The Hydrologic Feasibility of Building a Weir Within Lake Eildon in the Vicinity of Bonnie Doon

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Abstract

Lake Eildon is Victoria's most popular inland recreational water destination and the only lake which allows registered houseboat access. It is in North-Central Victoria. The township of Bonnie Doon is located within the northern-most catchment area of Lake Eildon. Water is supplied from the lake for the Bonnie Doon township. When surface water is absent, during drought or releases greater than inflows, recreational boating and fishing suffer, along with water availability for the township and firefighting collection. This occurs when water levels of the main dam drop below 46% storage. This impacts on the local and regional economies as visitor numbers decline when water is absent.

The aim of this research was to explore the viability, based on consideration of hydrologic data and reference to water quality, geological, structural, and general issues, for the construction of an additional weir, either near the Bonnie Doon pumping point below the road bridge, on the Mooroondah Highway, or within three kilometres downstream of that point. The primary purpose of the weir will be to provide and maintain a secure local body of water whilst the main dam at Lake Eildon continues to meet its Goulburn-Murray Water responsibility for downstream irrigation, townships' drinking water supply and for a range of environmental purposes.

The main methodology was a quantitative approach, with three potential weir sites chosen and at each site, a weir with crest elevations at each of 272 and 275 mAHD was considered.

The components factored into the models created included precipitation, surface area of potential weir sites, evaporation, streamflows, and resulting water movement (water levels below crest heights or volumes passing downstream into the main dam, where that dam failed to overtop the weir crest).

Models were constructed, firstly to assess their viability using historical data for forty years from 1980 to 2019. These six sets of models showed that the weirs were viable. However, the more important test was to determine their viability with climate change factored in.

With predictions for climate change, modelling used projections for the year 2065 (for worst outcomes) as supplied by the (Victorian) Department of Energy, Environment and Climate Action (DEECA). These projections were also modelled with probabilities of 50 and 90 percent. Only the worst forecasts for the year 2065 were used, as it was considered that those for year 2040 had already started to appear to some extent earlier than expected.

The outcomes reached using climate change models indicated that all six weir options were still viable. An extra model to determine the outcome if there was no water overtopping by the main dam ever occurring, and the weir still delivered a viable result.

Also, as the absence of water in this location seriously impacts on recreational pursuits in the Bonnie Doon arm of the lake, including fishing, powered boating, houseboats and canoeing, this research, with feasibility proven, may influence future government strategic water infrastructure planning for regional Victoria.

Declaration

"I, Frank Ross Deans, declare that the Master of Applied Research thesis entitled "The hydrologic feasibility of building a weir within Lake Eildon (Victoria) in the vicinity of Bonnie Doon" is no more than 60,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes. This thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work".

"I have conducted my research in alignment with the Australian Code for the Responsible Conduct of Research and Victoria University's Higher Degree by Research Policy and Procedures".

Signature: Date: 14/12/2022

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My principal acknowledgement is to my supervisors, who oversaw the development of my thesis. Lead supervisor was Dr. Nitin Muttil, assisted by Mr. Peter Lechte. It was a difficult period for supervision, firstly because of the ramifications of Covid-19, moving from face-to-face meetings on campus to many by zoom. In addition, there were periodic interruptions to progress of the thesis caused by personal health procedures for the candidate. Due to these issues above, the contribution and assistance of my supervisors cannot be underestimated.

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List of Abbreviations

BOM	(Australian) Bureau of Meteorology
COAG	The Council of Australian Governments
DEECA	Department of Energy, Environment and Climate Action
DEW	Department of Environment and Water (SA)
DSEWPC	Department of Sustainability, Environment, Water, Population and Communities
EPA	Environmental Protection Authority
FSL	Full Supply Level
GHD	GHD Group Pty Ltd
GMID	Goulburn-Murray Irrigation District
G-MW	Goulburn-Murray Water
GSA	Geological Society of Australia
GVW	Goulburn Valley Water
mAHD	metres Australian Height Datum
NHMS	National Hydrological Modelling Strategy
SMEC	SMEC Holdings Limited
UNSW	University of New South Wales
USBR	United States Bureau of Reclamation

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Chapter 1 : Introduction

1.1. Background

Lake Eildon is Victoria's most popular inland water destination and the only lake which allows registered houseboat access. It is in North-Central Victoria, approximately two hours by road from Melbourne. Lake Eildon was previously known as Eildon Weir, then Eildon Dam and now Lake Eildon. It can be accessed from any of three highways, the Hume Freeway, the Melba Highway and Maroondah Highway, plus a lesser road via Flowerdale, all merged at Yea into the Maroondah Highway. Figures 1.1 shows the location of Lake Eildon within Victoria.

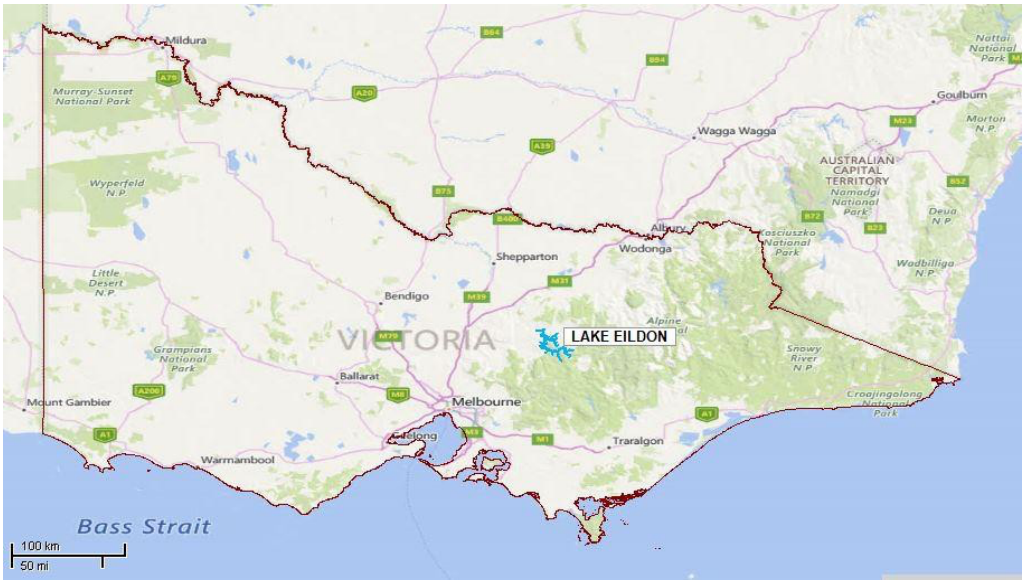

Figure 1.1: Map of Victoria showing location of Lake Eildon
(Source: Maps Victoria, 2019)

The township of Bonnie Doon is located within the northern-most catchment area of Lake Eildon, as can be seen in Figure 1.2. The local water supply is pumped from below the road bridge across the lake on Maroondah Highway, which can also be seen in Figure 1.2. The figure also shows the Brankeet arm of Lake Eildon at the northern end of the lake, where four northern creeks (Merton, Brankeet, Tallangalook

and Glen Creek) enter the lake. There is a confluence between Merton and Brankeet creeks close to entering the lake, whilst Tallangalook and Glen creeks enter independently.

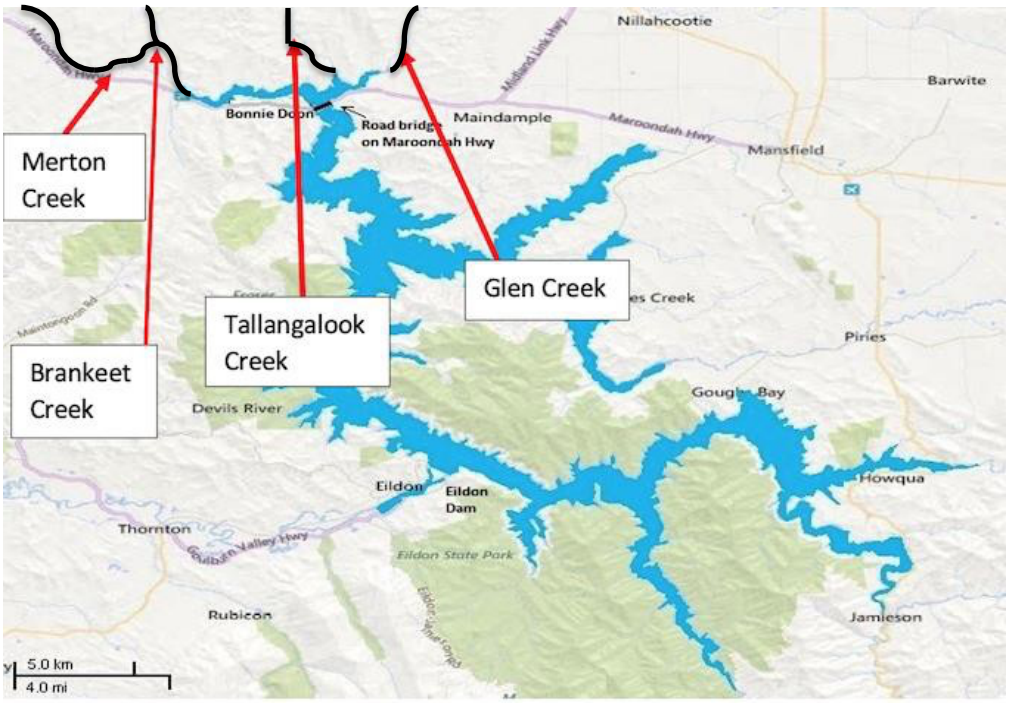

Figure 1.2: Lake Eildon with some key features and the northern creeks entering the 'Brankeet Arm'
(Source: G-MW, 2019)

1.1.1. The History of Eildon Dam and Lake Eildon

Eildon Dam was originally known as Sugarloaf Reservoir when its construction commenced in 1915. Another reservoir in the Melbourne catchment zone is now called Sugarloaf Dam. This reservoir is much closer to Melbourne and is relatively small (96 GL) and is aimed at meeting Melbourne's peak summer demand. Eildon Dam was modified in 1929, and again in 1935, to increase its storage capacity to 377,000 ML. With an even larger potential catchment, it was modified again between 1951 and 1955 to give it its current storage capacity of 3,334,158 ML, 8.8 times its size in 1935. This new storage was renamed Lake Eildon and is six times the capacity of Sydney Harbour and five times that of Port Philip Bay (which is larger by surface area, but uniformly shallow). The purpose of the significant storage enlargement

between 1951 and 1955 was to provide water for the largest irrigated farmland in Australia, known as the Goulburn-Murray Irrigation District (GMID). Information below for Lake Eildon was supplied by Scott Wikman from Goulburn-Murray Water, which manages the Lake Eildon storage (personal communication, 2018). The principal purpose of Lake Eildon, as stated in the Water Act (Victoria 1989), is to store and release water for irrigation purposes. Information about the Water Act is provided by the Victorian Department of Environment, Land, Water and Planning (DEECA) Water Act (1989).

Within this thesis, where reference is made to 'the dam' or 'main dam', these are to be interpreted as the 'Lake Eildon' storage, as opposed to the proposed weir, which will be referred to as 'Weir #1', #2, or #3.

Goulburn-Murray Water (G-MW), the Authority responsible for the lake's management, states that on average, 91% of water released from Lake Eildon is diverted for irrigation purposes and the lake supplies about 60% of water used in the GMID. Some 4% of water releases are also for urban water supply in townships downstream of Lake Eildon. In addition, it also supplies water for seasonal environmental flows. The lake's capacity is sufficient to meet those needs for two drought seasons. It also has a downstream flood mitigation purpose.

The potential for generating hydroelectricity was realized with turbines for 135MW generation. A smaller turbine unit was later retrofitted by Pacific Hydro at the pondage, located immediately below the dam's release point, aimed at holding water back to avoid flow surges when generation releases occur.

Lake Eildon is Victoria's most popular inland waterway for recreational boating activities. The Transport Safety Victoria report (2015) indicated that "58% of recreational boating happens on Port Phillip Bay & coastal areas, leaving 42% for inland waters; 25% (or 10.5% overall) of this boating activity happens at Lake Eildon (Murray River only 20%)".

1.1.2. Periodic absence of water at Bonnie Doon

Because of both drought and regular releases for irrigation from Eildon Dam downstream, there is a periodic absence of water in the lake at Bonnie Doon, which threatens water security for the township. As water release occurs at Eildon Dam, water frequently disappears at the Bonnie Doon Bridge if continual releases exceed inflows, especially over summer months. When surface water is absent, groundwater from the underlying sands is needed, and a slow rate of pumping occurs, placing residents on severe water restrictions. This situation prevailed throughout the entire millennium drought.

The absence of water not only threatens water security for the township, but also has a negative impact on recreational boating activities and fishing. Whenever water levels drop below 46% storage, water is absent at the Bonnie Doon Bridge. If storage significantly falls below 46%, all boating activities within the vicinity of Bonnie Doon cease. This has a negative impact on the local and regional economies. Thus, the unpredictable presence of water at Bonnie Doon has significant ramifications for the local domestic and commercial water consumers and recreational users. The periodic presence and absence of water in Lake Eildon in the vicinity of Bonnie Doon can be seen in Figures 1.3 and 1.4 below.

Figure 1.3: Lake Eildon at Bonnie Doon - storage at full supply level (FSL) in August 1993. (Source: G-MW, 2019)

Figure 1.4: Lake Eildon at Bonnie Doon at 36% storage in April 2019
(Source: Deans, 2019)

1.2. Motivation for this study

This research will investigate the hydrologic feasibility of constructing a weir within Lake Eildon in the vicinity of the township of Bonnie Doon.

The study is innovative in that building a weir within an existing weir is an unusual and rare occurrence. Only one such example was uncovered during research, occurring within the great lakes in the USA, constructed for the principal purpose of keeping non-indigenous fish species from accessing the main lake system. In this thesis, the primary purpose is to impound water when the main lake is discharging water for irrigation, leaving behind water for local supply security for a township, maintaining water for recreational purposes and as a pickup point for bushfire fighting and control.

The motivation for constructing such a weir is to provide and maintain a secure body of water in the vicinity of Bonnie Doon whilst the main dam at Lake Eildon continues to meet its Goulburn-Murray Water responsibility for downstream irrigation,

townships' drinking water supply and for a range of environmental purposes.

Other than to improve water security for Bonnie Doon, the proposed weir will enhance recreational boating and fishing access to water at this northern end of Lake Eildon. It will also create a water source for pick up by fire-fighting tankers and aircraft in the event of bushfires north to Benalla and west to Seymour. Overall, it will provide a more stable economy for the local region. These benefits are further discussed in Section 1.4.

1.3. Objectives of this study

The main objective of this study was to investigate the hydrologic feasibility of construction of a viable weir within Lake Eildon. The following specific objectives were considered in this study under the above-mentioned main objective:

a) To investigate the hydrologic feasibility of a weir within Lake Eildon at three different potential sites, each site with varying potential to satisfy the local water requirements. The proposed sites are discussed in detail in Chapter 3.
b) The impact of climate change on the weir's (and dam's) hydrology will be investigated closely, using future reduction in stream flows and precipitation and increases in evaporation. The outcomes will indicate the viability of a weir in the event overtopping upstream into the weir from the main dam is reduced in frequency.
c) Although the major focus of the research will be hydrologic, a basic assessment will also be included of different weir designs appropriate to the various sites, construction elements, materials, operational requirements, and geotechnical attributes for each possible site.
d) A simple analysis of cost of the weir will be made, and a cost estimate calculated, to determine the viability of building a weir at each of the three sites. Discussions in 2019 with engineers of the John Holland Group (responsible for the upgrade of the main dam in 1950-1955) advised that for the weir to be viable, the project cost should not exceed AUD$100 million in 2019 dollars.
e) As a way of placing this research in context, a similar structure was proposed to be built upstream within the Hume Dam, in New South Wales, known as The Narrows Project, but was not realized for several reasons. A comparison of the proposed weir in the Narrows Project will be made with the weir within Lake Eildon proposed in this study.

1.4. Research significance and stakeholders

If this research concludes that a weir within Lake Eildon is feasible, the regional benefits will include a reliable water supply locally, and equally important,

ensure the presence of water for tourists and recreational users of the water impounded by the new weir. Those tourists and users should generate a regular demand for goods and services in the area, a demand which currently disappears when water is absent. Furthermore, the research outcomes could become a precedent for other similar projects in Australia.

This research would be of significance to many stakeholders, who have an interest in a project to construct a weir within Lake Eildon.

These stakeholders include: -

a) G-MW, responsible for the management of Lake Eildon, have an interest arising from their withholding of water (by the dam) for their primary activity, being provision of water for irrigation, supply to townships along the Goulburn River and water decreed by government for environmental flows. They also have a pecuniary interest in how they are compensated for the loss from increased evaporation if a new weir within Lake Eildon is created. As a seller of water and water rights, G-MW's interest is in seeking cash recovery for additional water lost to higher evaporation, water locked up and unavailable for main dam release, and costs associated with management of any new weir.

   Since the Water Act states that Lake Eildon's purpose is primarily to supply water for irrigation, legislators would need the Victorian Parliament to pass an amendment to the Water Act to allow for the development and operation of a new weir.

b) Goulburn Valley Water (GVW) is a Victorian State Authority, which buys water from G-MW to treat and on-sell to residents of Bonnie Doon. Unlike G-MW, GVW would openly support the creation of a new weir, as it creates water security for their business. When water disappears from the bridge near the township, GVW has a reduction in water available for pumping from the road bridge base, within the sands of the original stream flowing through this site. In times of prolonged drought, the lower flows and their limited (50 ML) emergency storage pondage at the treatment works makes water delivery difficult and chemical treatment heavy in nature. It produces severe water

restrictions for residents. Their best outcome would be a weir at a site downstream of the bridges, as either of those two (Sites #2 and #3) would obviate any need to relocate pumping infrastructure.

c) Boating enthusiasts of water skiing and other activities, who currently must relocate to a site further south when water disappears from the bridges area. Often, an alternate viable boating site is several kilometres downstream of Bonnie Doon.

d) Fishermen, who, like boat operators, need to move downstream as water levels drop.

e) Country Fire Authority, which could use the lake for helicopter and tanker water pick up for firefighting north and west of the Brankeet Arm. As water levels recede, further travel is needed by helicopters and tankers to access high water volumes. Alternatively, water is picked up from farm dams, usually in summer, when opportunity for recharge of dams is unlikely, risking provision of a water asset for farm stock after the fire emergency is over.

f) Local traders, who, though not numerous, rely on a buoyant tourist presence to bring cash turnover to a supermarket, general store, fuel service centre, hotel, two motels, caravan park and boat repair operations. These traders provide local job opportunities in staffing.

g) Mansfield township, which is an extension of traders in the Bonnie Doon region, 20 km east of Bonnie Doon. It is the main restaurant, services, and shopping location for holiday makers at Bonnie Doon. There is limited scope for any cost-benefit analysis in this thesis, but with viability of the project established, Mansfield Shire Council might supply estimates of additional business turnover in years when water is present or absent at Bonnie Doon.

h) Residents along the shoreline whose property prices will escalate if water becomes permanently visible and available. In addition, more land for residential development could become available and find a market.

i) Environmentalists, zoologists, botanists, and bird watchers with an interest in wetlands. (A wetlands development has synergy with the proposed weir within Lake Eildon). It is not significantly developed or analyzed within the scope of this thesis but if further investigation is made of the potential of this proposed weir, a wetland might be included, possibly located after the confluence of the Brankeet and Merton creeks, above Lake Eildon's FSL).

1.5. Research approach and thesis structure

The research will adopt a mixed methods approach using both quantitative and qualitative data sources to support a rigorous and in-depth exploration of the question of feasibility. This approach will ensure that triangulation of data, the methodological vehicle for merging quantitative and qualitative research methods of data will guide and dictate the outcome of the research. It is envisaged that this research will make a unique and valuable contribution to future infrastructure strategic planning in regional Victoria.

It is envisaged that the core of the research will be a hydrologic analysis to compare and contrast three different sites for a weir, consider the changes to surface area and water stored with a range of weir heights for each site.

Analysis of hydrologic data for forty years will provide an understanding of what each weir site would have delivered in water benefit, compared with no weir. Historical data will give some insight into how often each weir would be overtopped for the minimum and maximum weir heights, in the absence of climate change impact.

The next step will be to apply a range of reductions in streamflow and precipitation arising from climate change, together with an increase in evaporation, with historical discharge rates from Eildon Dam, followed by changes arising from a reduced discharge from the dam. This data collection will be based on forecast reductions and increases outlined by the Department of Energy, Environment and Climate Action (DEEECA). The forecast changes are found in the DEECA information site

published as Final December 2016 “Guidelines for Assessing the Impact of Climate Change on Water Supplies” (DEECA, 2016).

This chapter (Chapter 1) is followed by a literature review presented in Chapter 2.

The thesis will then follow the outline shown below for chapters 3 to 7.

Chapter 3 – This chapter presents a compilation of hydrologic and other data used in this study. The data includes the following: -

1. Rainfall for the previous forty years
2. Streamflows for the northern creeks in both wet and dry seasons (40 years)
3. Discharge of the five main rivers flowing into the main dam (40 years)
4. The three potential weir sites and their relationship to each other

Factors that prevail for weirs at crest elevations of 272 and 275 mAHD are listed below in (1) to (5)

These two elevations have been chosen from the range 271 to 276 mAHD which gave weir heights from 3 to 16 metres across the three sites. For the three potential sites the elevations 272 and 275 mAHD were selected for testing, subjective choices based on what were considered realistic weir heights that delivered cost-viable construction heights and acceptable water surface areas for boating.

Relevant weir factors: -

1. Storage behind weirs at their FSL
2. Weir crest heights
3. Embankment lengths
4. Surface areas impounded
5. Geology of the sites
6. Discharge history of the main dam, for weir overtopping analysis

Chapter 4 - The hydrologic analysis of historical data is presented in this chapter. As was discussed earlier, this study will assess the possibility of constructing a weir at 3 potential sites within Lake Eildon. These potential sites are named as Site #1 (the

site closest to the bridges at Bonnie Doon), Site #2, and Site #3 (the most downstream site). The analysis includes the following:

Rainfall history and their trends, discharges from the four northern creeks into Lake Eildon and the five main river discharges into Lake Eildon, all over the past 40 years.

Comparing weir Sites #1, #2 & #3 at crest elevations of 272 and 275 mAHD will highlight their significant outcomes using the past 40 years of historical data. A comparison is made for various weir heights, being much less than the height at the main dam's FSL, to contain cost of construction. At dam FSL, any one weir would be submerged, but when the main dam is at levels less than 272mAHD, acceptable surface areas and volumes impounded by the weirs would meet the needs of recreational boating. The comparison is also made of the embankment lengths of each site, where length directly impacts construction cost.

The three sites were chosen to be in the vicinity of Bonnie Doon, where the issue of regular water absence prevails, affecting boating and water for transfer for treatment for local town usage. It was also seen as important to maximise the new weir's surface area, whilst minimizing its volume locked up and unavailable for release by the main dam for irrigation and other purposes. Evaporation losses at each site will be calculated, netted off against rainfall, as part of the calculation of water movement for each month that no overtopping by the main dam occurs.

Chapter 5 – This chapter models the hydrologic analysis using projections for and outcomes expected from climate change.

The analysis considers: -

1. Projections supplied by DEECA at both 50 and 90 percentile climate change impact for year 2065 for streamflows, precipitation and evaporation. With application of the range of reductions in streamflow, the impact of climate change will be assessed. After including the net effect of reduced rainfall and increased evaporation, the overall impact on the weirs will be determined.
2. Outcomes when applied to all three weir sites at the selected crest levels of 272 and 275 mAHD. These outcomes are the number of months the weirs would be

overtopped upstream from the main dam, number of months when the main dam's water level is less that the weir crest, and the volumes of water passing downstream from the weirs when their FSL is exceeded. It also assesses the frequency when water levels behind the weir and downstream are both below the weir crest.

