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CEE 552 River Basin Management

Term project

Optimizing Reservoir Storage for Ecological and Economical Balance in the Lachlan Catchment using GAMs and IHA

Haribansha Timalsina

Soyoung Sohn

Thea Hu

Ritu Rani Das

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Group member contribution description

Name __ Haribansha Timalsina _____ Signature _____Haribansha_____

1. The results visualization and analysis of IHA;
2. The results visualization and further analysis of GAMS;
3. Presentation: Part 3 Results and Discussion;
4. PPT design: Part 1 Introduction & 3 Results and Discussion;
5. Report Writing: Part 3.1 Ecological Analysis, Part 3.2 Optimization Model Results, Figure 2.3.2 River network

Name _____ Soyoung Sohn _____ Signature _____Soyoung Sohn_____

1. Data collection and preprocessing of streamflow and network information for IHA and GAMS set up;
2. Calculation of hydropower and monthly demands
3. Presentation: Part 2 Methodology;
4. PPT design: Part 2 Methodology;
5. Report Writing: Part 2.3.1 River Network, Part 2.3.2 Data and Assumptions, Part 4 Conclusion (except the portion related to Part 3.3).

Name _____ Thea Hu _____ Signature _____ Thea Hu _____

1. Background information collection and Literature Review;
2. Preliminary coding for GAMS;
3. Presentation: Part 1 Introduction;
4. Report Writing: Part 1 Introduction, Part 2.1 Study Area, Part 2.2 IHA Method, Part 2.3.3 Model Description, Appendix A Preliminary GAMS Code.

Name _____ Ritu Rani Das _____ Signature _____ Ritu Rani Das _____

1. Presentation: Part 4 Conclusion;
2. PPT design: Part 4 Conclusion;
3. Report Writing: Part 3.3 System Response to Varying IHA Loss Coefficients: Balancing Flow Compliance and Economic Objectives, and Portion of Part 4 Conclusion (related to Part 3.3), Appendix B Updated GAMS code for Part 3.3 Analysis.

1. Introduction

1.1 Project objective

This project investigates the Lachlan Catchment within Australia's Murray–Darling Basin (MDB), aiming to achieve a balance between ecological sustainability and economic efficiency. To assess the environmental impacts of water management, we analyzed stream flow data from Hillston Weir, located downstream of the catchment, with Indicators of Hydrologic Alteration (IHA). The IHA analysis evaluates the hydrological changes caused by the 1970 enlargement of Wyangala Dam, which increased its capacity by over 300% for flood control purposes. Building on this, we developed an optimization model using GAMS (General Algebraic Modeling System), integrating ecologically significant RVA Targets into a water allocation framework. Through a one-year simulation of storage operations, the model seeks to optimize economic outcomes while ensuring that environmental flow requirements are met as effectively as possible.

1.2 Background

Wyangala Dam was initially built in 1935 by the New South Wales (NSW) Government, with a capacity of 360 gigalitres (GL) at first. Due to historically severe water security issues in NSW, proposals to expand Wyangala Dam have been raised multiple times since its construction. In 1970, the dam's capacity was successfully increased to 1,200 GL; in 2019, the government proposed another expansion, but the plan was abandoned in 2024 through concerted efforts by academics, indigenous communities, and other stakeholders (Kandulu et al., 2024; Murray–Darling Basin Authority, 2023). Wyangala Dam supports a wide range of local water demands, providing irrigation for approximately 300,000 hectares of farmland and supplying drinking water for nearly 100,000 residents. In addition, the dam is also responsible for providing environmental flows to important downstream ecological conservation areas, while simultaneously contributing to a Gross Regional Product of approximately A$7 billion (Infrastructure NSW, 2023; WaterNSW, 2024).

Concerns about the negative impacts of artificial barriers on native fish populations have been repeatedly raised in studies of Lachlan River, which is one of the most highly regulated rivers within the MDB (Baumgartner et al., 2014; Kerezsy, 2025; Saintilan & Overton, 2010). Local authorities have recognized the severity of the ecological issues and have implemented multiple measures to improve fish populations, like fish passage, fish-protection reaches, and stock-enhancement (Murray−Darling Basin Authority, 2020). Since the 1970s, Golden Perch have been the most numerous species in the Lachlan River's stock-enhancement program, supported by three operating hatcheries that release an average of 20,000 fish annually. However, recent genetic and chemical analyses of upstream samples found only hatchery-reared individuals, with wild-born fish appearing only downstream. This indicates that successful fish recovery in the Lachlan Catchment still requires coordinated effort from all stakeholders (Shams et al., 2020).

Moreover, due to the lack of consideration for environmental flow requirements in early flow management, along with the limited effectiveness of restoration programs implemented over the past decade, nearly 88% of wetlands in the Murray–Darling Basin are not receiving adequate water supply (Chen et al., 2020). The Great Cumbung Swamp, the terminal wetland of Lachlan River with a long regulated history, is facing the same condition. It is one of the most important wetlands in the southwestern NSW due to its vast area as a habitat of many endangered bird species. Although the degradation of wetland conditions is a recognized fact, studies have shown that the condition of reed beds in the Great Cumbung Swamp can be improved through multiple deliveries of sufficient environmental water (Higgisson et al., 2022).

2 Methodology

2.1 Study Area

Lachlan River is one of the major water supply rivers located in the southern part of the Murray–Darling Basin in Australia, originating from the Great Dividing Range and stretching for over 1,300 kilometers to the Great Cumbung Swamp. The Lachlan Catchment covers an area of over 80,000 square kilometers, with major water demands from agriculture, as well as providing critical supply for livestock, communities, and ecosystems. (Commonwealth Environmental Water Holder, 2025; Murray–Darling Basin Authority, 2023). The map of the Lachlan River and Murray–Darling Basin is shown in Figure 2.1. Multiple Australia-endemic native freshwater fish inhabit the Lachlan Catchment, including Golden Perch, Murray Cod, Silver perch, Eel-tailed catfish, and the endangered Olive Perchlet (Commonwealth Environmental Water Holder, 2025).

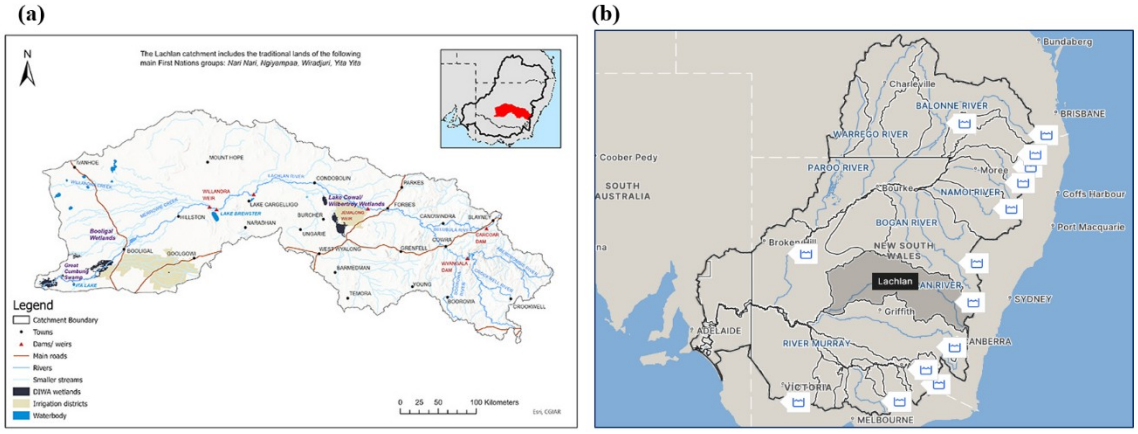

Figure 2.1. Map of the Study Area:
(a) Lachlan Catchment (b) the Murray–Darling Basin

There are four major water storages within the system, listed from upstream to downstream (Australian Bureau of Meteorology, 2024):
(1) Wyangala Dam, located on the upper Lachlan River;
(2) Carcoar Dam, located on the Belubula River, a tributary that flows into the Lachlan River shortly downstream of Wyangala Dam;
(3) Lake Cargelligo; and
(4) Lake Brewster, both located in the lower reaches of the river system.

2.2 IHA Method

Indicators of Hydrologic Alteration (IHA) method, which is proposed by Richter et al. (1996), is the most commonly used approach in recent years for assessing the impact of human activities on ecological flow features (Xue et al., 2017). IHA method includes 32 indicators in total, which are classified into 5 hydrological feature groups. The impact of human activities, such as dam construction, on river flow will be reflected through the differences in these indicators between the pre-impact and post-impact periods. In addition, Richter et al. proposed the Range of Variability Approach (RVA) in 1997, which conducts statistical analyses of these indicators before and after the impact. It defines an RVA Target —a range for each indicator—that can be used as a reference in river management.
This project focuses on the impact of the capacity enlargement of Wyangala Dam in 1970 on the downstream water environment of the Great Cumbung Swamp. We selected Hillston station (ID 412039), located upstream of the Great Cumbung Swamp on the Lachlan River, to conduct the IHA analysis. The stream flow data is downloaded from the Bureau of Meteorology of Australia Government (http://www.bom.gov.au/waterdata/). The pre-impact and post-impact periods are 1941-1969 and 1970-2025. As our project aims to optimize water allocation to increase environmental flows reaching the terminal wetland, we will select the indicators from the IHA results that represent flow reduction, while align with the temporal scale of the GAMS optimization model.

