is important to note that clarity in understanding the systems of systems to be analyzed is extremely important before the methods can be applied. However, one of the limitations of this research is the lack of expert elicitation. As stated previously, in socio-economic research including stake holders throughout the decision-making process is extremely important. The initial methodology in the Cauvery River conflict research included expert elicitation as well. However, due to the global pandemic and subsequent lack of response from the subject matter experts in this area, the expert elicitation section of the research was modified to document analysis. The expert elicitation documents are shown in the Appendix B. Another limitation of this work is that the application of a systems of systems methodology is highly subjective. The socio-economic and political nuances can change at any given period of time.

In future work, expert elicitation should be included in the research. The framework developed by the International Association for Public Participation (IAP2) can be used to inform, consult, involve, collaborate, and empower the stakeholders (A. Davis & Andrew, 2017). Also, the Shared Socioeconomic Pathways (SSPs) also need to be part of the expert elicitation. As demonstrated by Schweizer & O'Neill (2014), expert elicitation substantially assists in development of scenarios. A more participatory approach can be utilized for calculating the judgment scores. In early 2021, a cross-impact balance analysis was carried out for understanding global energy transition scenarios (Kurniawan et al., 2022). The lead investigator in the research conducted a remote workshop to gather the judgment scores and rationale of those judgment scores from the subject matter experts. Finally, for complex system analysis, systems of systems analysis can be applied to successfully understand the nuances of the system. The following steps may be taken:

1. Identify the systems interacting on the target complex system.
2. Analyze the individual systems using the appropriate methodology.
3. Identify the interactions among these systems.
4. Develop a causal loop diagram.
5. Find subject matter experts and gather contextual data from them. Update the causal loop diagram if required.
6. Develop robust models capable of handling qualitative and quantitative data like CIB.
7. Find a decision support system, like GMCR, that can provide strategic insights into resolving complex issues.

The above-mentioned steps can be taken as standard operating procedures for carrying out a system of systems analysis of a wickedly complex system.

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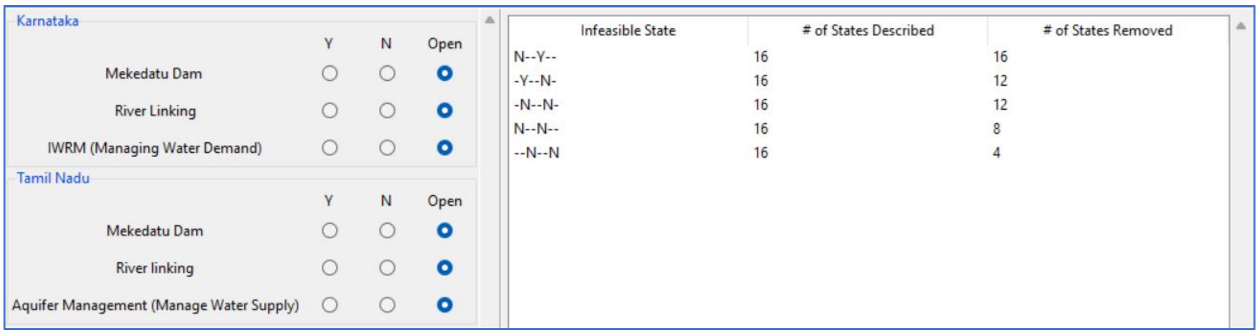
Appendix

A. The infeasible States in the conflict.

The following is a screenshot from the GMCRplus software. The figure below demonstrates the infeasible states and the process of removal.



B. Expert Elicitation (Key Informant Interviews) Documents

UNIVERSITY OF WATERLOO

Notification of Ethics Clearance to Conduct Research with Human Participants

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Principal Investigator: Vanessa Schweizer (Knowledge Integration)

Student investigator: Ajar Sharma (Systems Design Engineering)

File #: 43682

Title: Analyzing the Cauvery River Dispute using a system of systems approach

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The Human Research Ethics Board is pleased to inform you this study has been reviewed and given ethics clearance.

Initial Approval Date: 10/27/21 (m/d/y)

University of Waterloo Research Ethics Boards are composed in accordance with, and carry out their functions and operate in a manner consistent with, the institution's guidelines for research with human participants, the Tri-Council Policy Statement for the Ethical Conduct for Research Involving Humans (TCPS, 2nd edition), International Conference on Harmonization: Good Clinical Practice (ICH-GCP), the Ontario Personal Health Information Protection Act (PHIPA), the applicable laws and regulations of the province of Ontario. Both Boards are registered with the U.S. Department of Health and Human Services under the Federal Wide Assurance, FWA00021410, and IRB registration number IRB00002419 (HREB) and IRB00007409 (CREB).

This study is to be conducted in accordance with the submitted application and the most recently approved versions of all supporting materials.

Expiry Date: 10/28/22 (m/d/y)

Multi-year research must be renewed at least once every 12 months unless a more frequent review has otherwise been specified. Studies will only be renewed if the renewal report is received and approved before the expiry date. Failure to submit renewal reports will result in the investigators being notified ethics clearance has been suspended and Research Finance being notified the ethics clearance is no longer valid.

Level of review: Delegated Review

Signed on behalf of the Human Research Ethics Board

Karen Pieters, Manager, Research Ethics, karen.pieters@uwaterloo.ca, 519-888-4567, ext. 30495

This above named study is to be conducted in accordance with the submitted application and the most recently approved versions of all supporting materials.

Documents reviewed and received ethics clearance for use in the study and/or received for information:

file: 2. Recruitment Email Current v2.docx

file: 5. Email Interview Reminder Email v2.docx

file: 3. Project Information Document Current v2.docx file: 6. Reference letter providing contacts for interview Current v2.docx

file: Recruitment Email for UW Professor Current v2.docx

file: 7. Questions Final Draft.docx

file: 4. Information Consent Document_v2.docx

file: Consent Log Sample.docx

file: Oral Consent Script.docx

file: 8. Appreciation Email Current_v2.docx

Approved Protocol Version 3 in Research Ethics System

This is an official document. Retain for your files.

You are responsible for obtaining any additional institutional approvals that might be required to complete this study.

Questionnaire

Following are the questions sent to the experts.

Tamil Nadu Incumbent

1. This conflict is posing challenges for the province and the country for more than a hundred years. In your opinion, why is this conflict not getting resolved?
2. Over the last thirty years, the rainfall in the province of Tamil Nadu has faltered occasionally which has caused major distress to the people. What policies has the government proposed to mitigate the future water demand issues in the province?
3. How effective would the current and proposed policies be if the water demand in the province is increased by 7-10% in the next three decades, and why? (Highly effective, effective, not effective)
4. Over the last five years, the citizens of the province, occasionally have caused unrest on the streets due to this conflict. When such unrest occurs, how does it affect the negotiations between TN and K, if at all? What can be done to avoid civil unrest?
5. Paddy is a staple food in the country that the province of Tamil Nadu grows in abundance in three crop cycles. Paddy is a water-intensive crop. In managing water resources, Is there a role for crop diversification?
6. Would you consider a water infrastructural investment agreement between the two provinces as a solution for the conflict?
7. Do you think that the conflict can be resolved internally between the provinces, or do we need the Tribunal?
8. What would it take to have a meaningful water-sharing discussion between the province of Tamil Nadu and the province of Karnataka?
9. Based on the above policy options discussed, what options do you think should be implemented first? On roughly what timeline should other options be implemented?

10. Among the options discussed above, which ones do you prefer the most and which ones do you prefer the least?

Tamil Nadu Opposition

1. This conflict is posing challenges for the province and the country for more than a hundred years. Over the last thirty years, the rainfall in the province of Tamil Nadu has faltered occasionally which has caused major distress to the people. What are your views on the current government's policies to address water demand in the province?
2. If you come to power in the next elections, which water management policies will you keep, and which new ones will you introduce?
3. Do you think that the current government is properly negotiating with the province of Karnataka? What changes will you make to the approach?
4. Do you think that the conflict can be resolved internally between the provinces, or do we need the Tribunal?
5. Over the last five years, the citizens of the province, occasionally have caused unrest on the streets due to this conflict. When such unrest occurs, how does it affect the negotiations between TN and K, if at all? What can be done to avoid civil unrest?
6. Would you consider a water infrastructural investment agreement between the two provinces as a solution for the conflict?
7. What would it take to have a meaningful water-sharing discussion between the province of Tamil Nadu and the province of Karnataka?

Tamil Nadu Industry

1. 35% of the state's GDP comes from the industrial sector, and 15-25% of water extracted from the Cauvery River is for industrial purposes. The province has seen unprecedented growth in the last thirty years. If historical trends continue, how do you think the industry should address increased water demand? Policy-wise, do you have any expectations from the government? If so, what are they?
2. With rapid advancements in technology, do you think a water-related foreign investment is imminent in the province?
3. [Exact wording of the question will depend on what came up during the interview] Some policy interventions for water management/use/sharing that [you mentioned/are in the literature] include [relevant examples]. How would you prioritize such policy options? In other words, what options do you think should be implemented first? On roughly what timeline should other options be implemented?
4. Among the options discussed above, which ones do you prefer the most and which ones do you prefer the least?

Tamil Nadu Agriculture

1. Over the last thirty years, the rainfall in the province of Tamil Nadu has faltered occasionally due to climate change which has caused major distress to the people. What adaptation options would you like to take in the agriculture sector to overcome policy gaps?
2. The current reservoirs have helped the farmers a great deal over the years. 60% of the state's GDP comes from the agricultural sector. How do you expect to address the increasing water demand in the next thirty years?
3. Canal systems are the other major method of irrigation in the region. However, the canals are in high need of restoration. Also, with increasing food demand leading to increasing water demand, are the current canals enough to help farmers meet their water demands? Have you had any discussions with the administration (government) to prioritize the repair works on the important canals?
4. Wells are used for irrigation in nearly half the irrigation area in the province. Over the years a majority of the wells have run dry due to overconsumption of the groundwater in the province. This demand will now have to be met by water from the Cauvery River also. What provisions are you hoping to receive from the government?
5. Paddy is a staple food in the country that the province of Tamil Nadu grows in abundance in three crop cycles. Paddy is a water-intensive crop. In a 2015 review of the State Water Policy by India Water Partnership, it was suggested that the farming community should use an alternate wetting and drying technique for water-intensive crops. Do you think the farmers would adopt such new techniques?
6. Do you think the farmers can diversify their crop cultivation and grow less water-intensive crops?
7. Drip irrigation methods are extremely efficient. Will the farmers accept such a major change in irrigation practices?
11. [Exact wording of the question will depend on what came up during the interview] Some policy interventions that [you mentioned/are in the literature] include [relevant examples]. How would you prioritize such policy options? In other words, what options do you think should be implemented first? On roughly what timeline should other options be implemented?
12. Among the options discussed above, which ones do you prefer the most and which ones do you prefer the least?