3. Outcomes when climate change is applied to the main dam. Dam levels are calculated using climate change modelling for reduced precipitation and streamflows, increased evaporation, and a variety of rates of water discharge from the main dam, where the aim is to meet release targets for irrigation, without the risk of draining the main dam to exceptionally low storage levels.

Chapter 6 – This chapter includes other considerations for assessing the viability of a weir in the vicinity of Bonnie Doon.

There are three primary considerations, identified below: -

1. Topographic and geological considerations - selecting weir sites that minimize embankment length, ideally with abutment to relatively steep slopes either end.
2. Structural considerations and access to materials – identifying structures suitable for regular overtopping without major erosion, containment of construction cost, construction in a reasonable timeframe and access to local materials.
3. Economics – basic cost of weirs and benefits arising from creation of a weir – a simple extrapolation of costs, based on The Narrows project's recommended options. Primary benefits arising from a weir holding permanent water at the Bonnie Doon end of Lake Eildon will be identified.

Other considerations, beyond the three primary considerations above will be reviewed briefly. These areas impacted are: -

1. Water quality, which may be impacted if a shallow water depth affects temperature, oxygen levels and promotion of algal growth.

2. Environmental issues which may be raised by the Environmental Protection Authority (EPA), together with the impact on flora and fauna with the possible introduction into the project of a wetland.
3. The Water Act, which legislatively denotes the core purpose of water stored in Lake Eildon and the changes implied by a weir's operations.
4. Planning permit requirements, which could be through various authorities such as local council, the EPA, and other.
5. Native Title requirements, although these may already be met since the weir would be established within an existing water body.
6. Social impact upon residents in the area surrounding the proposed weir and for tourists to the region.
7. Traffic impact assessment arising during construction and with increased visitors after completion.
8. Heritage and cultural assessment, which may be satisfied by the weir's inclusion in an existing lake.
9. Management plan, for the proposed construction and operation of the weir.
10. The possibility of incorporating a wetland as part of the weir project.

This chapter also presents a comparison of Lake Eildon weir options with that proposed for The Narrows in Lake Hume (see Chapter 2 – Section 2.7). The Narrows project was selected for comparison with the Lake Eildon weir, as it mirrored aspects of this project and offered insight into potential weir design and costs. It also emphasized the need for such a project to achieve a cost-benefit analysis that exceeded '1', not achieved with the Lake Hume project, causing the project to be abandoned.

Chapter 7 – The outcomes, conclusions and recommendations from this study are finally presented in this chapter. Several positive and negative social issues are also presented in this chapter.

Chapter 2 : Literature

2.1. Introduction

This research project aims to determine the viability of building a weir within an existing reservoir, Lake Eildon, with a focus on hydrologic issues. Little was found within contemporary literature that mirrored this project, except for The Narrows project planned for Lake Hume, which did not proceed. One which was constructed was a dam within the Great Lakes in the USA. Its purpose was to prevent a non-native fish from reaching other parts of the lake system. It differs from this project in that no overtopping the dam wall upstream was an option. Within Lake Eildon, water could pass either upstream or downstream of a proposed weir, depending on the volume of water in the main dam or the volumes delivered by the northern creeks (refer Section 1.1 and Figure 1.2).

Historically, many design options exist for a weir. Adoption of any one weir type over another might be influenced by a range of factors. One weir site might resemble another, yet the same weir suitable for one site might fail scrutiny in another. Weir design options can be seen in Appendix A. Some designs would suit such a weir if the weir height matched the main dam, or no overtopping upstream was to occur. However, with a much lower weir height proposed (to contain cost) and projected frequency for being submerged by several metres, they cannot be considered.

2.2. Basic hydrologic parameters and their measurement

"The hydrologic cycle may be treated as a system whose components are precipitation, evaporation, runoff, and other phases of the hydrologic cycle.
A watershed is the area of land draining into a stream at a given location.
The processes of precipitation and evaporation, in which the atmosphere interacts with surface water, are the most important for hydrology." Ven Te Chow, Maidment and Mays, (1988)

Fondriest (2017) states that: “A range of hydrologic aspects need to be considered, both before and after introduction of a weir into an existing system. Answers can be sought for forecast streamflows, impact of climate change, localized changes to evaporation, turbidity, water temperature expectations, dissolved oxygen, and coloured dissolved organic matter”.

Forecast inflows may be extrapolated for existing creeks adding to the newly impounded water (subject to climate change modelling), to establish the level of drought proofing that would occur for a township’s treated water supply. This can be contrasted with the volume lost to evaporation.

2.2.1. Precipitation

The Australian Bureau of Meteorology (BOM) freely offers current forecasting to the public, and the site also has links to historical rainfall data.

Precipitation is recorded and uploaded from many 'stations' in Lake Eildon's vicinity and is accessible from 'Climate Data Online'. Precipitation records commenced in late 1879 and many data collection stations continue through today. Precipitation data is included in Chapter 3, and also in Appendix B & C.

In the Goulburn basin which includes Lake Eildon there are eight recording stations.

In Western Australia, a study was made by the Department of Water of Capel River Hydrology in which a centroidal daily rainfall series was developed for the upper part of the catchment. This used the Thiessen weighted polygon method to combine information from six of the gauges selected for use in their study. This is similar to what is available at Lake Eildon with the existing significant recording stations, in order to find an average for precipitation for the area. These polygons and their relationship to Lake Eildon can be seen in Chapter 3, Figure 3.3.

"Precipitation includes rainfall, snowfall, and other processes by which water falls to the land surface, such as hail and sleet. Ven Te Chow, Maidment and Mays (1988)

2.2.2. Evaporation

"The two main factors influencing evaporation from an open water surface are the supply of energy to provide the latent heat of vaporization and the ability to transport the vapor away from the evaporative surface. Solar radiation is the main source of heat energy.

Evaporation from the land surface comprises evaporation directly from the soil and vegetation surface, and transpiration through plant leaves. The processes of evaporation from the land surface and transpiration from vegetation are collectively termed evapotranspiration.

Actual evapotranspiration drops below its potential level as the soil dries out."

Ven Te Chow, Maidment and Mays (1988)

A significant amount of conjecture surrounds the measurement of evaporation, (particularly in open water) in part due to what is included or excluded in the process.

The QLD Govt Dept of Natural Resources and Mines in its Technical Report (2005) outlined the Australian synthetic daily Class A pan evaporation process.

The report outlined that: -

> "The Class A pan evaporimeter is the standard instrument used for such observations in Australia.
>
> The synthetic pan model does not include wind. Wind increases pan evaporation on dry days by moving water vapor away from the surface of the pan. The synthetic pan model does not include wind, because there is no reliable, readily available, gridded daily wind dataset for Australia".

The report further states that: -

> "To create a pan evaporation model suitable for climate change analysis, the following factors need to be considered:
>
> - A high-quality observed pan evaporation dataset is required. Creating a universally applicable pan evaporation model which correctly represents observed trends will be impossible without detailed, historical information about the pan environment and observing practices. Such information will either need to be parameterized and included in the synthetic pan model, or else a smaller 'homogeneous' dataset, consisting only of stations without complicating local factors, will need to be complied.
> - Reliable, gridded, daily, historical wind data is required. As demonstrated in Section 9.1, the error in the synthetic pan is high on days with high wind-run. In coastal regions, the direction of the wind, and the variation in wind throughout the day, should also be investigated.
> - The effect of rainfall on pan evaporation should be examined in greater detail.
> - Changes in the heat energy of the pan water could be included in the model.
> - Daily pan evaporation is the integration of diurnal variations in air temperature, solar radiation, wind, humidity, and pan water temperature. There must be a limit to how well this integral can be modelled using daily climate data. It would be very useful to have some idea what this limit is.
> - The model should include both solar radiation and long-wave radiation.

- Finally, all the above factors need to be synthesized into a physically based model for pan evaporation, along the lines of Linacre (1994)."

G-MW uses an evaporative Class A Pan to record daily evaporation, in which evaporation readings are read simply by refilling the pan using a measuring cylinder and entering the data in a BOM spreadsheet.

This pan is located within the Eildon Office compound in the Eildon township, below the main dam wall of Lake Eildon.

Land & Water Australia (2011) indicated that "while the focus is large scale storage (e.g., reservoirs) where evaporative losses can exceed 40% of water stored, it is hoped that delivery infrastructures and on-farm storages will benefit from this research".

Applied research is being undertaken in the application and benefit of advanced film technology. This includes the use of benign chemicals to provide a barrier to the loss of water through evaporation. "Reducing evaporation is an obvious way of pushing our water further and improving productivity."

For this project, evaporation has critical relevance, especially for weir sites with relatively shallow depth at their full capacity. With the main dam at full supply, it is less critical since the weir would be submerged by several metres of water above the weir's crest. However, if the main dam levels are lower than 40% storage, the weir becomes reliant upon in-feed from the creeks north/upstream, some of which may not be flowing for part of any one year. If water levels fall behind the weir and storage become shallow, higher summer temperatures could see the rate of evaporation per hectare increase.

To calculate lake evaporation within the developed models, the Bureau of Meteorology provides pan coefficients for the basin considered. Melbourne Water (2013) states that the methodology used "is based on measured pan evaporation that is multiplied by monthly pan coefficient factors. The pan evaporation approach is a 'point' method, rather than an 'areal' method".

A Comparison of Methods for Estimating Open-Water Evaporation in Small Wetlands was reported in Wetlands (2010) by Masoner, et al.

This American report stated that: -

"The pan evaporation method is one of the simplest and least expensive methods for quantifying evaporation in small open-water surfaces. Evaporation pans naturally incorporate the integrated effects of radiation, wind, temperature, and humidity on evaporation (Allen et al.,1998). Most evaporation pans in the United States are Class A pans set up on land. While evaporation pans on land integrate environmental effects on evaporation, land pans also alter the environmental effects to some degree. Although pan evaporation methods are widely used, resulting values cannot be considered to represent evaporation in nearby open-water surfaces without applying an empirically derived pan coefficient. Annual evaporation from lakes is commonly estimated by using nearby land pan observations and a pan coefficient ranging from 0.7 to 0.8 (Kadlec and Knight, 1996). For a season or less, use of a 0.7 to 0.8 pan coefficient can introduce large unpredictable errors, attributable to differences in turbulence, surface reflectance, heat storage, heat transfer, surface temperatures, and the temperature and humidity of air above the respective surfaces (Allen et al., 1998). Without the use of an empirically derived pan coefficient, standard Class A land pans usually overestimate actual evaporation" (Koerselman and Beltman, 1988, Sumner and Jacobs, 2005).

Evaporation measured with a floating pan submerged in an open-water surface has been shown to simulate physical conditions that control evaporation from the open-water surface more closely than evaporation measured with a standard Class A land pan (Masoner et. al.2008). Errors in evaporation caused by differences in turbulence, heat storage, heat transfer, surface temperatures, and vapor pressures above the respective surfaces are reduced because the floating pan better simulates these physical conditions of the open-water surface in which the pan is submerged. While the use of a floating pan has been shown to simulate physical conditions that control evaporation from small open-water surfaces, how floating pan evaporation measurements compare to standard measurements of evaporation is not known. Additional research is needed to compare evaporation measured with a floating pan deployed in small open-water surfaces to other common approaches to estimate

evaporation such as a land pan and Priestley-Taylor (PT) method as well as more accurate measurements made with a calibrated evaporation chamber".

2.2.3. Streamflow

"Excess rainfall, or effective rainfall, is that rainfall which is neither retained on the land surface nor infiltrated into the soil. After flowing across the watershed surface, excess rainfall becomes direct runoff." Ven Te Chow, Maidment and Mays (1988)

Management and reporting streamflow across Victoria are part of the range of activities carried out by DEECA.

Under 'Water and catchments', the 'water management information system' provides surface water sites where streamflow is measured on creeks assigned a streamflow gauge.

Figure 2.1 shows the site used to collect streamflow data, which for some of these rivers and creeks is reported in Chapter 3.

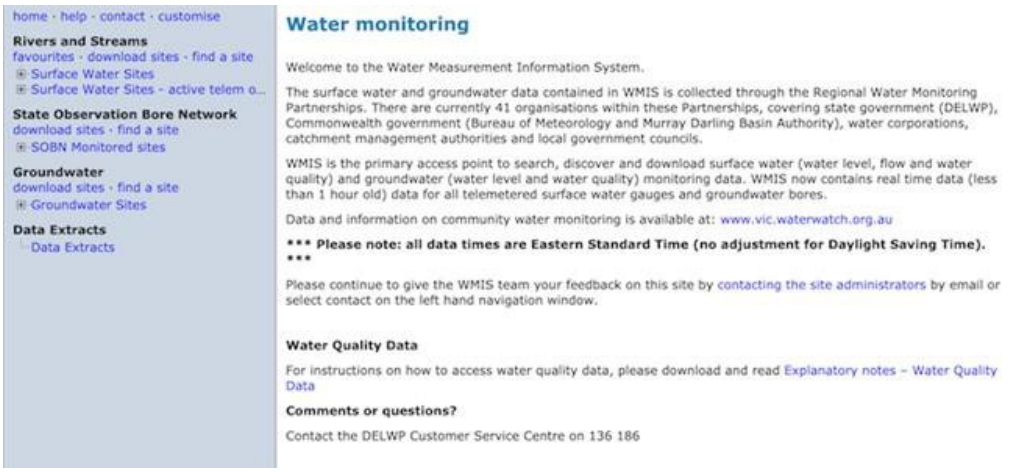

Figure 2.1: Streamflow Data - Water monitoring
(Source: DEECA, 2020)

Streamflow gauges are not always placed at the entry of the stream to a lake. They may be several kilometres upstream. Such placement might be for several reasons: -

- site chosen for easiest access to gauge for maintenance.
- a site closer to a reservoir might otherwise be under water at full supply level.
- runoff from land below the gauge might be intercepted by farm dams and would not have added to recorded data, so a site further upstream can still deliver a valid reading.

Some reporting stations have extensive histories of data recording, whilst others had a shorter life, especially where the stream was found to be unreliable with respect to continuity of flow.

Fondriest (2015) describes streamflow as "a measurement of the amount of water flowing through a stream or river over a fixed period. Streamflow cannot be measured directly, say, by plunging an instrument into a river. Instead, it must be calculated in a process known as stream gauging".

The South Australian Government, through its Department of Environment and Water (DEW), manages the state's waterways. It states that: -

"Surface water (such as water in rivers, lakes, wetlands, and estuaries) is a limited resource in South Australia and its sustainable management is vitally important to the environment and the economy of the state. Surface water data recorded through monitoring assists with the: -

- Efficient operation of the River Murray (by the department)
- Implementation of water planning and management across the state (by the department and the Natural Resources regions)
- Management of South Australia's hazards, such as flood and black water events (by government hazard agencies)
- Monitoring and reporting of the quality of the state's surface water resources (by the Environment Protection Authority), such as the annual aquatic ecosystem condition reports".

"Water level, discharge rate and volume, salinity, pH, dissolved oxygen, and turbidity are measured at 245 gauging stations in watercourses in South Australia. Most of the sites provide a near real time continuous dataset. Ecological monitoring is undertaken in conjunction with these parameters at some sites." DEW (2020). These parameters may have relevance to this project, especially at Site #1, where water depth at weir crest elevation 272 mAHD might be shallow.

Stream gauges are sometimes installed, capture data for a few years and are then removed. Cessation of record keeping creates a gap for comparison of data between water sources in the same or nearby catchments. If this data is fundamental to analysis, then how can an absence of data years be addressed? Is there any linear relationship with nearby streams? Can precipitation records give some help? Is it possible to extrapolate data using that of other streams?

In answer, rainfall within catchment for the northern creeks (those outlined in Chapter 1) gives some indication of likely streamflows. In addition, some historical streamflow reports prior to measurement ceasing shows how the different rainfall rates translate into the lower streamflows from one creek to another. For modelling purposes, the streamflow relationship that existed before reporting ceased was used to extrapolate data for the non-reported periods. This is outlined in Chapter 3, Tables 3.3 to 3.6.

2.3. Key hydrologic factors in weir site selection

A range of hydrologic parameters would be used to test locations for siting a weir.

Site options may change in mAHD, their invert levels and therefore weir height, creating an increasing reservoir of water with greater surface area, volumes, and evaporation loss.

G-MW manages many reservoirs and informs on its website that capacity of many storages has been designed to allow for irrigation supplies to be provided over at least two drought seasons. Although not exclusively intended to be flood control storages, considerable potential exists to mitigate floods in rivers downstream of storages. G-MW (2020) states that "Operation of the (Lake Eildon) power station during the irrigation season (August to May) is governed mainly by release of water to meet irrigation demands, but it may also be operated during winter and spring when flood releases can be used to generate electricity".

Their many storages are part of a regulated system, fed by a large collection of streams and rivers that create reservoirs which are then managed for release as required. One key hydrologic factor for weir site selection will be what is considered by G-MW as the maximum percentage of total capacity that can be allocated for reserved use by local water supply and boating and not for release for irrigation. Ideally, even in drought conditions, the aim would be to retain such water in as close to maximum weir FS volume to service local community domestic water needs and provide for recreational boating.

Hydrologic modelling would play an important role for management decision-making around selecting potential weir sites.

DEECA (2019) states that "The Council of Australian Governments (COAG) endorsed a National Hydrological Modelling Strategy (NHMS) in 2008 to support and enhance hydrologic modelling and to ensure future water planning and management across Australia is informed by best practice modelling. An integrated river basin water resources modelling platform known as Source is the key deliverable of the strategy. The platform is developed and maintained by eWater Limited, a joint government-owned, not-for-profit partnership, of which the State of Victoria is a company member". DEECA has developed a strategy to transition from REALM (platform prior to SOURCE) to SOURCE. This modelling might be done

beyond this project's thesis by consultants employed to assess its integrity for the adoption of a larger pilot program.

G-MW provides a raw water product to its customers and does not provide treatment services. It states that "As the water is untreated, the open nature of the water storage and supply systems means that G-MW cannot guarantee any particular quality of water. Water supplied by G-MW is not suitable for drinking without first being properly treated. G-MW is responsible for the management of blue-green algae in its storages and irrigation areas. (It) undertakes regular basic water quality monitoring within its storages and supply systems."

As a further part of this project, for site selection and recommendation, an evaluation would be needed on the impact of different depths of the newly created weir on water quality; what changes might occur in turbidity and evaporation, what risks arise for the incidence of blue-green algae if water temperature rises in shallow areas and oxygen levels decrease? These will be highly relevant for water pumped for treatment and delivery to domestic customers.

2.4. Potential impacts of climate change on local hydrology

Historical data to 2019 indicates that rainfall and streamflows have already shown signs of climate change impact with streamflow reduction for both creeks and rivers feeding Lake Eildon. DEECA forecasts for the years 2040 and 2065 predict an even greater reduction. Modelling will measure the degree of impact.

DEECA (2019) states that the department's purpose is that: -

"DEECA brings together Victoria's climate change, energy, environment, water, forests, planning, local government, and emergency management functions into a single department to maximise connections between the environment, community, industry, and economy. Our challenge is to improve Victoria's livability with a population that is expected to almost double by 2050, while responsibly tackling climate change and protecting our natural environment, infrastructure, and heritage for future generations".

The reality and impact of climate change is now accepted by most people in the field of science.

Many examples of a changing environment have found prominence, from prolonged droughts, melting of glaciers, higher frequency of critical environmental incidents for floods and fires and events not experienced before, like rising sea levels.

DEECA (2016) notes:

"The latest climate research from the Victorian Climate Initiative has identified clear reductions in cool season (April to October) rainfall over recent decades. This trend has continued despite some wetter years since the Millennium Drought. This has significant implications for water corporations as it represents a shift in the reliability of rainfall during the traditional storage filling and aquifer recharge season. Climate change, both globally and in Victoria, has manifested to date as a mix of gradual and step changes".

This has significant implications for a weir within a weir, including: -

- If the frequency of overtopping from rising downstream water reduces, do the upstream creeks keep the weir filled?
- What will water levels be for the three weir options if greater reliance is placed on water feed from upstream?
- Do the changes caused by forecast climate change render one or more of the weir sites non-viable?

The impact of prolonged drought in many parts of Australia in recent times, and still existing in some Australian states has precipitated the formation of a project called Dead Tree Detectives. Project participants upload photographs of dead trees to the Atlas of Living Australia website.

Associate Professor at the Hawkesbury Institute for the Environment at Western Sydney University, Brendan Choat, (2019), said it was an important project which monitors impacts of climate change.

DEECA (2019) has committed that: -

"Our water sector will be a leader in the state's climate change mitigation and adaptation actions, equipped with the most up-to-date understanding of climate change and associated risks to water resources."

Its mission is to: -

- "Achieve net-zero emissions in the water sector by 2050,
- Understand and apply climate science to water management,
- Lead climate change adaptation across Victoria's water sector."
- The Millennium Drought in south-east Australia, between 1996 to 2010 was the driest period experienced since European settlement began in 1788."

The Victorian Department of Energy, Environment and Climate Action (DEECA) predicts an even greater decrease in streamflow as the impact of climate change occurs. In its paper "Preparing for and responding to climate change", updated 20/2/2019, DEECA reported: -

"Over recent decades Victoria's climate has become drier and warmer. The recent Millennium Drought was the worst drought on record in south-east Australia. Streamflows dropped to record lows and many communities faced severe water restrictions. By 2065, it is predicted that streamflows in some catchments could reduce by around 50 per cent. This would have serious consequences for everyone: households, industry, agriculture, recreation, cultural values, livability, waterway health, and our environment."

University of NSW (UNSW) Researchers stated in their UNSW Newsroom, (2020): -

"Reservoir reliability – or the frequency with which a reservoir can supply surrounding urban or rural populations without invoking water restrictions – will fall across the country as we head towards the end of the century. In other words, if a current reservoir is designed to face water restrictions 10% of the time today, by the end of this century this figure will rise to 30%."

Warragamba Dam, shown in Figures 2.2 below, supplies water to 3.7 million people in Sydney and the lower Blue Mountains and was sitting at 42.6% full in January 2020 (96% May 2021).

It is often stated that irrespective of actions taken now to mitigate the impact of climate change, there will be a lag time before any reversal of global warming is evident. This is exemplified with Sydney's Warragamba Dam. When built in 1960, it was for a much smaller population than in 2020, but it was built to service a forecast larger population. The problem now is whether it can be regularly filled as runoff reduces. Currently, an unexpected significant weather event has significantly added to storage (at 96% capacity in May 2021).

Figure 2.2: Warragamba Dam at 42.6% storage
(Source: Shutterstock, 2019)

The UNSW scientist Sharma notes: -

"In our previous research we found that for each degree rise in temperature, you have roughly 10 to 15% reduction in the flood peak. This is even though with increased temperature; you store more moisture in the sky and hence cause more intense storms.

Why this happens is because the higher temperatures are drying out the soils faster than before. So now when it rains, a lot of the water that would have previously ended up in the dams is now being absorbed into the parched soil. And so, these frequent flood events are now delivering less water to natural reservoirs" (Sharma et al. 2020).

The UNSW scientists, Sharma et al. (2020) showed that for 222 catchments to which six of the latest climate models were applied, all showed a forecast reduction in supply.

"Historically, when rains fell, the ground was often saturated, and runoff occurred. With rising temperatures, the ground is drier, so to maintain runoff, higher falls of rain are needed. With that not happening, except when very occasional significant events occur, streamflows reduce."

The impact of climate change will need to be modelled to ensure that proposed weirs would regularly be holding back water, not sitting on dry land.

The impact of prolonged drought was highlighted by Peterson et al. (2021) who stated that:

"An analysis of Victoria's river catchments shows we can't assume water levels above and below ground bounce back to normal when a drought ends."

