Water Conservation & Management (WCM)

DOI: http://doi.org/10.26480/wcm.01.2024.11.19

ISSN: 2523-5664 (Print)
ISSN: 2523-5672 (Online)
CODEN: WCMABD

RESEARCH ARTICLE

ASSESSMENT OF PROJECTED EXTREME CLIMATE CHANGE IMPACT ON THE OPERATIONAL PERFORMANCE OF SURFACE WATER RESERVOIRS

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ARTICLE DETAILS

Article History:

Received 18 July 2022
Revised 21 August 2023
Accepted 25 September 2023
Available online 29 September 2023

ABSTRACT

This study investigated the impacts of the extreme climate change projections on the performance of Lake Hume in southeast Australia. The study utilised the Australian Climate Change Website tools and leveraged publications from reliable sources to project future inflows and demand. The study revealed that the Lake Hume reservoir could withstand extreme wet conditions with an insignificant impact on the downstream environment. Additionally, for these inflow conditions, the simulation results showed that the storage capacity was adequate for meeting the demand with enhanced performance. However, the release exceeded the downstream channel capacity on one occasion, but the impact was insignificant. On the other hand, the modelling of the extreme-dry conditions showed that the reservoir might drain all its stored water almost 53% of the time, with knock-on effects on systems reliability, resilience and vulnerability. Both of these results are expected, but isolating the effects of extreme wet and dry, as done in this study, will assist water managers to better prepare for coping with water security issues. That may arise from extreme weather events, which are now projected to occur more frequently with climate change.

KEYWORDS

Climate Change, Performance of Surface Water Reservoirs, time-based reliability, volume-based reliability, resilience.

1. INTRODUCTION

The Australian and international Climate organisations identify climate change as the greatest threat that the world should be prepared for as it affects the sustainable development of all countries (Stefen, 2015). Overcoming this global risk requires collaboration across governments, businesses, and individuals. The Climate Council of Australia highlighted that global temperatures have been rising rapidly, and carbon emissions have increased (Steffen et al., 2018). Thus, it is recommended that the carbon emissions in a country like Australia should be reduced by 2030 to 45-65% below 2005 levels to tackle climate change effectively (Steffen et al., 2018). In the same context, the Intergovernmental Panel on Climate Change (IPPC), which is the United Nations body for assessing the science related to climate change, emphasised in its fifth assessment report (AR5) that the more we disturb our climate, the more we risk severe, pervasive, and irreversible impacts (IPPC Secretariat, 2020).

Climate change manifests itself in many forms nowadays, such as:

- Variations in air temperature,
- Change in seasons and amounts of precipitation,
- A rise in sea level.

Most of these forms affect the freshwater cycle in Australia by decreasing the rainfall frequency while increasing its intensity. The long dry season raises the air temperature, accelerates water evaporation, and lowers water flow in streams. On the other hand, flood-producing rainfalls occur more frequently. A group researcher concluded that the increase in the annual mean surface temperature in southeast Australia results in an increase in the rainfall intensity (depth) proportionally (Ball et al., 2019). Likewise, the analysis done by the Australian Bureau of Meteorology (BoM) highlighted that a warming climate could decrease annual rainfall while increasing flood-producing rainfall (Ball et al., 2019). The Australian Rainfall and Runoff guide suggest an increase in rainfall intensity (or depth) of 5% per 1ºC of local warming (Ball et al., 2019).

BoM issued a number of flood warnings for the Murray River upstream of Hume Dam due to a series of forecasted intense rainfall events posing risks to downstream land farmers (BoM, 2020). Hume Dam is vital in controlling Lake Hume's flow downstream to the Murray River. It regulates the flow to satisfy the demand and prevents floods during the low and high flow seasons, respectively. Not only does this improve the availability of surface water for various uses, but it also preserves the environmental ecosystem in Southeast Australia.

The Bureau of Meteorology and other data sources related to Hume Dam provide either raw data or short-term projections of the Lake Hume reservoir planning and operation. Therefore, there is a need for developing long-term reservoir planning and deploying the data provided in these resources.

This paper studied the climate change impacts on the performance of the water reservoir formed by Hume Dam "Lake Hume", Southeast Australia, under extreme climate projections (Extreme Dry & Extreme Wet) for the next years from 2021 to 2030. The specific objectives were to:

1. extract representative extreme dry and extreme inflow sequences from the projected future inflows into the reservoir;
2. force the reservoir simulation with the extreme wet inflow to assess

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Cite The Article: Amr Mostafa Khalaf, Rabee Rustum (2024). Assessment of Projected Extreme Climate Change Impact on The Operational Performance of Surface Water Reservoirs. *Water Conservation & Management, 8(1): 11-19.*

the performance;

3. force reservoir simulation with the extreme dry inflow to assess performance;
4. review the respective performances and make recommendations.

Several reports and documents were used to generate the required data and climate change projections at the Hume Dam. The study used some of the reservoir planning techniques and performance measurement tools. It leveraged some of the official short-term projection reports issued by the Australian Government as sources of data.

2. Methods and Materials

2.1 Reservoir Simulation

Performance evaluation requires simulating the behaviour of the reservoir over the available data horizon (Adeloye, 2012). The simulation uses the reservoir mass balance equation as shown in Equation (1) (see also McMahon and Adeloye, 2005; McMahon and Adeloye, 2006; Adeloye et al., 2017; Rustum et al., 2022).

$$S_{t+1} = S_t + Q_t - D_t - V_t - E_t \,;\; 0 \leq S_{t+1} \leq K_a \qquad (1)$$

where,

S_{t+1} = storage at the end of t (m^3),

S_t = storage at the beginning of t (m^3),

Q_t = inflow during t (m^3),

Y_t = Release (including spilling, if any) during t, (m^3),

E_t = Net evaporation during t (m^3),

L_t = Other losses during t (m^3),

K_a = Minimum required capacity of the reservoir (m^3),

However, because both evaporation and rainfall are normally measured in mm, the net evaporation cannot be used directly. It must first be converted to the volume of water by multiplying by the surface area (A_v) of the reservoir in interval t i.e.

$$S_{t+1} = S_t + Q_t - D_t - V_t - e_t A_v \qquad (2)$$

where e_t is the net evaporation in interval t (mm).