Karnataka Incumbent

1. This conflict is posing challenges for the province and the country for more than a hundred years. In your opinion, why is this conflict not getting resolved?
2. Over the last thirty years, the rainfall in the province of Karnataka has faltered occasionally which has caused major distress to the people. What policies has the government proposed to mitigate the future water demand issues in the province?
3. The total demand for domestic consumption of water in urban areas is projected to increase from 46 thousand million cubic feet (TMC) per year in 2011 to about 84 TMC by 2030. An additional supply of about 49 TMC annually would be needed to close the demand-supply

gap. The Greater Bengaluru region will account for two-thirds of the additional water requirement. How are you addressing the anticipated increase in water demand?

4. The per capita usable water availability in Karnataka falls below 1,000 cubic meters per person per year. Based on this assessment Karnataka would be classified as a region experiencing "Water Scarcity". What is the government planning to enhance water security?
5. Over the last five years, the citizens of the province, occasionally have caused unrest on the streets due to this conflict. When such unrest occurs, how does it affect the negotiations between TN and K, if at all? What can be done to avoid civil unrest?
6. Would you consider a water infrastructural investment agreement between the two provinces as a solution for the conflict?
7. Do you think that the conflict can be resolved internally between the provinces, or do we need the Tribunal?
8. The Asian Development Bank has invested a considerable amount of money in the province like the 'Karnataka Integrated and Sustainable Water Resources Management Investment Program - Tranche 2' program. Do you think that such projects have helped mitigate the water security problem in the province despite accelerating [population/economic] growth?
9. What would it take to have a meaningful water-sharing discussion between the province of Karnataka and the province of Tamil Nadu?
10. Based on the above policy options discussed, what options do you think should be implemented first? On roughly what timeline should other options be implemented?
11. Among the options discussed above, which ones do you prefer the most and which ones do you prefer the least?

Karnataka Opposition

1. Over the last thirty years, the rainfall in the province of Karnataka has faltered occasionally which has caused major distress to the people. What are your views on the current government's policies to mitigate water demand in the province?
2. With Bengaluru being the IT hub of India, the population of the province has increased exponentially. Industrial water use is primarily from thermal power plants, steel manufacturing plants, and other sectors in the province. With the high population, power consumption is also high. If historical growth trends continue, what will you do to address increased water demand?
3. If you come to power in the next elections, which water management policies will you keep, and which new ones will you introduce?
4. The total demand for domestic consumption of water in urban areas is projected to increase from 46 thousand million cubic feet (TMC) per year in 2011 to about 84 TMC by 2030. An additional supply of about 49 TMC annually would be needed to close the demand-supply gap. The Greater Bengaluru region will account for two-thirds of the additional water requirement. How would you tackle this need for increased water demand?

5. Do you think that the current government is properly negotiating with the province of TN? What changes will you make to the approach?
6. Do you think that the conflict can be resolved internally between the provinces, or do we need the Tribunal?
7. Over the last five years, the citizens of the province, occasionally have caused unrest on the streets due to this conflict. When such unrest occurs, how does it affect the negotiations between TN and K, if at all? What can be done to avoid civil unrest?
8. Would you consider a water infrastructural investment agreement between the two provinces as a solution for the conflict?
9. What would it take to have a meaningful water-sharing discussion between the province of Karnataka and the province of Tamil Nadu?

Karnataka Industry

1. With Bengaluru being the IT hub of India, the population of the province has increased exponentially. Industrial water use is primarily from thermal power plants, steel manufacturing plants, and other sectors in the province. With the high population, power consumption is also high. If historical growth trends continue, how do you think the industry should address increased water demand? What are your expectations, policy-wise from the government?
2. The Asian Development Bank has invested a considerable amount of money in the province like the 'Karnataka Integrated and Sustainable Water Resources Management Investment Program - Tranche 2' program. Do you think that such projects have helped mitigate the water security problem in the province despite accelerating [population/economic] growth?
3. [Exact wording of the question will depend on what came up during the interview] Some policy interventions that [you mentioned/are in the literature] include [relevant examples]. How would you prioritize such policy options? In other words, what options do you think should be implemented first? On roughly what timeline should other options be implemented?
4. Among the options discussed above, which ones do you prefer the most and which ones do you prefer the least?

Information Consent Document

Information Letter

Title of the study: *Analyzing Cauvery River Dispute using a system of systems approach.*
Principal Investigator/Faculty Supervisor: Vanessa Schweizer, Department of Knowledge Integration, Faculty of Environment, University of Waterloo, Canada.

Student Investigator: *Ajar Sharma, Systems Design Engineering, Faculty of Engineering, University of Waterloo, Canada.*

To help you make an informed decision regarding your participation, this letter will explain what the study is about, the possible risks and benefits, and your rights as a research participant. If you do not understand something in the letter, please ask one of the investigators prior to consenting to the study.

Invitation to participation/What is the study about?

You are invited to participate in a research study about the Cauvery River dispute in the southern part of India. The Cauvery River conflict is a water-sharing dispute between the Indian provinces of Karnataka and Tamil Nadu. This conflict has persisted for over a hundred years. With the help of our literature review and preliminary research we have identified gaps in the conflict resolution methods applied until now. A targeted expert elicitation can help to bridge the gaps. The study is being carried out to include the perspectives of the stakeholders and the decision makers in the decision-making process. The insights of the stakeholders will be used to enhance decision support for the conflict.

1. Your responsibilities as a participant

What does participation involve?

Participation in the study will consist of short 60 minutes remote semi-structured interviews in which you will be asked to share your opinions about subject matter pertaining to political administration/ water resources/ climate change policy. The session will be scheduled based on your time zone and your availability. The interview will be conducted over an online platform (Microsoft Teams. Zoom or Skype for Business). These platforms have implemented technical, administrative, and physical safeguards to protect the information provided via the Services from loss, misuse, and unauthorized access, disclosure, alteration, or destruction. However, no Internet transmission is ever fully secure or error free. University of Waterloo researchers will not collect or use internet protocol (IP) addresses or other information which could link your participation to your computer or electronic device without first informing you.

Who may participate in the study?

The study will involve up to 14 people and to participate in the study you must be an expert in the field of political administration, water resources, and or climate policy and working at either consultancy, in the government, in the private sector, or in academia. You can either belong to the Cauvery River basin and or be a key stakeholders with knowledge about the basin.

2. Your rights as a participant

Is participation in the study voluntary?

Your participation in this study is voluntary.

- You may decline to answer any question(s) you prefer not to answer (e.g., by requesting to skip the question).
- You can request your data be removed from the study at any time.

What are the benefits of the study?
There shall not be any direct benefit to the experts/participants from the study, however, the participant's insights may help us in making informed policy recommendations for the conflict. Also, the responses may be useful in building the water resources model and a decision support systems.

What are the risks associated with the study?
This is a minimal risk study. The conversations that the participants will have are the same that they will have daily with either their colleagues or students.

Will my identity be known? Will my information be kept confidential?

Personal information will not be reported or published anywhere but the research team will know the identities of participants. Data will be stored on Microsoft Teams platform. Only the research team will have access to study data. The data will be stored for a period of seven years as per the NSERC guidelines. You will be asked for verbal consent for audio recording the interview. No identifying information will be used in my thesis, or any presentations or publications based on this research without participant consent. You will provide verbal consent to what identifier you are comfortable with us using, if any, in any publications. For example, you will be asked how you would like to be identified in the reports, publications, etc. and may choose to be identified as an expert, an expert from the province of Tamil Nadu and or Karnataka, or an expert in a particular field.

You can request your data be removed from the study up until April 2022 as it is not possible to withdraw your data once papers and publications have been submitted to publishers.

3. Questions, comments, or concerns

Who is sponsoring/funding this study?

This study is funded/sponsored by the NSERC Discovery grant held by Prof. Vanessa Schweizer.

Has the study received ethics clearance?

This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB***#43682***). If you have questions for the Board, contact the Office of Research Ethics, at 1-519-888-4567 ext. 36005 or reb@uwaterloo.ca.

Who should I contact if I have questions regarding my participation in the study?

If you have any questions regarding this study or would like additional information to assist you in reaching a decision about participation, please contact Ajar Sharma by email at ajar.sharma@uwaterloo.ca. You can also contact my supervisor Prof. Vanessa Schweizer of Knowledge Integration Department at University of Waterloo, Canada.

C. Methods, Results, Conclusions, and Calculations from the Sharma, et al., (2020) paper.

Methodology

The Graph Model for Conflict Resolution (GMCR) is used to analyze a conflict at a specific point in time. GMCR has been used in the past for water-related conflicts, like the Jordan river conflict, and general environmental conflicts. For this project, the time right after the 2013 verdict of the Supreme Court is modeled and analyzed. In this verdict, the Supreme Court revised the 2007 CWDT ruling to increase the water retention for Karnataka and reduce the water to be released for the state of Tamil Nadu.