The study by Peterson et al. (2021) found that one-third of 161 catchments from across the state still had not recovered seven years after the Millennium Drought ended in 2010.

Peterson et al. (2021) continued: -

"It tells us that hydrological droughts — the ways our rivers and aquifers respond — can continue long after the meteorological drought ends."

Not only had these catchments not recovered, about 80 per cent appeared to have got stuck in drought mode. Peterson noted that "100 millimeters of rain before the drought produced more stream flow than 100 mm now. There's effectively 30 per cent less rain making it into the stream. Drought seemed to push [the streams] into a different way of behaving."

Figure 2.3 gives a clear indication of the decline in rainfall across south-western Australia over the last century, with the moving average showing a decline of 100mm in the last century.

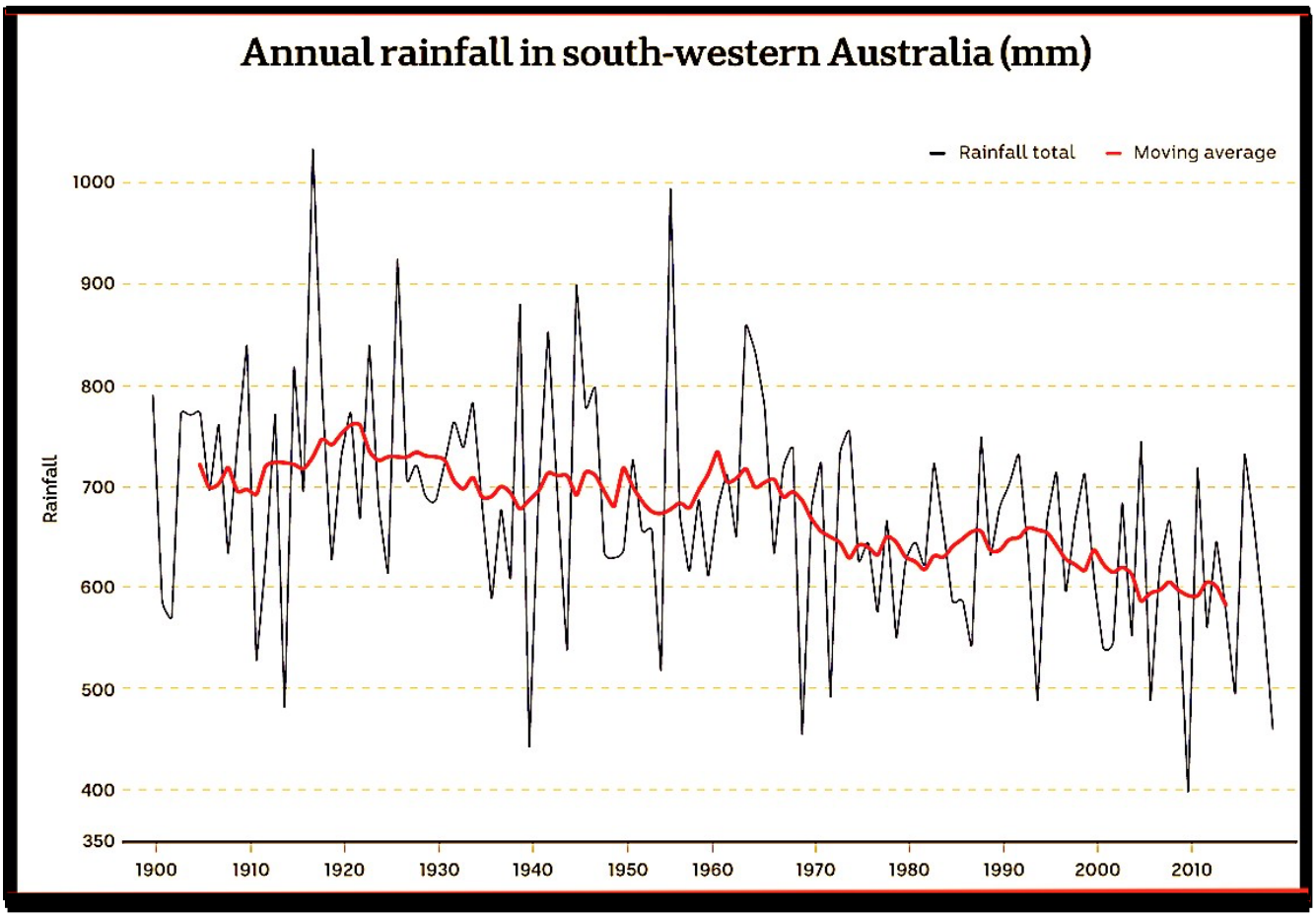

Figure 2.3: Declining moving average in rainfall in south-western Australia 1900-2020
(Source: Science, May 2021)

The BOM (2020) has data for streamflows for gauging sites Australia-wide. Figures 2.4 and 2.5 below show facts for the example taken, Murrindindi River, and graphs the variation from the average flow. This river is downstream of Lake Eildon.

The Millennium Drought from 1996 until 2010 is very apparent, with streamflows consistently below average for almost thirteen years. This has also been shown for rivers feeding Lake Eildon.

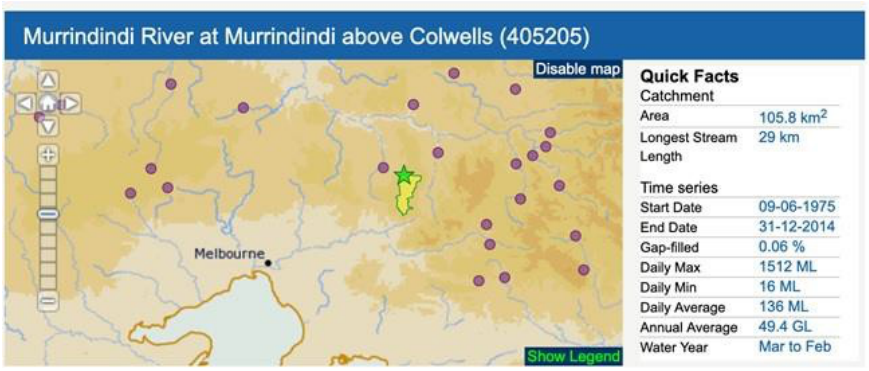

Figure 2.4: Murrindindi River location and Quick Facts
(Source: BOM, 2020)

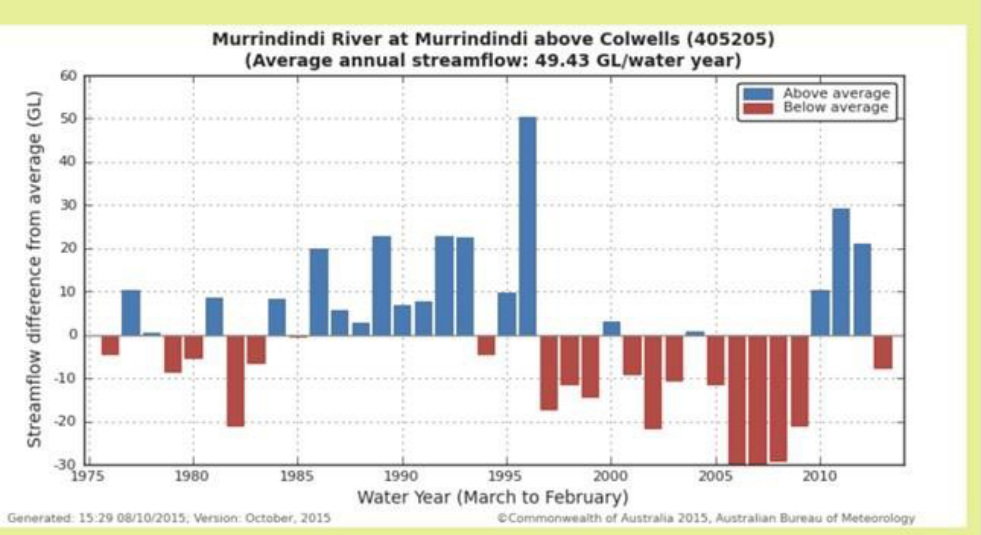

Figure 2.5: Murrindindi River streamflow difference from average
(Source: BOM, 2020)

'Climate variability and change' data is also available from BOM (2020), as follows and tracks the annual mean temperature anomaly. Figure 2.6 below presents the Australian climate variability & change – Time series graph. The figure shows the "mean temperature anomalies averaged over Australia (as calculated from the 1961-1990 average). The black line shows the 11-year moving average. Each year can be selected to show the anomaly)".

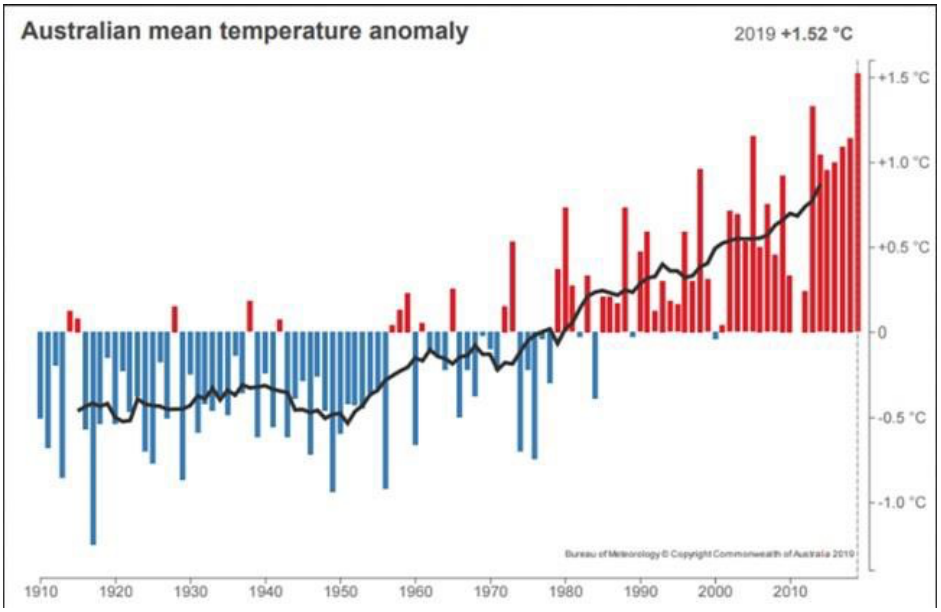

Figure 2.6: Mean Temperature Anomaly
(Source: BOM, 2020)

2.5. Primary considerations for weir viability

Three primary considerations for the viability of building a weir within Lake Eildon are outlined in sections 2.5.1, 2.5.2 and 2.5.3. Other than these three, there are several other considerations listed in Section 2.6, which are also important but are not considered in great detail in this study.

2.5.1. Topographic and geologic considerations

The United States Bureau of Reclamation (USBR) (1987) indicates that "topography, in large measure, dictates the first choice of type of dam."

They suggest that low rolling plains are best suited by an earthfill dam.

The topography for the most ideal weir sites is a location where embankment length is minimized. It is an advantage if the weir ends on a relatively steep slope.

Topography considers: -

- Surface configuration of the weir site and retained reservoir behind it (e.g., the concept of storage-excavation ratio, an unusual issue here re storage-excavation, i.e., balance between surface area + & -, and volume held back by weir)
- Ease of access to the building site,
- Location of materials, either a concrete base station on site or earth and stone imported from local quarrying.

USBR (1987) states that geologic questions include the suitability of local rock and soil types as foundation and construction materials. "The foundation geology at a damsite often dictates the type of dam suitable for that site. The strength, thickness, and inclination of strata; permeability; fracturing; and faulting are all important considerations in selecting the dam site (page 65).

Different foundations commonly encountered include: -

- Rock,
- Gravel,
- Silt or fine sand,
- Clay,
- Nonuniform.

These different foundations influence the type of dam that can be constructed on them".

The Geological Society of Australia – Victorian Division (GSA Victoria) can be accessed for an extract of Victoria's geology. A detailed survey can be obtained for a given area, identifying that local geology.

2.5.2. Structural considerations and access to materials

In the USBR (1987) text Designs for Small Dams, it was indicated that there are three main dam material types, earthfill, rockfill and concrete. Variations of these can occur, such as rock and earthfill or also with a concrete core. Site availability of

excavated earth or local rock may influence the structural components. Concrete dams are considered the most expensive to construct but may be used where there is no option for a very wide footprint (as in Site #1), as needed for alternatives. Structural design differences arise for dams and weirs according to a variety of parameters.

These include: -

- Their purpose, being storage, diversion, or detention - USBR (1987) states that "Dams may be classified according to the broad function they serve",
- The geology of a proposed site,
- Location of building material (stone, rock, clay, or concrete),
- Proximity of other structures (such as bridges or roads) and
- Proposed weir height.

Structural design options will also affect cost. These options could include a gated barrage as seen on the Fitzroy River near Rockhampton, Queensland (Appendix A), an overtopped weir, as proposed in the Narrows Project on Lake Hume (Section 2.6), or some other structure. Location of the weir/barrage will also influence which structure is an option, as a wide embankment wall footprint might fit one site, whilst being impossible at another, if there is close proximity to existing structures.

USBR (1987) states that "Earthfill dams require appurtenant structures to serve as spillways and outlet works. The principal disadvantage of an earth fill dam is that it will be damaged or may even be destroyed under the erosive action of overflowing water if sufficient spillway capacity is not provided."

This project, in which a weir is proposed to be constructed within a weir, implies that there may be no designated spillway, as periodically the weir's entire crest will be overtopped, either from water upstream, or from the main dam rising and overtopping from the downstream storage as it fills. This rules out a barrage structure.

Rip rap is often applied to a dam wall batter to stabilize it, but not ordinarily for any overtopping purpose. It could be a significant material component in a weir wall within Lake Eildon, avoiding erosion from frequent overtopping.

Since it is assumed that such a weir would not normally be overtopped, for this to happen, with regularity but without damage, consideration could be given to following that applied in construction of the Horsetooth Dam, (Colorado) constructed by Bureau of Reclamation.

Figure 2.7: Rip Rap with 60 years of history, Horsetooth Dam
(Source: USBR, 2012)

Chanson (2015) reported on overtopping protection systems that "The overtopping protection systems include concrete stepped overtopping protection, minimum energy loss (MEL) spillway, gabion stepped spillways and precast concrete block protection systems".

Hepler et al. (2012) outlined that "the design and construction of overtopping protection for dams is increasingly being viewed as a viable alternative to

constructing larger spillways or increasing reservoir storage by raising the dam crest".

Allowing for overtopping by design is therefore very contemporary thinking, for the reasons above, so an overtopped weir within a reservoir from either upstream or downstream (as the main reservoir fills above the weir crest height) is no longer an unusual proposition. *What is irregular is the potential for the weir to remain underwater for varying lengths of time, even more than one year*.

Other considerations are inclusions or exclusions of fish ladders, gates, and locks. These will be dealt with in the concluding chapter. Steep abutment slopes are also critical in minimizing the length of the embankment.

2.5.3. Economics

In the case of the Narrows Project (2014), (see section 2.7) recreational use was the sole benefit and measurement of that benefit alone failed to justify the expense of two of the four options.

In the Lake Eildon project, benefits accrue to recreational boating users, township water consumers via a treatment plant and as a storage for pick up for fire-fighting purposes.

However, certain sites might dictate a structure that is significantly more expensive than can be justified for the benefit delivered. This could be the case for a weir site close to the bridges at Bonnie Doon, necessarily constructed of concrete, but for low storage volume and little boating surface area.

2.6. Other considerations

2.6.1. Water quality is of critical importance if it is to enter a treatment plant to service a local community's domestic water supply, as at Bonnie Doon. The better the raw water quality, the easier the treatment, with less chemical application. Fondriest (2015) outlines the 'elements' impacting on water quality.

2.6.2. Planning processes in today's natural and human environment requires an awareness of the environmental impact of a project. Some are required at Local Government level, with others applied by state authorities, e.g., EPA (Victoria).

2.6.3. A new Environment Protection Act was scheduled for release in 2021. "The Governor in Council has proclaimed that the new EP Act which commenced on 1 July 2021.

'Proposed final' versions of the new subordinate legislation – the Regulations and ERS – are available to support Victorians to prepare for the new Environment Protection Laws". EPA and DEECA worked together to develop the proposed final Regulations and ERS in consultation with community, government, and industry stakeholders" EPA (2021).

2.6.4. Inclusion of a wetlands within the area where Brankeet Creek enters Lake Eildon is seen as strengthening the project, being an environmental addition to the overall brief, and an expansion to tourist value for the project.

In its outline of Inland Riverine Wetlands in Australia, The Australian Government's Department of Sustainability, Environment, Water, Population and Communities (DSEWPC) (2021) indicates that: -

- "Inland riverine wetlands are mostly in eastern Australia where the rainfall is higher and there are more rivers.
- They have evolved to cope with the country's dry, but highly variable climate.
- These wetlands provide refuges for wildlife during drought.
- They can store flood waters during floods."

Many plants and animals benefit from wetland environments. These include:

- Platypuses, which live readily in inland riverine wetlands, feeding on small crayfish and worms.
- Migratory birds often using wetlands as staging points in their travels, to rest and feed.
- Native reed plants finding a ready habitat.
- Native fish finding them an ideal nursery.

Issues, other than those covered above, include environmental, Water Act, Native Title, social, traffic, heritage and cultural, and management planning.

Additional other issues and risks within this project will be outlined in Chapter 6.

2.7. The Narrows project.

Literature (from both SMEC and GHD reports) relating to The Narrows Project is reviewed in some detail as there are many elements of that project which parallel aspects of the Lake Eildon project.

The proposed (but rejected by a cost-benefit analysis undertaken) Narrows Project (2014) is an example of a weir, within a dam. It was designed to be overtopped, to fill an upstream dam from a rising large existing dam, or from a river passing from upstream of the weir.

A review of weir types in Australia was undertaken, as seen in Appendix A, and the weir proposed in the Narrows Project is also considered a suitable contender and is possibly aligned with the needs of this project.

The Narrows Project, located at The Narrows (3km west of Tallangatta in Victoria and within Lake Hume), was promoted to deliver a consistent water level for boating and tourism for peak seasonal (mostly summer) activities, along with economic and social benefits for the local township. Its proposed weir was to be filled (a) from upstream by the Mitta Mitta River, or (b) by overtopping from a filling Hume Dam.

The project was driven by the Towong Shire Council, firstly by the engagement in 2014 of consultants SMEC who prepared a technical feasibility study report of building a water control structure across the Mitta Mitta River on Lake Hume.

2.7.1. Hydrologic considerations for The Narrows

The Lake Hume project had no need for community water security, as the reliable Mitta Mitta River flows nearby and supplies water for Tallangatta residents.

The river's water security is provided by Dartmouth Dam, upstream of Tallangatta. Water security for local residential use was therefore not a new benefit of the project.

Lake Hume periodically releases water for irrigation and environmental use, to the extent that water for recreational use disappears in the vicinity of Tallangatta. This was said to impact on the local economy and forced boating operators to look elsewhere, such as Lake Eildon or Yarrawonga Weir. Maintaining seasonal boating water above The Narrows was the core value of the project.

One significant cost attributable to both Lake Hume and Lake Eildon is that of the value applied to evaporation loss. Withholding water that would otherwise be discharged for irrigation purposes increases the surface area of a combined lake and weir. This increases annual evaporation above what would occur in the absence of water impounded behind a new weir. This implies the need to purchase water rights from the market. An alternative might be to include in the project's overall cost a trade-off such as converting an open channel to a closed pipe water transfer, downstream in part of the channel delivery system.

Its variable cost was a function of the proposed range of weir height options.

SMEC (2015) indicated that for an increase in crest level of six metres (from mAHD184 to 190), evaporation increased from 2.8 GL to 10.8 GL (as can be seen in Table 2.1).

Table 2.1: Crest level and evaporation increases

The Narrows Crest Level	**Total Average Annual Incremental Evaporation**	
(mAHD)	(ML)	(GL)
190	10080	10.1
188	7800	7.8
186	4800	4.8
184	2800	2.8
Source: Table 5.3 from SMEC (2015)		

Note: The weir site at The Narrows has an assumed foundation level of EL 176m AHD (Source: SMEC, 2019)

That is, a 75% increase in weir height (8 to 14 metres) delivered a 386% increase in evaporation (2.8 to 10.8 GL), a factor to be considered when determining the ideal weir height. With water trading prices in 2019 at around $2,800 per ML and forecast to increase with time, the cost implied in a project for evaporation is significant. For the Narrows Project this evaporation cost, for a weir of lowest height of 8m, was AUD$7.8 million, with an ongoing annual headworks storage charge of some $33,000.

2.7.2. Geological considerations for The Narrows

The consultants for the Narrows Project gave significant consideration to the local geology for the proposed site, as to its suitability for the proposed weir.

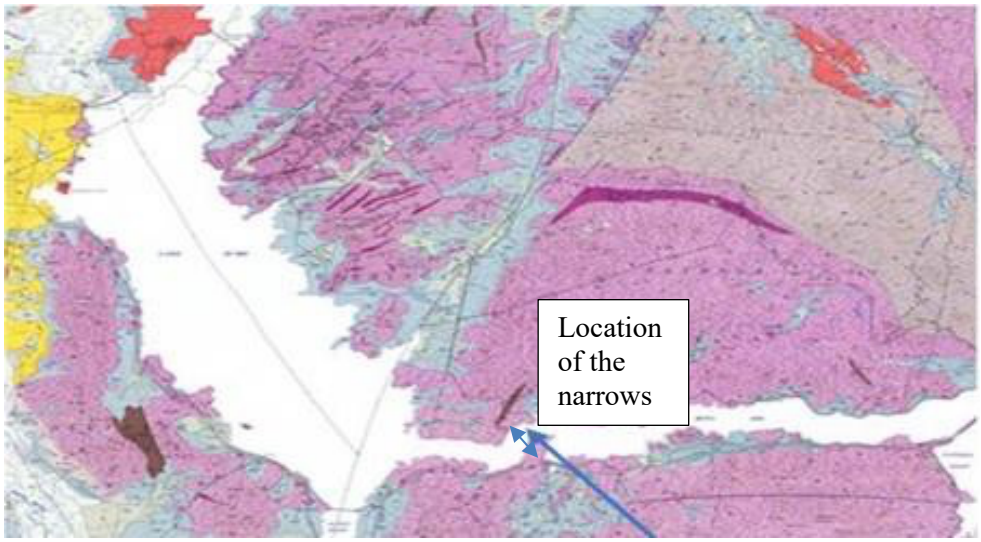

Figure 2.8: Location of The Narrows, and its surrounding geology (Source: SMEC, 2015)

The blue arrow in Figure 2.8 shows the location of the 'Narrows' and its adjacent geology.

2.7.3. Structural and cost considerations of The Narrows

Phase Two of the Narrows study was undertaken by GHD (2015) to develop a cost benefit analysis (CBA) for two (of four) structures considered. The two options considered were (a) Rockfill structure with a core cut-off; and (b) Zoned earth and rockfill structure with a core cut-off. Both are shown in Figure 2.9 below.

GHD considered the construction costs for the two different material mixes, together with ongoing cost estimates to operate the new weir.

Within both CBAs, addition of a fish ladder was included at slightly more than five million dollars.

Additional cost accrued to the Narrows Project by way of an elevated road across the Narrows. No road is needed nor included in the Lake Eildon project. The main similarity between both projects is the provision of a weir within a lake's arm at a height which would allow it to be periodically overtopped.

Cost for option (a) weir was estimated at $64,690,100, and for weir (b) $52,665,040, with, for each case, an extra $25,200,000 for the roadway and $5,040,000 for the fishway.