2.3 Optimization Model

We used GAMS IDE 2.0.10.0 to model the river system in the Lachlan Catchment. Due to data availability, we selected the 1-year period for the water year of July 2015 to June 2016 to run the GAMS model. The preliminary code for analysis and results in Part 3.2 is attached in Appendix A. The analysis under different scenarios is generated by changing the initial storage data in preliminary code. In addition, the updated GAMS code for Part 3.3 analysis is attached in Appendix B.

2.3.1 River Network

Figure 2.3.1 shows the river network, adapted from the River Diagram for Lachlan Catchment in the Bureau of Meteorology of Australia Government (2024). Due to the lack of upstream inflow data for Carcoar Dam, which is located on the Belubula tributary and does not generate hydropower, we excluded it from our network. For the inflow from the Belubula tributary into the Lachlan River, we used the release stream data from Carcoar Dam (ID 412077). Additionally, the downstream end of our river network was set just upstream of the Hillston station (ID 412039). Since the IHA analysis estimates downstream environmental flow requirements based on Hillston station, components located downstream of this station—such as the Great Cumbung Swamp—were not included in the model.

In Figure 2.3.1, circle represents river node, square represents demand site, and triangle represents reservoir. The meaning of each component (river node, demand site and reservoir) is shown in Table 2.3.1.

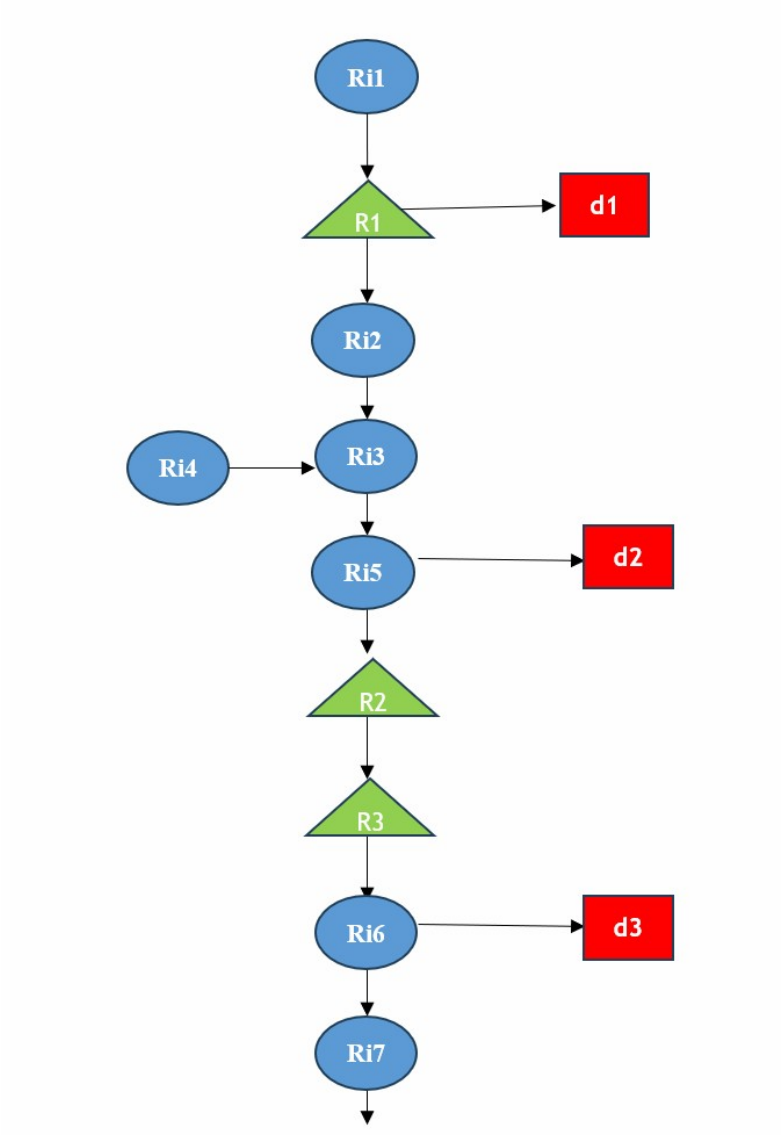

Figure 2.3.1 River network for GAMS program

Table 2.3.1 Meaning of the component in river network of Lachlan Catchment

Network ID	Name	Description
R1	Wyangala Dam	Hydropower generation from release Storage constraints (dead storage, capacity)
R2	Lake Cargelligo	Storage constraints (dead storage, capacity)
R3	Lake Brewster	Storage constraints (dead storage, capacity)
Ri1	Inflow to Wyangala dam	
Ri2	Lachlan river at Cowra	
Ri3	Lachlan river near Eugowra	
Ri4	Carcoar dam release to Lachlan	Inflow to the network
Ri5	Lachlan river near Condobolin	
Ri6	Lachlan river between Lake Brewster and Hillston Weir	
Ri7	Lachlan river at Hillston Weir	Outflow contributes to the ecological demand
d1, d2, d3	Demand site 1, 2, 3	

2.3.2 Data and Assumptions

The description and sources of the data used for this study are summarized in Table 2.3.3. Monthly streamflow data served as the input for the IHA analysis, while the remaining datasets (reservoir information, network inflow and demand, hydropower generation details) were utilized in GAMS modeling. As the raw data of the streamflow was flow rates measured in cubic meter per second, the water volume entering the river network was calculated by integrating the instantaneous flow rates over time, multiplying each flow value by the time interval between measurements. These interval-based volumes were then aggregated by year and month to produce the monthly streamflow volumes used in the analysis.

Table 2.3.2 Description of dataset and source

Data Category	Description	Unit (Value)	Source
Reservoir information	Capacity	ML	Water NSW
	Dead storage	ML	
	Elevation	m	
Inflow to the network	Monthly streamflow volume	ML/month	Bureau of Meteorology
Demand of the network	Monthly usage	ML/month	Department of Climate Change, Energy, the Environment and Water
Hydropower generation	Profit	$7.5 AUD/kWh	Australian Energy Market Operator
	Generation capacity	20MWh/hour	Global Energy Observatory

To estimate monthly water demands at target river nodes where only annual usage data is available, we applied a proportional disaggregation method based on a reference seasonal usage pattern. Specifically, we utilized the monthly distribution of general security regulated river usage from the Murrumbidgee catchment, which lies adjacent to our study area and exhibits similar hydrological characteristics. The demand for each month (i) was estimated using the formula:

$$D_i = D \times \frac{v_i}{\sum_{i=1}^{12} v_i}$$

where D is the known total annual demand at the target node, and v_i is the monthly usage from the Murrumbidgee pattern. This approach assumes that the observed seasonal pattern in the reference catchment reflects typical intra-annual variability and is transferable to our nodes of interest. The 2015–2016 water year was selected as the reference because its seasonal profile closely aligns with the long-term average, showing stable pattern and minimizing the extremes of outliers.

2.3.3 Model Description

The objective function maximizes the hydropower profit from Wyangala Dam, while trying to ensure that the flow at the most downstream river node reaches the RVA Target values identified through the IHA analysis as closely as possible (See Table 3.2 for specific values). The objective function will be maximized by dNLP solver in GAMS.

$$Obj = Max\left[\sum_m profit_m - loss\right]$$

The $profit_m$ represents the monthly profit from hydropower, calculated by:

$$profit_m = H * \eta * g * \rho * Q_m$$

where
H: Head of the Wyangala Dam;
η: efficiency to generate hydropower;
g: gravity acceleration;
ρ: water density;
Q_m: monthly release from Wyangala Dam.

The $loss$ represents the IHA loss function, calculated by:

$$loss = \lambda \sum_{i=0}^{n} \left(IHA_{cal,i} - IHA_{target,i} \right)^2$$

where
$IHA_{cal,i}$: IHA parameter i that is calculated based on the simulation flow in GAMS model;
$IHA_{target,i}$: the RVA target value of IHA parameter i from IHA results.
λ: loss coefficient.

The following constraints are used in the GAMS model:
(1) Water balance constraint for reservoir;
(2) Water balance constraint for river node;
(3) Water supply ≤ Water demand;
(4) Dead Storage ≤ Storage of the reservoir ≤ Reservoir capacity;
(5) Hydropower generation ≤ Capacity of the Dam.