Decision-Makers and Options

The Cauvery water dispute has many interested parties due to the river's multifaceted uses. The decision-makers are as follows: Karnataka state, Tamil Nadu state, Kerala state, Pondicherry (Puducherry) union territory (UT), Central government, Cauvery Water Dispute Tribunal (CWDT), Cauvery River Authority (CRA), Cauvery Monitoring Committee (CMC), Supreme Court of India, and Cauvery Management Board. The integrated development theme attracted the interests of non-governmental organizations (NGOs) and environmental protection agencies, which were not present during the establishment of the CWDT. Therefore, such agencies along with the people from urban and rural areas automatically become stakeholders, rather than actual decision-makers given that they do not have any decision-making authority. The farming community, especially the Farmers' Association of *Thanjavur* (Tamil Nadu) is very active, as the allocation of water affects them the most. The green eastern part of Figure 1 is the land irrigated using the water from the Cauvery River.

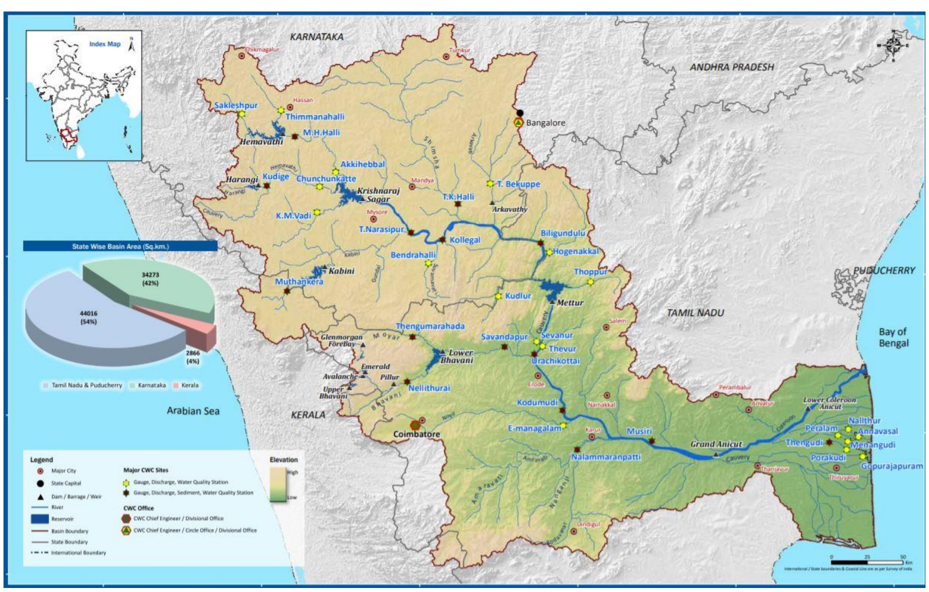

Figure C1. 1 Map of Cauvery Basin

As the central governing bodies are all intertwined and do not generally have conflicting interests, they will be represented by the moniker Supreme Court (SC) hereafter. The rulings from the governing bodies as of 2013 can be classified as win-lose decisions. Ideally, the SC should strive for a win-win situation and GMCR can be a viable tool in determining how to achieve that. Table 1 summarizes the water-sharing quantities among the states in the region for both the 2007 and 2013 verdicts. These partitions are based on the annual flow/discharge of the river at the Mettur Dam, which is the point of division of water among the states of Karnataka and Tamil Nadu.

Some readers may wonder whether the partitions decided by the SC in Table 1 account for long-term factors that might affect future water demand, like urbanization. The methodology of GMCR is to look at a conflict at a certain point in time rather than to put new options on the table. In this study, we look at the current stalemate between Karnataka and Tamil Nadu. Possible influences of future developments on water demand and water availability that are currently considered tangential to the conflict, such as urbanization and climate change, are therefore also tangential to the scope of this conflict analysis. The data used primarily comprise what the literature tells us about the positions of the parties in the conflict and the nature of their governance. The purpose of this study is to understand the present-day conflict to investigate any possible ways the governments might move toward productive resolution.

*Table C1. 1 Water sharing comparison based on the two verdicts**.** These partitions are based on the annual flow/discharge of the river at the Mettur Dam, which is the point of division of water among the states of Karnataka and Tamil Nadu.*

	Tamil Nadu	**Karnataka**	**Kerala**	**Pondicherry**
Share for each state as per the CWDT Verdict 2007 (TMC thousand million cubic feet)	419	270	30	7
Share for each state as per the Supreme Court Verdict 2013 (TMC thousand million cubic feet)	404	285	30	7

Due to the growing of paddy in three crops, water use in Tamil Nadu has been deemed wasteful. Therefore, the SC has an option of crop diversification as one of the possible courses of action. In the majority of developing countries, including India, water pricing is a difficult issue to tackle. As electricity is subsidized for farmers, the pumping of water using bore wells is common. Effectively, the farmers pay for the pumping costs, and not the value of the water itself. The SC has the option of including the value of water in the water pricing clause. This should help the farmers and other users of this water to comprehend the real importance of the resource. Since there are no fool-proof methods of predicting the climate and rainfall thereof, the water division should be founded on a relative (pro-rata basis), rather than an absolute one. Utilization of technologically advanced methodology in farming is also outlined by experts in the field. However, it is important that the options suggested are feasible and can be implemented in a short period of time due to political and administrative issues (the government is in power for only five years) and the increasing deficiency of water availability in the region. Therefore, the options mentioned in Table 2 include such options, which are not considered in this study.

Table C1. 2 Players and their options in the Cauvery River Dispute.

Players	Options
Tamil Nadu	1. Reinstate the previous ruling. 2. Appeal to modify and accept the pro-rata division of water. 3. Request to modify and accept the crop-diversification clause. 4. Ask to modify and accept the pricing of water.
Karnataka	5. Push to enforce the current ruling. 6. Accept the pricing of water clause. 7. Agree the pro-rata division of water clause.
Supreme Court and CMB (SC)	8. Support the current ruling. 9. Modify to include pricing of water. 10. Alter to include crop diversification. 11. Change to include pro-rata division of water.

Since the last ruling was not in favor of Tamil Nadu (TN), as its share of water was reduced, this state would appeal to the SC to modify the ruling. TN will take any option that can make sure that it receives more water than it is currently receiving. Therefore, accepting the crop-diversification clause will cause an enforcement challenge. However, it should guarantee the supply of appropriate quantities of water for those crops. Pro-rata division of water would mean that TN will not have to appeal during every low-monsoon year. Because the pricing of water will be enforced for both the states, TN should be able to accept this option. Karnataka will push to keep the existing ruling, as it is essentially a "win" situation for it. Pricing of water clause is going to help the state generate revenue. The pro-rata division would mean that a fixed amount of water will not have to be released during lean monsoons. Also, the conflict will arise only if TN appeals to the SC to modify the existing ruling by reinstating the previous ruling, which gave TN a higher share of water.

Karnataka has always maintained that since Tamil Nadu receives two monsoons, i.e., North-east (October-December) and South-west (June–September), it should not be given as much water as it demands. However, Tamil Nadu maintains that the water is required for agriculture and repeatedly cites the original CWDT decision. Many regional scholars feel that the treaty is an important source of information, but today's problems may not be solved by citing the old rulings. Social groups like "the Cauvery Family" are a step towards an integrated approach for solving complex issues. The Cauvery family consists of farmers from both Karnataka and Tamil Nadu. Researchers have engaged the farmers and conducted workshops on both sides of the state borders, thereby clarifying the expectations and struggles of the farmers from either side.

Discussion on Decision-Makers' Preferences

The preferences of the state governments are straightforward: try to secure as much water as possible for their respective states. The Tamil Nadu government published an action plan for the state in 2015. This plan was prepared in consultation with experts from Germany to assess the current water use situation and probable future requirements.

The majority fraction of demand is for the irrigation sector, i.e., 76% in 2011. As per the directives of the SC, the agricultural area in Tamil Nadu is not to be increased; hence, the demand is kept the same for the 2020 and 2045 projections. By the year 2045, the state of Tamil Nadu is assumed to achieve the highest irrigation efficiency. These are optimistic assumptions on the part of the SC, as the simple decision of not increasing the agricultural area in Tamil Nadu does not consider possible economic development or population growth in the next 25 years. The side-effects of such growth on water demand could continue to increase, even with a stable agricultural area.

The above-referenced report also mentions the issue of irrigation efficiency in the state, which stands at an abysmal 40%, compared to 75% in Israel. The government has organized several awareness programs. For instance, the farmers in the Tirupur region have increased their efficiency by using drip-irrigation methods. The Karnataka government also prepared and submitted a climate action plan in 2011, with a focus on Bangalore. Twenty percent of the state of Karnataka is covered by the Cauvery River Basin. A reduction in the rainfall by even ten percent can affect crops devastatingly. The average water yield in the basin will reduce from a simulated baseline scenario flow of 7000 cubic meters per second (cumecs) today to 6700 cumecs in 2030. This reduction is of great importance for the farmers of the state. Therefore, the preference for Karnataka should be to keep the new ruling as it is without modification.

After careful consideration of the options available to the decision-makers (Table 2), option number 2 of “pro-rata division of water” was scrapped in a 2013 decision by the CWDT. The decision mentioned that the division of water on a percentage basis will cause another complication to the already complex conflict. Hence, the absolute division of water was kept as the basis of division. Setting aside that absolute division is unlikely to be a wise approach to water sharing for a prolonged amount of time, especially for an economically developing country and under a changing climate, it is one of the options that characterizes the present-day conflict. For these reasons, in this analysis, option number 2 was removed, and the remaining options were renumbered accordingly.

With eight options across all the decision-makers, the number of possible states would be 2^8 (256). We use the formula of 2^n because each option can either be accepted or rejected. Out of these states, many of them are mutually exclusive and hence infeasible. For example, TN cannot support modification of the current ruling and get the previous sentence re-instated together. Similarly, the Karnataka government cannot support the existing ruling and accept modifications. The actual feasible number of states were calculated using the GMCR+ software. Two types of states are removed from the total possible outcomes, namely mutually exhaustive and generally infeasible conditions. Table 3 represents the modified decision-makers’ options.

Table C1. 3 Modified Decision-Makers and their Options.

Decision-Makers (DM)	Options
Tamil Nadu (DM1)	1. Reinstate the previous ruling.