The weir diagrams provided by SMEC in Figure 2.9 below lack some parameters, which are: -

- Weir height of 8m.
- Crest width of 5m.
- Core cut-off of 8m x 5m x 400m. Note: Crest is reported as 10m and core cut-off is assumed as 5m, as stated in SMEC/GHD reports, despite not to that scale in Figure 2.9 below.
- Batter slope upstream 5:1, downstream 3:1.

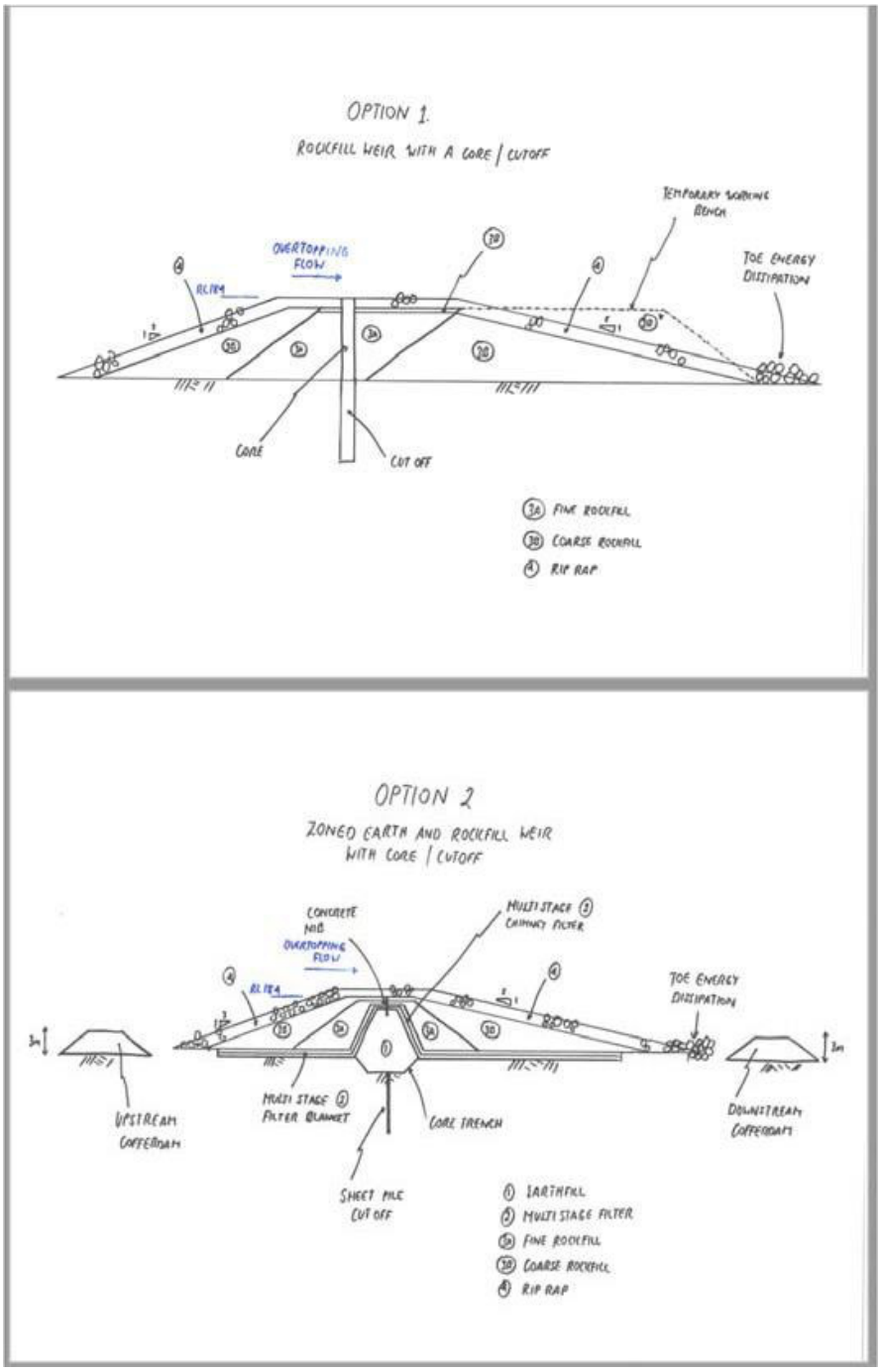

Figure 2.9: Two of four construction options chosen for Narrows Project (Source: SMEC, 2015)

Chapter 3: Compilation of hydrologic and other data

This chapter outlines and reflects the range of data required for the investigation of the hydrology around Lake Eildon and the proposed weir sites under consideration. Analysis of rainfall and streamflow data presented in Chapter 3 will be made within Chapter 4.

3.1. Introduction

There are five rainfall stations in the vicinity of Lake Eildon with a long history of records service. Four relevant stations were selected, details of which are shown in Table 3.1. The fifth station, Alexandra PO, is excluded as it was considered too remote from Lake Eildon to have any influence.

Table 3.1: Rainfall stations in detail/location with "metres Australian Height Datum" (mAHD)

Station Name	Station Number	Open year	Coordinate #1	Coordinate #2	mAHD
Lake Eildon	088023	1887	37.30*S	146.04*E	230
Mansfield PO	083019	1901	37.05*S	146.09*E	316
Strathbogie	082042	1902	36.85*S	145.73*E	502
Strathbogie North	082043	1879	36.81*S	145.82*E	557

Other rain gauge stations exist, but those only have a recent/short history of records. These are Lima East (Charnwood), Merton (Enderlee) and Eildon Fire Tower. The four selected stations (listed in Table 3.1) provide the minimum history sought for forty years. These are included as part of the eight stations in Figure 3.1 below.

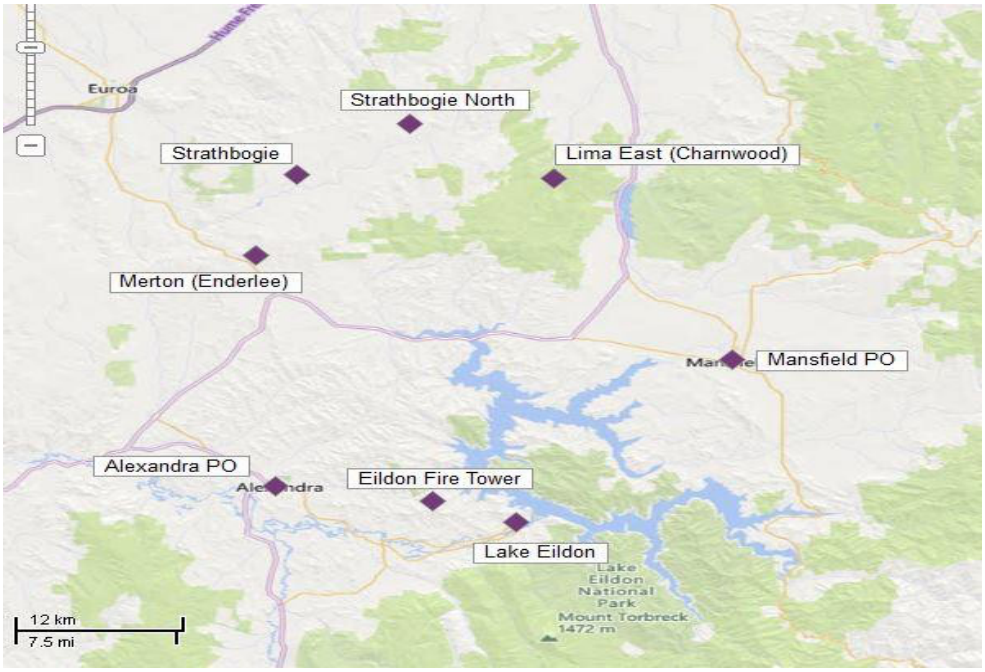

Figure 3.1: The eight raingauge stations in vicinity of Lake Eildon (Source: G-MW, 2020)

The three rainfall districts impacting Lake Eildon are shown in Figure 3.2. These three districts indicate the rainfall reporting stations with long data history impacting Lake Eildon. District No. 1 includes Strathbogie and Strathbogie North, District No. 2 includes Lake Eildon and District No. 3 includes Mansfield PO.

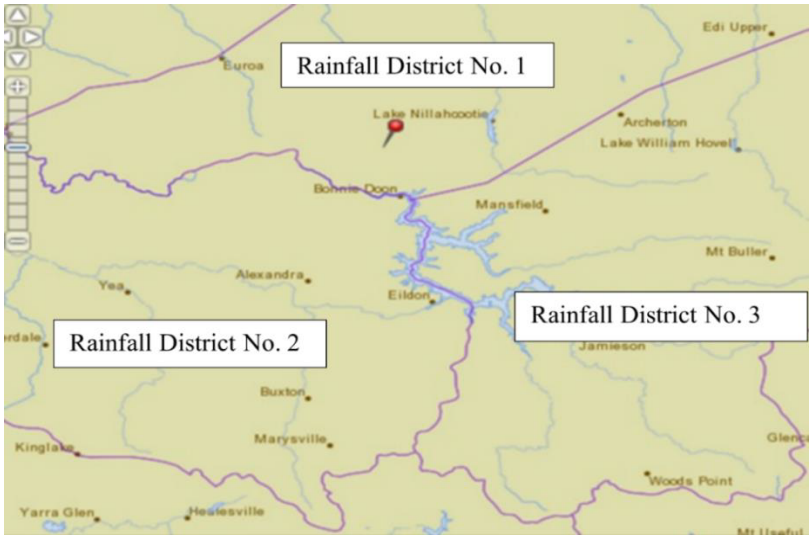

Figure 3.2: Three major rainfall districts feeding Lake Eildon. (Source: BoM, 2020)

3.2. Total rainfall over 40 years at four reporting stations

Rainfall for the four selected long term reporting stations around Eildon are graphed in Figure 3.3 and 3.4 below. As can be seen in the figures, the heaviest rainfall was recorded at Strathbogie North, which impacts the streamflow, but its precipitation does not directly fall on the lake.

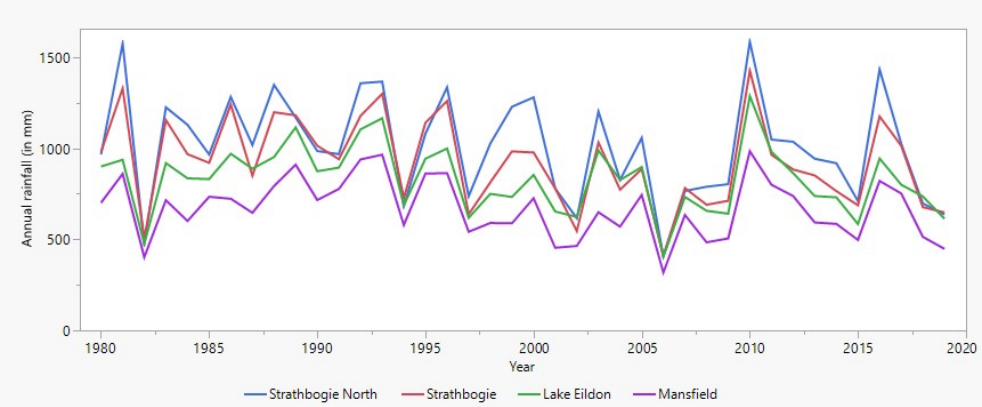

Figure 3.3: Four major rainfall stations near Lake Eildon (40 years 1980 – 2019) (Source: BOM, 2020)

Figure 3.4 below presents the same rainfall data as in Figure 3.3 graphed as a bar chart.

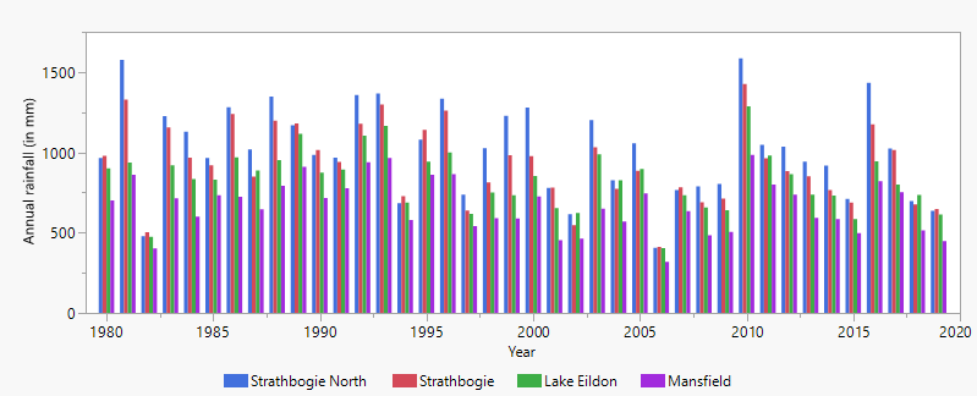

Figure 3.4: Rainfall values for the four stations presented as a bar chart (40 years 1980 – 2019)

(Source: BOM, 2020)

The rainfall characteristics for the selected four stations over the 40 years is presented in Table 3.2.

Table 3.2: Rainfall over 40 years in Lake Eildon catchment – four stations

Rainfall station	**Strathbogie North**	**Strathbogie**	**Lake Eildon**	**Mansfield**
Rainfall over 40 years (mm)	40,478	36,995	33,144	26,784
Average (mm per annum)	1,012	925	829	670
Ranking	1 (100)	2 (91) [1]	3 (82) [1]	4 (66) [1]
[1] The values in brackets are percentages of rainfall (over 40 years) at Strathbogie North				

3.3. Streamflows

3.3.1. Creeks north and northwest of Bonnie Doon

Four significant creeks are upstream of lake Eildon and will be analyzed in chapter 4 for their importance in discharging into the Brankeet Arm of the lake, feeding the new weir, especially in times when no overtopping is occurring upstream from the

main dam. Figure 3.5 below indicates that the greatest deliveries per 5-year intervals are made by Brankeet Creek, followed by Merton Creek. Tallangalook and Glen creeks have much less significant streamflows. Throughout summer, Brankeet creek may continue with low flow, whilst the other three would normally cease to flow except (briefly) following summer storms.

Streamflow varies significantly between the wet and dry seasons, where the wet season is July to October and the dry season is November to June. Each total creek's discharge is reflected in Figure 3.5 and Table 3.3 below. Estimates, for the non-reporting years for Merton, Tallangalook and Glen creeks are based upon their recorded history as a percentage of Brankeet Creek, extrapolated.

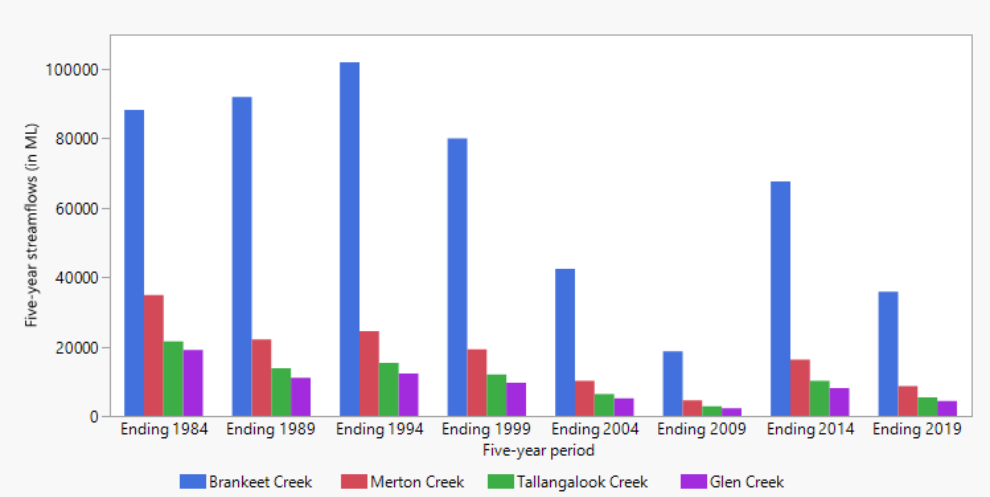

Figure 3.5: Five-year streamflows in the Northern Creeks

(Source: DELWP, 2020)

Figure 3.6 below shows the location of the Northern Creeks at the northern extremity of Lake Eildon, being the Brankeet Arm of the lake. The red dots indicate the location of the gauging stations on each creek.

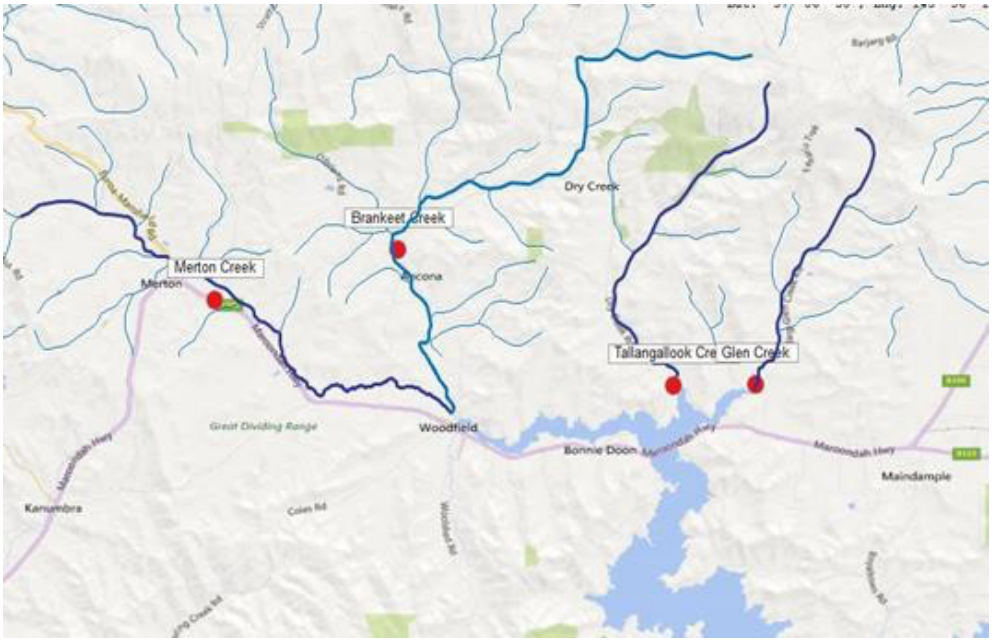

Figure 3.6: Location of the Northern Creeks discharging into Brankeet Arm of Lake Eildon

(Source: G-MW, 2020)

Whilst Brankeet creek has data for the full forty years, the remaining three, Merton, Tallangalook and Glen creeks have actual data briefly, from 1/1/1980 until 1/11/1982. Estimated streamflows, based on Brankeet Creek flows were used for the remaining years, with actual fractions for Brankeet Creek extrapolated to give these estimates.

Table 3.3: Northern Creeks discharge volumes, wet and dry seasons and combined.

Creek / Season	Actual recorded volumes (ML)	Estimated volumes (ML)	Total volumes 40 years (ML) incl. estimates
Brankeet Creek – Dry	181,385	NA[1]	181,385
Brankeet Creek – Wet	276,377	NA[1]	276,377
Brankeet Creek - Full Year	457,762	NA[1]	457,762
Merton Creek – Dry	4,468	49,272	53,740 (30)[2]
Merton Creek – Wet	51,082	134,090	185,173 (67)[2]
Merton Creek - Full Year	55,550	183,362	238,913 (52)[2]
Tallangalook Creek - Dry	3,065	40,373	43,438 (24)[2]
Tallangalook Creek - Wet	30,726	80,654	111,380 (40)[2]
Tallangalook Creek - Full Year	33,791	121,028	154,818 (34)[2]
Glen Creek – Dry	3,679	36,418	40,097 (22)[2]
Glen Creek – Wet	23,559	61,842	85,400 (31)[2]
Glen Creek - Full Year	27,238	98,260	125,498 (27)[2]

[1] The Brankeet values were available for 40 years and an estimation was not required. For the other 3 stations, since data was available for about 3 years, 37 years of estimates were based on available data from Brankeet.

[2] Values in brackets are percentages of Brankeet streamflow

Table 3.4 below reports average streamflows for the five major rivers feeding lake Eildon, all entering the lake well south (downstream) of the Bonnie Doon bridges. The Goulburn River is the major contributor and is also the river named after discharge from Eildon Dam.

Table 3.4: Streamflows from major rivers flowing into Lake Eildon

River	Commenced reporting	Years to 30/6/2020	Discharge ML/annum over reporting period	Discharge ML/annumAverage over 40 years	Discharge ranking
Goulburn	1968	52.5	314,209	287,415	1
Big	1970	49.8	286,640	273,414 (95)[1]	2
Jamieson	1959	60.75	203,572	190,144 (66)[1]	3
Howqua	1974	46	160,517	154,886 (54)[1]	4
Delatite	1957	63	100,185	92,367 (32)[1]	5

[1] The numbers in brackets are percentages of Goulburn River's streamflow over the 40 years

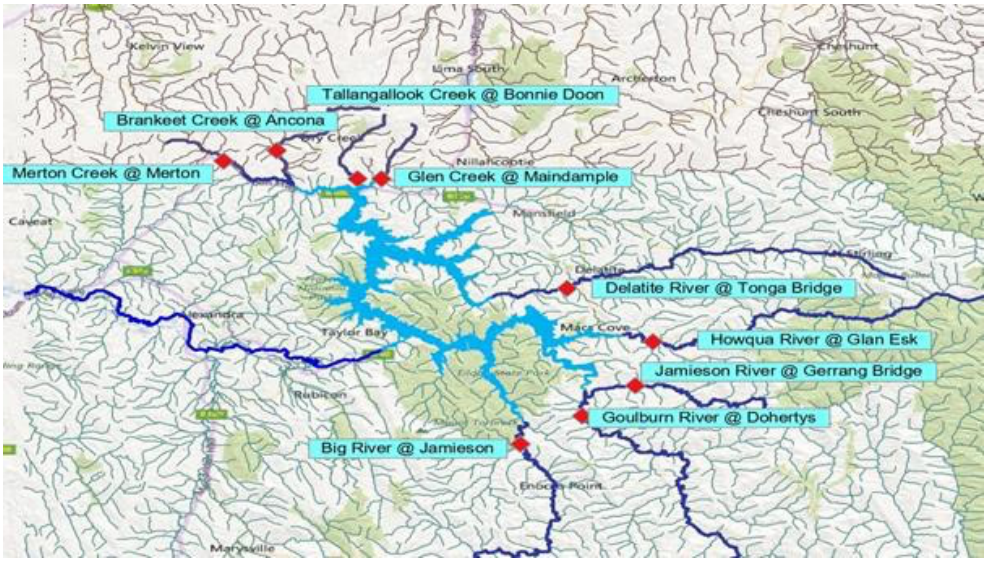

Figure 3.7: Five major rivers and four creeks impacting Lake Eildon (Source: G-MW, 2020)

Figure 3.8 reports the major river flows in graphed form. The Goulburn and Big rivers are the most significant.