3 Results and Discussion

3.1 Ecological Analysis

The enlargement of Wyangala Dam in 1970 marked a critical turning point in the regulation of the Lachlan River. The subsequent flow alterations observed at the Hillston gauge (Station ID: 412039), located downstream of the dam, reveal profound changes in river hydrology that have disrupted the ecological functioning of the system, particularly for native fish species. Many of these fish, such as golden perch (*Macquaria ambigua*), silver perch (*Bidyanus bidyanus*), and Murray cod (*Maccullochella peelii*), depend on flow variability for key life history processes including migration, spawning, recruitment, and access to nursery habitats. The Indicators of Hydrologic Alteration (IHA) metrics provide a quantitative basis to assess these changes and their implications. The IHA analysis of Hilston gauge at the Lachlan River is shown in Table 3.1.1.

The IHA analysis shows that there was indeed a notable shift in the flow regime in the river with substantial ecological implications for the Great Cumbung Swamp and broader floodplain in the downstream (Figure 3.1.2). The mean monthly flow pre and post impact period (IHA parameter #group 1) suggests that the overall flow significantly decreased for most of the months. During the high flow months from June to September the peak decreased by about 40%. Historically, flows in these months have been reported to contribute to the floodplain inundation and wetland connectivity in the lower Lachlan (Kingsford, 2000; Roberts & Marston, 2011).

Another significant ecological consequence of dam enlargement is the reduction in high-flow events. The IHA results show a marked decline in the magnitude and frequency of high flows, with 30-day and 90-day maximum flows reduced by 19% and 23%, respectively (Table 3.1.1, Parameter #group 2). High pulse counts and durations also declined, reducing opportunities for fish to detect and respond to natural spawning cues. These flow pulses are crucial for stimulating upstream migrations, especially in species like golden perch that require overbank flows to trigger spawning. Without adequate flow magnitude or duration, the ecological signal for reproduction is diminished, often resulting in recruitment failure (Mallen-Cooper & Stuart, 2003).

Moreover, there is an observed shift in the timing of peak flows. The IHA indicates that the annual maximum flow now occurs almost two months later than before the dam enlargement, shifting from late August (day 233) to late October (day 288). This temporal displacement can decouple natural spawning periods from hydrological triggers, particularly for fish adapted to initiate reproduction in late winter or early spring. The altered seasonality of flows reduces larval survival by disrupting access to suitable floodplain habitats during critical developmental windows (King et al., 2009). Such mismatches between flow timing and biological requirements undermine the viability of native fish populations.

Post-regulation flows exhibit reduced rise and fall rates (−28.6% and −20.6%, respectively) and a dramatic increase in the number of flow reversals, from 49 to 93 per year. These changes indicate a highly managed flow regime with limited variability. For fish, the loss of dynamic flow conditions translates into habitat homogenization, reduction in transient habitats like backwaters and flood runners, and a general decline in in-stream habitat diversity. Many native species require such hydraulic complexity for feeding, refuge, and spawning. Moreover, the increase in flow reversals causes behavioral confusion, as fish may begin to migrate or spawn only to be interrupted by a rapid shift in flow direction or magnitude (Bunn & Arthington, 2002).

Connectivity is another essential component for sustaining healthy fish communities. The reduction in low and high flow pulses, coupled with fewer overbank flood events, severely limits hydrological connectivity between the main river channel and the adjacent floodplain wetlands, including the Great Cumbung Swamp. This disconnect hampers the dispersal of larvae and juvenile fish into productive floodplain nursery habitats. For migratory species, the lack of access to upstream or downstream reaches inhibits gene flow and reduces population resilience (Baumgartner et al., 2014). Furthermore, the Great Cumbung Swamp, once a crucial breeding and feeding ground, now experiences infrequent inundation, reducing its role as a recruitment hotspot.

Table 3.1.1: IHA analysis (parametric) results for Lachlan river at Hillston weir

Parameters	MEANS		COEFF. of VAR.		DEVIATION FACTOR		DEV. of C.V.	
	Pre	Post	Pre	Post	Magnitude	%	Magnitude	%
Parameter Group #1								
January	8.18	9.32	1.30	1.34	1.14	13.90	0.04	2.77
February	6.72	8.10	1.41	1.26	1.38	20.56	-0.15	-10.69
March	8.40	6.62	1.31	1.23	-1.78	-21.19	-0.08	-6.23
April	8.67	6.05	1.90	1.49	-2.62	-30.26	-0.41	-21.76
May	10.52	8.03	1.78	1.83	-2.49	-23.63	0.06	3.12
June	13.11	8.26	1.66	1.72	-4.85	-36.98	0.06	3.86
July	19.63	10.91	1.45	1.67	-8.73	-44.45	0.22	15.18
August	28.85	15.50	1.28	1.45	-13.35	-46.26	0.17	13.32
September	31.97	20.52	0.94	1.15	-11.45	-35.81	0.21	22.29
October	25.27	23.02	1.03	1.20	-2.25	-8.92	0.17	16.78
November	22.64	20.11	1.12	1.32	-2.52	-11.14	0.20	17.54
December	14.62	12.80	1.29	1.42	-1.82	-12.44	0.13	9.86
Parameter Group #2								
1-day minimum	0.84	1.51	1.76	1.06	0.67	79.09	-0.70	-39.72
3-day minimum	0.90	1.64	1.70	1.08	0.74	81.73	-0.61	-36.12
7-day minimum	1.01	1.95	1.59	1.17	0.94	92.52	-0.42	-26.21
30-day minimum	1.68	2.72	1.27	1.20	1.04	61.89	-0.07	-5.81
90-day minimum	3.12	3.67	1.63	1.21	0.55	17.73	-0.42	-25.81
1-day maximum	57.84	49.07	0.63	0.64	-8.77	-15.16	0.01	1.18
3-day maximum	57.14	48.58	0.62	0.65	-8.55	-14.97	0.03	4.46
7-day maximum	56.04	47.25	0.63	0.67	-8.80	-15.69	0.04	5.80
30-day maximum	50.09	40.63	0.69	0.78	-9.46	-18.89	0.09	13.28
90-day maximum	36.76	28.30	0.81	0.90	-8.46	-23.02	0.09	11.53
Number of zero days	16.86	0.13	2.72	7.48	-16.74	-99.26	4.76	175.20
Base flow index	0.05	0.18	0.96	0.67	0.13	239.90	-0.29	-29.81
Parameter Group #3								
Date of minimum	181.60	187.30	0.30	0.23	5.70	3.12	-0.07	-23.43
Date of maximum	232.70	288.10	0.23	0.16	55.37	30.25	-0.07	-28.97
Parameter Group #4								
Low pulse count	4.48	3.05	0.86	1.43	-1.43	-31.88	0.57	65.99
Low pulse duration	20.98	16.91	0.97	1.40	-4.07	-19.41	0.43	44.80
High pulse count	1.28	1.04	1.09	1.29	-0.24	-18.82	0.20	18.59
High pulse duration	45.10	40.54	0.79	1.05	-4.56	-10.11	0.26	32.97
Low Pulse Threshold	1.31							
High Pulse Threshold	41.31							
Parameter Group #5								
Rise rate	0.91	0.65	0.51	0.52	-0.26	-28.64	0.01	1.65
Fall rate	-0.75	-0.60	-0.73	-0.56	0.16	-20.60	0.17	-22.88
Number of reversals	49.69	92.98	0.48	0.20	43.29	87.13	-0.29	-59.04

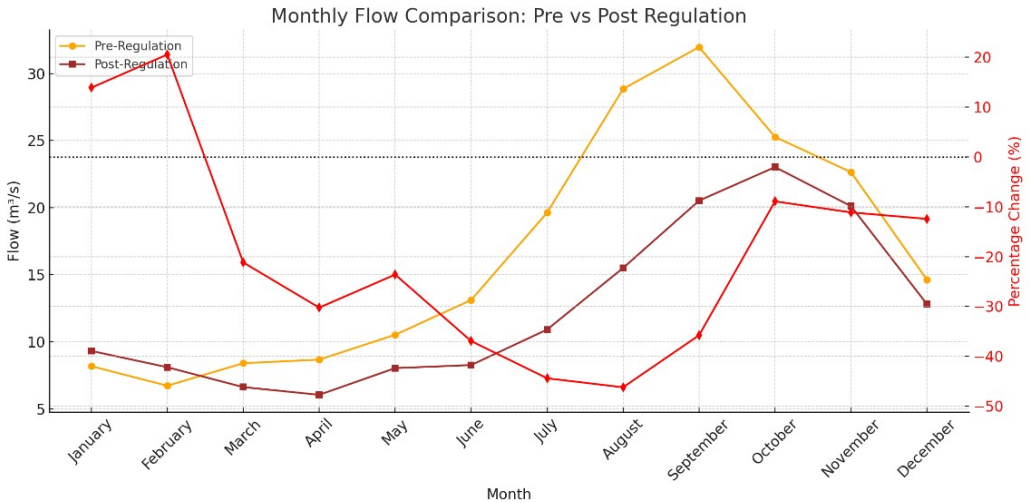

Figure 3.1.2: Monthly average flow shift before and after the impact period in Lachlan river at Hillston weir

Interestingly, the IHA also reveals a near-complete elimination of zero-flow days and a 240% increase in the baseflow index, signaling the establishment of artificial perennial flows downstream. While this may appear beneficial in maintaining water availability, it creates an ecologically unnatural flow regime. Many native species are adapted to boom-bust hydrology characterized by alternating wet and dry phases. The continuous baseflow disrupts predator-prey dynamics, suppresses ecological resets that limit exotic species, and removes important spawning cues tied to dry season breaks. In contrast, introduced species such as common carp (*Cyprinus carpio*) thrive in stable, regulated flow environments, often outcompeting natives and exacerbating ecological degradation (Kopf et al., 2019). Overall, the hydrological alterations caused by the post-1970 expansion of Wyangala Dam have fundamentally changed the flow regime of the Lachlan River. Since it is not practicable to manage the dam operations to regulate the peak timings and flow pulses, there can be certain management options which we consider can help restore the natural ecology downstream. Especially, the reduced flow availability and the peaks have severely impacted the native fish species in the lower Lachlan and Great Cumbung Swamp. Successful management of fish populations in this region now depends on the re-establishment of environmentally sensitive flow regimes. Thus, the subsequent section will consider the environmental flow regulations using the following key IHA observations to include in the GAMS model optimization.