Figure 1 is a schematic illustration of the various components of inflow and outflow contained in Equation 1.

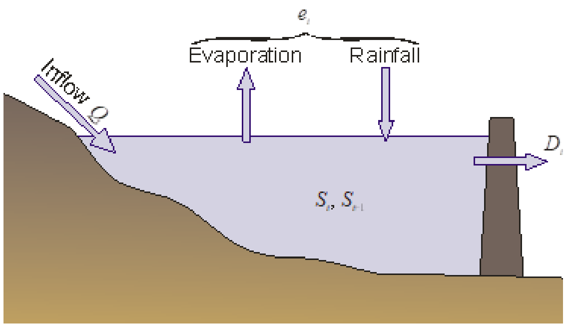

Figure 1: Schematic of the components of the reservoir water balance equation.

As shown, the surface area of a reservoir depends on the storage: as the storage increases, so does the exposed surface area. The area A_v for a time interval can then be represented by the average of its value at the beginning and end of the interval as follows in Equation (3).

$$A_v = 0.5(A_t + A_{t+1}) \qquad (3)$$

Once the simulation has been completed, the reservoir's performance is evaluated using the commonly used indices of reliability, resilience and vulnerability as described below (see also McMahon and Adeloye, 2005).

2.1.1 Reliability

Reservoir reliability represents the proportion of time or volume over which the reservoir will be able to meet the demand. The reliability can be applied on either time or volume at any time interval, i.e., monthly, quarterly, or yearly. The time interval used in this study for reservoir planning and performance measurement is quarterly. Equation (4) is used for time-based reliability, whereas Equation (5) is used for volumetric-based reliability.

$$R_t = 1 - N_s/n \qquad (4)$$

$$R_v = 1 - V_s/v \qquad (5)$$

Where;

R_t is time-based reliability,

N_s is the number of failures (number of periods where the reservoir failed to meet the demand),

n is the total number of the planning period.

R_v is the volume-based reliability,

V_s is the total volume of shortage over the planning period,

v is the total volume of water demand over the planning period.

2.1.2 Resilience

Resilience is a measure of the reservoir's ability to recover from failure and is defined in Equation (6) (Dau and Adeloye, 2021).

$$\Phi = f_s/f_d \qquad 0 < \Phi \leq 1 \qquad (6)$$

where

Φ is reservoir resilience,

f_s is the number of continuous sequences of failure periods,

f_d = total duration of failures.

2.1.3 Vulnerability

Vulnerability measures the impact of storage failures by finding the average shortfalls occurring in each of the continuous failure periods as seen in Equation (7).

$$\mu' = \frac{\sum_{k=1}^{fs} max\,(Dt - D\prime t)}{fs} \qquad (7)$$

where

μ' is vulnerability, max () is the maximum shortfall during the k^{th} continuous failure sequence, and f_s is the number of continuous failure sequences in the simulation.

2.2 Case Study

River Murray is an interstate water stream that stems from Queensland in northeast Australia. It flows through New South Wales (NSW), Australian Capital Territory (ACT), Victoria, and South Australia. The river is about 2,508 kilometres long and 40-50 meters deep (MDBA, 2020). The river plays a crucial role in navigation and irrigation; it fulfils 40% of the water demand throughout the south of Australia. In addition, its basin is Australia's most important agricultural region as it supplies one-third of the Australian national food (MDBA, 2019).

In the 1860s, the basin community started discussing ways to control the river's flow following several droughts and floods. After 50 years, NSW, Victorian, and South Australia governments agreed to build a dam 16 kilometres west of Albury on the NSW-Victoria border. The work started in 1919 and took 17 years to complete. The dam was named after the explorer Sir Hamilton Hume (MDBA, 2019). The storage capacity of the Hume Dam was 1,522 x 10^6 m^3 when the project was completed in 1936. Additional work between 1950 and 1961 enlarged Hume Reservoir's capacity to 3,005 x 10^6 m^3. Hume Dam is currently the major regulating structure and the biggest reservoir across the River Murray (MDBA, 2020). The characteristics of the dam were collected from different sources and are shown in Table 1.

Table 1: The characteristics of the Dam (WaterNSW, 2020)

Characteristics of the Dam	Numerical Values
Dead storage of the reservoir	23,000,000 m^3
Height of Main Wall	318 meters
Embankment Wall on NSW Side	131 meters
Embankment Wall on Victorian Side	1,166 meters
Total Wall Length	1,615 meters
Number of Regulating Gates	29
Dimensions of the Gate	6.10 meters long by 7.92 meters high
Reservoir Service Area	20.091 hectares
Catchment Size	16,000 km^2

The maximum channel capacity of the River Murray from Hume Dam to Yarrawonga weir (downstream of Hume Dam) is 25,000 ML/day. Therefore, flows greater than 25,000 ML/day may cause inundation and impact downstream lands. Also, a minimum release must be maintained at 600 ML/day to preserve environmental conditions downstream of the dam (Murray–Darling Basin Authority, 2020). Figure 1 shows the downstream channel between Hume Dam and Yarrawonga Weir.