	2. Request to modify and accept a crop-diversification clause. 3. Ask to modify and accept pricing of water clause.
Karnataka (DM2)	4. Push to enforce the current ruling. 5. Agree to the pricing of water clause.
Supreme Court, CRA, CMC (SC) (DM3)	6. Support the current ruling. 7. Modify to include crop diversification clause. 8. Alter to include pricing of water.

The preferences of both states have been devised based on climate action reports they each developed. TN's primary preference is to get the previous ruling re-instated so that it can receive more water than Karnataka on paper. Tamil Nadu has suffered from its insistence of pushing for growing paddy crops because the yield is abysmal; however, the profits are high.

Tamil Nadu included the pricing of domestic use of water in its policy development interventions. As mentioned above, farmers' use of water for irrigation is highly subsidized, and the pricing of water there can also be included in the policy. In this situation, Tamil Nadu will keep receiving the water as intended, and it will part with a portion of its profit to Karnataka. Karnataka should use that money to invest in its own water infrastructure system improvement. This divisional method is based on the Coase Theorem, which is an economic and legal theorem that asserts that if a conflict arises over property rights, parties will tend to settle on the efficient set of inputs and outputs, given that the property can be divided, defined, and the property rights are defendable. This improvement will lead to more efficient use of water and hence reduce the water requirements of the state. A basic cost-benefit analysis carried out in the Macquarie River in New South Wales, Australia, can be used as a reference. Also, Karnataka recently received a loan of 135 million dollars from the Asian Development Bank (ADB) to improve its water resource infrastructure. Instead of taking the loan from an external institution, it is more viable to use the money available within the country. As Karnataka and Tamil Nadu will benefit from it, the option of pricing agriculture water is formed.

Ghosh et al. (2018) wrote an advisory paper advising the Supreme Court of India to make the three modifications mentioned in Table 2. The Supreme Court, in general, will have its priorities the same for all the options as long as the two states can find a solution among themselves. However, whenever a plea against a court ruling is lodged, due process must be carried out. It took the Supreme Court nearly seven years to pass the verdict in 2007 after the CMA and CMC were established in 2000. Due to the demographic expanse of the country, the hydrological and hydraulic investigations, calculations of water demands, environmental flows, and similar exercises, a fair number of human resources were utilized. Also, bringing together all the officials from various levels of government and the courts to reach an all-inclusive verdict is a logistical challenge. Therefore, if another plea is filed against the Supreme Court, the CMC and CMA will have to work again, and this may take another seven years to reach a potential verdict, thereby hampering the growth of the region. Hence, the Supreme Court would prefer the current ruling, but will intervene if a modification in the previous ruling is requested and they see merit in it.

Stability Analysis using Graph Model for Conflict Resolution (GMCR)

For stability analysis, the preference matrix of all three decision-makers (DM) is analyzed, individually and then together. Every preference state value has a payoff value for the decision-maker, with the highest payoff being for the most preferred state. The conflict model will now be subjected to stability analysis. If a state is rational for the decision-maker, it would mean that there are no unilateral improvements from that state for the decision-maker. It is a stable state if moving to any of the unilateral improvement (UI) states will cause the decision-maker to be rendered worse-off. A UI is defined as a movement by a decision-maker towards a state, which is more favorable than the current state. A state is unstable if moving from the current state to a UI can improve the decision-maker's position. The rational and stable states for all the decision-makers are then analyzed to find common states that form the solution concepts.

Each state is analyzed for stability for each DM using each solution concept: Nash stable (R), General Meta-Rational (GMR), Symmetric Meta-Rational (SMR), and Sequential stable (SEQ). An equilibrium is said to be Nash stable if moving to a different state brings no benefit to the focal decision-maker. If the focal decision-maker's (DM) UI can be sanctioned (i.e., blocked) by the opponent decision-maker's movement in such a way that the focal DM will be worse off, then the current state is GMR stable for the focal DM. In SMR, the focal DM can counter-respond. If the focal DM's UI is sanctioned by the opponent DM in such a way that the focal DM is in a worse-off position in both that state and the counter-responded state, the current state is said to be SMR stable. If the focal DM's UI can be sanctioned by the opponent DM's UI in such a way that the focal DM will be worse off, then the current state is SEQ stable for the focal DM. These four solution concepts are used to identify the different states reached in the Cauvery River conflict.

For Tamil Nadu (TN), the highest priority is that the previous ruling gets reinstated, and hence it is positioned on the extreme left. State 17, as mentioned in Table 3, has the second-most preferred state as it reaches an agreement in which TN would get more water, and the other two DMs agree. State 7 is the next preferred state as it would cause the two states to resolve the issue without involving the Supreme Court of India (SC). State 15 is the next preferred state because even if Karnataka does not take the pricing option, SC can take the money from TN and invest it in central government schemes in Karnataka. State 8 and 4 are least preferred for TN as it would mean staying with the current ruling.

Table C1. 4 Options and Decision-Makers' Preference Statements.

Decision-Makers	Options	
Tamil Nadu	Reinstate the previous ruling	Option 1
	Request to modify and accept the crop-diversification clause	Option 2
	Ask to modify and accept the pricing of water	Option 3
Karnataka	Push to enforce the current ruling	Option 4
	Agree to the pricing of water clause	Option 5
Supreme Court, CRA, CMC (SC)	Support the current ruling	Option 6
	Modify to include crop diversification	Option 7
	Alter to include pricing of water	Option 8

Preference Statements		
Tamil Nadu (DM1)	Option 1	Ω1
	−(Option 4 and Option 6)	Ω2
	Option 3 if and only if (Option 5 and Option 8)	Ω3
	Option 2 if and only if Option 7	Ω4
Karnataka (DM2)	Option 4	Ω1
	Option 6	Ω2
	−Option 1	Ω3
	Option 5 if and only if (Option 3 and Option 8)	Ω4
Supreme Court (DM3)	Option 6	Ω1
	−Option 1	Ω2
	Option 8	Ω3
	Option 7	Ω4

Karnataka wants to keep the current ruling and that is visible in its preference matrix. Both State 4 and 8 are situations where the current ruling is enforced. State 17 is the next preferred state, as it will bring in money for the state, which can be used to bolster the water resources infrastructure. State 10 is the next preferred state, as it does not cause the state of Karnataka to lose water. State 7 is next preferred due to the same reasons as it is preferred by TN. It causes the state of Karnataka and TN to resolve the matter without involving the SC, which could be highly likely as it will considerably reduce the administrative effort, unless needed. State 16 is preferred next, as it means that the state of Karnataka receives money from SC to improve its infrastructure instead of TN. Using federal budgets, the Supreme Court can help and fund the states. State 1 is the least feasible, as it causes the state of Karnataka to receive less water.

For the Supreme Court, the priority is to keep the current ruling as well, which is visible through state 8 being most preferred. State 17 is preferred next, as it is beneficial for both the states, and it sets positive precedence for any future water-related conflict in the country. State 7 is also higher up in the preference ranking, as it would not cost the SC the human resource and logistical expenses. State 4 is far behind, as the SC would not want to seem partial by preferring Karnataka's most preferred option. State 16 is not preferred by the SC, as there will be no ecosystem-service generated revenue for the state of Karnataka. Clearly, from Karnataka's perspective, it would be beneficial to receive payouts from water pricing (setting aside whether the SC has any funds to payout). The results are shown in Table 5.

Table C1. 5 The Feasible States in the Cauvery Conflict

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
(DM1) Tamil Nadu																	
1. Reinstate Previous Ruling	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
2. Appeal for crop-diversification	N	Y	N	N	N	Y	N	N	N	Y	N	Y	N	Y	N	N	N
3. Appeal for water pricing	N	N	Y	N	N	N	Y	N	N	N	N	N	N	N	Y	N	Y

(DM2) Karnataka																	
4. Enforce current ruling	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N
5. Accept water pricing	N	N	N	N	Y	Y	Y	N	N	N	Y	Y	N	N	N	Y	Y
(DM3) Supreme Court of India																	
6. Support Current Ruling	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N
7. Modify to crop-diversification	N	N	N	N	N	N	N	N	Y	Y	Y	Y	N	N	N	N	N
8. Modify to water pricing	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y

After sensitivity analysis of the 17 feasible options, 7 states were found to be in Nash equilibrium. The calculations are performed in the GMCR+ space using the same solution concepts defined earlier in this section. Demonstration of GMR and SMR stability is a little cumbersome; however, SEQ can be shown easily. Of the solution concepts, if a state is Nash stable, it is also GMR, SMR, and SEQ stable.

Consider state 5 for TN, which has two unilateral improvements (UIs) to state 6 and state 7. If TN moves to state 6, Karnataka (which has a UI from 6 to 2) can move to state 2. State 2 is rational for Karnataka; however, it is more preferred than state 6 for TN. Also, SC has a UI from state 6 to state 5, where state 5 is rational for SC. Hence, by definition, state 6 is SEQ unstable for TN. If SC was the only other DM other than TM, state 6 would have been SEQ stable for TN.

Exploring Fuzzy Preferences

A possibility may arise with the water pricing option, which will, ironically, only work in a strict coalition between the two states. In order to address this uncertainty, an option prioritization approach was carried out in conjunction with the fuzzy preference methodology. The following sub-sections introduce the step-by-step methodology and the various definitions concerned in carrying out Fuzzy GMCR.

Theoretical Description of the Graph Model for Conflict Resolution (GMCR)

A (crisp) Graph Model (GMCR) of conflict entails a set of decision-makers, a set of states, the decision-maker's strategy, or directed path of 'moves' through alternative states to the desired state, and the preference relation of the decision-makers over the states. These preferences are given by binary relations, i.e., 1 (Yes) and 0 (No), and are "crisp" in nature. This is where the fuzzy Graph Model differs from the crisp Graph Model. In the fuzzy Graph Model, preferences are given by fuzzy binary relations on the set of the feasible states. The mathematical notations used to describe a conflict are as follows:

The set of decision-makers, $N = \{1, 2, . . ., n\}$, and

The set of feasible states, $S = \{s_1, s_2, . . ., s_m\}$

The decision-makers in this conflict will be Tamil Nadu and Karnataka with 17 feasible states. The Supreme Court of India's preferences is not considered for this analysis as it is assumed that they will accept the decision taken by the two states. For $k \in N$, A_k = Cartesian product of S with itself (S X S), represents the moves controlled by decision-maker k, so that for $s_i, s_j \in S$, $(s_i, s_j) \in A_k$, if and only if the decision-maker k can cause the conflict to move from s_i to s_j in one step. Then, D_k is the directed graph of the decision-maker k, $D_k = (S, A_k)$.