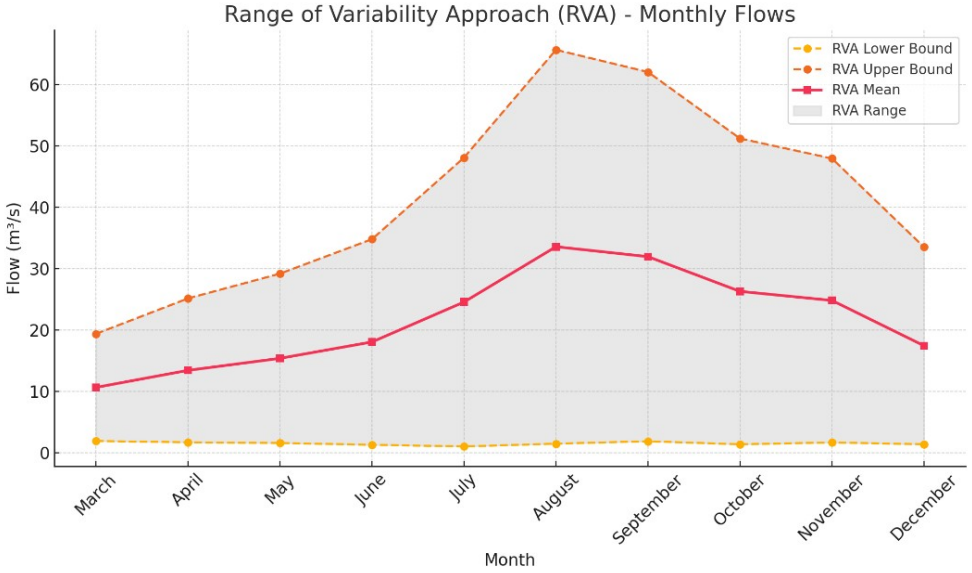

Figure 3.1.3 RVA targets for monthly flows used in GAMS model optimization

Based on the IHA results and the criteria stated in Part 2.2, we selected 10 parameters as the ecological constraints in GAMS model, as shown in Table 3.1.4.

Table 3.1.4 Selected RVA targets (Parametric, Unit: m^3/s)

IHA Parameter	RVA lower bound	RVA upper bound	RVA mean
March Mean	1.912	19.39	10.65
April Mean	1.698	25.16	13.43
May Mean	1.582	29.20	15.39
June Mean	1.292	34.82	18.06
July Mean	1.019	48.12	24.57
August Mean	1.474	65.70	33.59
September Mean	1.869	62.08	31.97
October Mean	1.371	51.24	26.31
November Mean	1.673	47.98	24.83
December Mean	1.375	33.53	17.45

3.2 Optimization Model Results

We analyzed three different scenarios to find the optimal solution of hydropower generation while satisfying the IHA targets. The analysis was performed for wet, normal and dry precedent years, where 100% scenario represents the full/near full reservoir in the initial condition when the previous year was wet and had sufficient water to store. Similarly, 70% initial storage (of the total capacity of reservoir) conditions signify precedent normal year and 55% represents the dry scenario respectively as shown in Figure 3.2.1.

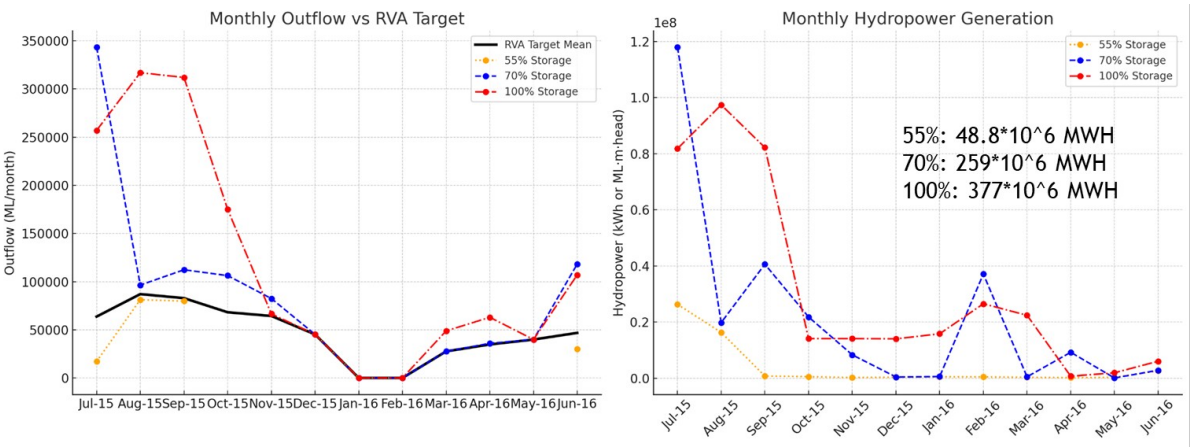

Figure 3.2.1 GAMS optimization for multiple reservoir storages (precedent year scenario): a) Monthly outlet flow from the Lachlan River catchment along with the IHA target (black); b) Monthly hydropower generation

When the initial reservoir storage was full, there was an annual hydropower energy generation of 377×10^6 MWh with the highest generation during August followed by September and July. The dam on the first reservoir operates at the level of 128 m, 122 m and 133 m respectively during these months (Figure 3.2.2). Since hydropower energy generation is the function of the product of the hydraulic head and the discharge, dam release and storage can be optimized for a more consistent release when the dam has enough water during these months. The IHA targets were totally satisfied during all the months (Figure 3.2.1 a). In addition, during the full initial reservoir condition, the peak flow (August) was automatically satisfied in correspondence to IHA target even if the flow timing was not taken into consideration for optimization.

For the normal year scenario (70% initial storage), the model generated 259×10^6 MWh of energy, with the majority of the generation frontloaded in July, when both head and discharge were relatively high. While IHA flow targets were still satisfied throughout the year, the generation pattern showed a sharp decline post-July (Figure 3.2.1 b and Figure 3.2.2), which may not be operationally ideal due to the sudden ramp-down in generation. Such an outcome suggests the potential need for operational constraints in the optimization model to smoothen power output and prevent peaking behavior, which can be disruptive to both power systems and riverine ecosystems. This could be managed through the additional constraints such as limit in peak hydropower generation.

Under the dry year scenario (55% initial storage), water availability was insufficient to generate consistent hydropower or meet monthly IHA targets beyond September Annual generation dropped sharply to 48.8×10^6 MWh, with generation restricted to July through September, and IHA compliance achieved only in August and September (Figure 3.2.1 a). Limited storage and inflow in this scenario led to minimal releases in the remaining months, highlighting the vulnerability of hydropower and environmental flows during drought years.