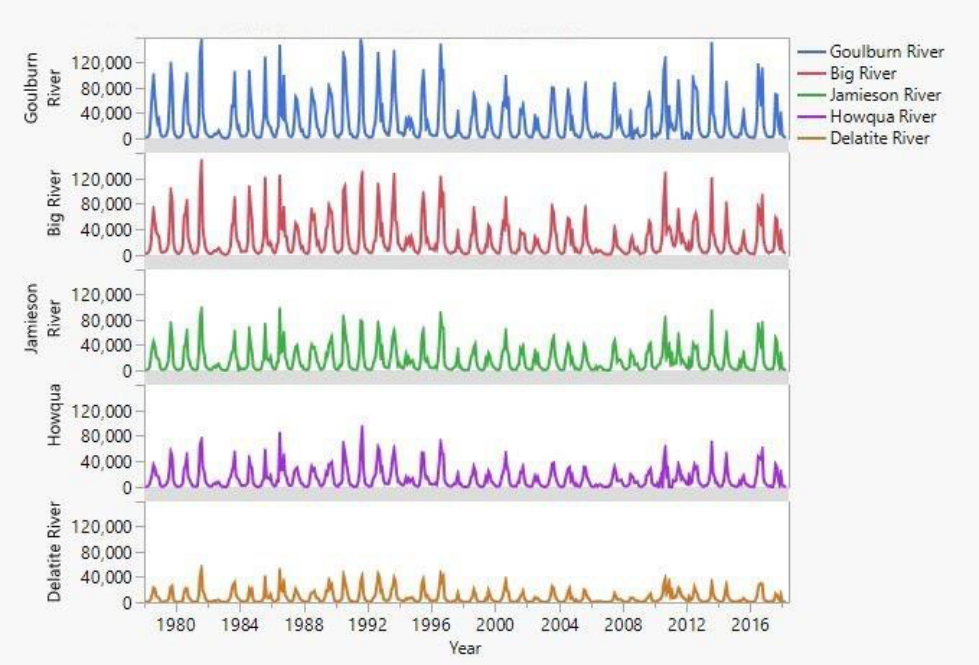

Figure 3.8: Streamflows in the five major rivers (in ML per month)
(Source: DELWP, 2020)

3.4. Evaporation

Monthly egross in mm for a Class A evaporation pan were derived from data provided in 2019 by Murray-Goulburn Water (M-GW). The Pan is located adjacent to the M-GW office within the Eildon township. The given reduction factors are applied for respective months. The sum of monthly rainfall is then deducted from the resulting egross and then multiplied by the surface area/100 to give ML of net egross for evaporation. In this study, the coefficient used for historical data was a constant value of 0.67, increased to 0.75 for climate change.

The monthly egross used are shown in Table 3.5 below, adjusted by the coefficients 0.67 or 0.75. From these figures are deducted the rainfall for respective months, becoming a part of the multiple for surface area, to derive the evaporation applied to the Volumes spreadsheet.

Table 3.5: Egross (mm) to be applied to historical (Chapter 4) and climate change modelling (Chapter 5) spreadsheets

Month	Evaporation (mm)	Historical data Factor	Egross (mm)	Evaporation (mm)	Climate change data factor	Egross (mm)
January	175	0.67	117	175	0.75	131
February	175	0.67	117	175	0.75	131
March	150	0.67	101	150	0.75	113
April	80	0.67	54	80	0.75	60
May	40	0.67	27	40	0.75	30
June	30	0.67	20	30	0.75	23
July	30	0.67	20	30	0.75	23
August	50	0.67	34	50	0.75	38
September	80	0.67	54	80	0.75	60
October	125	0.67	84	125	0.75	94
November	150	0.67	101	150	0.75	113
December	150	0.67	101	150	0.75	113

3.5. Weir Sites

Three weir sites have been proposed for investigation, with Site #1 being located adjacent to the two bridges at Bonnie Doon. Sites #2 & #3 move downstream from Site #1 by 1.1km and 3.2km respectively. As site numbers increase, so do weir heights, surface areas, volumes impounded, cost to create the infrastructure and benefits to most stakeholders (except G-MW who will seek remedy for water removed from their storage, cost of evaporation and ongoing maintenance.)

Each site has been chosen to minimize length of embankment, to minimize construction cost, and for its potentially stable geology. Maximizing surface area for boating is a major consideration, subject to associated weir height and comparative cost of construction against alternatives. Ease of access for construction was also considered.

For each site, the same two elevations were chosen to establish weir heights. These are 272 and 275 mAHD. With increasing depth of water from Site #1 to Site #3, there is a corresponding increase in weir height. If there was a weir at each of the three sites, each would overtop by the main dam at the same elevation.

Figure 3.9 below displays the distance site #2 (downstream) is from site #1 (bridges). The two relevant contours, for both 272 and 275 mAHD are shown (see Legend). The potential weir site #1, located upstream of the two bridges, is 1.1 km from site #2.

All maps displayed in the site figures were from the use of MapWindow as the base.

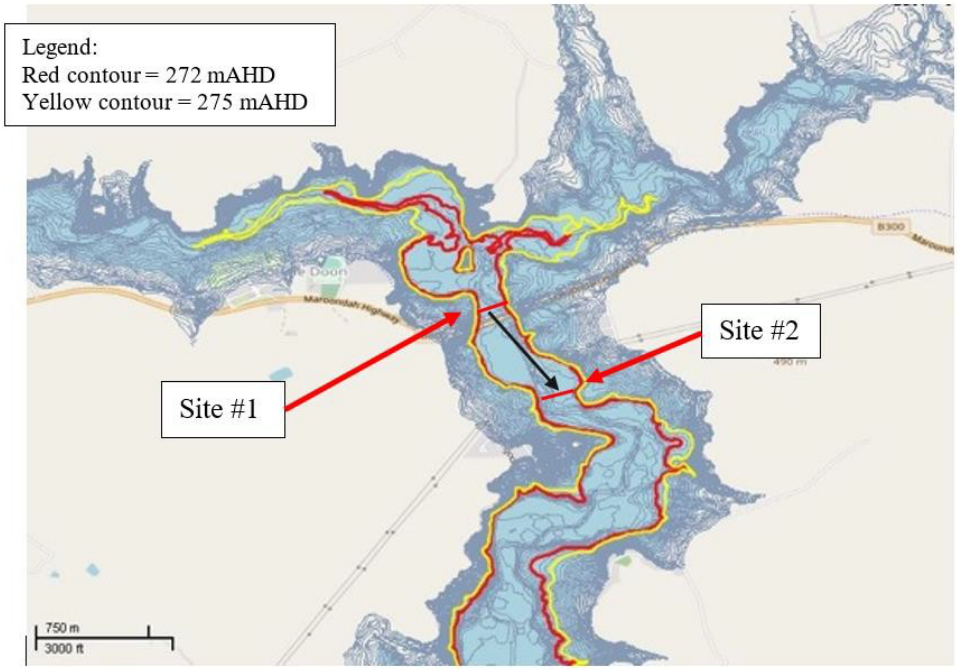

Figure 3.9: Distance of 1.1 km between sites #1 (bridges) and #2 (downstream)

Figure 3.10 below displays the distance (2.2 km) site #3 (downstream) is from site #2.

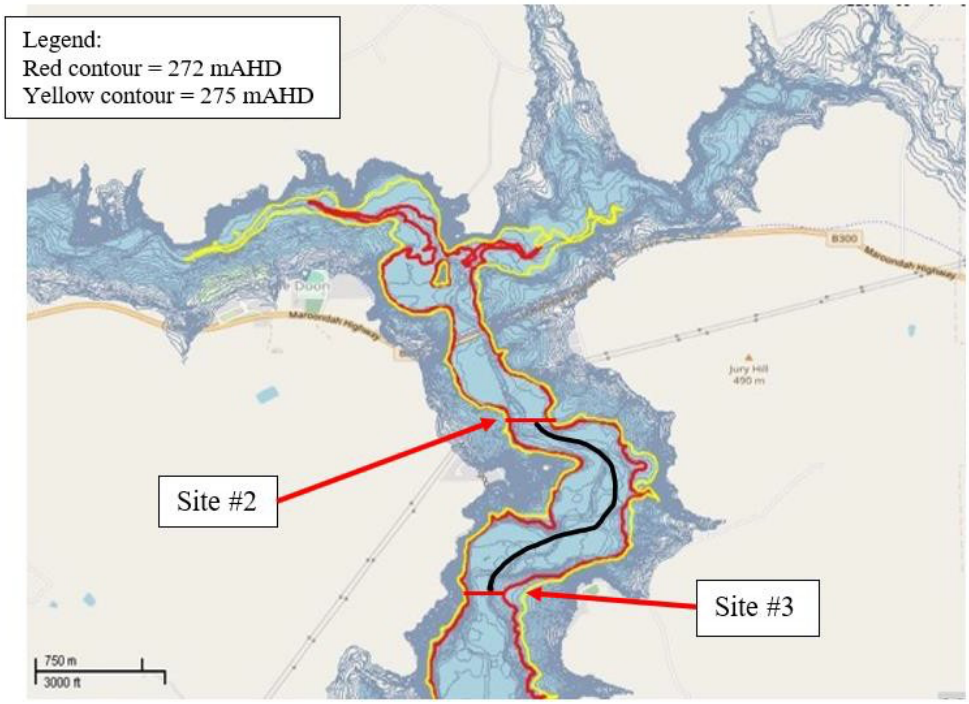

Figure 3.10: Distance of 2.1 km between sites #2 and #3

3.5.1. Site #1

This section relates to Site #1, located at the two bridges. Figures 3.11 and 3.12 show the parameters for surface areas and embankment lengths for each of the chosen two elevations of 272 and 275 mAHD.

With an increase in depth of three metres, for weir heights of 4 and 7 metres, Weir #1 surface area increases from 37 to 82 hectares providing a much larger boating area.

Figure 3.11 below displays the main weir characteristics for Site #1 at crest elevation 272 mAHD.

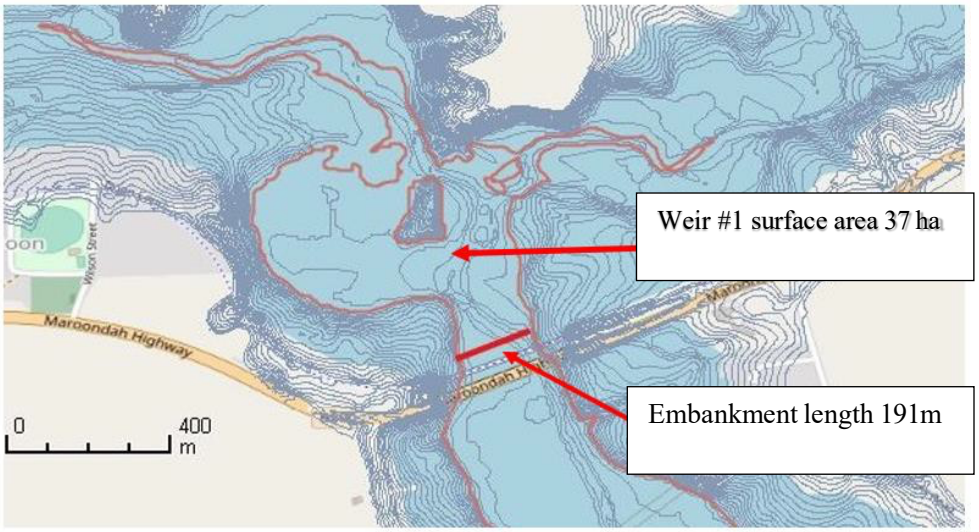

Figure 3.11: Site #1 weir characteristics for elevation 272 mAHD

From Site #1 at crest elevation 272mAHD (weir height 4 metres), surface area increases 222% when weir height (7 metres) is at crest elevation 275mAHD, as seen in Figure 3.12 below.

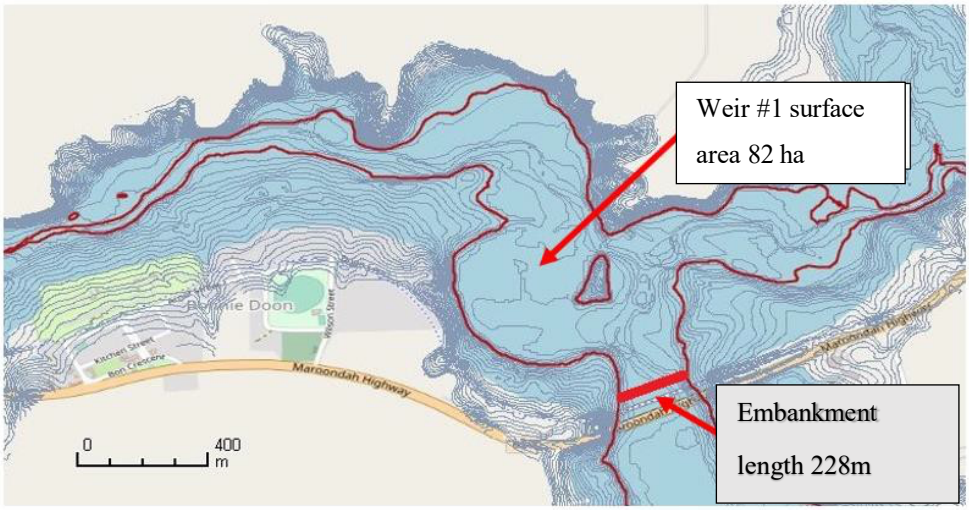

Figure 3.12: Site #1 weir characteristics for elevation 275 mAHD

In Table 3.6 below, the range of site areas in column 1 (commencing with Area 3) indicate the parameters that exist for the weir at Site #1 at increasing weir heights. The areas are named as per the corresponding weir height, for example Area 3 is the surface area for a weir height of 3m. Using MapWindow software, the surface area, embankment length, and volume stored at the weir FSL were identified. Areas 4 and 7 show the two weir optional elevations of 272 and 275 mAHD chosen for investigation (which are shaded in Table 3.6). It is to be noted that the range of 'area' numbers match the one metre increase from the invert level to match a selection of weir heights and crest elevations.

Table 3.6: Site #1 – weir characteristics for a range of crest elevations

Site #1	Weir height in m	Crest elev. in mAHD	Invert level in mAHD	Weir Storage GL	Storage % of main dam FSL	Embank't length in m	Surface Area in ha	Cumul. Volume in ML
Area 3	3	271	268	1,466	44	180	18	182
Area 4	4	272	268	1,544	46	191	37	457
Area 5	5	273	268	1,626	49	203	50	892
Area 6	6	274	268	1,710	51	211	68	1,482
Area 7	7	275	268	1,796	54	228	82	2,317
Area 8	8	276	268	1,886	57	252	115	3,387

3.5.2 Site #2

This section relates to Site #2, approximately 1.1km from the bridges and Site #1.

Surface area for Site #2 at 272mAHD is slightly less than for Site #1 at 275mAHD as seen in Figure 3.11 above. However, for the crest elevation 275 mAHD for each site, surface area increases from 82 to 121 hectares, a 48% increase.

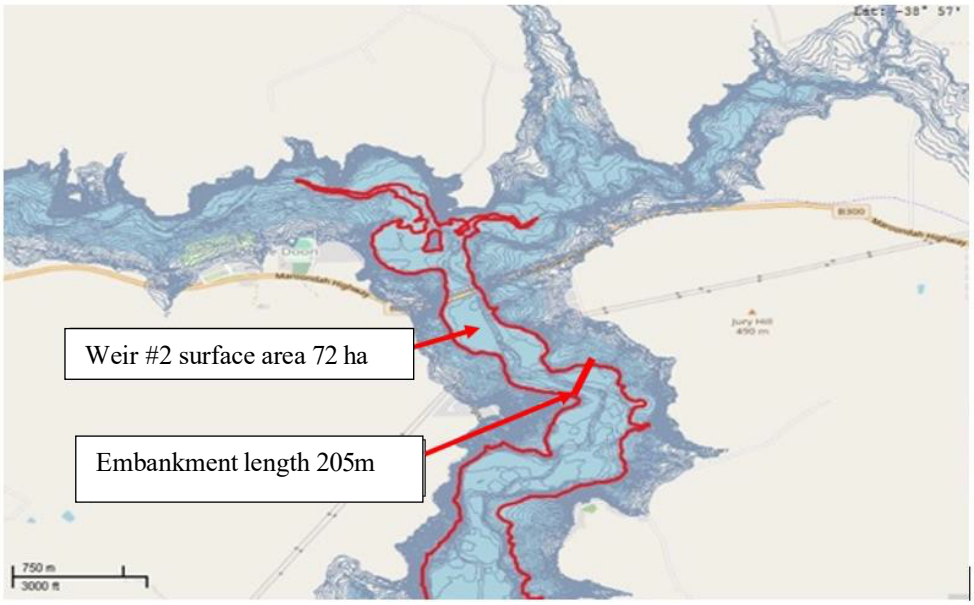

Figure 3.13: Site #2 weir characteristics for elevation 272 mAHD

Figure 3.14 below shows that surface area has increased 68% for Site #2 at 275mAHD compared with 272mAHD and embankment length has increased 28m.

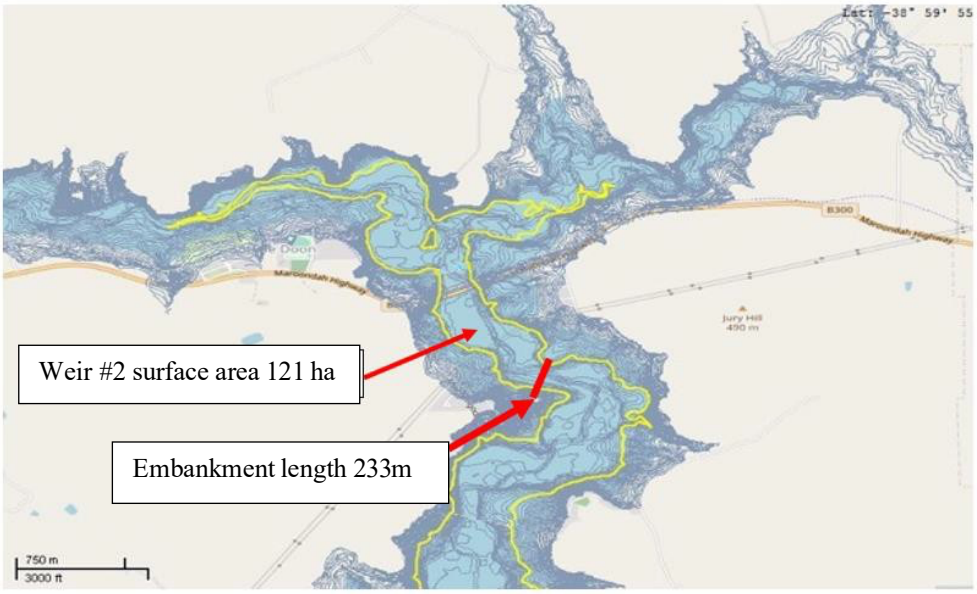

Figure 3.14: Site #2 weir characteristics for elevation 275 mAHD

Table 3.7 below provides data for weirs at Site #2 at elevations 272 and 275 mAHD and a range of weir heights from 7 to 12 metres, with relative embankment lengths of 205 and 233 metres. Area increases from 72 to 121 hectares with elevation increases from 272 to 275 mAHD.

Table 3.7: Site #2 - weir characteristics for a range of crest elevations

Site #2	Weir height in m	Crest elev. in mAHD	Invert level in mAHD	Weir Storage GL	Storage % of main dam FSL	Embank't length in m	Surface Area in ha	Cumul. Volume in ML
Area 7	7	271	264	1,466	44	275	64	1,445
Area 8	8	272	264	1,544	46	205	72	2,180
Area 9	9	273	264	1,626	49	316	98	3,085
Area 10	10	274	264	1,710	51	330	120	4,175
Area 11	11	275	264	1,796	54	233	121	5,450
Area 12	12	276	264	1,886	57	373	150	6,875

3.5.2. Site #3

This section relates to Site #3, where greatest surface area is achieved at either crest elevation. However, weir height for both elevations increases from 8 to 12 metres (at 272 mAHD) and 11 to 15 metres (at 275 mAHD) with associated construction cost increases.

Figure 3.15 below displays the main weir characteristics for Site #3 at crest elevation 272 mAHD.

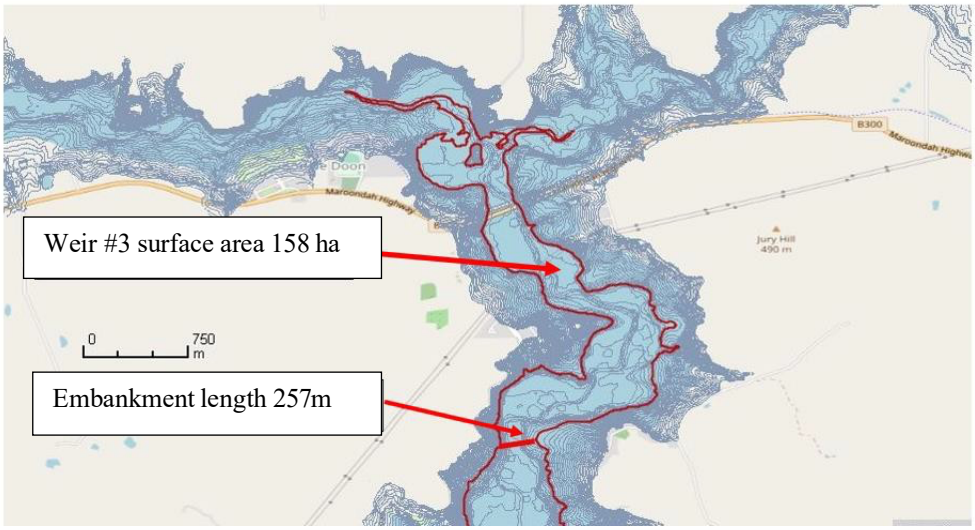

Figure 3.15: Site #3 weir characteristics for elevation 272 mAHD

The largest surface area (233ha) is achieved at Site #3 at elevation 275mAHD with weir height 15m. This weir also has the longest embankment length at 407m. This is demonstrated in Figure 3.16 below.

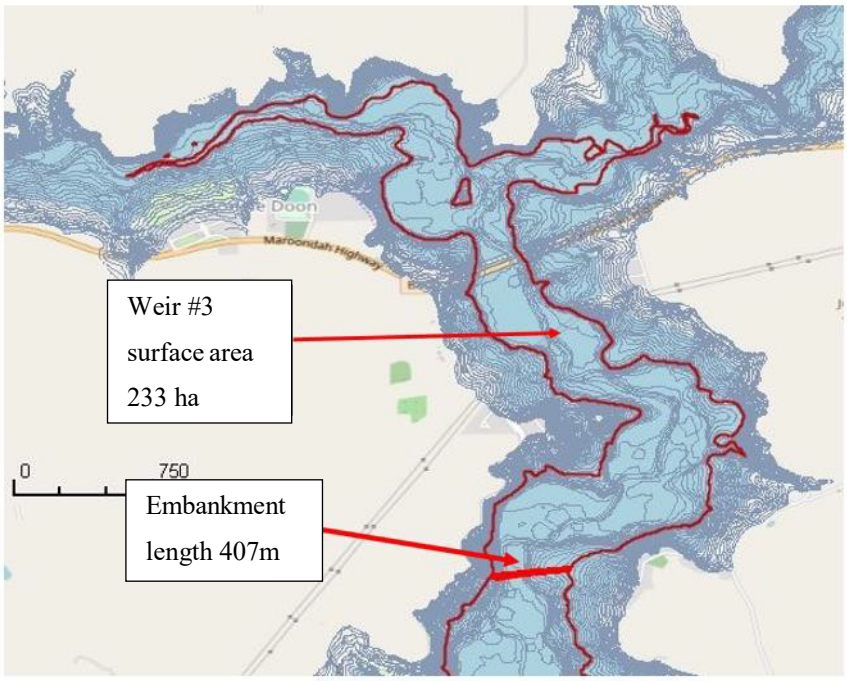

Figure 3.16: Site #3 weir characteristics for elevation 275 mAHD

Table 3.8 below provides data for the weir at Site #3 at different crest elevations, with 272 and 275 mAHD being the chosen options. The volume at 275 mAHD of 11,185 ML represents just 0.34% of Lake Eildon's capacity (FSL).

Table 3.8: Site #3 - weir characteristics for a range of crest elevations

Site #3	Weir height in m	Crest elev. in mAHD	Invert level in mAHD	Weir Storage GL	Storage % of main dam FSL	Embank't length in m	Surface Area in ha	Cumul. Volume in ML
Area 11	11	271	260	1,466	44	220	128	5,160
Area 12	12	272	260	1,544	46	257	158	6,510
Area 13	13	273	260	1,626	49	322	145	7,945
Area 14	14	274	260	1,710	51	410	165	9,495
Area 15	15	275	260	1,796	54	407	223	11,185
Area 16	16	276	260	1,886	57	440	275	13,425

3.5.3 Sites comparison (at 272m AHD)

This section includes a table (3.9 below) which compares data for all three weir sites at crest elevation 272 mAHD, especially for the elements of weir height, embankment length, surface area and volume impounded at the weir's FSL.