If the crisp preferences over the feasible states are recorded by a binary relation, $\gtrsim_k$, then a crisp Graph Model is represented as:

$$N, S, \{(D_k, \quad \gtrsim): k \in N\} \tag{1}$$

On the other hand, if a decision-maker's preferences over the feasible states are represented by a fuzzy binary relation given by a matrix $\mathcal{R}^k$, where $\mathcal{R}^k$ represents the degree of preference of row states over the column states for the decision-maker k, then the fuzzy Graph Model can be represented as follows:

$$N, S, \{(D_k, \quad \mathcal{R}^k): k \in N\} \tag{2}$$

The *preference degree* ($\mathcal{R}^k$) is calculated by using the fuzzy truth values and the fuzzy score intervals of each pair of states.

Procedure for Calculating the Preference Degree

The fuzzy *truth degrees* (x) are represented by numerical values from the closed interval of [0,1]. The x-values are the truth values of a preference statement at a given state in the conflict. To efficiently capture these truth degrees, two transformation functions, i.e., a lower transformation function, and an upper transformation function, are specially designed:

$$l(x) = x^p, \text{ lower transformation function} \tag{3}$$

$$u(x) = 2x - x^p, \text{ upper transformation function} \tag{4}$$

where, $p \in [1,2]$, and $x \in [0,1]$. The value of p depends upon the certainty of the choices in x-values. If the consultant (the person doing the conflict analysis) is sure about the x values, then the value of p shall be fixed to 1; else, it will be greater than 1. If the consultant is certain about the x-values, the fuzzy interval is narrower (more precise). If the consultant is less certain, the fuzzy interval is wider (less precise). In the current conflict, the value of p was fixed at 1.5.

Let $\sigma_t(s)$ denote the decision-maker's *truth degree for preference statement* Ω_t at state s with t preference statements for a decision-maker (t = 1, 2, 3, . . ., q). Then:

$$\sigma_t^L(s) = l(\sigma_t(s)), \qquad \sigma_t^U(s) = u(\sigma_t(s)) \tag{5}$$

The interval $[\sigma_t^L(s), \sigma_t^U(s)]$ is called the decision-maker's fuzzy *truth value interval of preference statement* Ω_t at state s. The $\sigma_t^L(s)$ and $\sigma_t^U(s)$ values are then multiplied by a real number α, where α needs to satisfy the condition:

$$\alpha > \alpha^2 + \alpha^3 + \ldots\ldots + \alpha^q \tag{6}$$

By keeping the value of α in this conflict equal to 0.2, it was made sure that equation 6 is satisfied. The *incremental* fuzzy score interval of state s for preference statement Ω_t is defined as:

$$\tilde{\psi}_t^L(s) = \alpha^t \sigma_t^L(s), \qquad \tilde{\psi}_t^U(s) = \alpha^t \sigma_t^U(s) \tag{7}$$

From the incremental fuzzy score interval, we calculate the decision-maker's *fuzzy score interval* for state s, which is defined as:

$$\tilde{\psi}^L(s) = \sum_{t=1}^{q} \tilde{\psi}_s^L(s), \qquad and \qquad \tilde{\psi}^U(s) = \sum_{t=1}^{q} \tilde{\psi}_s^U(s) \tag{8}$$

The summation above is carried over all the preference statements for each state for each decision-maker. Any number in the interval $[\tilde{\psi}^L(s), \tilde{\psi}^U(s)]$ can be interpreted as a possible *fuzzy score* of state s for the decision-maker.

A *fuzzy preference* is expressed using numerical values between 0 and 1, interpreted as pairwise preference degrees. It is defined as $r\left(s_i, s_j\right)$ for any $\left(s_i, s_j\right) \in S$. It is interpreted as the degree of likelihood that a number in $[\tilde{\psi}^L(s_i), \tilde{\psi}^U(s_i)]$ is greater than or equal to a number in $[\tilde{\psi}^L(s_j), \tilde{\psi}^U(s_j)]$. Mathematically, $r\left(s_i, s_j\right)$ is defined as:

$$\begin{aligned} r\left(s_i, s_j\right) &= \max\{\min\{\frac{\tilde{\psi}^U(s_i) - \tilde{\psi}^L(s_j)}{\mathcal{L}_i + \mathcal{L}_j}, 1\}, 0\}, && if\ \mathcal{L}_i + \mathcal{L}_j \neq 0 \\ r\left(s_i, s_j\right) &= \max\left\{\frac{\tilde{\psi}^U(s_i) - \tilde{\psi}^L(s_j)}{\left|\tilde{\psi}^U(s_i) - \tilde{\psi}^L(s_j)\right|}, 0\right\}, && if\ \mathcal{L}_i + \mathcal{L}_j = 0, and\ \tilde{\psi}(s_i) \neq \tilde{\psi}(s_j) \\ r\left(s_i, s_j\right) &= \frac{1}{2}, && if\ \mathcal{L}_i + \mathcal{L}_j = 0, and\ \tilde{\psi}(s_i) = \tilde{\psi}(s_j) \end{aligned} \tag{9}$$

where, $\mathcal{L}_i = \tilde{\psi}^U(s_i) - \tilde{\psi}^L(s_i)$, $and\ \mathcal{L}_j = \tilde{\psi}^U(s_j) - \tilde{\psi}^L(s_j)$

In summary, *r* mentioned above is an S X S matrix. In order to make the definitions and the values, they describe distinctively, the following are defined. A fuzzy preference over S is represented by $\mathcal{R} = (r_{ij})_{s\,x\,s}$, with the membership function, $\mu_{\mathcal{R}} : S\ X\ S \longrightarrow [0,1]$, where $\mu_{\mathcal{R}}(s_i, s_j) = (r_{ij})$, and the preference degree of s_i over s_j satisfies $r_{ij} + r_{ji} = 1$, and $r_{ii} = 0.5$ for all $i, j = 1,2, \dots, s$. Table 7 (C1) and Table 8 (C1) represent these values for the decision-makers, Tamil Nadu and Karnataka, respectively. If the value of r_{ij} is equal to 1, then it indicates that s_i is definitely preferred to s_j. However, if the value of r_{ij} is greater than 0.5, it indicates that state s_i is likely to be preferred to state s_j. If r_{ij} is equal to 0.5, it would mean that either of the states is equally preferred. On the other hand, if r_{ij} is equal to 0, it would mean that state s_j is more or definitely preferred to state s_i. The decision-maker's fuzzy preference over the states is a pairwise relationship. In order to reach a comparative structure to carry out the fuzzy equilibrium calculations, two sets of parameters are defined.

Fuzzy Relative Certainty of Preference (FRCP): Let $k \in N$, and let $r^k(s_i, s_j)$ denote the preference degree of state s_i over s_j for decision-maker *k*. Then the *k*th decision-maker's FRCP for state s_i over s_j is denoted as $\alpha^k(s_i, s_j)$, and is defined as:

$$\alpha^k(s_i, s_j) = r^k(s_i, s_j) - r^k(s_j, s_i) \tag{10}$$

where $\alpha^k(s_i, s_j) \in [-1,1]$

The matrix representing the $\alpha^k(s_i, s_j)$ is a skew matrix, i.e., for all the decision-makers $k \in N$, and for all the states, $\alpha^k(s_i, s_j) = -\alpha^k(s_j, s_i), and\ \alpha^k(s_i, s_i) = 0$. Also, if $\alpha^k(s_i, s_j) = 1$, it indicates that the decision-maker k definitely prefers state s_i to s_j, and so on and so forth.

Fuzzy Satisficing Threshold (FST): The major component of the Graph Model is to determine whether it is favorable for the decision-maker to move from one state to another or not. In fuzzy theory, the decision-maker can identify value in their FRCP matrix to determine whether a move is possible or not. This value is referred to as the FST of the decision-maker. Therefore, for all decision-makers and the states belonging to the state space, a decision-maker *k* shall move from a state s_i to s_j if and only if $\alpha^k(s_i, s_j) \geq \gamma_k$. The threshold determines the behavioral pattern of the decision-maker, and as per the definition above, must be positive with a maximum value of 1. In this study, the γ_k values for both the decision-makers are ascertained by a fair bit of sensitivity analysis.

Fuzzy Stability Definitions

For every decision-maker, there is a set of states they can move to, and that is defined as their reachability matrix. For a decision-maker *k*, it is denoted as $R_k(s)$ for all states reachable from state s. Therefore, a state s_j reachable from state s_i is called a Fuzzy Unilateral Improvement (FUI) if and only if $\alpha^k(s_i, s_j) \geq \gamma_k$ and the set of all the FUIs from a state for a decision-maker is called the Fuzzy Unilateral Improvement List (FUIL). This list is denoted by $\tilde{R}_k^+(s)$. The following definitions are for a two-decision-maker system, where one decision-maker is denoted as *k*, and the second decision-maker as *l*.

Fuzzy Nash (FR) Stability: A state *s* is Fuzzy Nash stable for a decision-maker *k* if and only if $\tilde{R}_k^+(s) = null$. The state *s* is FR stable for decision-maker *k* if it has no FUIs from state *s*.

Fuzzy General Metarationality (FGMR): A state is FGMR for decision-maker *k* if and only if, for every $s_1 \in \tilde{R}_k^+(s)$, there exists $s_2 \in R_l(s_1)$, such that $\alpha^k(s_2, s) < \gamma_k$.

Fuzzy Symmetric Metarationality (FSMR): A state is FSMR for decision-maker *k* if and only if, for every $s_1 \in \tilde{R}_k^+(s)$, there exists $s_2 \in R_l(s_1)$ such that $\alpha^k(s_2, s) < \gamma_k$ and $\alpha^k(s_3, s) < \gamma_k$ for all $s_3 \in R_k(s_2)$.