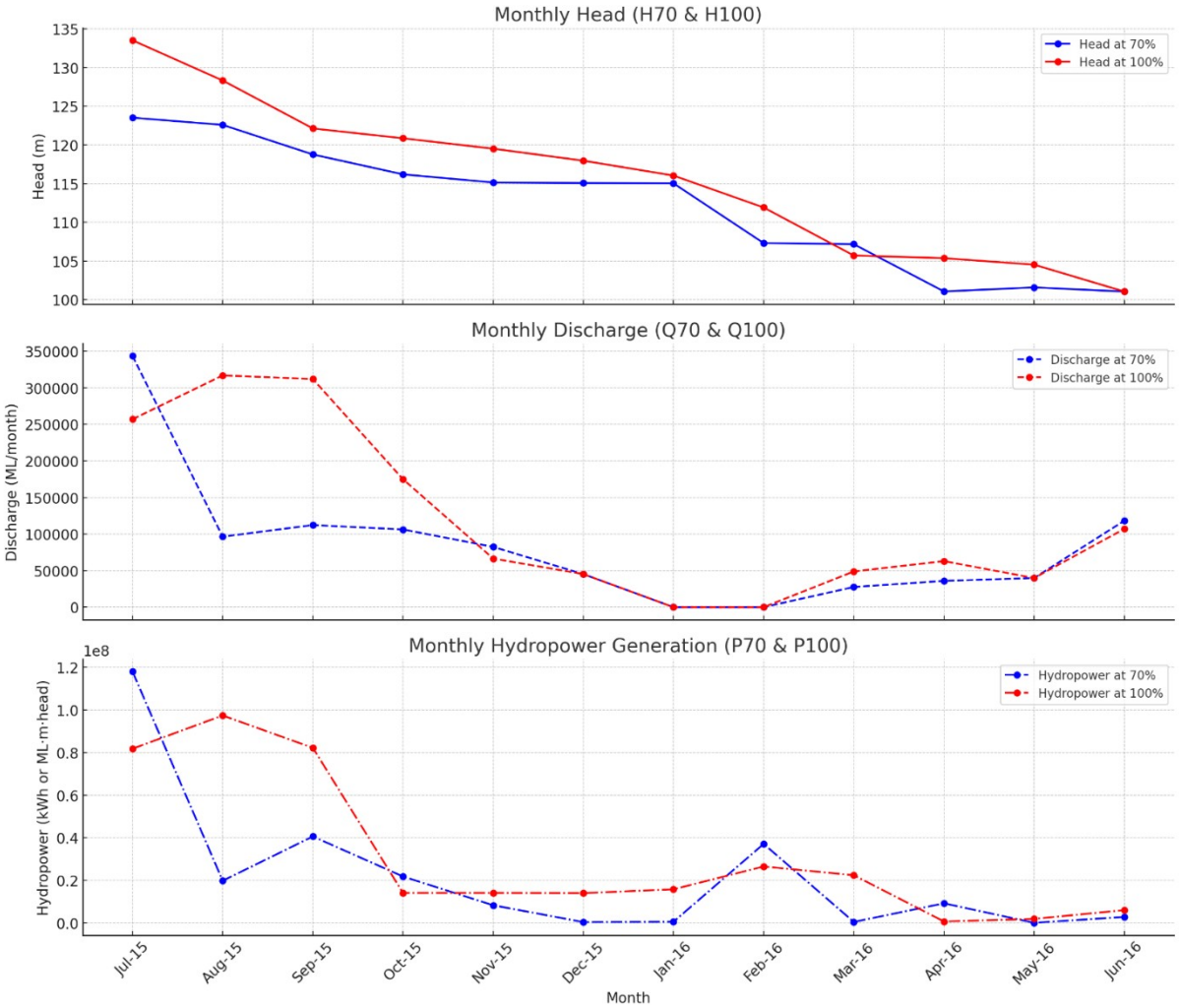

Figure 3.2.2 Monthly head, discharge and hydropower generation in 2015-2016 for optimization using GAMS model for normal and wet precedent years

3.3 System Response to Varying IHA Loss Coefficients: Balancing Flow Compliance and Economic Objectives

3.3.1 Impact of IHA Loss Coefficient on Objective Function

Figure 3.3.1 shows the relationship between the Objective Function (in Australian million dollars) and the IHA Loss Coefficient (λ) on a logarithmic scale. At very low values of λ (around 0.01 to 1), the system focuses primarily on maximizing hydropower generation, with little concern for meeting the IHA targets. As a result, the objective function remains stable at around 200 million dollars, prioritizing energy production overflow regulation. As λ increases to around 10^3 to 10^4, the penalty for deviating from the IHA targets starts to have an effect. The system begins sacrificing some hydropower to reduce the IHA loss, leading to a slight decrease in the objective function. At $\lambda \approx 10^5$, the penalty becomes more significant, and the system sacrifices more hydropower to further minimize the loss, causing a notable increase in the objective function. Finally, at $\lambda \geq 10^6$, the penalty for IHA loss dominates, and the objective function sharply rises. This indicates that the system has adjusted its water releases to align more closely with the IHA targets, but at the cost of a substantial increase in the objective function. This plot highlights the trade-off between hydropower generation and IHA compliance, where higher λ values lead to greater IHA compliance but also significantly higher operational costs.

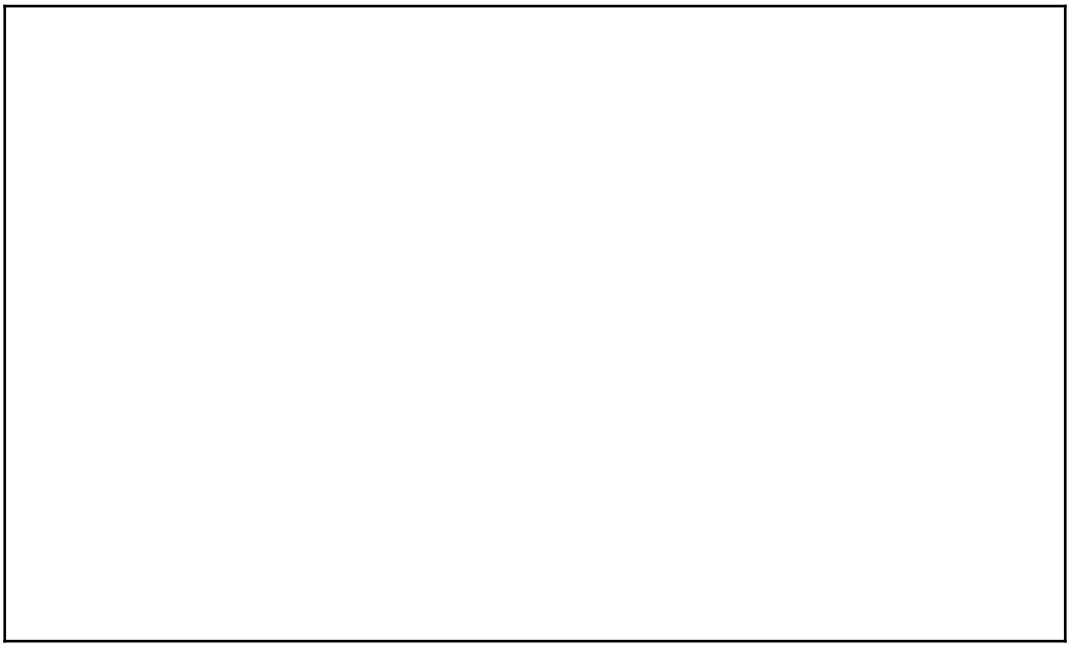

Figure 3.3.1: Objective Function Vs IHA Loss Coefficient

3.3.2 Impact of IHA Loss Coefficient on Hydropower Profit

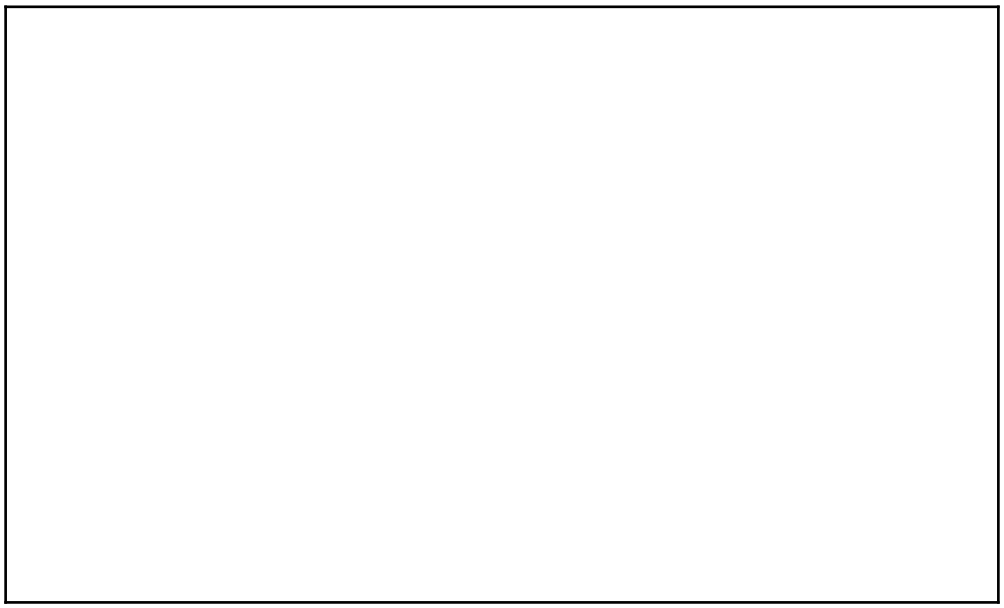

Figure 3.3.2: Hydropower Profit Vs IHA Loss Coefficient

Figure 3.3.2 shows the relationship between Hydropower Profit (in million dollars) and the IHA Loss Coefficient (λ), with λ represented on a logarithmic scale. At very low λ values (0.01 to 1), the hydropower profit remains relatively constant at around 20 million dollars, indicating that the system is primarily focused on maximizing energy production and is not giving much weight to minimizing IHA losses. During this phase, the penalty for deviating from the IHA targets is minimal, and the system prioritizes hydropower generation. As λ increases to around 10^3 to 10^4, the system starts to balance hydropower generation with IHA compliance, but the hydropower profit remains relatively stable, indicating that only a slight emphasis is being placed on reducing the IHA loss. At approximately $\lambda \approx 10^5$, the system shifts its focus significantly towards minimizing the IHA loss, leading to a sharp increase in hydropower profit. The model starts sacrificing more hydropower generation to meet the IHA targets, but this adjustment results in a substantial rise in the overall profit. At $\lambda \geq 10^6$, the hydropower profit continues to increase sharply, reflecting a strong commitment to meeting IHA

targets. The system adjusts its operations to align more closely with IHA flows, showing that, at higher λ values, the model effectively balances IHA compliance with energy generation, resulting in higher profits.