2.3 Data Collection

The primary source of climate projections in Australia is the Future Climate Web Tool developed by CSIRO and Australia's Bereau of Meterology (BOM) (CSIRO, 2020). The tool is called Climate Change in Australia (CCIA), developed in 2015 and updated regularly. The website offers a variety of online sources and information regarding climate change in Australia, along with learning materials and tutorials. The "Projection and Data" link provides the researchers with the climate projections data required for different assessments. The Australian Climate Projection Tool CCIA considers different future climate scenarios based on various variables and elements. Some of the key elements are Greenhouse Gas Emissions and Concentration Pathways, Global Climate Models to predict climate changes, Regionalisation, and Climate phenomena such as El Nino-Southern Oscillation (ENSO) (CSIRO, 2020; L'Heureux, 2014; BoM Commonwealth of Australia, 2021). For example, ENSO has always affected the catchments of Lake Hume. From extreme rainfall events called the La-Nina phase to droughts during the El-Nino phase, ENSO has influenced the inflow to the reservoir and hence its storage and release. Figure 3 is a graphical presentation showing how ENSO has historically influenced the inflow into the Hume Dam. The cycle between La Nina and El Nino has recurred every three to four years and has affected the inflow to the reservoir. La Nina occurred in early 2013, late 2016 and late 2020. Thus, understanding the ENSO climate phenomenon and its cycle has helped establish a realistic inflow forecast for Lake Hume in this study.

Figure 1: Area map showing the location of Hume Dam

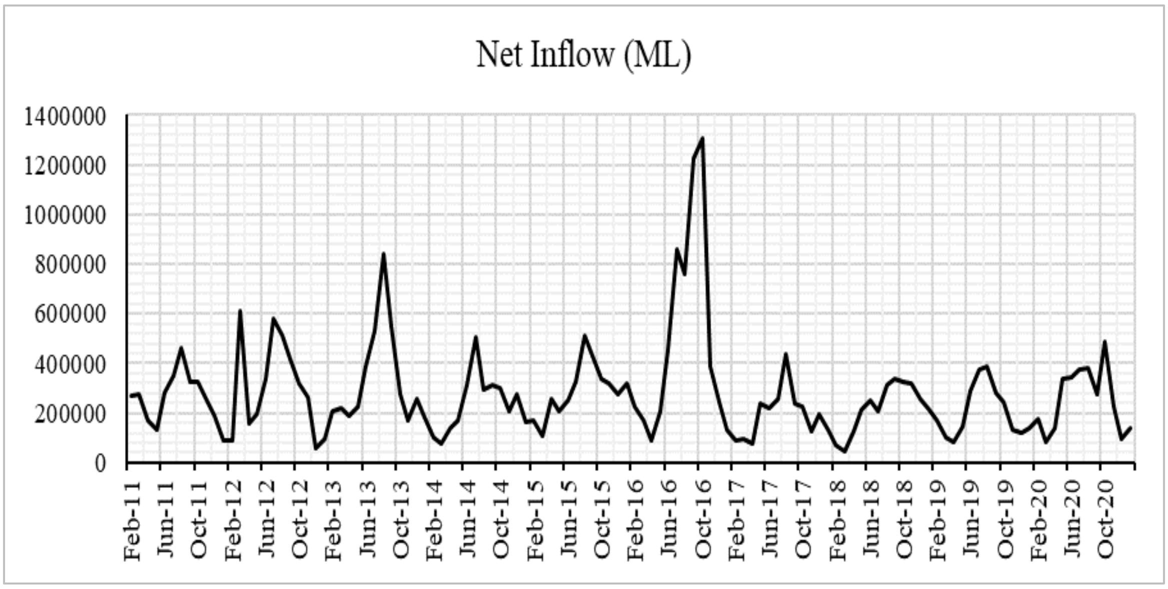

Figure 2: Representation of the occurrences of La Nina and El Nino and their impact on the inflow to Lake Hume reservoir. Real data was measured by (WaterNSW, 2020).

WaterNSW website provides real-time data for Hume Dam. This work used the rainfall, inflow, storage volume, release, and evaporation data downloaded from the website for the past years, from February 2011 until December 2020 (WaterNSW, 2020). The climate in southeast Australia varies throughout the year. The summer starts in December and continues till March when Autumn starts. The winter comes in June, and the Spring begins in September (CSIRO, 2015). This paper adopts seasonal time intervals. The historical data for the past ten years have been totalled and averaged quarterly to establish historical mean values for the four main seasons. Table 2 shows the historical data for the past years on a quarterly basis based on the climate seasons, and the average values per season for the past ten years are summarised in Table 3.

Table 2: Historical Data for Hume Dam from Feb 2011 to Dec 2020

Year		Total Net Inflow (ML)	Mean stored Volume (ML)	Total Release (ML)	Total Rainfall (mm)	Total Evap. (mm.)
2011	MAM	580,862.40	2,827,377.33	836,217.40	111.20	214.08
	JJA	1,094,108.90	2,848,302.33	1,004,649.50	135.60	99.58
	SON	900,138.60	2,881,535.67	1,075,512.10	229.20	288.65
2012	DJF	365,050.40	2,309,798.33	1,116,001.40	127.60	512.58
	MAM	965,112.50	2,605,780.67	441,921.90	271.00	202.40
	JJA	1,424,139.20	2,885,752.00	1,246,124.30	187.20	99.90
	SON	1,004,320.00	2,919,255.67	1,140,296.90	112.80	336.13
2013	DJF	368,302.40	2,148,491.00	1,298,333.50	47.80	578.40
	MAM	637,744.70	1,464,140.33	801,669.00	118.40	283.73
	JJA	1,760,687.00	2,169,021.00	365,898.40	254.60	115.13
	SON	992,147.40	2,788,184.00	1,533,181.30	85.20	323.15
2014	DJF	533,987.40	1,941,723.33	1,465,125.60	130.00	636.26
	MAM	383,308.60	1,175,963.67	516,270.50	246.60	228.81
	JJA	1,106,548.70	1,807,405.00	201,437.90	142.00	96.93
	SON	817,291.20	2,197,198.33	1,076,553.70	159.60	392.40
2015	DJF	611,920.10	1,558,800.67	1,396,137.70	175.40	558.58
	MAM	571,107.40	734,268.67	952,731.40	147.20	286.30
	JJA	1,086,411.20	1,070,893.00	454,941.60	192.80	93.75
	SON	1,085,877.40	1,415,438.00	1,171,609.10	89.00	399.15
2016	DJF	817,579.90	1,163,139.33	1,172,035.40	135.00	599.63
	MAM	471,101.20	715,934.67	719,954.20	177.00	297.30
	JJA	2,072,366.20	1,629,290.67	78,029.70	255.20	101.20
	SON	2,917,449.90	2,944,276.67	2,762,938.30	237.80	330.33
2017	DJF	462,847.40	2,638,871.67	1,185,566.40	83.60	582.60
	MAM	412,522.40	1,938,155.67	741,860.70	197.00	273.23
	JJA	914,978.70	2,239,990.33	200,559.00	160.40	100.05
	SON	590,507.40	2,588,060.67	992,156.10	139.60	344.83
2018	DJF	398,061.80	1,991,558.67	1,053,289.10	182.60	599.38
	MAM	383,756.30	1,135,254.67	873,599.10	59.20	298.51
	JJA	768,643.70	1,329,147.00	339,308.80	137.00	119.16
	SON	978,062.50	1,477,662.33	1,215,030.70	107.40	362.20
2019	DJF	643,643.80	1,065,263.67	1,105,234.70	75.60	649.18
	MAM	329,825.40	553,326.00	652,140.00	134.20	285.53
	JJA	1,047,756.20	884,391.33	248,085.30	104.20	101.50
	SON	657,592.50	1,194,458.67	943,077.40	70.40	381.78
2020	DJF	430,541.90	695,402.33	933,869.20	79.60	621.78
	MAM	554,814.70	497,950.67	312,582.60	278.60	230.18
	JJA	1,097,164.80	1,318,070.33	55,222.00	192.00	97.28
	SON	994,618.30	2,175,567.33	621,889.30	121.00	329.08