Fuzzy Sequential Stability (FSEQ): A state is FSEQ for decision-maker *k* if and only if, for every $s_1 \in \tilde{R}_k^+(s)$, there exists $s_2 \in \tilde{R}_l^+(s_1)$, such that $\alpha^k(s_2, s) < \gamma_k$. These definitions and their calculations are explained in detail in the Results and Discussion section.

Table 3 (C1) depicts the preference statements (Ω) of these options among the DMs. These statements are mentioned in decreasing order of preferences for each decision-maker. The option prioritizing approach is a general version of the "preference tree" method. Using a priority list of preference statements, a decision-maker's preference is modeled. These statements are generally composed of logical connectors, like "and", "if", "if and only if", "if-then" and listed from most preferred to the least preferred. The option prioritization methodology relies on the absolute "yes", and "no" of each preference, where the truthfulness or "yes" of a more preferred state is greater than its falsity or "no" in calculating the decision-maker's preference.

The option preference statements of the decision-makers in this conflict were listed in decreasing order of importance. Tamil Nadu's first option, as mentioned in Table 3 (C1), is to get the previous ruling of the

Supreme Court reinstated, and it in no circumstances would want the current ruling to stay. The option of water pricing (Option 3) will be accepted by Tamil Nadu if and only if both Karnataka and the Supreme Court agreed to take up that option as depicted in Table 3 (C1). Water pricing would be complicated for only the states to figure out; they would require a governing body to mediate. However, it will also require more political will than the actual conflict has seen. In the last two decades of this conflict, the political landscape in the region has seen less effective governance and more deficient politics.

Crop diversification (Option 2) would be accepted by Tamil Nadu only if the Supreme Court agrees with the conditions that come along with it. Crop diversification may or may not help the smallholder farmers (those with an agricultural area less than 2 hectares) and therefore would require assistance in terms of subsidies to counter income fluctuations.

On the other hand, Karnataka would want the current ruling to stay and would dislike going back to having a smaller proportion of the available water in the river. They would agree with the water pricing (Option 5) if and only if Tamil Nadu and the Supreme Court agrees with it. If this option is accepted, over time, the share of Karnataka would reduce as the influx of funds from Tamil Nadu improve the efficiency of its water distribution infrastructure. The Supreme Court is generally neutral in these terms; however, managing this conflict has been a huge administrative and economic burden for them. Therefore, they would want to stay with the current decision and avoid going back to the previous ruling.

Results and Discussion

This region suffers from indecisive governments and their inaction towards the impacts of climate change. The governments are still trying to govern using archaic methods that do not account for possible future stressors. Instead of solving this transboundary water-sharing issue, they resort to vote-bank politics. While applying crisp GMCR, multiple equilibriums were found. However, they were not useful because the states did not take up those options. This reflected that the states may be unaware of the possible solutions and which one of those would work best for them individually and be mutually agreed upon. Fuzzy preference optimization can help streamline the available solutions by introducing cardinal values, which define a certain threshold to isolate the most preferred solutions. This section discusses and presents the results from both the crisp GMCR and the Fuzzy GMCR with example calculations.

Crisp GMCR

As mentioned in the previous section, for the eight-option model out of the total 256 states, 100 states were found to be feasible states. Without applying option prioritization, 39 states were found to be Nash stable in the analysis. Many of the stable states seem unstable intuitively; therefore, the infeasible strategies were changed. For the purpose of simplification of the analysis, the options are kept irreversible (i.e., once an option is taken, the decision-maker cannot go back). Also, the decision-makers' options are mutually exhaustive within themselves. Hence, for instance, Tamil Nadu can either opt to reinstate the previous ruling or modify to crop-diversification or modify to the pricing of water. Due to a total of 3 decision-makers, 8 options, and 17 feasible states, manual calculations will become complicated. The 17 feasible states are displayed in Table 5 (C1). The 'Y' means that the option is taken, and 'N' means that the option is not taken.

For calculating the stabilities, the preferences of all the decision-makers are written from most preferred on the left towards least preferred on the right. The preference matrix of all the three decision-makers is shown in Figure 2 below.

Preference Ranking of DM1 (Tamil Nadu)

[1, 17, 7, 15, 3, 10, 12, 2, 6, 14, 5, 9, 11, 13, 16, 8, 4]

Preference Ranking of DM2 (Karnataka)

[4, 8, 17, 10, 7, 16, 15, 12, 2, 3, 5, 6, 9, 11, 13, 14, 1]

Preference Ranking of DM3 (Supreme Court of India)

[8, 17, 10, 7, 15, 12, 4, 2, 3, 5, 6, 9, 11, 13, 14, 16, 1]

Figure C1. 2 Decision Makers (DM) Preference Ranking.

From the equilibriums shown, State 1, 4, and 8 are individual Nash stable states for the respective DMs. They seem to reach equilibrium because the removal of infeasible states and option prioritization are set in such a way to exclude mutually exhaustive options from the analysis. Intuitively, these equilibriums do not make any sense. The states were checked by manual calculations as well to make sure that any feasible states are not accidentally deleted. State 12 is a special case in which the state of TN agrees with SC to include crop-diversification and the state of Karnataka insists that crop-pricing is included in the scheme. The profit generated from crop-diversification can be shared with Karnataka, which, in turn, it will invest in its infrastructure so that it will require less water in the future. Ideally, more water will also then become available for TN. This equilibrium seems to be possible only if the immense political will is in effect and there is faith in the scheme, which judging from the political system in India, is far-fetched. The evolution of the conflict towards state 17 would be as shown in Figure 3.

	13	**15**	**17**
(DM1) Tamil Nadu			
1. Reinstate Previous Ruling	N	N	N
2. Appeal for crop-diversification	N	N	N
3. Appeal for water pricing	N	Y	Y
(DM2) Karnataka			
4. Enforce current ruling	N	N	N
5. Accept water pricing	N	N	Y
(DM3) Supreme Court of India			
6. Support Current Ruling	N	N	N
7. Modify to crop-diversification	N	N	N
8. Modify to water pricing	Y	Y	Y
Decimal (State Number)	128	132	148

Figure C1. 3 Evolution of the conflict towards state 17.

On the other hand, for Karnataka, State 10 is the equilibrium in which it is not involved at all, and the state of TN works with SC to include crop-diversification in their state. State 14 is nearly the same case as state 12, with the exception that the state of Karnataka is not involved. Karnataka is not involved in both state 10 and 14. State 14 has the SC modify to water pricing while TN appeals for crop-diversification. These are states in transition. The SC would use the revenue generated from the crop-diversification practices and invest it in Center-funded projects in Karnataka, without involving its government. State 17 is the case in which all the three DMs are involved in the same project of utilizing the revenue generated from the water-pricing to be used in the state of Karnataka, and in turn, the state of Karnataka starts releasing more water immediately.

Sensitivity Analysis with Option Prioritization

The preference order of the states mentioned in the previous sections is highly uncertain as it pertains to governmental policies. The model calibration was carried out based on a literature review. For example, Tamil Nadu is not able to reinstate the previous ruling and does not have a clear preference for either the pricing of water or crop-diversification. It is completely dependent on the governance and environmental situation within the state. Using the GMCR methodology, the preferences were changed to check whether these details would affect the final equilibrium; however, no difference was observed. The same four states were found to be the equilibrium ones.

In global conflicts involving more than two decision-makers, two or more of them may form a coalition in order to be collectively better off at the end of the conflict. However, coalition preference is not evident in this conflict as both states have high political dividends to be reaped from this basin. For Tamil Nadu, it is the biggest river basin and for Karnataka, it powers their biggest city of Bangalore. Therefore, a coalition between them is near impossible.

Fuzzy GMCR

From equation (1) to (10) in the methodology section, the $\mathcal{R}$ matrices for Tamil Nadu and Karnataka are calculated. Some of the example calculations are shown below. Using equations 3 and 4 and considering an example of the decision-maker Tamil Nadu, state 7 and state 17 have been ascertained to have x values of 0.5 and 1.0 for the most preferred option (Ω_1). Then, for state 7, the value of $l(0.5) = 0.35$, and $u(0.5) = 0.65$. Using equation 7 for TN and state 7, the $\tilde{\psi}_1^L(7) = 0.071$, and $\tilde{\psi}_1^U(7) = 0.129$. For state 17, the $\tilde{\psi}_1^L(17) = 0.2$, and $\tilde{\psi}_1^U(17) = 0.2$. Using equation 8, for TN and state 7 the $\tilde{\psi}^L(7)$ = 0.245, and the $\tilde{\psi}^U(7) = 0.475$. For TN and state 17, the $\tilde{\psi}^L(17)$ = 0.551, and the $\tilde{\psi}^U(17) = 0.689$. Using equation 9, the degree of likelihoods for TN ($\mathcal{L}_7 = 0.230$ and $\mathcal{L}_{17} = 0.137$) were calculated. Using equation 10, the α^k values were calculated, e.g., Tamil Nadu, $\alpha^k(7{,}17) = -1.0$, and $\alpha^k(17{,}7) = 1.0$.

For simplicity, the Supreme Court (the third decision-maker), is assumed to not have any participation in the conflict, as it would honor the decisions taken by the other two decision-makers. Also, the Supreme Court is a governing body and hence such a simplifying assumption is acceptable. Table 7 (C1) and Table 8 (C1) represents the fuzzy preference values for Tamil Nadu and Karnataka, respectively. The $\mathcal{R}$ value in the tenth row and second column above of 0.9 represents that state 10 is preferred over state 2 by a factor of 0.9. It represents Tamil Nadu's preference of state 10 over state 2. Also, the ninth row and seventh column represent the preference of state 9 over state 7. The value of 0.3 represents that state 9 is less preferred over state 7. In row six and column fourteen, the value of 0.8 represents the preference for Karnataka for state 6 over state 14. Karnataka prefers state 6 over state 14 by a factor of 0.8, which would mean that it is definitely more preferred. State 13 is less preferred over state 8 because the preference value in the thirteenth row and eighth column is 0.2.