3.3.3 Impact of IHA Loss Coefficient on Squared Differences of Monthly Mean Flows Across IHA Parameters



Figure 3.3.3: Squared Difference of Monthly Mean Flows for Different IHA Parameter Vs IHA Loss Coefficient

Figure 3.3.3 shows the monthly mean flow values for various IHA Loss Coefficients (λ)**,** ranging from 0.01 to 10,000,000,000**,** reflecting how the system adjusts its water releases to minimize the squared differences between actual and target flow values for each IHA parameter. At very low **λ** values (0.01 and 1), the system focuses primarily on maximizing hydropower generation with minimal regard for IHA compliance. As a result, the flow values for each IHA parameter remain relatively stable, and deviations from the IHA target flows are high, indicating the system's focus on energy production rather than reducing the IHA loss. As λ increases, especially beyond 1000, the system begins adjusting the water releases to minimize the squared differences between the actual and target flows for each IHA parameter. This adjustment leads to a gradual alignment, where the actual flow values start stabilizing and almost equalizing with the target values. By the time λ reaches values like 100,000 to 10,000,000, the system effectively reduces the loss, and the flow values for each IHA parameter align very closely with the target flows.

However, August (IHA 6) proves to be the most challenging IHA parameter to control. Although August shows the highest deviation from the target values initially, and the system attempts to adjust the releases, August still leaves some residual loss at the end, with a small difference of 0.004. This makes August the hardest parameter to fully optimize and align with the IHA target.

In contrast, September (IHA 7) shows higher deviation initially, but as λ increases, the system successfully aligns the flow values with the target, achieving zero loss by the end. This demonstrates that while September presents greater challenges initially, it is controlled effectively at higher λ values and meets the target flow.

July (IHA 5), though it shows improvement with increasing λ, still leaves some residual loss with a difference of 0.004, indicating that the flow for July does not fully meet the IHA target, although it is

closer than August. Similarly, March (IHA 1) and April (IHA 2) also show small discrepancies with the target flow, with a loss of 0.002 each. These months are easier to control compared to July and August but still require some adjustments to achieve complete alignment with the IHA targets. In conclusion, all IHA parameters are almost balanced and very close to the target flows as λ increases, with only very small residual losses remaining.

4 Conclusion

The expansion of Wyangala Dam and subsequent flow regulation along the Lachlan River have profoundly altered the hydrological regime, with cascading ecological consequences for downstream systems, in this case the terminal wetland Great Cumbung Swamp. Significant decreases in high-flow events, postponed seasonal peaks, and decreased flow variability are highlighted in the IHA analysis. These elements are essential for maintaining native fish populations and floodplain ecosystems such as the Great Cumbung Swamp. Optimization modeling demonstrated that under wet initial storage conditions, both hydropower generation and environmental flow targets can be met simultaneously. Yet, during typical dry years, when operational or ecological goals have been compromised, performance declines. These results highlight the need for reservoir operations to be flexible and adaptive in order to respond to changing hydrological conditions.

The system's response to increasing IHA loss coefficients (λ) reveals a clear trade-off between ecological compliance and economic performance. At low λ values, hydropower generation is prioritized with minimal ecological consideration. As λ increases, the system effectively aligns flows with IHA targets, improving ecological outcomes but increasing operational costs. While most IHA parameters are well-controlled at high λ values, a few months like August and July remain challenging to optimize. Overall, the results demonstrate that with proper tuning, reservoir operations can be managed to support both environmental and economic objectives.

Nevertheless, the study has a number of restrictions pertaining to the model's assumptions and the availability of data. First, upstream inflow data for Carcoar Dam on the Belubula tributary were unavailable, leading to its exclusion from the network despite its hydrological relevance although it might have little influence due to its storage volume scale. Additionally, due to the absence of monthly water demand data at key river nodes, demand was approximated using seasonal patterns from a neighboring catchment, which may not fully reflect local demand behavior. Most critically, the model does not account for precipitation inputs, a key driver of inflow variability and catchment response. Precipitation dynamics influence both river discharge and reservoir inflow, and their exclusion limits the model’s ability to simulate realistic hydrological conditions. To increase the resilience of ecological flow assessments and water management plans, future works could include historical or real-time precipitation and runoff data, as well as groundwater interactions. To balance environmental and financial goals, more precise and climate-resilient reservoir operations can be developed by filling in these data gaps.