Table 3: Average Historical Data from Feb 2011 to Dec 2020

	Total Net Inflow (ML)	*Mean Volume (ML)*	*Total Release (ML)*	*Total Rainfall (mm)*	*Total Evap. (mm.)*
DJF	514,659.46	1,723,672	1,191,732.56	115.24	593.15
MAM	529,015.56	1,364,815	684,894.68	174.04	260.01
JJA	1,237,280.46	1,818,226	419,425.65	176.10	102.45
SON	1,093,800.52	2,258,164	1,253,224.49	135.20	348.77

As shown in Table 2 and Table 3, the catchment receives an average of 600 mm of annual rainfall. Almost 80% of the precipitation occurs in the winter-spring, while the conditions in summer-autumn are usually drier. Nevertheless, there were periods of prolonged droughts, such as from Jun 2019 to Mar 2020, followed by above-average extreme rainfall events. Historically, the rainfall varied considerably from year to year (WaterNSW, 2020).

The reservoir has received an average of 3,297,674,000 m^3 of water in the last decade, with a year-to-year coefficient of variation amounting to 60%. The highest in the record was in 2016, when 6,246 x 10^6 m^3 of water flowed into the reservoir, followed by the lowest on record with 2,336 x 10^6 m^3 received in 2017. This resulted in floods downstream of the dam in the year of peak precipitation. The inflow has since been stable in the following years.

The stored water volume also varied significantly. One of the lowest monthly storage volumes in history occurred in April 2020, when the reservoir storage went below 12.5% of its effective storage capacity. The catchment received a high amount of rainfall throughout the rest of 2020, and the reservoir was refilled, with the storage reaching 78% of its capacity by November 2020. The reservoir reached full capacity in many instances in history. Those instances caused spelling and flooding conditions in the downstream catchment (WaterNSW, 2020).

The release reaches its lowest level in summer when the rainfall conditions are normally dry but peaks in winter due to the wetter conditions. In 2016, following a heavy rainy season, the reservoir released about 1.4 times its average release. There have been periods of drought in the past ten years, from April to July 2016 and from April to September 2020, when the release was too low (WaterNSW, 2020). Evaporation proportionally increases when temperature increases. Unlike other climate aspects, evaporation does not vary much from year to year. According to historical data, the average depth of water evaporated every year from the Hume Reservoir is about 1,304 mm (WaterNSW, 2020). This may increase in the future if temperatures go higher than their current averages due to global warming.

On average, 70 % of the inflow to Lake Hume occurs during Winter-Spring when the conditions are wet in the Murray Basin. The inflow into the reservoir comes from three main sources (Murray–Darling Basin Authority, 2020):

- The Upper River Murray catchment contributes to the largest amount of inflow and depends on the surface runoff upstream of the reservoir. Refer to Figure 1 for the location of River Murray location.
- Water is transferred from the Snowy Mountains Scheme through the Snowy River. The scheme diverts between 600 to 1,200 GL/year from the Snowy Mountains towards the southeast to support agricultural production. Almost 70% of the transfer occurs in Winter-Spring when the snow falls on the Australian Snowy Mountains. This is a regulated flow and is governed by agreements between the Snowy Mountains Scheme and the Murray-Darling Basin Authority. However, the actual amount of transfer may vary, and the agreement may be revised depending on the climate conditions and water availability. The inflow from Snowy Mountain is being fed into Hume Dam through Mitta Mitta River; please refer to Figure 1.
- Release from Dartmouth reservoir through Mitta Mitta river. This is also a regulated release that varies between 73 to 640 GL/year depending on the storage capacity and inflows into Dartmouth Reservoir.

The storage volume increases in Winter-Spring and decreases in Summer-Autumn. In Spring, the average quarterly storage volume reached 75% of the reservoir's active storage capacity, which is almost 26% above the yearly average. In Autumn, the storage volume dropped by 24% below the yearly average and amounted to less than 45% of the active storage capacity of the reservoir. Real data is measured by (WaterNSW, 2020). The dam has released a yearly average of 3,549 GL in the past ten years. 35% of this release occurred in Spring after the reservoir received high water in the Winter-Spring wet season. 34% of release occurred in Summer to maintain environmental conditions during the dry season downstream the dam. Real data is measured by (WaterNSW, 2020).