In order to carry out the fuzzy stability analysis of the Cauvery conflict, the $\mathcal{R}$ values above were checked with the $'\gamma'$ values. The fuzzy preference values are checked against the fuzzy satisficing threshold (FST). The results are presented in calculations section, where a 'Y' in a cell indicates that the state in the corresponding row is fuzzy stable for the indicated decision-maker or a fuzzy equilibrium (FE) under the indicated fuzzy stability definitions. To identify how the fuzzy satisficing threshold (FST) behavior works, four sets of FSTs of the decision-makers are considered.

The FSTs used in the analysis are; 1) $\gamma_{TN} = 0.4, \gamma_K = 0.2$; 2) $\gamma_{TN} = 0.4, \gamma_K = 0.4$; 3) $\gamma_{TN} = 0.6, \gamma_K = 0.2$; and, 4) $\gamma_{TN} = 0.6, \gamma_K = 0.4$. The results are available in calculations section.

There were no states available to perform an FSEQ analysis for Karnataka. State 7 (water pricing is accepted by both Karnataka and Tamil Nadu) and state 17 (water pricing is accepted by all the three decision-makers) are the two states in fuzzy equilibrium in all the four combinations. State 17 is an extension of state 7, as it also includes the agreement on part of the Supreme Court for the water pricing option.

Conclusions

Although the Cauvery conflict is old, there has not been enough literature discussing the conflict holistically. The Cauvery River basin conflict, despite being of immense importance, is still far from resolved. This study is aimed at providing a fresh look into the Cauvery conflict by applying the methodology of GMCR along with fuzzy preferences. The approach here is to view the dispute from the perspectives of the parties and their preferences, whereas previous studies of the region have focused on single issues such as the hydrological cycle, or the economic condition of the region.

Using the GMCR methodology, the complicated nature of different options and preferences have been condensed into workable (17) states. GMCR found four stable states that could be a possible way forward; State 10 (crop diversification clause accepted by Tamil Nadu and the Supreme Court), State 12 (Tamil Nadu wants crop diversification; however, Karnataka is pushing for water pricing, but the Supreme Court accepts Tamil Nadu's option), State 14 (water pricing is accepted in principle by Tamil Nadu and Karnataka), and State 17 (water pricing option is accepted by all the three decision-makers. GMCR offers insights into the evolution of the conflict in terms of change in the preferences of the decision-makers as they converge towards a mutual agreement. However, there is not enough contextual information behind the four possible agreements in order to predict the most probable solution.

There has been little progress in this conflict since 2013 due to the indecisiveness of the decision-makers. This inspired the researchers to apply methodologies that can help the decision-makers focus on a solution that has a higher chance of success. Therefore, a fuzzy preference methodology was applied. The water pricing option, which demands the cooperation of both decision-makers, has emerged as the most favorable option (state 17). However, water pricing is only a solution if price has an impact on agricultural practices and if it is effectively feasible and socially accepted. In addition, high political will is also required to implement such a mutual agreement between Tamil Nadu and Karnataka. This option shall ensure that

Tamil Nadu receives enough water every year, and in turn, Karnataka will receive a compensatory sum of money, which it will invest in its own infrastructure development. If Karnataka accepts the water pricing option and invests that money in improving its water supply infrastructure, they would not be required to incur a loan from a foreign entity like ADB. This option also utilizes Ostrom's idea, where the two states can become dependent on each other and not require intervention from regulatory bodies.

A study limitation is that the GMCR+ software cannot carry out fuzzy preference optimization. The results mentioned here were calculated using Microsoft Excel. In addition, the methodology for fuzzy preferences calculation requires key values on the part of the person carrying out the study (the consultant). The x-values mentioned in equations 3 and 4 are to be entered manually by the consultant and therefore may incur a human error. Other input values like p in equations 3 and 4 and α in equation 6 are all input variables in the methodology. However, these input variables have a fixed range of values that they can take to satisfy several mathematical conditions. The consultant, as a third party, makes judgments on the preferences of the decision-makers, hence possibly adding considerable bias. However, for complex calculations like those of FR, FGMR, FSMR, and FSEQ, a panel in the current GMCR+ module can be added. In future work, to further reduce consultant bias, input models can be used. One option can be PROSA (PROMETHEE for Sustainable Assessment); as a decision tool, it may be used for sustainability-related challenges. It boasts of a lower degree of criteria compensation, which can help in categorizing sustainability problems effectively. Another option would be Cross Impact Balances as an input model for the socio-economic indicators used implicitly in the current GMCR model.

In addition, hydrological modeling is not part of the scope of this paper, as it focuses on positions that could be taken by the two states in the present-day conflict to help them move forward from their political standoff. However, the importance of climate change and its effect on water availability and water demand will affect water sharing immensely. Apart from these limitations, GMCR provides a set of tools that a consultant can explore to understand the nuances of a conflict. Although it is common knowledge that complex problems can be solved if parties work together, GMCR showcases specific opportunities for cooperation to resolve conflict. With the permanent monitoring committee being established in early 2019, this research is timely and can be used by them.

Calculations

This section contains the remaining three combinations of calculations.

Table C1. 6 Equilibrium Results for the conflict

	Ordered		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	Decimal	Filter	1	2	4	8	16	18	20	32	64	66	80	82	128	130	132	144	148
1 - Tamil Nadu	Reinstate the previo	-	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
	Appeal for crop-dive	-	N	Y	N	N	N	Y	N	N	N	Y	N	Y	N	Y	N	N	N
	Appeal for pricing o	-	N	N	Y	N	N	N	Y	N	N	N	N	N	N	N	Y	N	Y
2 - Karnataka	Appeal to enforce th	-	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N
	Accept water pricing	-	N	N	N	N	Y	Y	Y	N	N	N	Y	Y	N	N	N	Y	Y
3 - Supreme Court of	Support current ruli	-	N	N	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N
	Modify to crop-diver	-	N	N	N	N	N	N	N	N	Y	Y	Y	Y	N	N	N	N	N
	Modify to water pric	-	N	N	N	N	N	N	N	N	N	N	N	N	Y	Y	Y	Y	Y
Payoff For:	Tamil Nadu	-	17	10	13	1	7	9	15	2	6	12	5	11	4	8	14	3	16
Payoff For:	Karnataka	-	1	9	8	17	7	6	13	16	5	14	4	10	3	2	11	12	15
Payoff For:	Supreme Court of Ind	-	1	10	9	11	8	7	14	17	6	15	5	12	4	3	13	2	16
	Nash	-	Y			Y				Y		Y		Y		Y			Y
	GMR	-	Y			Y				Y		Y		Y		Y			Y
	SEQ	-	Y			Y				Y		Y		Y		Y			Y
	SIM	-	Y			Y				Y		Y		Y		Y			Y
	SEQ & SIM	-	Y			Y				Y		Y		Y		Y			Y
	SMR	-	Y			Y				Y		Y		Y		Y			Y

Table C1. 7 Fuzzy Preference ($\mathcal{R}$) values for Tamil Nadu in the Cauvery Conflict

	s1	**s2**	**s3**	**s4**	**s5**	**s6**	**s7**	**s8**	**s9**	**s10**	**s11**	**s12**	**s13**	**s14**	**s15**	**s16**	**s17**
s1	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0	0.2
s2	0.0	0.5	1.0	1.0	0.7	0.6	0.3	1.0	0.4	0.1	0.7	0.7	1.0	0.3	0.4	0.6	0.0
s3	0.0	0.0	0.5	0.6	0.3	0.1	0.0	0.6	0.0	0.0	0.3	0.1	0.5	0.0	0.0	0.1	0.0
s4	0.0	0.0	0.4	0.5	0.1	0.0	0.0	0.5	0.0	0.0	0.1	0.0	0.4	0.0	0.0	0.0	0.0
s5	0.0	0.3	0.7	0.9	0.5	0.3	0.0	0.9	0.2	0.0	0.5	0.4	0.7	0.1	0.1	0.4	0.0
s6	0.0	0.4	0.9	1.0	0.7	0.5	0.2	1.0	0.4	0.1	0.7	0.6	0.9	0.3	0.3	0.6	0.0
s7	0.0	0.7	1.0	1.0	1.0	0.8	0.5	1.0	0.7	0.4	1.0	1.0	1.0	0.6	0.6	0.9	0.0
s8	0.0	0.0	0.4	0.5	0.1	0.0	0.0	0.5	0.0	0.0	0.1	0.0	0.4	0.0	0.0	0.0	0.0
s9	0.0	0.6	1.0	1.0	0.8	0.6	0.3	1.0	0.5	0.2	0.8	0.7	1.0	0.4	0.4	0.7	0.0
s10	0.1	0.9	1.0	1.0	1.0	0.9	0.6	1.0	0.8	0.5	1.0	1.0	1.0	0.7	0.8	1.0	0.0
s11	0.0	0.3	0.7	0.9	0.5	0.3	0.0	0.9	0.2	0.0	0.5	0.4	0.7	0.1	0.1	0.4	0.0
s12	0.0	0.3	0.9	1.0	0.6	0.4	0.0	1.0	0.3	0.0	0.6	0.5	0.9	0.2	0.2	0.4	0.0
s13	0.0	0.0	0.5	0.6	0.3	0.1	0.0	0.6	0.0	0.0	0.3	0.1	0.5	0.0	0.0	0.1	0.0
s14	0.0	0.7	1.0	1.0	0.9	0.7	0.4	1.0	0.6	0.3	0.9	0.8	1.0	0.5	0.5	0.8	0.0
s15	0.0	0.6	1.0	1.0	0.9	0.7	0.4	1.0	0.6	0.2	0.9	0.8	1.0	0.5	0.5	0.7	0.0
s16	0.0	0.4	0.9	1.0	0.6	0.4	0.1	1.0	0.3	0.0	0.6	0.6	0.9	0.2	0.3	0.5	0.0
s17	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5