Table 3.9: Sites' comparative figures for crest elevation 272 mAHD

Sites	Site #1 Weir Area 4	Site #2 Weir Area 8	Site #3 Weir Area 12
Proposed weir height (m)	4	8	12
Distance from bridge (km)	0	1.1	3.2
Crest elevation in mAHD	272	272	272
Lake Eildon storage at weir height (GL)	1544	1544	1544
Lake Eildon storage as % of FSL	46.3	46.3	46.3
Embankment length (m)	191	205	257
Site surface area behind weir (ha)	37	72	158
Volume behind weir (ML)	457	2180	6510
Weir volume as % of Eildon at 272 mAHD	0.03	0.14	0.42
Invert Level mAHD	268	264	260

The increasing weir heights from Site #1 to #3 can be seen in the table above. The table also shows that at 272 m AHD, the main dam's storage is 1544 GL, which is 46.3% of its full supply potential. As one moves from Site #1 to #3, the surface area and stored volumes increase.

3.5.3. Sites comparison (at 275m AHD)

This section includes a table (3.10 below) which compares data for all three weir sites at crest elevation 275 mAHD, especially for the elements of weir height, embankment length, surface area and volume impounded at the weir's full supply capacity.

Weir height more than doubles from Site #1 to Site #3, with significant consequent construction cost increases. Greater benefits accrue with respect to surface area, volumes impounded and water depth.

Table 3.10: Sites' comparative figures for crest elevation 275 mAHD

Sites	**Site #1 Weir Area 7**	**Site #2 Weir Area 11**	**Site #3 Weir Area 15**
Proposed weir height (m)	7	11	15
Distance from bridge (km)	0	1.1	3.2
Crest elevation in mAHD	275	275	275
Lake Eildon storage at weir height (GL)	1,796	1,796	1,796
Lake Eildon storage as % of FSL	53.9	53.9	53.9
Embankment length (m)	228	233	407
Site surface area behind weir (ha)	82	121	223
Volume behind weir (ML)	2,317	5,450	11,185
Weir volume as % of Eildon at 275 mAHD	0.13	0.30	0.62
Invert Level mAHD	268	264	260

Table 3.11: Characteristics of main dam

Parameter	**Value**
Main dam height (m)	84.5
Full supply level elevation in mAHD	288.9
Lake Eildon storage at FSL (GL)	3,334
Embankment length (m)	1,085
Surface area (in hectares) behind dam at FSL	13,832

Table 3.11 summarises the significant fundamentals for the main dam and illustrates, when compared with data for any of the weirs, that the weirs are relatively small in their main parameters of surface areas, volumes impounded and embankment lengths and consequent construction costs.

Table 3.12: Significant geological data for all three weirs at both crest elevations 272 & 275 mAHD

Significant geological data for proposed weirs in Lake Eildon	
Site details	Geology at abutments
Site #1	
At east abutment	Sje-Sandstone, siltstone
At west abutment	Sjw-Siltstone, minor sandstone
Site #2	
At east abutment	Sjd- Sandstone, siltstone
At west abutment	Sje- Sandstone, siltstone
Site #3	
At east abutment	Sje- Sandstone, siltstone
At west abutment	Sjs- Sandstone, siltstone

Table 3.12 provides an indication of the geology prevailing at each weir abutment for both crest elevations 272 and 275 mAHD.

3.6. Discharge data - releases from the main dam into Goulburn River at Eildon.

The following data was provided by Goulburn-Murray Water, manager of Lake Eildon. The full data set of monthly releases are listed via a link in Appendix B.

Total releases (monthly reports) for the forty-year period = 49,133,684 ML Average annual releases over that period = 1,228,342ML.

Figure 3.17 below shows main dam releases over 40 years to 2018, generally consistent except for a high (flood) release in 1993 when the dam was already at FSL and much reduced releases during the Millennium Drought from 1996 to 2010.

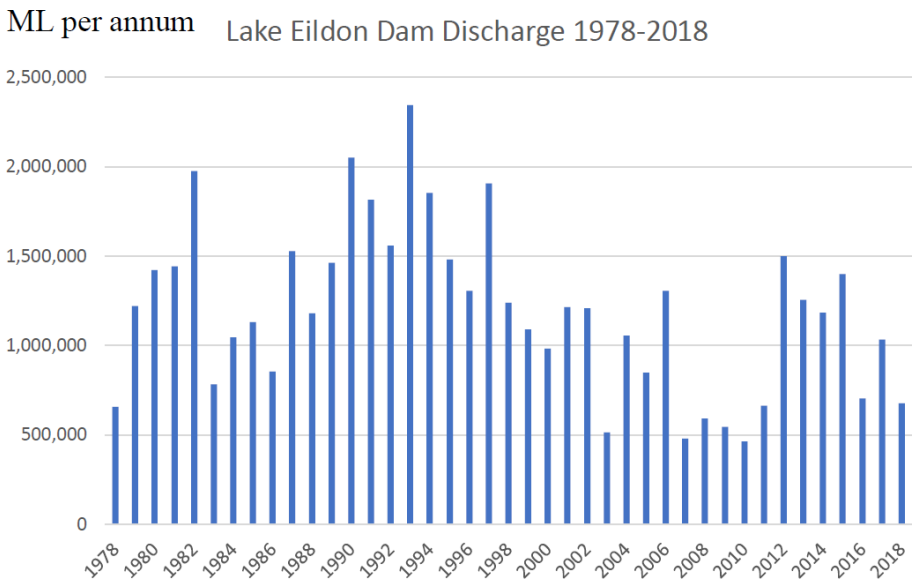

Figure 3.17: Eildon Dam releases for 40 years from 1978 to 2018 (Source: G-MW, 2020)

3.7. Lake Eildon reported volumes.

The 'Eildon Volumes' graph is presented in Figure 3.18 below, which indicates the point at which water is absent at the Bonnie Doon bridges, which is also the location for Site #1. When volume of the lake falls to 1,544 GL, at 46% of full supply level, the water departs from Site #1.

The extended period (in Figure 3.17) below 46% of weir capacity reflects the impact of the Millennium Drought, between 1996 and 2010.

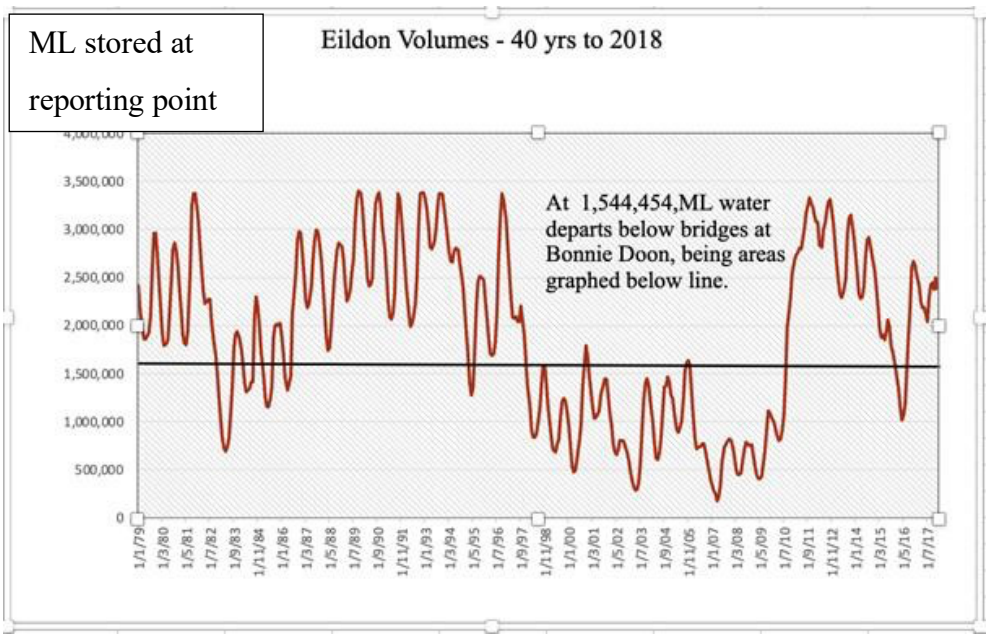

Figure 3.17: Eildon Dam volumes over 40 years from 1979 to 2018 (Source: G-MW, 2020)

Chapter 4 : Hydrologic analysis of historical data

Introduction

This chapter presents a range of hydrologic data for Lake Eildon which then translates into outcomes for the various weir sites. It reviews the precipitation for the three reporting stations in the region which have modelling relevance to Lake Eildon across a 40-year period ending 2019. These stations provide locations for a Thiessen polygon to be drawn.

Focus is then given to Brankeet Creek discharge, being the most significant creek feeding the lake from the north and northwest. It also indicates the streamflow reduction that has commenced across the 40-year period because of climate change. The five main rivers discharging into the lake downstream of the weir sites are then reviewed for the 40-year period.

Following the above, analysis will be made for all weir sites at crest elevations 272 and 275 mAHD. These results, plus additional data for each weir is tabulated for both elevations.

4.1. Precipitation

Whilst there are at least seven reporting stations in the vicinity of Lake Eildon, there are only five with long histories for data recording. Three of these were selected to provide a forty-year record of precipitation, dictated by the Thiessen polygon below in Figure 4.2.

The three significant stations are listed in Table 4.1 below

Table 4.1: Long term rainfall reporting stations near Lake Eildon

Rainfall station	Reporting from	Mean mm over full period	Mean mm across 40 years	Lowest year mm	Highest year mm
Strathbogie	1902	960	925	411	1,733
Lake Eildon	1887	847	828	405	1,401
Mansfield PO	1901	701	671	318	1,093

The graphed data for forty years, collated for the three relevant stations, is shown in Figure 4.1 below. All data has been taken from reports available from the Bureau of Meteorology (Victoria).

A Thiessen polygon (or Voronoi Diagram) is shown in Figure 4.2 below and creates an area with rainfall stations as polygons in which each has one generating point and every point in any one polygon is closer to that generating point than to any other point. It shows the catchment area for the group of three rainfall stations which impact directly on Lake Eildon.

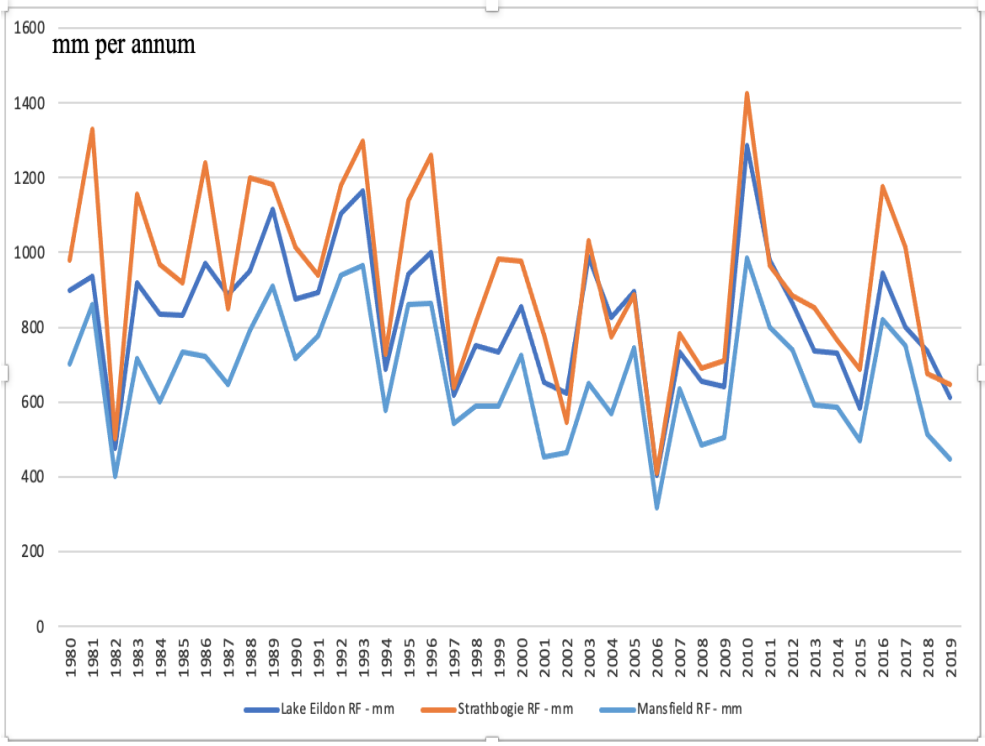

Figure 4.1: Rainfall, three stations relevant to models, with long term data – 40 years 1980-2019

(Source: BOM, 2019)

The dominating results for the northern station of Strathbogie has significance, as it indicates heavier precipitation north of the Bonnie Doon bridges and would therefore feed the Brankeet Arm of Lake Eildon, upstream of any of the three possible weir sites. This might be found to be critical in adding volume to the weirs if there are periods when no overtopping from the main dam is occurring (see Section 4.3). Section 4.3 will analyze the impact of this precipitation on streamflow and volumes delivered to this arm of the lake.

The Thiessen polygon in Figure 4.2 was created to identify which rainfall stations have a distinct relationship with Lake Eildon, and three were found, being Strathbogie, Mansfield PO, and Lake Eildon. From this polygon, areas were attributed to each station. Strathbogie area alone is used for modelling input for Weir #1, Strathbogie and Lake Eildon determine areas for Weirs #2 and #3, and for the main dam, Mansfield PO is included.

The areas relevant to each site are: -

- Weir #1 – 100% Strathbogie
- Weirs #2 and #3 – 84.25% Strathbogie / 15.75% Lake Eildon
- Main dam – 2.78% Strathbogie / 22.09% Mansfield PO / 75.13% Lake Eildon

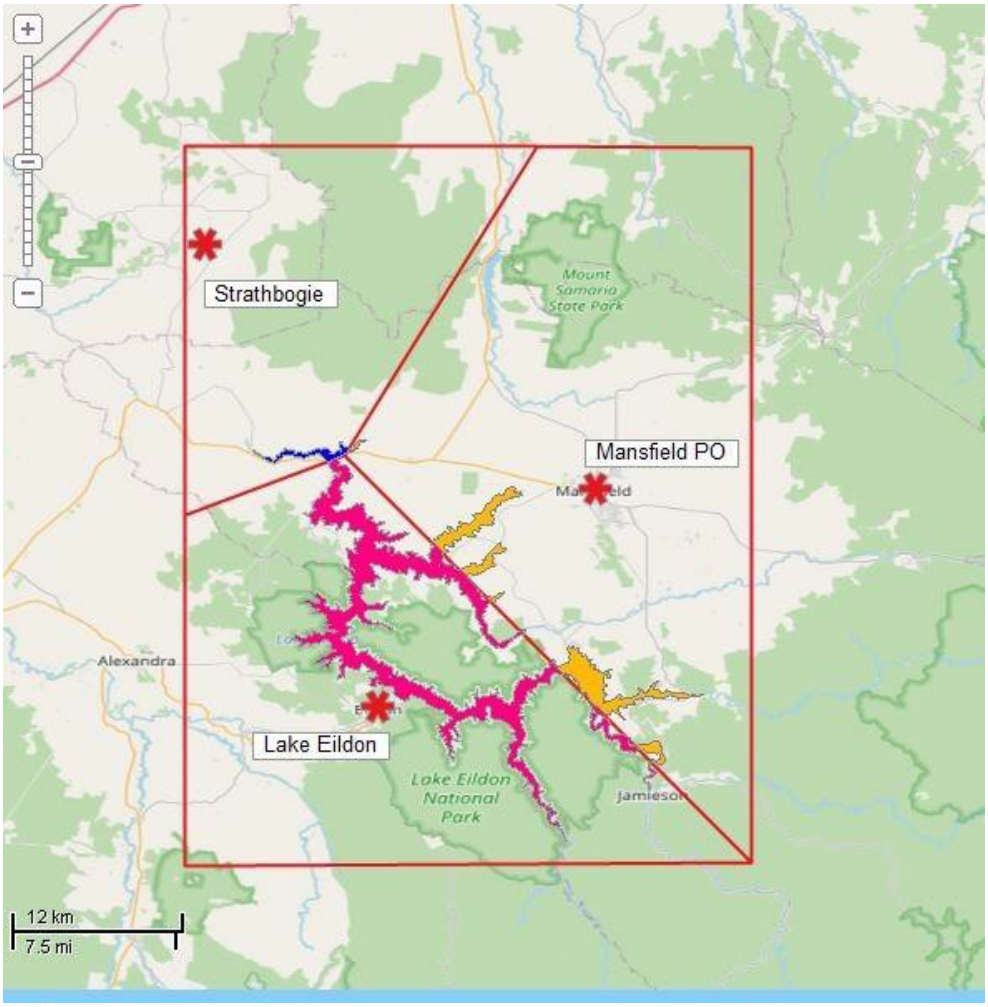

Figure 4.2: Thiessen polygon for Lake Eildon

4.2. Streamflow and discharge volumes by four creeks feeding the Brankeet Arm

Four creeks feed into Lake Eildon upstream from the bridges at Bonnie Doon. In the absence of overtopping of the weir from downstream, where the main dam must exceed the crest height of the weir, additional infeed can only occur from these creeks. In the event of a long dry spell, as occurred with the Millennium Drought, any flows from upstream creeks will add to the volume and surface area of the weir. An analysis of discharge by these creeks will disclose whether there were years in which this occurred.

Of the four creeks, Brankeet is the most significant, though there are occasional months when this creek also fails to flow. There are years when it has continuous flow throughout both wet and dry seasons. The two smallest creeks (Tallangalook and Glen) generally fail to flow during the dry season, except when summer storms occur.

The second major creek in this group is Merton Creek, which over the forty-year period reviewed has a discharge of 52% of that for Brankeet. Merton Creek has a confluence with Brankeet Creek close to its entry with Lake Eildon. Third in the ranking and behind Merton Creek is Tallangalook Creek at 34% of Brankeet. Lastly, Glen Creek is at 27% of Brankeet Creek.

Discharge over 40 years for Brankeet Creek is graphed in Figure 4.3 below and highlights the 15-year Millennium Drought (red arrow). It also shows significant spikes in streamflow, especially the 12,000 ML in the period 1981-82. Table 4.2 reports the volumes discharged over 40 years in 5-year intervals. It reports a significant reduction over the 5th to 8th intervals, possibly indicating the impact of climate change from the year 2000 forward and after the end of the millennium drought.

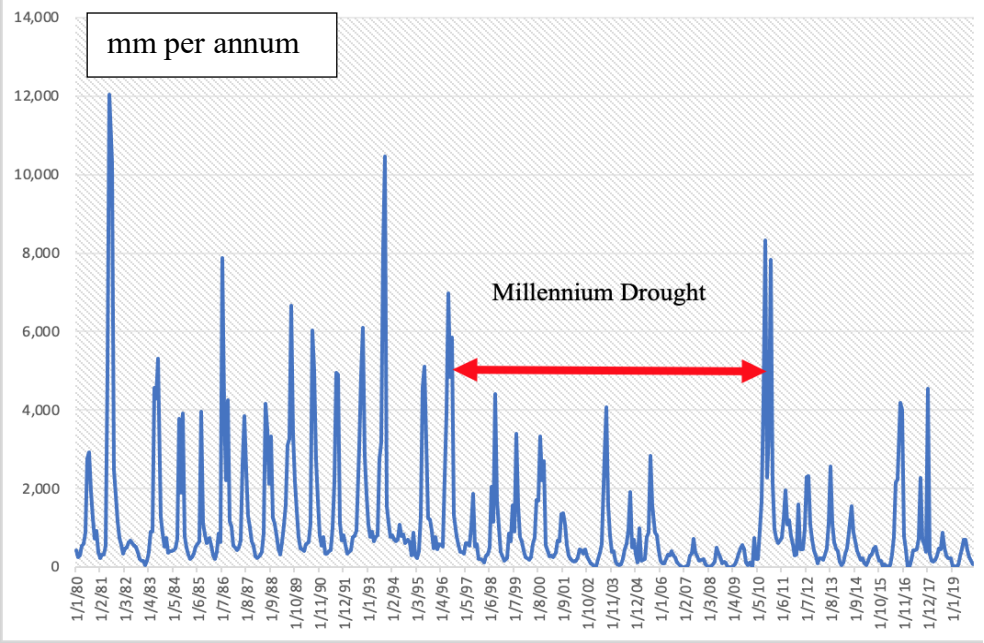

Figure 4.3: Discharge 40 years to 2019 Brankeet Creek

(Source: DELWP, 2019)

Table 4.2: Discharge change in Brankeet Creek over 40 years

Five-year intervals	5-Year total ML	Change outcome
1984	88,240	100.0
1989	91,980	104.2
1994	101,989	115.6
1999	80,056	90.7
2004	42,444	48.1
2009	18,704	21.2
2014	67,610	76.6
2019	35,858	40.6

(Source: DELWP, 2019)

Table 4.2 above indicates that Brankeet Creek has seen a trending reduction in monthly creek inflows in volume over the 40-year period. The 2014 period indicates a strong recovery from the Millennium drought which ended in 2010.

4.3. Streamflow and discharge volumes by five rivers into Lake Eildon

Of greater streamflow significance are the five main rivers which discharge into Lake Eildon. These are shown in Table 4.3 below. Goulburn and Big rivers are the most significant, with Goulburn giving 3.1 times the discharge of the smallest river, the Delatite. It should be noted that there has already been an annual decrease in discharge when the full reporting period is compared with the shorter forty-year period. Using the ranking of 1 to 5, these percentage decreases are: - 9% (Goulburn), 5% (Big), 7% (Jamieson), 4% (Howqua), and 8% for the Delatite River, for the 40-year period.

Table 4.3: Five rivers discharging into Lake Eildon

River	Commenced Reporting	Years to 30/6/2020	Discharge ML/annum over reporting Period	Discharge ML/annum over 40 years	Discharge ranking
Goulburn	1968	52.5	314,209	287,415	1
Big	1970	49.8	286,640	273,414	2
Jamieson	1959	60.75	203,572	190,144	3
Howqua	1974	46	160,517	154,886	4
Delatite	1957	63	100,185	92,367	5

(Source: DELWP, 2019)

Figure 4.4 below shows the discharge history for the Goulburn River, graphed, with the millennium Drought highlighted.

Table 4.4 reports the 40-year discharge for the Goulburn River in 5-year intervals.

Graphs and tables for the other four major rivers, Big, Jamieson, Howqua, and Delatite are included in Appendix C.