As for evaporation, the mean quarterly data are calculated and presented in Table 3. On average, 1,304 mm/year of water evaporated from Lake Hume during the past ten years. 65% of evaporation occurred during the hot season, Summer-Autumn, and 35% occurred during Winter-Spring. Original data is measured by (WaterNSW, 2020). The yearly and quarterly data introduced in this section will be used to establish climate change scenarios and future inflow, outflow, and evaporation from Lake Hume. The climate projections will follow the same seasoning structure used to present the historical data, which is the quarterly structure (DJF, MAM, JJA & SON).

2.3.1 Inflow Projections (Q)

The study leverages published reports for short-term projections and raw climate change data in simple forms of a percentage increase in inflow, evaporation, demand, etc. The study was meant to marry the extreme cases from different sources altogether to draw Extreme Wet & Extreme Dry scenarios. For example, the study undertaken by Murray Darling Basin Authority (MDBA) in July 2020 explored six possible climate scenarios and established the water inflow and operating strategy for the River Murray system in the current water year 2020-21 (Murray–Darling Basin Authority, 2020). The six scenarios introduced in that report were established based on historical inflow data of the basin. Two scenarios out of six were used in this study which are:

1- Extreme dry – This scenario corresponds to the second-lowest inflow in the record (recorded in 2006-07) and assumes dry conditions to prevail in the year 2020-21. The scenario assumes an annual inflow of 1,500 GL across the whole River Murray system.

2- Very wet – This scenario presents the extreme wet case and assumes a total inflow across the River Murray system to equal 20,700 GL. This is comparable to the inflow recorded in 2010-11.

The MDBA report provides projected inflows for each section of the basin under each climate scenario for the 2020-21 water year. As noted previously, the inflow to Lake Hume comes from three main sources: Snowy Mountains, Dartmouth Dam, and Upper Murray Catchments. In this study, the data published in MDBA's outlook report were used to estimate the inflow to Lake Hume for the coming ten years from these three sources as they are affected by extreme climate change as follows.

(a) Snowy Mountain's contribution

The release from Snowy Mountains supplies water to the River Murray system via Snowy River, which meets the River Murray at a point upstream of the Lake Hume Reservoir. That is why the release from Snowy Mountains contributes to the inflow into the Lake Hume reservoir. This paper uses the Snowy Mountains release under extreme scenarios, which are the 600 GL under the 'Extreme Dry' case and the 1,200 GL under the 'Extreme Wet' case. This is a regulated flow and not a natural resource. Therefore, the study assumes this estimated flow to form the baseline flow from Snowy Mountains for the coming ten years. Table 4 provides the assumed seasonal flow from Snowy Mountains under each extreme scenario following the historical inflow per season.

(b) Dartmouth Reservoir contribution

Dartmouth Reservoir is located 66 km southeast of Hume Dam in Victoria. The release from Dartmouth contributes to the inflow into the Lake Hume reservoir. This study uses the Dartmouth release data for the Extreme Dry and Very Wet cases, which are 676.80 GL/year (640 GL from Nov. to May and 200 ML/day for the rest of the year) and 73 GL/year (200 ML/day) respectively. Table 4 provides the seasonal (quarterly) inflow used in this paper. As the inflow from the Dartmouth dam is regulated, this study assumes that the inflow estimate remains the same throughout the 10-year planning period.

Table 4: Projected Inflow from Snowy Mountains and Dartmouth (x 10^3 m^3)

		DJF	MAM	JJA	SON
Quarterly Projected Release from Snowy Mountains Scheme	Extreme Dry	90,000	96,000	222,000	192,000
	Extreme Wet	180,000	192,000	444,000	384,000
Quarterly Flow Forecast from Dartmouth to Hume	Extreme Dry	384,000	198,200	18,400	76,200
	Extreme Wet	18,000	18,400	18,400	18,200

(c) Upper Murray catchment contribution

The Upper Murray catchments are the third source of inflow to Lake Hume. The inflow from upper Murray catchments comes mainly from precipitation and surface runoff (Murray–Darling Basin Authority, 2020). The Annual Outlook report (Murray–Darling Basin Authority, 2020) does not provide an estimation of the inflow from Upper Murray Catchments. Therefore, this paper relies on the historical inflows measured by WaterNSW website (WaterNSW, 2020) for the past years to estimate the Upper Murray catchments inflow. The historical Upper Murray inflow is calculated by subtracting the inflow from Mitta Mitta River (downstream of Dartmouth dam) and Snowy Mountains from the total inflow (All data obtained from WaterNSW). Table 5 shows the seasonal (quarterly) mean values of the inflow from Upper Murray catchments for the past years.

Table 5: Historical Inflow from Upper Murray Catchments into Lake Hume from 2011 to 2020

Season	Months	Mean	Percentage
Summer	DJF	83,329.04	5%
Autumn	MAM	244,649.20	15%
Winter	JJA	795,781.08	48%
Spring	SON	538,281.54	32%
	Total	1,662,040.85	100%

The data from Table 5 is used to simulate extreme conditions. The simulation assumes that the inflow from upper Murray catchments will decrease under extreme dry scenarios and increase under the extreme wet scenario. The amount of decrease and increase is obtained from the rainfall-runoff modelling forecast report published by CSIRO in 2008 (Chiew et al., 2008; CSIRO, 2008). The report provides an estimated increase and decrease of surface runoff considering climate change and other risks that affect water availability across the Murray Basin. Projections of the future rainfall and runoff in each region by 2030 under three different climate conditions: Dry, Best Estimate, and Wet, were published by Chiew et al. (2008). As explained before, this paper uses the extremely dry and wet changes to estimate the future inflow from the upper Murray catchments.

As per the report, the runoff change percentages for 2030 relative to 2006 are -38% and +6% for forecasted Dry and Wet scenarios, respectively. This study uses interpolated percentages from those presented in the report to establish the changes in 2030 relative to the mean values from 2011 to 2020 obtained from the Water NSW website. The interpolated percentages are-24% and +4% for Dry and Wet scenarios, respectively. The mean inflow projections from Upper Murray Catchments for 2030 are calculated using the historical inflow represented in Table 5 and the interpolated change percentages. The forecasted inflow by 2030 from Upper Murray catchments is presented in Table 6.