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Appendix A Preliminary GAMS Code

```
* all the unit that not specified for water is mageliter(ML);
* all the unit that not specified for profit is Australia dollars;

$inlinecom{ }

SETS
t time periods /1*12/
r reservoirs /r1*r3/
ri river nodes /ri1*ri7/
d demand sites /d1*d3/
iha IHA parameters /iha1*iha10/

;

alias(r, r_up);
* reservior subsets: upper reservior
alias(ri, ri_lo);
* river subsets: lower river
alias(ri, ri_up);
* river subsets: upper river
alias(r, r_lo);
* river subsets: lower reservoirs


SETS
{up_rev(r) upstream reservoirs /r1,r2/}
up_ri(ri) upstream river nodes  /ri1, ri4/
* upstream river: which provide inflow

ri_d(ri, d) water supply link between river and demand site /ri5.d2, ri6.d3/
r_d(r, d) water supply link between reservior and demand site /r1.d1/
{ret_d(d, ri) return flow link between river and demand site /d1.ri3, d2.ri4/}
rilink(ri_up, ri_lo) river link /ri2.ri3, ri4.ri3, ri3.ri5, ri6.ri7/
rlink(r_up, r_lo) reservior link /r2.r3/
rirvlink river node to reservoir /ri1.r1, ri5.r2/
rvrilink reservoir to river node /r1.ri2, r3.ri6/

{sinklink(ri_up, ri_lo) sink node link /ri6.ri7/  }

mon_mean_iha(iha,t)/iha1.'9', iha2.'10', iha3.'11', iha4.'12', iha5.'1', iha6.'2', iha7.'3', iha8.'4', iha9.'5',
iha10.'6'/

;


Scalars
* water in r1 should be between ds0 and k
{ret       return flow coefficient /0.5/}
ep         electricity unit price A$ per kWh /7.5/
lambda     loss coefficient /100/

cc         portion that consumed in total water usage /0.01/
```

```
*hydropower constants, for storage in million m^3, head in meter:
H0       elevation at dead storage/100/
a_coef   coefficient a for r1/1.23382/
b_coef   coefficient b for r1/0.47971/
eff      efficiency of the hydropower generated/0.874/
rou_w    water density in kg m^-3/1000/
gra      gravity acceleration in m s-2/9.81/
;


Parameters
* days in each month
dm(t) days in each month
/
1 31, 2 28, 3 31, 4 30,
5 31, 6 30, 7 31, 8 31,
9 30, 10 31, 11 30, 12 31
/

* storage capacity (ML)
k(r)  storage capacity
/
r1 1217761
r2 153620
r3 36533
/

* dead storage (ML)
ds(r)   dead storage
/
r1 725
r2 4561
r3 6370
/

* initial storage (ML)=95% of the capacity
s0(r) initial storage
/
r1 1156872.95
r2 145939
r3 34706.35
/

*IHA target value in unit of m^3/s
iha_t(iha) IHA tagert value only for monthly mean flow
/
iha1  10.65
iha2  13.43
iha3  15.39
iha4  18.06
iha5  24.57
iha6  33.59
iha7  31.97
iha8  26.31
iha9  24.83
```

```
iha10 17.45
/
;
*Unit: ML
Table i(ri, t) inflow
     1          2          3        4        5        6      7        8        9       10       11       12
ri1  15153.84     30247.44    6407.75   1829.75   2705.36   79.36   1867.17   3332.15   727.01   49.38
1326.94   10898.58
ri4  4.69        8.73        1.31     0.56     0.56     12.60   11.14    9.91     11.92    2.41     0.83     20.08
;
* Month 1 here means the July in 2015. Same as below.


*Water demand unit ML
Table demand(d,t)   water demand
     1        2        3        4        5        6        7        8        9        10       11       12
d1   67.93     154.04   117.85    285.73   360.96   532.65   743.62   684.71   482.81   252.41    97.08
218.21
d2   186.66    423.28   323.85    785.14   991.88   1463.66  2043.38  1881.5   1326.71  693.58    266.76
599.6
d3   435.54    987.64   755.65    1831.99  2314.38  3415.21  4767.9   4390.17  3095.66  1618.35   622.44
1399.07
;

Variables
obj  objective varaible
;


Positive Variables
*** Part 1: water allocation
s(r, t)  storage in reservior
re(r, t) release of reservior

ws_r(r, d, t)   water supply from a reservoir to a demand site
ws_ri(ri, d, t) water supply from a river to a demand site
wc_c(d,t)       water consumption in demand site

r_ri(r, ri, t)   flow from reservoir to river
ri_r(ri, r, t)   flow from river to reservoir
ri_ri(ri, ri, t) flow from river to river
r_r(r,r,t)       flow from reservior to reservior

fout(t)          the water to the outlet

*** Part 2: IHA
loss_mean(iha)      loss function value for IHA monthly mean

loss                total loss function value
a_mean_month(t)     Actual Monthly mean in m3 per s(only March to Dec)


*** Part 3: hydropower
head_v(t)       Head of the reservior(that not a constant)
m_hydropower(t) hydropower generated monthly
```

```
T_hydropower   hydropower generated in total

;


Equations

objfunc              objective func
*** Part 1: water allocation
wb_rv(r,t)           water balance for reservoirs
wb_ri(ri,t)          water balance for river nodes

Cal_release(r,t)      cal. water release from reservior

s_min(r, t)          the minimum storage for reservoir
s_max(r,t)           the maxmum storage for reservoir

Cal_fout(t)          cal. the water to the outlet

*** Part 2: loss function
Cal_loss_mean(iha)    Cal. loss function value for IHA monthly mean
{Cal_loss_max(sea)    Cal. loss function value for IHA maximum target
}
Cal_a_mean_month(t)   Cal. Monthly mean in m3 per s
{Cal_max_season(sea)  Cal. 90-day-maximum
}
Cal_loss             Cal. total loss function value

water_con(d,t)        water constraint. water to demand less than water supply
Lower_IHA(t)          lower bound for mean flow monthly

*** Part 3: hydropower
Cal_head_v(t)         Cal. Head of the reservior(that not a constant)
Cal_m_hydropower(t)   Cal. hydropower generated monthly
Cal_total_hydropower  Cal. hydropower generated in total

;
*** Objective function
* in unit of million dollars
objfunc ..
obj =e= (T_hydropower*ep - lambda*loss)/1e6;


***Part 1: water allocation

Cal_release(r,t)..
re(r, t) =e= sum(ri$rvrilink(r, ri), r_ri(r, ri, t))
;

*water balance for reservoirs
wb_rv(r, t) ..
s(r, t) =e= s0(r)$(ord(t)=1) + s(r, t-1)
          - re(r,t)
*water from reservior to river node
          +  sum(ri$rirvlink(ri, r), ri_r(ri, r, t))
```

```
*Inflow from upstream river node to this reservior
        - sum(d$r_d(r,d),ws_r(r, d, t))
*water flow to demand site
        +  sum(r_up$rlink(r_up,r), r_r(r_up,r,t))
*water from upstream reservior
        - sum(r_lo$rlink(r,r_lo),r_r(r,r_lo,t))
*water to the downstream reservior
;

* water balance for river (below)
wb_ri(ri, t) $(ord(ri) NE 7) ..
* ord means except for river 5, because we don't care the sink node
* ri is specified, so others should be specified in the equations below
        i(ri, t)$up_ri(ri)
* inflow for river node 1 & 4
        + sum(r$rvrilink(r, ri), r_ri(r, ri, t))
*flow from reservoir to river
        - sum(d$ri_d(ri, d), ws_ri(ri, d, t))
*flow from river to demand site
{           + sum(d$ret_d(d, ri), ret*ws_ri(ri, d, t))
*return flow from demand site
}
        + sum(ri_up$rilink(ri_up, ri), ri_ri(ri_up, ri, t))
* flow from upstream river to this river
        - sum(r$rirvlink(ri, r), ri_r(ri, r, t))
*flow from river to reservior
        - sum(ri_lo$rilink(ri, ri_lo), ri_ri(ri, ri_lo, t)) =e= 0
* flow from  this river to downstream river

;

* Water in the sink node ri7 (ML)
Cal_fout(t)..
fout(t) =e=  sum(ri_up$rilink(ri_up, 'ri7'), ri_ri(ri_up, 'ri7', t))
;

*Storage should between dead and capacity
s_min(r,t) ..
s(r,t) =g=  ds(r);

s_max(r,t) ..
s(r,t) =l= k(r);


water_con(d,t) ..
demand(d,t) =l= sum(ri$ri_d(ri, d), ws_ri(ri, d, t))
          + sum(r$r_d(r, d), ws_r(r, d, t));
* the water consumed by crops should be <= water supply


*** Part 2: IHA loss function
Cal_a_mean_month(t)..
a_mean_month(t) =e= fout(t)*1000/(60*60*24*dm(t));
*Actual mean flow monthly in m3/s, converted from ML/month
```

```
Cal_loss_mean(iha) ..
loss_mean(iha) =e= sum(t$mon_mean_iha(iha,t), abs(a_mean_month(t)- iha_t(iha)*dm(t)+1e-10)**2);
* only calculate the monthly mean flow IHA here

Lower_IHA(t)..
a_mean_month(t) =g= sum(iha$mon_mean_iha(iha,t),iha_t(iha));

Cal_loss..
loss =e= sum(iha, loss_mean(iha))
        {+ sum(sea, loss_max(sea))}
;


*** Part 3: hydropower
*Below calculates the monthly elevation head(m)
Cal_head_v(t)..
head_v(t) =e= H0+a_coef*(s('r1',t)/1000+1e-10)**b_coef
*Only rev1 will generate hydropower, storage should be in unit of million m^3
;

*Below calculates the monthly hydropower generated (kWh)
Cal_m_hydropower(t)..
m_hydropower(t) =e= eff*rou_w*gra*
                re('r1',t)*1000
                /(3.6e6)*
                head_v(t)
;
*release should in m^3

*Below calculates the total hydropower generated in a year (million kWh)
Cal_total_hydropower..
T_hydropower =e= sum(t,m_hydropower(t))
;


model wyangla  /all/;
wyangla.optfile=1;

Solve wyangla USING dNLP MAXIMIZING obj;
display T_hydropower.l,a_mean_month.l;
```

Appendix B Updated GAMS code for Part 3.3 Analysis

```
* System response to varying IHA Loss Coefficients: balancing flow compliance and economic objectives: Ritu Rani Das
* all the unit that not specified for water is mageliter(ML);
* all the unit that not specified for profit is Australia dollars;

$inlinecom{ }

SETS
t time periods /1*12/
r reservoirs /r1*r3/
ri river nodes /ri1*ri7/
d demand sites /d1*d3/
iha IHA parameters /iha1*iha10/

;

alias(r, r_up);
* reservior subsets: upper reservior
alias(ri, ri_lo);
* river subsets: lower river
alias(ri, ri_up);
* river subsets: upper river
alias(r, r_lo);
* river subsets: lower reservoirs


SETS
{up_rev(r) upstream reservoirs /r1,r2/}
up_ri(ri) upstream river nodes  /ri1, ri4/
* upstream river: which provide inflow

ri_d(ri, d) water supply link between river and demand site /ri5.d2, ri6.d3/
r_d(r, d) water supply link between reservior and demand site /r1.d1/
{ret_d(d, ri) return flow link between river and demand site /d1.ri3, d2.ri4/}
rilink(ri_up, ri_lo) river link /ri2.ri3, ri4.ri3, ri3.ri5, ri6.ri7/
rlink(r_up, r_lo) reservior link /r2.r3/
rirvlink river node to reservoir /ri1.r1, ri5.r2/
rvrilink reservoir to river node /r1.ri2, r3.ri6/

{sinklink(ri_up, ri_lo) sink node link /ri6.ri7/  }

mon_mean_iha(iha,t)/iha1.'9', iha2.'10', iha3.'11', iha4.'12', iha5.'1', iha6.'2', iha7.'3', iha8.'4', iha9.'5', iha10.'6'/;

set lamset / l0 , l1, l1e2 , l1e3 , l1e4 , l1e5 , l1e6, l1e7, l1e8 /;
parameter lamval(lamset) /
  l0    0.01,
  l1    1,
  l1e2  1e2,
  l1e3  1e3,
  l1e4  1e4,
  l1e5  1e5,
  l1e6  1e6,
```

```
  l1e7  1e7,
  l1e8  1e8
/;

scalar lambda  loss coefficient /0.01/;


Scalars
* water in r1 should be between ds0 and k
{ret       return flow coefficient /0.5/}
ep         electricity unit price A$ per kWh /7.5/
tol        tolerance limit /0.1/

cc         portion that consumed in total water usage /0.01/

*hydropower constants, for storage in million m^3, head in meter:
H0       elevation at dead storage/100/
a_coef   coefficient a for r1/1.23382/
b_coef   coefficient b for r1/0.47971/
eff      efficiency of the hydropower generated/0.874/
rou_w    water density in kg m^-3/1000/
gra      gravity acceleration in m s-2/9.81/
;

Parameters

dm(t) days in each month
/
1 31, 2 31, 3 30, 4 31,
5 30, 6 31, 7 31, 8 29,
9 31, 10 30, 11 31, 12 30
/

* storage capacity (ML)
k(r)  storage capacity
/
r1 1217761
r2 153620
r3 36533
/

* dead storage (ML)
ds(r)   dead storage
/
r1 725
r2 4561
r3 6370
/

* initial storage (ML)=95% of the capacity
s0(r) initial storage
/
r1 1156872.95
r2 145939
r3 34706.35
```