Table C1. 8 Fuzzy Preference ($\mathcal{R}$) values for Karnataka in the Cauvery Conflict

	s1	**s2**	**s3**	**s4**	**s5**	**s6**	**s7**	**s8**	**s9**	**s10**	**s11**	**s12**	**s13**	**s14**	**s15**	**s16**	**s17**
s1	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
s2	1.0	0.5	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
s3	1.0	0.9	0.5	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0
s4	0.0	1.0	1.0	0.5	0.9	0.7	0.3	0.3	1.0	0.7	0.7	0.6	0.7	1.0	0.4	0.3	0.0
s5	1.0	1.0	1.0	0.1	0.5	0.4	0.1	0.1	1.0	0.4	0.4	0.3	0.4	0.8	0.2	0.1	0.0
s6	1.0	1.0	1.0	0.3	0.6	0.5	0.2	0.2	1.0	0.4	0.5	0.4	0.5	0.8	0.3	0.2	0.0
s7	1.0	1.0	1.0	0.7	0.9	0.8	0.5	0.5	1.0	0.7	0.8	0.7	0.8	1.0	0.6	0.5	0.0
s8	1.0	1.0	1.0	0.7	0.9	0.8	0.5	0.5	1.0	0.8	0.8	0.7	0.8	1.0	0.6	0.5	0.0
s9	1.0	0.9	0.5	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0
s10	1.0	1.0	1.0	0.3	0.6	0.6	0.3	0.2	1.0	0.5	0.6	0.5	0.6	0.9	0.4	0.3	0.0
s11	1.0	1.0	1.0	0.3	0.6	0.5	0.2	0.2	1.0	0.4	0.5	0.4	0.5	0.8	0.3	0.2	0.0
s12	1.0	1.0	1.0	0.4	0.7	0.6	0.3	0.3	1.0	0.5	0.6	0.5	0.6	0.9	0.4	0.3	0.0
s13	1.0	1.0	1.0	0.3	0.6	0.5	0.2	0.2	1.0	0.4	0.5	0.4	0.5	0.8	0.3	0.2	0.0
s14	1.0	1.0	0.7	0.0	0.2	0.2	0.0	0.0	0.7	0.1	0.2	0.1	0.2	0.5	0.0	0.0	0.0
s15	1.0	1.0	1.0	0.6	0.8	0.7	0.4	0.4	1.0	0.6	0.7	0.6	0.7	1.0	0.5	0.4	0.0
s16	1.0	1.0	1.0	0.7	0.9	0.8	0.5	0.5	1.0	0.7	0.8	0.7	0.8	1.0	0.6	0.5	0.0
s17	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5

Table C1. 9 Fuzzy Stability Results of the Cauvery Conflict (FST: Fuzzy Satisficing Threshold, FR: Fuzzy Nash, FGMR: Fuzzy General Metarational, FSMR: Fuzzy Symmetric Metarational, FSEQ: Fuzzy Sequential Stability, FE: Fuzzy Equilibrium)

FSTs	**States**	**FR**				**FGMR**				**FSMR**				**FSEQ**			
		SC	**TN**	**K**	**FE**	**SC**	**TN**	**K**	**FE**	**SC**	**TN**	**K**	**FE**	**SC**	**TN**	**K**	**FE**
$\gamma_{TN} = 0.4$, $\gamma_K = 0.2$	s1	Y				Y				Y				Y			
	s2	Y				Y				Y				Y			
	s3	Y				Y				Y				Y			
	s4	Y				Y				Y				Y			
	s5	Y				Y				Y				Y			
	s6	Y		Y		Y		Y		Y		Y		Y		Y	
	s7	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	s8	Y				Y				Y				Y			
	s9	Y				Y	Y			Y	Y			Y			
	s10	Y	Y			Y	Y			Y	Y			Y	Y		
	s11	Y				Y				Y				Y			
	s12	Y				Y				Y				Y			
	s13	Y				Y				Y				Y			

	s14	Y	Y			Y	Y			Y	Y			Y	Y		
	s15	Y	Y			Y	Y			Y	Y			Y	Y		
	s16	Y		Y		Y		Y		Y		Y		Y		Y	
	s17	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

The process for computation is very straightforward. The α^k values are calculated using the equation number 10. These α^kvalues are then checked against the γ^k value, as the α^k are the relative representation of the two sets of states. It is clear from table 9 (C1) that state 7 and state 17 have a higher degree of stability—they are fuzzy stable for all the decision-makers under all the FSTs. Sample calculations are performed as for the combination $\gamma_{TN} = 0.4, \gamma_K = 0.2$, as follows:

FR: State 10 is Fuzzy Nash stable for TN because the α^k value of 0.5 is greater than the γ_k value of 0.4.

FGMR: State 16 has an FUI towards state 17 for TN. This moves the conflict to state 17. Karnataka can move from state 17 to state 15, taking the conflict to state 15. Since the α^k value of state 16 is less than that of state 15, state 16 is not FGMR.

FSMR: State 16 has an FUI towards state 17 for TN. This brings the conflict to state 17. Karnataka can move from state 17 to state 15, taking the conflict to state 15. TN can move the conflict to state 13 as it is in its reachability list. Since the α^k value of state 16 is less than that of state 15, and the α^k value of state 16 is less than that of state 13, state 16 is not FSMR.

FSEQ: State 13 for TN has an FUI to state 15, taking the conflict to state 15. Karnataka has an FUI from state 15 to state 17. State 13 is less preferred than state 17 for TN; therefore, state 13 is not FSEQ.

The calculation for the α^k for the other $\gamma_{TN} = 0.6$ for TN is like above, except for the fuzzy Nash stable. State 10 is not Fuzzy Nash stable for TN because the α^k value of 0.5 is less than the γ_k value of 0.4. Similar calculations for Karnataka are also carried out for the combination $\gamma_{TN} = 0.6, \gamma_K = 0.2$.

FR: State 16 is Fuzzy Nash stable for K because the α^k value of 0.5 is greater than the γ_k value of 0.2.

FGMR: State 15 has an FUI towards state 17 for K. This brings the conflict to state 17. TN can move from state 17 to state 16, taking the conflict to state 16. Since the α^k value of state 15 is less than that of state 16, state 15 is not FGMR.

FSMR: State 15 has an FUI towards state 17 for K. This brings the conflict to state 17. TN can move from state 17 to state 16, taking the conflict to state 16. TN does not have any moves from this state and hence the process stops. In the absence of the third step, and the α^k value of state 15 being less than that of state 16, state 15 is not FSMR.

Table C1. 10 Fuzzy Stability Results of the Cauvery Conflict

FSTs	States	FR				FGMR				FSMR				FSEQ			
		SC	TN	K	FE	SC	TN	K	FE	SC	TN	K	FE	SC	TN	K	FE
$\gamma_{TN} = 0.4$, $\gamma_K = 0.4$	s1	Y				Y				Y				Y			
	s2	Y				Y				Y				Y			

	s3	Y				Y				Y				Y			
	s4	Y				Y				Y				Y			
	s5	Y				Y				Y				Y			
	s6	Y		Y		Y		Y		Y		Y		Y		Y	
	s7	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	s8	Y				Y				Y				Y			
	s9	Y				Y	Y			Y	Y			Y			
	s10	Y	Y			Y	Y			Y	Y			Y	Y		
	s11	Y				Y				Y				Y			
	s12	Y				Y				Y				Y			
	s13	Y				Y				Y				Y			
	s14	Y	Y			Y	Y			Y	Y			Y	Y		
	s15	Y	Y			Y	Y			Y	Y			Y	Y		
	s16	Y				Y				Y				Y			
	s17	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Table C1. 11 Fuzzy Stability Results of the Cauvery Conflict

FSTs	States	FR				FGMR				FSMR				FSEQ			
		SC	TN	K	FE	SC	TN	K	FE	SC	TN	K	FE	SC	TN	K	FE
$\gamma_{TN} = 0.6$, $\gamma_K = 0.2$	s1	Y				Y				Y				Y			
	s2	Y				Y				Y				Y			
	s3	Y				Y				Y				Y			
	s4	Y				Y				Y				Y			
	s5	Y				Y				Y				Y			
	s6	Y		Y		Y		Y		Y		Y		Y		Y	
	s7	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	s8	Y				Y				Y				Y			
	s9	Y				Y				Y				Y			
	s10	Y				Y				Y				Y			
	s11	Y				Y				Y				Y			
	s12	Y				Y				Y				Y			
	s13	Y				Y				Y				Y			
	s14	Y	Y			Y	Y			Y	Y			Y	Y		
	s15	Y	Y			Y	Y			Y	Y			Y	Y		
	s16	Y		Y		Y		Y		Y		Y		Y		Y	
	s17	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Table C1. 12 Fuzzy Stability Results of the Cauvery Conflict

FSTs	States	FR				FGMR				FSMR				FSEQ			
		SC	TN	K	FE	SC	TN	K	FE	SC	TN	K	FE	SC	TN	K	FE
$\gamma_{TN} = 0.6$, $\gamma_K = 0.4$	s1	Y				Y				Y				Y			
	s2	Y				Y				Y				Y			
	s3	Y				Y				Y				Y			
	s4	Y				Y				Y				Y			
	s5	Y				Y				Y				Y			
	s6	Y		Y		Y		Y		Y		Y		Y		Y	
	s7	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	s8	Y				Y				Y				Y			
	s9	Y				Y				Y				Y			
	s10	Y				Y				Y				Y			
	s11	Y				Y				Y				Y			
	s12	Y				Y				Y				Y			
	s13	Y				Y				Y				Y			
	s14	Y	Y			Y	Y			Y	Y			Y	Y		
	s15	Y	Y			Y	Y			Y	Y			Y	Y		
	s16	Y				Y				Y				Y			
	s17	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

The restriction on the value's "x" can take, as mentioned above, is another modification that may help in controlling the bias of the consultant. These values can be controlled for the type and/or quality of conflict and a fixed value may be arrived at. However, that may need a large enough database of conflicts. Currently, the only restriction is on the preference value per preference statement, per state. This can be normalized in such a way that the column representing the preference 'chances' for a decision-maker and for a state are values from 0 to 1. This shall further optimize the options within the preference statements as well. The effect of such an exercise is beyond the scope of the current work, although it can be included in future works.