Table 6: Inflow Projections for Upper Murray Catchments

Season	Mean Inflow from 2011 to 2020	2030 Projections		
		Dry	Dry	Dry
DJF	83,329.04	63,330.07	77,496.01	86,662.20
MAM	244,649.20	185,933.39	227,523.75	254,435.17
JJA	795,781.08	604,793.62	740,076.41	827,612.33
SON	538,281.54	409,093.97	500,601.83	559,812.80
Total	1,662,040.85	1,263,150.81	1,545,697.93	1,728,522.53

The values in Table 6 are 2030 projections, and the behaviour analysis module designed for this study covers the period from 2021 to 2030. The module applies ascending percentages in the Extreme Wet case and descending percentages in the Extreme Dry case, starting from current mean values as of 2020 until it reaches the forecasted values by 2030. There is also a need to mention that the ENSO phenomenon is driving the climate patterns in Eastern Australia and has three states: El Nino, La Nina, and Neutral. As noted earlier, the La Nina state results in an above-average inflow to the Hume Dam. In the past ten years, it has been obvious that La Nina has hit the Lake Hume catchments three times in 2013, 2016 and late 2020. As of December 2020, La Nina state has just started. Therefore, the planning model has considered the current La Nina state and its recurrence every three years (see Figure 3 for evidence). The La Nina induced inflow has been estimated using the historical inflow data downloaded from the WaterNSW website for 2013 and 2016. Table 7 provides a comparison between the inflow data in 2013 and 2016 and the average inflow to establish the induced inflow by La Nina.

The year 2016 was wetter, and rainfall was more intense than in 2013. This additional La Nina Induced inflow has been assumed to recur every three years. The planning module used in this work adjusts the inflow forecast to account for this additional inflow every three years. For the sake of modelling the extreme cases in this work, the Extreme Wet case uses the additional inflow of 2016, which is wetter than 2013, whereas the Extreme Dry case uses the 2013 inflow. These additional inflows have been assumed to recur in 2021, 2024, 2027, and 2030.

Table 7: La Nina Induced Inflow to Hume Dam based on Historical Records (x 10^3 m^3).

Seasons	Historical Mean Inflow	(2013)		(2016)	
		Total Inflow	La Nina Induced Inflow	Total Inflow	La Nina Induced Inflow
DJF	514,659.46	533,987.40	19,327.94	817,579.90	302,920.44
MAM	529,015.56	637,744.70	108,729.14	471,101.20	
JJA	1,237,280.46	1,760,687.00	523,406.54	2,072,366.20	835,085.74
SON	1,093,800.52	992,147.40		2,917,449.90	1,823,649.38

2.3.2 Evaporation (E)

WaterNSW provides Lake Hume's historical total evaporation depth (mm) from 2011 to 2020, as shown in Table 2 (WaterNSW, 2020). The estimation of evaporation requires the forecast evaporation depth as well as the Storage-Area relationship. Evaporation depth is estimated based on the historical data downloaded from (WaterNSW, 2020). The Area-Storage relationship is derived from the Global Reservoir and Dam Database (GRanD) developed by (Lehner et al., 2011). GRanD aims to provide a geographical database for more than 7300 reservoirs in the world.

The Area-Storage relationship for the Lake Hume reservoir has been downloaded from the GRanD website and used in this study. Figure 5 shows the relationship based on the downloaded data (Lehner et al., 2011). This study interpolated the storage levels (S_t & S_{t+1}) into the Storage-Area curve in Figure 4 to obtain the storage areas at the beginning and the end of each time interval (A_t & A_{t+1}). The average area for each time interval (A_v) was then calculated using Equation 3. The areas were multiplied by the projected evaporation depth (e_t) to obtain the volume of evaporated water (E_t).

A group researchers suggest that evaporation over Australia will show increases by 2030, with the largest increases projected in the north and east (Ball et al., 2019). The expected change varies from a minor change to a 6% increase in evaporation depth. This study uses this suggestion and assumes no change under the Extreme Wet scenario. As for the Extreme Dry scenario, the study applies a 6% increase by 2030. The increase is applied incrementally from 2021 to 2030.

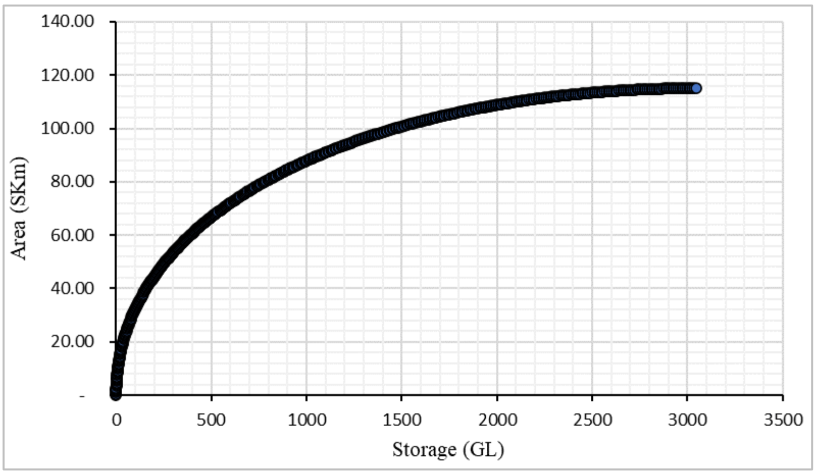

Figure 3: Storage-Area Relationship for Lake Hume. Data obtained from (Lehner et al., 2011)

2.3.3 Demand Projections (D)

Hume Dam regulates the flow throughout River Murray to meet the domestic, agricultural, and stock demand as well as environmental needs (Murray–Darling Basin Authority, 2020). The Annual Operating Outlook of River Murray provides information regarding expected demand and release from Hume Dam. Release from Hume Dam provides the water needed to maintain sustainable environmental conditions downstream. The annual environmental release under each climate scenario is presented in the Annual Operating Outlook for 2020-21 (Murray–Darling Basin Authority, 2020).