/

*IHA target value in unit of m^3/s
iha_t(iha) IHA tagert value only for monthly mean flow
/
iha1 10.65
iha2 13.43
iha3 15.39
iha4 18.06
iha5 24.57
iha6 33.59
iha7 31.97
iha8 26.31
iha9 24.83
iha10 17.45
/
;
*Unit: ML
Table i(ri, t) inflow
    1   2   3   4   5   6   7   8   9   10   11   12
ri1 15153.84   30247.44   6407.75   1829.75   2705.36   79.36   1867.17   3332.15   727.01   49.38   1326.94   10898.58
ri4 4.69   8.73   1.31   0.56   0.56   12.60   11.14   9.91   11.92   2.41   0.83   20.08
;
* Month 1 here means the July in 2015. Same as below.

*Water demand unit ML
Table demand(d,t)   water demand
    1   2   3   4   5   6   7   8   9   10   11   12
d1   67.93   154.04   117.85   285.73   360.96   532.65   743.62   684.71   482.81   252.41   97.08   218.21
d2   186.66   423.28   323.85   785.14   991.88   1463.66 2043.38 1881.5   1326.71 693.58   266.76 599.6
d3   435.54   987.64   755.65   1831.99 2314.38 3415.21 4767.9   4390.17 3095.66 1618.35   622.44 1399.07
;

Variables
obj objective varaible
;

Positive Variables
*** Part 1: water allocation
s(r, t) storage in reservior
re(r, t) release of reservior

ws_r(r, d, t)   water supply from a reservoir to a demand site
ws_ri(ri, d, t) water supply from a river to a demand site
wc_c(d,t)   water consumption in demand site

r_ri(r, ri, t)   flow from reservoir to river
ri_r(ri, r, t)   flow from river to reservoir
ri_ri(ri, ri, t) flow from river to river
r_r(r,r,t)   flow from reservior to reservior

```
fout(t)         the water to the outlet

*** Part 2: IHA
loss_mean(iha)      loss function value for IHA monthly mean

loss                total loss function value
a_mean_month(t)     Actual Monthly mean in m3 per s(only March to Dec)


*** Part 3: hydropower
head_v(t)       Head of the reservior(that not a constant)
m_hydropower(t) hydropower generated monthly
T_hydropower    hydropower generated in total

;


Equations

objfunc             objective func
*** Part 1: water allocation
wb_rv(r,t)          water balance for reservoirs
wb_ri(ri,t)         water balance for river nodes

Cal_release(r,t)       cal. water release from reservior

s_min(r, t)         the minimum storage for reservoir
s_max(r,t)          the maxmum storage for reservoir

Cal_fout(t)         cal. the water to the outlet

*** Part 2: loss function
Cal_loss_mean(iha)     Cal. loss function value for IHA monthly mean
{Cal_loss_max(sea)     Cal. loss function value for IHA maximum target
}
Cal_a_mean_month(t)    Cal. Monthly mean in m3 per s
{Cal_max_season(sea)   Cal. 90-day-maximum
}
Cal_loss            Cal. total loss function value

water_con(d,t)         water constraint. water to demand less than water supply

*** Part 3: hydropower
Cal_head_v(t)          Cal. Head of the reservior(that not a constant)
Cal_m_hydropower(t)    Cal. hydropower generated monthly
Cal_total_hydropower   Cal. hydropower generated in total

;
*** Objective function
* in unit of million dollars
objfunc ..
obj =e= (T_hydropower * ep - lambda*loss)/1e6;
```

```
***Part 1: water allocation

Cal_release(r,t)..
re(r, t) =e= sum(ri$rvrilink(r, ri), r_ri(r, ri, t))
;

*water balance for reservoirs
wb_rv(r, t) ..
s(r, t) =e= s0(r)$(ord(t)=1) + s(r, t-1)
        - re(r,t)
*water from reservior to river node
        +  sum(ri$rirvlink(ri, r), ri_r(ri, r, t))
*Inflow from upstream river node to this reservior
        - sum(d$r_d(r,d),ws_r(r, d, t))
*water flow to demand site
        +  sum(r_up$rlink(r_up,r), r_r(r_up,r,t))
*water from upstream reservior
        - sum(r_lo$rlink(r,r_lo),r_r(r,r_lo,t))
*water to the downstream reservior
;

* water balance for river (below)
wb_ri(ri, t) $(ord(ri) NE 7) ..
* ord means except for river 5, because we don't care the sink node
* ri is specified, so others should be specified in the equations below
        i(ri, t)$up_ri(ri)
* inflow for river node 1 & 4
        + sum(r$rvrilink(r, ri), r_ri(r, ri, t))
*flow from reservoir to river
        - sum(d$ri_d(ri, d), ws_ri(ri, d, t))
*flow from river to demand site
{           + sum(d$ret_d(d, ri), ret*ws_ri(ri, d, t))
*return flow from demand site
}
        + sum(ri_up$rilink(ri_up, ri), ri_ri(ri_up, ri, t))
* flow from upstream river to this river
        - sum(r$rirvlink(ri, r), ri_r(ri, r, t))
*flow from river to reservior
        - sum(ri_lo$rilink(ri, ri_lo), ri_ri(ri, ri_lo, t)) =e= 0
* flow from  this river to downstream river

;

* Water in the sink node ri7 (ML)
Cal_fout(t)..
fout(t) =e=  sum(ri_up$rilink(ri_up, 'ri7'), ri_ri(ri_up, 'ri7', t))
;

*Storage should between dead and capacity
s_min(r,t) ..
s(r,t) =g=  ds(r);

s_max(r,t) ..
s(r,t) =l= k(r);
```

```
water_con(d,t) ..
demand(d,t) =l= sum(ri$ri_d(ri, d), ws_ri(ri, d, t))
            + sum(r$r_d(r, d), ws_r(r, d, t));
* the water consumed by crops should be <= water supply


*** Part 2: IHA loss function
Cal_a_mean_month(t)..
a_mean_month(t) =e= fout(t)*1000/(60*60*24*dm(t));
*Actual mean flow monthly in m3/s, converted from ML/month

Cal_loss_mean(iha) ..
*loss_mean(iha) =e= sum(t$mon_mean_iha(iha,t), abs(a_mean_month(t)- iha_t(iha)*dm(t)
+1e-10)**2);
loss_mean(iha) =e= sum(t$mon_mean_iha(iha,t), power(a_mean_month(t) - iha_t(iha), 2));


Cal_loss..
loss =e= sum(iha, loss_mean(iha))
        {+ sum(sea, loss_max(sea))}
;


*** Part 3: hydropower
*Below calculates the monthly elevation head(m)
Cal_head_v(t)..
head_v(t) =e= H0+a_coef*(s('r1',t)/1000+1e-10)**b_coef
*Only rev1 will generate hydropower, storage should be in unit of million m^3
;

*Below calculates the monthly hydropower generated (kWh)
Cal_m_hydropower(t)..
m_hydropower(t) =e= eff*rou_w*gra*
                re('r1',t)*1000
                /(3.6e6)*
                head_v(t)
;
*release should in m^3

*Below calculates the total hydropower generated in a year (million kWh)
Cal_total_hydropower..
T_hydropower =e= sum(t,m_hydropower(t))
;


model wyangla / all /;

wyangla.optfile=1;


* Storage for scalar outputs
parameter lambda_results(lamset, *)
        fout_store(lamset, t)
        a_mean_store(lamset, t)
```

```
      loss_mean_store(lamset, iha);

loop(lamset,

  lambda = lamval(lamset);

  solve wyangla using dNLP maximizing obj;

  display mon_mean_iha, loss_mean.l;

  lambda_results(lamset, 'lambda')     = lambda;
  lambda_results(lamset, 'obj')        = obj.l;
  lambda_results(lamset, 'loss')       = loss.l;
  lambda_results(lamset, 'hydropower') = T_hydropower.l;

*Store monthly outlet flows
  loop(t,
    fout_store(lamset, t)     = fout.l(t);
    a_mean_store(lamset, t)   = a_mean_month.l(t);
  );

*Store per-IHA loss
  loop(iha,
    loss_mean_store(lamset, iha) = loss_mean.l(iha);
  );

);

display lambda_results;
display fout_store;
display a_mean_store;
display loss_mean_store;


*Solve wyangla USING dNLP MAXIMIZING obj;
*display obj.l,loss.l,a_mean_month.l, loss_mean.l,T_hydropower.l,a_mean_month.l;
```