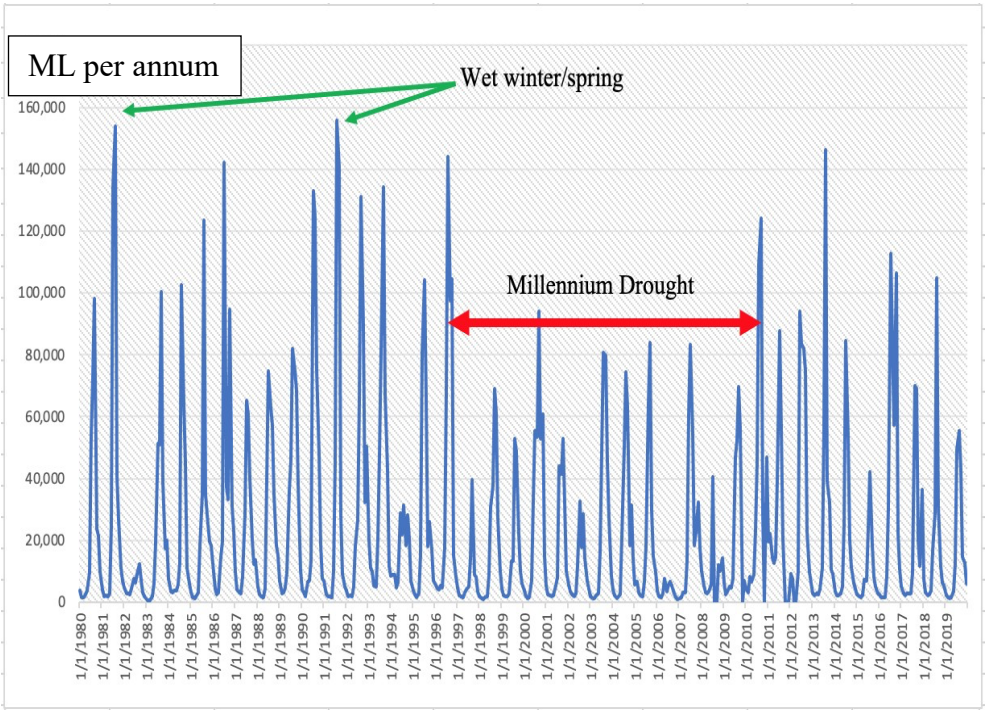

Figure 4.4: Discharge, 40 years to 2019, Goulburn River

(Source: DELWP, 2019)

Table 4.4: Discharge change in Goulburn River over 40 years

Five-year intervals	5-Year total ML	% of 1984
1984	1,357,416	100.0
1989	1,674,429	123.4
1994	1,947,473	143.5
1999	1,354,148	99.8
2004	1,320,285	97.3
2009	975,221	71.8
2014	1,640,476	120.9
2019	1,227,155	90.4

(Source: DELWP, 2019)

Total discharge over 40 years was 11,496,603 ML, an average of 287,415ML per annum and 23,951 ML per month. Table 4.4 indicates that Goulburn River has seen a general reduction in volume over the last 40 years, despite early increases. The increase in the 2014 interval shows recovery after the end of the Millennium Drought. The Delatite River is the stream with the lowest discharge over the period reviewed. It is also the river that showed the largest decline, from the 5-year period to 1984. The period to 2009 covers a portion of the Millennium Drought, where a significant decreased volume was expected.

Chapter 5 will consider the further impact on these streamflows of climate change. That data will be translated into its impact on the weir sites and their potential to maintain healthy storage.

4.4. Analysis of weir sites

Six analyses of weir sites were needed, using the crest elevations of 272 and 275 mAHD for each of the three weirs. The height of the six weir options ranged from 4 to 15 metres. Whilst there is no modelling of water release other than overtopping the crest, a valve might be included in weir design. This would meet the need for water release in a crisis, or under the Water Act as a request to release, or for maintenance needs upstream or of the weir itself. The models of data for streamflow, precipitation, consumption, and evaporation are found using the link within Appendix C, in Chapter 5 Models.

Modelling for weir outcomes – the model development process: -

The models are designed to deliver outcomes, in the absence of overtopping of the weir by the main dam, of (a) water volumes entering the weir from the northern creeks and how much of that is passed over the weir crest into the main dam, and (b) the

number of months where the water stored behind the weir drops below its FSL and by how much.

Outcomes for weir operations is a two-step process: -

(1) A calculation is made for evaporation. The Pan gross evaporation values in mm (referred to in Chapter 3) are obtained from the BOM (2019) for the Goulburn Basin. Coefficients applied to discount the different months for variable rates of evaporation were supplied by Goulburn-Murray Water and are reflected within the spreadsheets.

(2) In the case of the Main Dam, evaporation data saved as a constant was copied to the Volumes (sheet). Unless transferred as a constant, the result becomes circular and continuously changes data.

(3) Mean rainfall is calculated for the relevant month and the net egross is derived by deducting the rainfall from the month's egross. The net evaporation in ML is then derived by applying surface area for the weir in question.

(4) The outcome from (1) is then transferred to sheet 2. Creek inflows monthly are then added to the storage level of the previous month, with evaporation and town water supply withdrawal deducted to form the new storage level. If this volume exceeds supply at weir height, then that excess is passed downstream into the main dam. If less than storage level, this indicates a weir level below its FSL for that month. These calculations are made for the months in which the main dam fails to overtop the weir, called 'incidents'. The result for the total period indicates the total inflows from the northern creeks and the volumes passed over the weir crest, with the difference being evaporation, water withdrawal or change in storage level.

The following listings show the significant outcomes for each of the six weir options and a further summary follows these.

<u>Weir Site #1 at crest elevation 272 mAHD – summary of significant outcomes</u> (refer model HD-1 - 21/10/2021)

1. At crest elevation 272 mAHD, FSL for Weir #1 is 457 ML water stored.
2. This FSL occurs when Lake Eildon storage is at 46.3%, or 1,544,454 ML.

3. Across the 480 months (40 years) reviewed there were 186 months in which the main dam failed to overtop Weir #1 crest.
4. In just 2 months out of 186 months (1%), there was no streamflow & discharge into weir.
5. In 93 months (50%) rainfall exceeded losses through evaporation/supply.
6. In 12 months (6.4%) water level fell slightly below 457 ML storage, meaning no water flowed downstream in those months.
7. The volume of water which overtopped the crest of Weir #1, flowing downstream was 317,346 ML, just 431 ML less than the volume fed by the northern creeks, of 317,777 ML.
8. The volume in (7) has a mean discharge of 1,706 ML per month.
9. The lowest storage point reached was 85.1%, mid Millennium Drought (March 2009).

Weir Site #1 at crest elevation 275 mAHD– summary of significant outcomes (refer model HD-2 – 21/11/2021)

1. At crest elevation 275 mAHD, FSL for Weir #1 is 2,317 ML water stored.
2. This FSL occurs when Lake Eildon storage is at 54%, or 1,800,000ML.
3. Across the 480 months (40 years) reviewed there were 216 months in which the main dam failed to overtop Weir #1 crest.
4. In just 2 months (1%), there were no streamflows & discharge into weir.
5. In 107 months (49.5%) rainfall exceeded losses through evaporation/supply.
6. In 19 months (8.8%) water level fell slightly below 2,317 ML storage, meaning no water flowed downstream for those months.
7. The volume of water which overtopped the crest of Weir #1, flowing downstream was 373,523 ML, just 327 ML less than the volume fed by the northern creeks, being 373,850.

8. The volume in (7) has a mean discharge of 1,729 ML per month.

The lowest storage point reached was 92.4%, past the mid-point of the Millennium Drought (March 2009).

Weir Site #2 at crest elevation 272 mAHD– summary of significant outcomes (refer model HD-3 – 21/11/2021)

1. At crest elevation 272 mAHD, FSL for Weir #2 is 2,180 ML water stored.
2. This FSL occurs when Lake Eildon storage is at 46.3%, or 1,544,454ML.
3. Across the 480 months (40 years) reviewed there were 186 months in which the main dam failed to overtop Weir #2 crest.
4. In just 2 months (1%), there was no streamflow & discharge into weir.
5. In 42 months (22.6%) rainfall exceeded losses through evaporation/supply.
6. In 8 months (4.3%) water level fell slightly below 2,180 ML storage, meaning no water flowed downstream for those months.
7. The volume of water which overtopped the crest of Weir #2, flowing downstream was 335,402 ML, 17,406 ML more than the volume fed by the northern creeks, being 317,996.
8. The volume in (7) has a mean discharge of 1,803 ML per month.
9. The lowest storage point reached was 93.8%, (February 2009) near the end of the Millennium Drought.

Weir Site #2 at crest elevation 275 mAHD– summary of significant outcomes (refer model HD-4 – 21/11/2021)

1. At crest elevation 275 mAHD, FSL for Weir #2 is 5,450 ML water stored.
2. This FSL occurs when Lake Eildon storage is at 54%, or 1,800,000 ML.
3. Across the 480 months (40 years) reviewed there were 216 months in which the main dam failed to overtop Weir #2 crest.
4. In just 2 months (1%), there was no streamflow & discharge into weir.

5. In 112 months (47.7%) rainfall exceeded losses through evaporation/supply.
6. In 22 months (10.2%) water level fell slightly below 5,450 ML storage, meaning no water flowed downstream for those months.
7. The volume of water which overtopped the crest of Weir #2, flowing downstream was 300,458 ML, just 500 ML less than the volume fed by the northern creeks, being 300,958.
8. The volume in (7) has a mean discharge of 1,391 ML per month.
9. The lowest storage point reached was 94.4%, (April 2009) late in the Millennium Drought.

Weir Site #3 at crest elevation 272 mAHD– summary of significant outcomes (refer model HD-5 – 22/10/2021)

1. At crest elevation 272 mAHD, FSL for Weir #3 is 6,510 ML water stored.
2. This FSL occurs when Lake Eildon storage is at 46.3%, or 1,544,454ML.
3. Across the 480 months (40 years) reviewed there were 186 months in which the main dam failed to overtop Weir #3 crest.
4. In just 2 months (1%), there was no streamflow & discharge into weir.
5. In 92 months (49.5%) rainfall exceeded losses through evaporation/supply.
6. In 26 months (14%) water level fell slightly below 6,510 ML storage, meaning no water flowed downstream for those months.
7. The volume of water which overtopped the crest of Weir #3, flowing downstream was 241,036 ML, 260 ML more than the volume fed by the northern creeks, being 240,776.
8. The volume in (7) has a mean discharge of 1,296 ML per month.
9. The lowest storage point reached was 93.7%, (April 2009) late in the Millennium Drought

Weir Site #3 at crest elevation 275 mAHD– summary of significant outcomes (refer model HD-6)

1. At crest elevation 275 mAHD, FSL for Weir #3 is with 11,185 ML water stored.
2. This FSL occurs when Lake Eildon storage is at 54%, or 1,800,000 ML.
3. Across the 480 months (40 years) reviewed there were 216 months in which the main dam failed to overtop Weir #3 crest.
4. In just 2 months (1%), there was no streamflow & discharge into weir.
5. In 112 months (51.9%) rainfall exceeded losses through evaporation/supply.
6. In 34 months (15.7%) water level fell slightly below 11,185 ML storage, meaning no water flowed downstream for those months.
7. The volume of water which overtopped the crest of Weir #3, flowing downstream was 299,587 ML, 28 ML less than the volume fed by the northern creeks, being 299,615 ML.
8. The volume in (7) has a mean discharge of 1,387 ML per month.
9. The lowest storage point reached was 94.8%, (March/April 2007, April 2009) late in the Millennium Drought.

Tables 4.5 and 4.6 below illustrate a summary of significant data for weirs at crest elevations of 272 and 275 mAHD, respectively.

Table 4.5: Comparing weirs at crest elevation 272 mAHD

Weir & relevant model	**Weir #1 (HD-1)**	**Weir #2 (HD-3)**	**Weir #3 (HD-5)**
Period of analysis 1980 - 2019	480 months	480 months	480 months
Weir height	4 metres	8 metres	12 metres
Surface area at full supply level of weir (with Site#1 the base area of 100%)	37 hectares (100%)	72 hectares (195%)	158 hectares (427%)
Lake Eildon storage when weir is at its FSL	1,544,454 ML (46.3%)	1,544,454 ML (46.3%)	1,544,454 ML (46.3%)
Weir volume at its FSL (Site#1 base volume of 100%)	457 ML (100%)	2,180 ML (477%)	6510 ML (1,425%)
Weir volume as a percentage of Lake Eildon at its FSL (all less than 1%)	0.014%	0.065%	0.195%
Number of months in 40 yrs without overtopping upstream from main dam	186 out of 480 (39%)	186 out of 480 (39%)	186 out of 480 (39%)
Number of months in 186 rainfall volumes exceeded volumetric losses from evaporation and town water supply	93 months (50%)	93 months (50%)	93 months (50%)
Volume fell below weir FSL (no overtopping into main dam)	12 months / 6.4%	8 months / 4.3%	26 months /14%
For the full 480-month history, percentage =	2.5%	1.7%	5.4%
Volume overtopping & flowing downstream into main weir	317,346 ML	335,402 ML	241,036 ML
Lowest incidence of weir volume below crest as percentage of its FSL	85.1%	93.8%	93.7%

Table 4.6: Comparing weirs at crest elevation 275 mAHD

	Weir #1 (HD-2)	**Weir #2 (HD-4)**	**Weir #3 (HD-6)**
Period of analysis - 1980 -2019	480 months	480 months	480 months
Weir height	7 metres	11 metres	15 metres
Surface area at FSL of weir (with Site#1 the base of 100%)	82 hectares (100%)	121 hectares (148%)	223 hectares (272%)
Lake Eildon storage when weir is at its FSL	1,800,000 ML (54%)	1,800,000 ML (54%)	1,800,000 ML (54)
Weir volume at its FSL (Site#1 base volume of 100%)	2,317 ML (100%)	5,450 ML (235%)	11,185 ML (483%)
Weir volume as a percentage of Lake Eildon at FSL (all less than 1%)	0.069%	0.163%	0.335%
Number of months in 40 yrs without overtopping upstream from main dam	216 out of 480 (45%)	216 out of 480 (45%)	216 out of 480 (45%)
Number of months rainfall volumes exceeded volumetric losses from evaporation and town water supply	104 months (48.1%)	102 months (47.2%)	103 months (47.7%)
Volume weir fell below its FSL (no overtopping into main dam)	19 months (8.8%)	22 months (10.2%)	34 months (15.7%)
For the full 480-month history, weir < FSL percentage =	4.0%	4.6%	7.1%
Volume overtopping & flowing downstream into main weir	373,523 ML	300,458 ML	299,587 ML
Lowest incidence of weir volume below crest as percentage FSL	92.4%	94.4%	94.8%

4.5. Analysis of data from Tables 4.5 and 4.6

The outcomes recorded in the tables indicate that all six sites are viable for the following critical parameters.

Summary for weirs at crest elevation 272 mAHD (Table 4.5): -

- Weir #1 at 272 mAHD, showed the largest fall in water level to 85.1%.
- Weirs #2 and #3 for 272 mAHD were both above 90% storage at their lowest point and all three results show that a healthy level of storage was held across the whole period and that outside of the reported events, overtopping had held the weir above crest height. Across the full 480 months, water level dropped below the crest for 272 mAHD on 2.5, 1.7 and 5.4 percent of the time for weirs 1,2 and 3 respectively.
- In 39% (186) of the 480 months there was no overtopping upstream from the main dam. The percentage without overtopping is the same for all weirs, as once overtopping occurs, it happens for all weirs due to the small surface areas, such that it occurs for each in the same month. Likewise, a lack of overtopping occurs for all weirs for the same month, being at the same crest elevation of 272 or 275 mAHD.
- Weir volume increases rapidly from Site #1 by almost five times and more than fourteen times at Site #3, from 457 to 6,510 ML. This grew surface area four times from Site #1 to #3 and reduced net evaporation.
- Rainfall exceeded the sum of evaporation and town supply usage by between 22.6% and 50% over the period reported within the 186 months.

Summary for weirs at crest elevation 275 mAHD (Table 4.6)

- Weir height more than doubles between Site #1 and #3, which at 15 metres becomes a significant structure at much greater cost to build.

- The lowest Weir #1 fell to was 92.4%, with weirs 2 & 3 being 94.4% & 94.8%, respectively, so there was never a period of low storage.
- All three weirs at 275 mAHD showed an increase from 39% (for weirs at 272mAHD) to 45 percent for months within the 480-month period where no overtopping from the main dam occurred. In part this reflects the higher weir heights to be overtopped.
- Weir volumes increased from 2,317 ML (#1) to 11,185 ML (#3), a factor of 4.8 times Weir #1.
- These higher crests and higher volumes were also delivering higher surface areas, from 82ha (#1) to 223ha (#3).

Based on the above outcomes, all six weir options could deliver a weir that met basic requirements of limited movement from a mean for each test. Selection from within the six options would be more subjective around desirable surface area for boating, water depth for water health and lower evaporation rates, and against any budget constraints for weir construction cost.

Chapter 5 : Hydrologic Analysis – projections for and outcome of climate change

5.1. Introduction

Historical records appear to show an accruing impact being displayed for climate change. It indicates the importance of not only modelling using the historical forty-year period to establish the expected performance of the three weir options, but for a future period where projections include reduced stream flows, reduced precipitation, and increased evaporation.

Planning for building a weir within Lake Eildon must account for the impact of climate change within Victoria, especially within the Goulburn Basin in which the lake sits. Modelling is needed to determine if such a weir is viable into a global warming future.

The three weirs are subject to inflows from the northern creeks, to fill the weirs to capacity after construction, but they are also subject to being replenished where the main dam is fed by the five main rivers and water levels exceed the height of the weirs, therefore overtopping from downstream back upstream. If this can be a regular event, it obviates any need for a fishway, as exchange can regularly and naturally occur with the flows each way.

Using MapWindow, each of the sites was identified for weir height, volume impounded and surface area from a minimum of 3 metres (minimum possible weir height, Site #1) to a maximum potential of 16 metres (Site#3). From this range, weir heights were subjectively selected based on what would be acceptable weir size for boating water depth, surface area for utilisation, potential construction cost, and the water withheld from use by G-MW for release for its core activities.

For a weir at Site #1 weir heights were adopted of 4 and 7 metres for crest elevations 272 and 275 mAHD. For Site #2 they were 8 and 11 metres and for Site #3, 12 and 15 metres. Whilst for many of the 480 months modelled, any one weir would be

submerged, a maximum weir height of 15 metres was assumed to be at the top of the range based upon cost and the acceptable percentage volumes locked away from release by G-MW for irrigation downstream.

Modelling the operation of both the weirs and the main dam will establish whether there is a strong link between both storages. Whilst this link is apparent when applying historical data, modelling is needed to see if the link persists under the influence of relatively severe climate change projections for year 2065 by DEECA.

For climate change modelling, the historical data for water level in 1980 will be the starting point. Streamflows, precipitation and evaporation indices at forecasts for climate change, adopted for modelling purposes are those shown for the year 2065 in Table 5.2.1. The year 2040 is ignored and the higher forecasts were adopted. Both these reductions are included in the DELWP "Guidelines for Assessing the Impact of Climate Change on Water Supplies in Victoria" (2016).

Initially, water discharged from the main dam will be kept constant with historical records and then it will be tested with a reduction of 15.9%. Also applied to the model will be the outcome for evaporation and water supply withdrawal.

Once new water levels have been calculated, they will be applied to see what change occurs to the six weir options if water fails to overtop their crests from the downstream main dam.

The outcome of this extensive modelling will create a conversation around the potential of the weirs to meet future needs, under a range of constraints.

5.2. Assumptions used in modelling.

5.2.1. Assumptions related to climate change projection.

The source of parameters to be applied in the models is the DEECA document (DEECA report [2016]). These are presented in Table 5.1 below.

The year 2040 has been included, solely to indicate the increases in parameters from year 2040 to 2065, the latter being those adopted for modelling purposes.

Table 5.1: DEECA climate change projections

Forecast Year	**2040**	**2040**	**2065**	**2065**
	50-percentile	90 - percentile	50 - percentile	90 - percentile
Streamflow reductions - average annual runoff % decrease	9.5	29.1	13.7	41.9
Precipitation reductions - % decrease	2.5	13.6	4	20.7
Evaporation increase - average annual PET % increase	4.9	5.8	8.2	11.4
Temperature increase – degrees C.	1.4	1.6	2.4	2.9

The projections used to model climate change are as set out in Section 5.3, with the most severe estimates being derived from the DEECA forecast (DEECA report 2016) for Year 2065 and using 90-percentile parameters. Temperature increases are not a parameter used within the models, as their impact is reflected in the rates of evaporation.

5.2.2. Impact of climate change on main dam releases

The forecasts impact stream flow/discharge from creeks and rivers, precipitation, and evaporation, but nowhere is any forecast made of a reduction in discharge from the main dam to form the Goulburn River outflow, to deliver water downstream to irrigators, towns and for environmental flows. A subjectively assumed release reduction is given in Section 5.2.3.

5.2.3. Main dam releases

A reduction in discharge from the main dam is needed to ensure its viability in meeting its core purpose, whilst avoiding unacceptably low levels of storage. The (90-percentile) discharge figure adopted is a reduction of 43%, exceeding the forecast reduction in discharge from the main rivers and northern creeks of 41.9%. For 50-percentile models, main dam discharge reduction is 15.9%, exceeding the streamflow reduction of 13.7%. The aim is to find an acceptable discharge reduction, to retain what is considered a 'healthy' dam, never reaching a persistently empty state, and possibly attaining levels that overtop the weirs at both 272 and 275 mAHD. When modelling the weirs, it is presumed that the weirs start at FSL, having been overtopped by the main dam, filling the weirs upon completion. The model then reports the events when there is no overtopping by the main dam upstream.

5.2.4. Surface areas

In the case of any modelling of the main dam, surface area is subject to change, using areas matching stored volumes, as calculated in models for the main dam of CC-4, 8, 12 and 16. New volumes are found using four models for each situation. Two of these are the more comprehensive, the first being 'Calculating evaporation', where precipitation is adjusted for the climate change forecasts. Calculating surface area is made using a quadratic equation for the final model 'Volumes'. Once all surface areas are calculated, and 'Net evaporation loss' is copied to the 'Volumes' model, the outcomes are calculated for water passing from the weirs downstream to the main dam. This also indicates months in which no water passes downstream.

In all modelling, any drop in volume is relatively small, with storage mostly staying within a 90-percentile range. Surface area must be assumed as constant for weirs, at their FSL, to calculate evaporation, which is then transferred to the Volumes model to calculate new weir volumes and discharge overtopped into the main dam by weirs.

If new volumes are below 100% and greater accuracy was sought, the new area needs to be transferred back into the evaporation sheet and recalculated. However, it already

contains a small error within the new volume. As this error rate is in the order of 15 ML in 10,000 ML (0.15%) no attempt to improve the accuracy was made, especially since evaporation has been overstated as a deduction. The outcome is therefore conservative.

5.2.5. Incorporation of a valved outlet in the weir wall

Another key assumption is that there is normally no transfer of water between a weir and the main dam except when the crest is overtopped (from either direction). Whilst a valved outlet may be built into the weir wall, its purpose would be to drain the weir for a significant event but would normally remain closed. It could also be left open if water levels for both weir and dam were the same or very close, as this would allow for fish exchange.

5.3. Climate change forecast factors by DEECA

DEECA stated on page 4 (DEECA report, 2016) that "The shortening of the baseline period, compared to historical baselines, is designed to reflect climate behavior at the current level of greenhouse gas concentrations. It recognizes the latest findings from the Victorian Climate Initiative that show current climate conditions and their influences are different to earlier decades of the 20th century, and that rapid global warming has occurred over this period. Techniques are presented to extend this baseline using the full historic climate record to incorporate a wider range of natural climate variability". The models would be used to determine three situations: -

(1) The impact of climate change on the main dam for both a 50- and 95-percentile impact for the year 2065 forecasts.

One question to answer is "what reduction in discharge from the main dam is needed to ensure there remains a healthy water storage, whilst attempting to still meet the dam's core activity of providing water downstream for irrigators, townships, and the environment?" The model adopted would then be assessed for its potential to overtop the weir from downstream, upstream, as this would satisfy any volume reduction within the weir below FSL.

It would also allow fish navigation upstream, since a fishway is not part of the proposal, unlike that for The Narrows Project on Lake Hume.

(2) The outcome from (1) would then be linked to the weirs at three sites, giving rise to the question "what is the weirs' behavior in the months when no overtopping was occurring from downstream back upstream?".

(3) Finally, the weirs would be modelled to determine their outcome if there did not exist a main dam. This is illustrated in model CC-17. It would answer the question "what happens if the weirs were never overtopped by the main dam?" That is, could they stand alone?