This paper uses the two extreme cases,' Extreme Dry' and 'Very Wet', for environmental demands, which are 110 GL/Year and 60 GL/Year, respectively, as presented in the report. Murray–Darling Basin Authority suggests that the environmental release from Hume Dam follows the same patterns as the natural release from the dam (Murray–Darling Basin Authority, 2020). Therefore, the annual environmental demand has been split into four quarterly seasons following the percentages of historical release per season, as presented in Table 3. Table 8 shows the expected quarterly environmental release from Hume Dam for each climate scenario.

The minimum release from Hume Dam under normal conditions is 600 ML/day, while the maximum channel capacity from Hume Dam to Yarrawonga Weir downstream of the dam is 25,000 ML/day (Murray–Darling Basin Authority, 2020). The minimum demand and maximum capacity determine the lower and upper release limits from Lake Hume, respectively. These limits are characteristic features of the downstream channel and are not expected to change under any climate condition. The behaviour analysis module designed for this study is guided by these limits such that the release from Hume Dam remains within the range of 600 ML/d < Y_t < 25,000 ML/d.

The behaviour analysis module used in this study is designed to determine the periods in future where the release hits any of the lower and upper limits. The estimates of the demand projections under extreme cases are based on the assumptions below:

- Environmental demand to follow the assumptions made for Extreme Dry and Very Wet conditions in the 20-21 outlook report.
- Domestic demand follows the same historical release pattern observed in the past ten years.
- Domestic demand to increase by 1% by 2030 to cater for additional developments and growing agricultural needs in the area, as suggested by Chiew et al. (2008).

This paper utilises the behaviour analysis technique for reservoir planning to calculate the reservoir capacity, release, and demand deficit under each climate condition for the coming ten years, 2021-2030. The procedure is summarised below.

- All scenarios start with actual storage, inflow, release, and evaporation conditions as of December 2020.
- Total quarterly inflow projections to Hume Dam from the three sources (Dartmouth, Snowy Mountains, and Upper Murray) are summed up to represent the total inflow.
- Total quarterly demand is calculated based on environmental needs as well as agricultural demand.
- The behaviour simulation is then carried out, and the performance indices are assessed.

Table 8: Expected Quarterly Environmental Release from Hume Dam

	Total (ML/year)	DJF 34%	MAM 19%	JJA 12%	SON 35%
Extreme Dry	110,000	37,400	20,900	13,200	38,500
Extreme Wet	60,000	20,400	11,400	7,200	21,000

3. Results and Discussion

The study of the extreme climate conditions impact on Lake Hume reservoir reveals some facts about the Lake Hume reservoir. The Extreme Wet scenario does not seem to impact the reservoir or its downstream environment. The results of the study show that the release meets the demand at all intervals under the extreme wet scenario. On the other hand, the results show that the impact under Extreme Dry conditions is significant. The reservoir dries out on many occasions, which results in time reliability (R_t) equals 53% while volume reliability R_v is 87%.

Figure 5 shows the forecasted average quarterly release volume under each climate change scenario for the next decade. The forecast released in the wet scenario is always higher than in the dry scenario, and, in both scenarios, the release increases in the hot-dry season (Summer – Spring).

Figure 6 is a graphical presentation of the average storage per season under both scenarios. The average storage in the dry scenario is noticeably lower than the storage in the wet scenario. This is due to the need to release most stored water to meet the demand under the dry scenario.

Simulating the extreme wet conditions of the reservoir for the coming ten years assumes an average inflow of 4,185,315 ML/year. This average inflow rate is 24% more than the historical average inflow recorded over the past ten years. The inflow estimated rates are based on the assumptions and calculations explained previously. The study concludes that the reservoir reliability is 100% under extreme wet conditions. The study forecasts a one-time flooding interval when the daily inflow exceeds 30,543 ML/day, 22% more than the downstream channel capacity (25,000 ML/day). The forecast expected a release of 3,959,100 ML/year, 12% greater than the past ten years' historical average. The extreme wet scenario simulation proves that the Lake Hume reservoir is adequately sized to withstand the extreme wet conditions without affecting the environment and the community downstream.

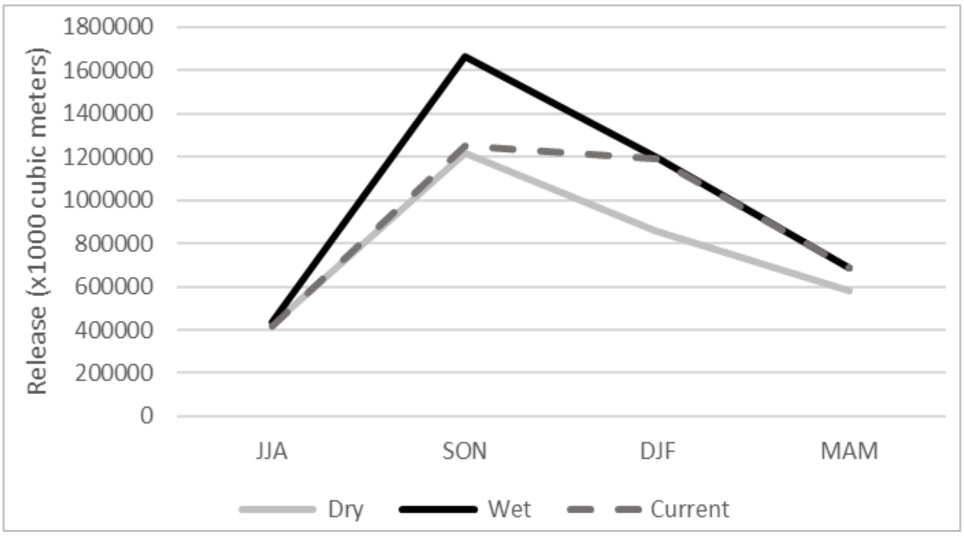

Figure 5: Forecasted Quarterly Release Volume for Lake Hume under Extreme Wet and Extreme Dry Conditions (From 2021 to 2030)

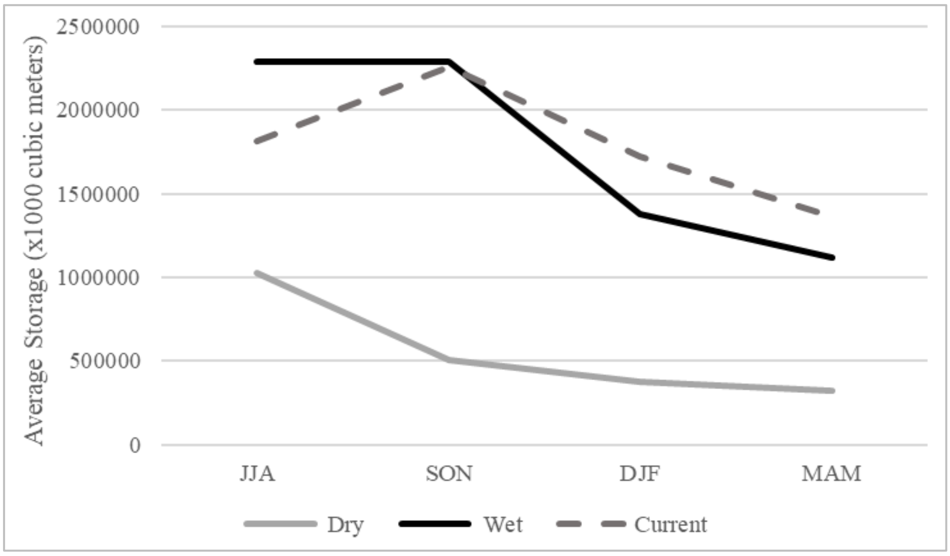

Figure 6: Forecasted Quarterly Average Storage Volume for Lake Hume under Extreme Wet and Extreme Dry Conditions (From 2021 to 2030)

Simulating the extreme dry conditions of the reservoir for the coming ten years assumes an average inflow of 2,946,065 ML/year. This average inflow rate is 13% less than the historical average inflow recorded over the past ten years. The inflow estimated rates are based on the assumptions and calculations explained previously. Unlike the extreme wet scenario, the extreme dry scenario has a significant impact on the Lake Hume reservoir performance. The reservoir discharges all the stored water and dries on many occasions. Over the 40 planning periods tested in this study, the failure periods where the reservoir may not provide the target demand are 18 periods (f_d = 18), and the failure periods come in sequence on 11 occasions (f_s = 11). Therefore, the resilience measure is 58%, and the vulnerability is 42%. However, the upside of the extreme dry modelling is that the reservoir never fails to supply the minimum environmental demand, which is 600 ML/day required to maintain ecological conditions downstream.

The extreme dry scenario simulation proves that the reservoir is not adequately sized to withstand the extreme dry conditions. The performance measurement indicators provide a quantitative review of the reservoir's performance. The time-based reliability is an indication of how many times over the planning period the reservoir has been able to provide the full supply (see Equation 6). The estimated time-based reliability (R_t) for the extreme dry scenario is 58%. Another performance indication calculated for the Lake Hume reservoir under extreme dry simulation is volume reliability. This indicator calculates the overall shortage volume (V_s), which in this case equals 4,842,050 ML against the total demand volume (v) of 35,647,955 ML. Applying Equation (7), the R_v is 87% compared to 98% current volume reliability obtained from the historical data. As expected, the assessed R_v is much higher than the R_t because the volume shortage is insignificant in some failed intervals.

4. Conclusions

The impact assessment of the extreme climate conditions on the Lake Hume reservoir was studied in this paper. The conclusion of the study can be summarised as follow:

- The extreme wet conditions may result in a 24% increase in the average inflow to the Lake Hume reservoir, resulting in a 12% increase in the average release.
- The reservoir is deemed adequately sized to store the additional inflow without spilling or affecting the downstream environment.
- The extreme dry conditions may result in a 13% decrease in both inflow and outflow from the reservoir.
- The reservoir is expected to fall short of supplying the demand in the summer-spring season and may completely dry out.
- The time and volume reliability indicators will both be 100% under extreme wet conditions. However, under extreme dry conditions, the time and volume reliability will be 58% and 87%, respectively.
- Resilience and Vulnerability measure maybe 58% and 42%, respectively, under extreme dry conditions.

The sustainability of the environment is one of the key objectives of designing water supply systems. Water reservoirs help control flooding during wet conditions and supply critical demand during dry conditions. This paper suggests that the Lake Hume reservoir is expected to provide good environmental conditions downstream. The reservoir can store the surface water under wet conditions and protect the downstream from inundation risks. It will also supply the minimum critical environmental water flow which is 600 ML/day under dry conditions. However, the demand for agricultural and domestic use downstream may be affected. Thus, the release needs to be controlled and cut back to avoid failures under dry conditions. It is worth noting that this cutback in demand may trigger an application of water restrictions and consumption control.

The paper is conducted on 10-year reservoir planning under two extreme climate conditions. The study provided results such as forecasted inflow, forecasted release, storage capacity, reliability, and resilience indicators under each climate scenario. It also introduced the environmental, domestic and consumption impacts without explicit recommendations on how the release and consumption could be controlled or restricted. The results of this work are expected to positively contribute to future studies on water restriction and release hedging to further improve performance under the extreme dry scenario. Furthermore, the methodologies used in this study to forecast the future reservoir planning parameters can inform further planning studies for the Hume Dam on longer time scales, i.e., beyond ten years. The forecast of future inflow, demand, evaporation etc., can simply be extrapolated and adjusted if needed to consider any limitations within this study.

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