5.4. Climate change projections for application to weir and dam models

The success of the project to build one of six weir options rests on whether the impact of climate change leaves any weir high and dry in the landscape.

To evaluate a climate change impact, with the worst-case scenarios of climate projections adopted, outcomes are reflected in Tables 5.2 and 5.3.

(a) Streamflow reductions

Climate change projections were applied to the forty-year data for Brankeet Creek and estimates for forty years made for the remaining three creeks, Merton, Tallangalook and Glen creeks (where continuity of gauging is absent).

Similar data was created for the five main rivers feeding the main dam, being Goulburn, Big, Jamieson, Howqua and Delatite rivers, using the same projections.

(b) Precipitation reduction

Projected decreases in rainfall were calculated for the weir locations using reporting stations Strathbogie, and Lake Eildon. In modelling for the main dam, Mansfield PO was added as a reporting station.

(c) Evaporation is predicted to increase between 8.2% and 11.4%, relatively, for year 2065 at a 50-percentile or 90-percentile probability.

Table 5.2: DELWP climate change projections applied to weir at 272 mAHD/dam models, based on Year 2065 projections

	Weir #1 at elevation 272 mAHD	Weir #2 at elevation 272 mAHD	Weir #3 at elevation 272 mAHD	Main dam
Climate impact	50-percentile	50-percentile	50-percentile	50-percentile
Streamflow % reduction	13.7	13.7	13.7	13.7
Precipitation % reduction	4	4	4	4
Evaporation % increase	8.2	8.2	8.2	8.2
Main dam % discharge reduction	N/A	N/A	N/A	15.9
Scenario No.	CC-1	CC-2	CC-3	CC-4
Climate impact	90-percentile	90-percentile	90-percentile	90-percentile
Streamflow % reduction	41.9	41.9	41.9	41.9
Precipitation % reduction	20.7	20.7	20.7	20.7
Evaporation % increase	11.4	11.4	11.4	11.4
Main dam discharge as % of historical values	N/A	N/A	N/A	43
Scenario No.	CC-5	CC-6	CC-7	CC-8

Table 5.3: DEWLP climate change projections applied to weir at 275 mAHD/dam

models based on Year 2065 projections

	Weir #1 at elevation 275 mAHD	Weir #2 at elevation 275 mAHD	Weir #3 at elevation 275 mAHD	Main dam
Climate impact	50-percentile	50-percentile	50-percentile	50-percentile
Streamflow % reduction	13.7	13.7	13.7	13.7
Precipitation % reduction	4	4	4	4
Evaporation % increase	8.2	8.2	8.2	8.2
Main dam % discharge reduction	N/A	N/A	N/A	15.9
Scenario No.	CC-9	CC-10	CC-11	CC-12

Climate impact	90-percentile	90-percentile	90-percentile	90-percentile
Streamflow % reduction	41.9	41.9	41.9	41.9
Precipitation % reduction	20.7	20.7	20.7	20.7
Evaporation % increase	11.4	11.4	11.4	11.4
Main dam % discharge reduction	N/A	N/A	N/A	43
Scenario No.	CC-13	CC-14	CC-15	CC-16

5.5 Outcomes of climate change modelling

5.5.1. Main dam impacts

Reduced dam discharges were applied in the range of 30-40% reduction and it was found that if (for 90-percentile models) reduction was less than 40% of historical releases, the main dam either gradually or rapidly approached a state of ‘empty’.

A discharge reduction of 43% was needed to avoid the main dam becoming empty at any point, where streamflow reductions were at 41.9%.

For the fifty percentile projections, modelling was made for dam discharges reduced by 15.9%, exceeding the reduction projected for streamflows of 13.7%.

This thesis does not, however, evaluate the impact a much-reduced Goulburn River has on meeting Lake Eildon's core operational purposes of irrigation, townships water supplies and environmental flows. That evaluation would require a whole separate thesis. G-MW has no doubt been modelling this.

Table 5.4: Summary of outcomes of climate change scenarios for main dam

Scenario No.	Main dam discharge reduction (Note 1)	Climate probability percentile	Highest storage level / lowest level	Number of months (out of 480) when dam fails to overtop weir	Main dam – storage mean for 480 months reported
CC-4	15.9%	50	Highest 99.6% Lowest 5.8%	184 (At 272 mAHD) 38.3%	55.2%
CC-8	43%	90	Highest 89% Lowest 7%	211 (At 272 mAHD) 44%	46.0%
CC-12	15.9%	50	Highest 99.6% Lowest 5.5%	211 (At 275 mAHD) 44%	55.2%
CC-16	43%	90	Highest 89.4% Lowest 7%	287 (At 275m AHD) 59.8%	45.9%

5.5.2. Impacts on the weirs.

Modelling for the main dam across the range of climate change projections indicated that it overtopped upstream the weirs at both heights 272 & 275 mAHD, with a frequency over the 480 months reported of between 40.2% and 61.7%.

Tables 5.5 and 5.6 present outcomes for weirs #1 to #3 for crest elevations of 272 and 275 mAHD.

Discharge from the northern creeks into the weirs kept their storage levels high when the main dam was below weir crest heights and allowed the weirs to overtop crests into the (lower) main dam for between 32.1 and 39.2% for crest elevations 272 mAHD and between 35.4 and 51.7% for 275 mAHD, out of the 480 months.

In Table 5.5, the frequency of storage below FSL for all three weirs at crest elevation 272, with climate change percentile at 50, was between 7.6% and 15.2%. With an increase in climate change prediction to 90-percentile, this frequency changes to a range 10.4% to 25.1%.

Table 5.6 shows the frequency of storage below FSL for all three weirs at crest elevation 275, with climate change percentile at 50, was between 10.9% and 19.4%. With an increase in climate change prediction to 90-percentile, this frequency changes to a range 13.2% to 28.9%.

These outcomes indicate that all weir models delivered a stable and satisfactory outcome across the range of climate change predictions.

One scenario, CC-17 (not included in tables), was modelled to show a weir's performance in the absence of any support from the main dam, treated as a stand-alone weir.

Commencing empty (from construction), it took just nine months for creek discharge to fill it (to 275 mAHD with capacity 11,185ML).

For 91 of the 480 months reported the weir was below FSL (19%).

Its lowest storage level was 89.7%, but noticeably, its mean storage level was 97.8%, indicating that the weir was not reliant upon the main dam for it to be a viable operation. This is important, given that the main dam could be operated at consistently low storage levels by its operator Goulburn-Murray Water, thereby offering little support for the weir's function.

Table 5.5: Summary of outcomes of climate change scenarios for weirs at 272 mAHD

Scenario No.	Weir & crest height in mAHD	Climate change percentile	Number of months weir not overtopped by dam & months weir below FSL	Frequency weir overtops downstream into dam	Main dam discharge reduction
CC-1	Weir #1 at 272	50	184 & 14 (7.6%/184)	170 out of 184 months (35.4%/480)	15.9%
CC-2	Weir #2 at 272	50	184 & 21/ 11.4%	163 out of 184 months (34%/480)	15.9%
CC-3	Weir #3 at 272	50	184 & 30/ 15.2%	154 out of 184 months (32.1%/480)	15.9%
CC-5	Weir #1 at 272	90	211 & 22/ 10.4%	188 out of 211 months (39.2%/480)	43%
CC-6	Weir #2 at 272	90	211 & 34/ 16.1%	176 out of 211 months (36.7%/480)	43%
CC-7	Weir #3 at 272	90	211 & 53/ 25.1%	158 out of 211 months (32.9%/480)	43%
These summaries are for weirs only. Main dam data is within CC 4,8,12,16					

Table 5.6: Summary of outcomes of climate change scenarios for weirs at 275 mAHD

Scenario No.	Weir & crest height in mAHD	Climate change percentile	Number of months weir not overtopped by dam & months weir below FSL	Frequency weir overtops downstream into dam	Main dam discharge reduction
CC-9	Weir #1 at 275	50	211 & 23/ 10.9%	188 out of 211 months (39.2%/480)	15.9%
CC-10	Weir #2 at 275	50	211 & 28/ 13.3%	183 out of 211 months (38.1%/480)	15.9%
CC-11	Weir #3 at 275	50	211 & 41/ 19.4%	170 out of 211 months (35.4%/480)	15.9%
CC-13	Weir #1 at 275	90	287 & 38/ 13.2%	248 out of 287 months (51.7%/480)	43%
CC-14	Weir #2 at 275	90	287 & 50/ 17.4%	235 out of 287 months (49%/480)	43%
CC-15	Weir #3 at 275	90	287 & 83/ 28.9%	202 out of 287 months (42.1%/480)	43%
These summaries are for weirs only. Main dam data is within CC 4,8,12,16					

Chapter 6: Other considerations for assessing viability of a weir at Bonnie Doon

6.1. Introduction

The focus of this study is hydrologic, but there are other key considerations for a weir like the one proposed. Of the 'other considerations' listed below, the *first three* are considered as being of primary importance for the construction of the weir.

Other considerations include: -

- *Topographic and geologic considerations*
- *Structural considerations and access to materials*
- *Economics*
- Water quality
- Environmental issues
- Water Act
- Planning permit requirements
- Native Title requirements
- Social impact assessment
- Traffic impact assessment
- Heritage and cultural assessments
- Management plan
- Wetlands

The first three in the list above will be expanded upon in Section 6.4 and others will follow, dealt with briefly.

As part of the literature review it was discovered that a not dissimilar Narrows Project had been developed by consultants to the Towong Shire Council in North-East Victoria.

That weir was to be across the Mitta Mitta River within Lake Hume, a further two hundred kilometres north of Lake Eildon.

Section 6.3 below draws the comparison between the two projects.

The principal difference between the projects was that the Narrows Project focussed only on creating a permanent boating surface for a year-round season, whilst at Lake Eildon the weir was aimed at boating, water security for Bonnie Doon residents, and a water facility for fire-fighting purpose.

6.2. A summary of weirs within Lake Eildon

Whilst the Narrows Project on Lake Hume proposed one site, at "The Narrows", three locations are tested for a weir within Lake Eildon, each with a different set of parameters: -

Weir #1

- Located within the vicinity of and upstream of the two bridges at Bonnie Doon.
- Modelled for two different crest elevations, being 272 and 275 mAHD.
- Embankment lengths are 191 and 228 metres, respectively.
- Surface areas for the weirs at their FSL are 37 and 82 hectares, respectively.
- Weir heights are 4 and 7 metres, respectively (invert level 268 mAHD)
- Volumes at the weirs' FSL are 457 and 2,317 megalitres, respectively.

Weir #2

- Located 1.1 kilometres downstream of the bridges.
- Modelled for the same crest elevations as Weir #1, being 272 and 275 mAHD.
- Embankment lengths are 205 and 233 metres, respectively.
- Surface areas for the weirs at their FSL are 72 and 121 hectares, respectively.
- Weir heights are 8 and 11 metres, respectively (invert level 264 mAHD).
- Volumes stored at the weirs' FSL are 2,180 and 5,450 megalitres, respectively.

Weir #3

- Located 3.2 kilometres downstream of the bridges.
- Modelled for the same crest elevations as Weirs #1 & #2, being 272 and 275 mAHD.
- Embankment lengths are 257 and 407 metres, respectively.
- Surface areas for the weirs at their FSL are 158 and 223 hectares, respectively.
- Weir heights are 12 and 15 metres, respectively (invert level 260 mAHD).
- Volumes stored at the weirs' FSL are 6,510 and 11,185 megalitres, respectively.

The location of the three weir sites can be seen in Figure 6.1 below.

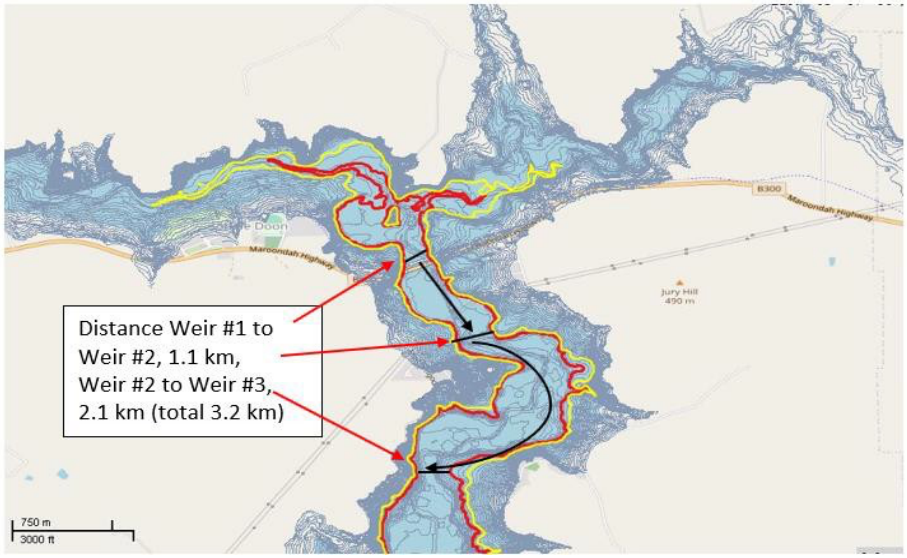

Figure 6.1: Location of the 3 weir sites, surface area and distance from Weir #1 to #3 for weirs at 272 mAHD/155 ha (red) and 275 mAHD/243 ha (yellow)
(Source: MapWindow, 2020)

6.3. Comparing weirs at Lake Eildon with The Narrows weir

Submerged heights above crests when main dam is at FSL: -

- When Lake Eildon is at FSL (288.9 mAHD), Weir #3 with the highest weir height of 15m at crest elevation 275 mAHD is 13.9m under water.
- When Lake Hume is at FSL (192.2 mAHD), The Narrows weir at the highest weir height proposed of 14M at crest elevation 190.2 mAHD is 2m under water.

Capacities at both locations: -

- The Narrows weir backs up several kilometres to the discharge point of the Mitta Mitta River into Lake Hume (see Figures 6.2 and 6.3 below). At Lake Eildon the greatest distance impacting surface area is 3.2 kilometres (see Figure 6.1 above).

Table 6.1 below shows the range of weir heights and volumes considered, between 4 and 15 metres for Lake Eildon weirs and 8 to 14 metres at The Narrows.

Capacity for the weirs is between 457 and 6,510 ML for Lake Eildon weirs at 272 mAHD and 2,317 and 11,185 ML at 275 mAHD. Capacity at The Narrows ranges from 28,000 to 100,000 ML.

Table 6.1: Comparing weir heights & volumes at the weirs' full supply level at both locations

	Lake Eildon Weirs		**The Narrows Weir**			
At crest elevations in mAHD	272	275	184	186	188	190
Weir height						
The Narrows			8m	10m	12m	14m
Eildon Weir #1	4m	7m				
Eildon Weir #2	8m	11m				
Eildon Weir #3	12m	15m				
Volumes stored behind weirs (ML)						
Narrows			28,000	45,000	70,000	100,000
Eildon Weir #1	457	2,317				
Eildon Weir #2	2,189	5,450				
Eildon Weir #3	6,510	11,185				

There are several differences of purpose between both weir locations: -

For the Narrows Project, water security for Tallangatta was not the issue it is for Bonnie Doon, as the Mitta Mitta River is a permanently flowing source, released from the very large upstream storage Dartmouth Dam.

By comparison, water is harvested at the road bridge at Bonnie Doon and pumped approximately two kilometres to a treatment plant. When water is released by the

main dam for irrigation there are regular summers when the water recedes to a level where the pick-up point is exposed. Water is slowly collected from a sand base within a tank, so greater reliance is placed upon a 50 ML reserve pondage at the treatment works to keep the township supplied, often with severe water restrictions.

Figure 6.2 below shows the relationship of The Narrows to Lake Hume and the Mitta Mitta River released from Lake Dartmouth.

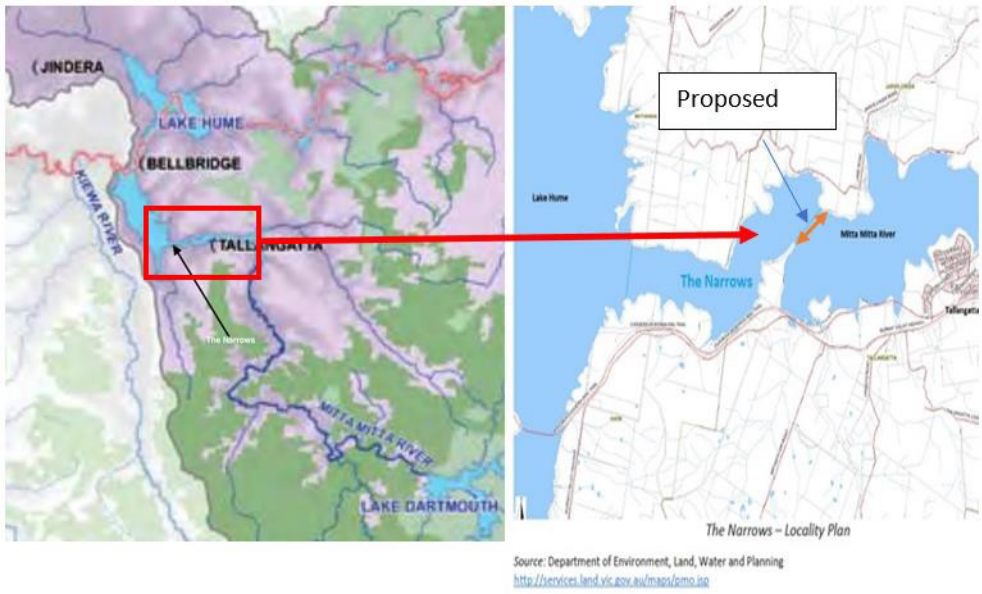

Figure 6.2: Illustrating the much larger storage behind The Narrows weir (Source: SMEC Report to Towong Shire Council, 2015)
Scale: LH Map 1cm=3km; RH Map 1cm=400m (approximate)

Figure 6.3 below shows that distance from the Narrows weir to inflow of Mitta Mitta River is approximately 7km (when Lake Hume is at FSL), with an average width of 1,000m. With weir heights of from minimum 8m to maximum14m, the weir embankment length range is 400-500m (400 metres was adopted for costing purposes). When the weir is at FSL the distance of new storage area from the weir is almost 4.5km. This compares with a maximum distance of 3.2km at Lake Eildon.

Figure 6.3: The Narrows Storage distance from weir to river inflow
(Source: Google Earth Pro. Scale: 1cm = 540m)

6.4. Primary considerations

6.4.1. Topographic and geologic considerations

In selecting optimal sites for a weir, four factors influenced these: -

1. Finding a location in the chosen area with narrow valley width that minimised embankment length, contributing to cost containment.
2. Then, ideally, steepness of side slopes kept embankment length short for a weir between the invert level and weir height option selected.
3. Assessment of the surface area offered by the options.
4. Finally, a site was selected provided the geology of the site is suitable, as Figure 6.7 shows there was a range of options.

In the absence of a detailed geotechnical investigation of all three weir sites in Lake Eildon, it was assumed that sites #2 and #3 might be little different from site #1 (see Figures 6.4 to 6.6 and the accompanying Figure 6.7 below). Bore logs (shown in feet) from bridge building at site #1 suggest that foundations to rock bed would be from a minimum of 1metre (abutment) to a maximum of 5 metres (centre of riverbed). This

compares with up to 40 metres at The Narrows. This would have a significant impact on construction cost of any of the weirs at Lake Eildon.

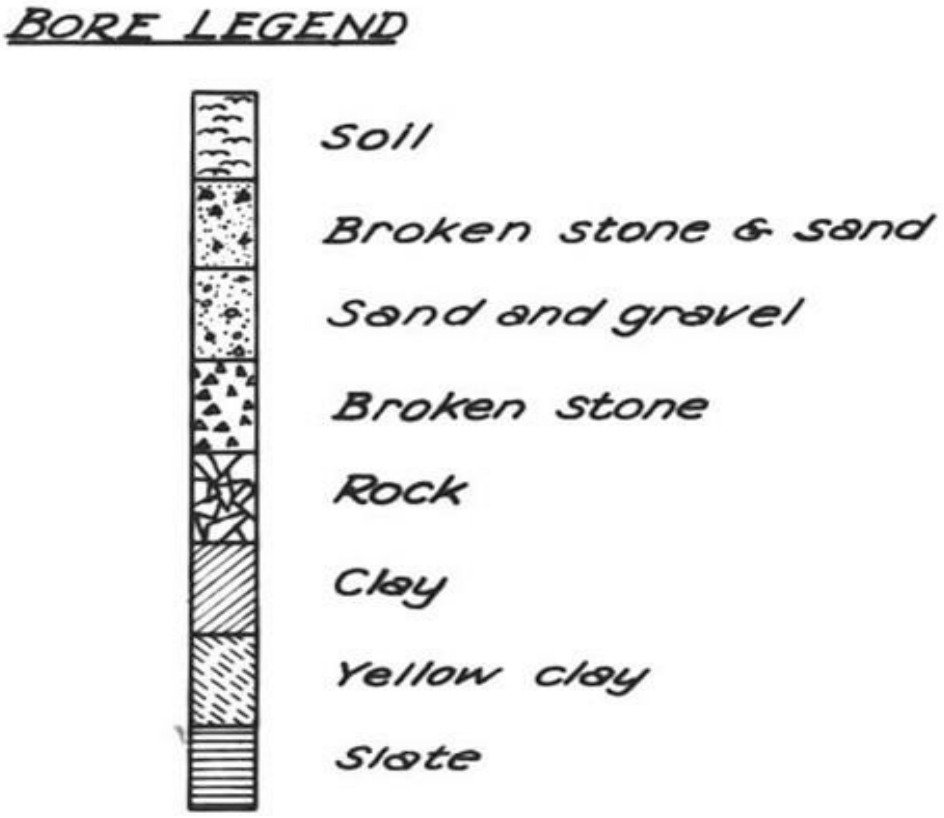

Figure 6.4: Bore Legend for the bore logs presented in Figures 6.5 and 6.6
Source: Legend and logs supplied by Country Roads Board (now VicRoads)

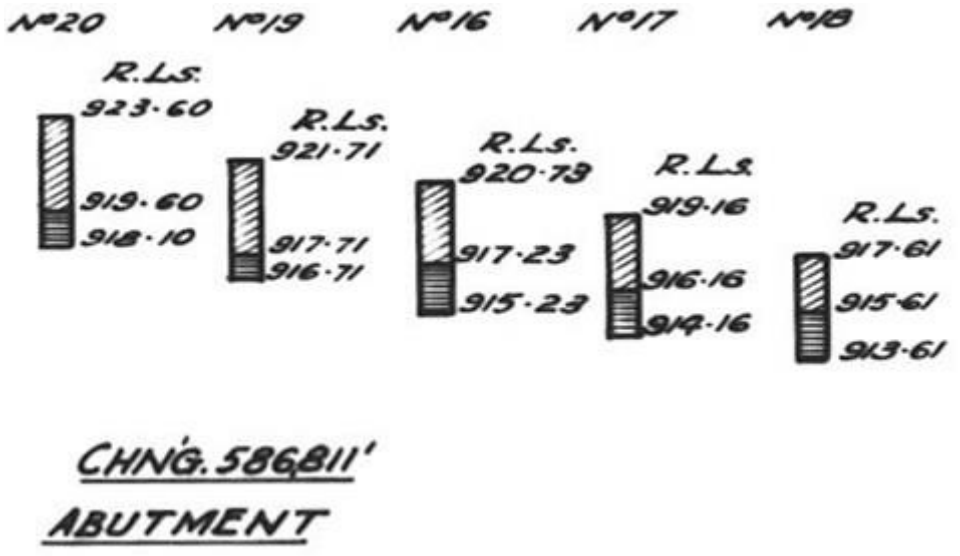

Figure 6.5: Bore log (in feet) for Abutment, Road bridge at Bonnie Doon (along the direction of flow)

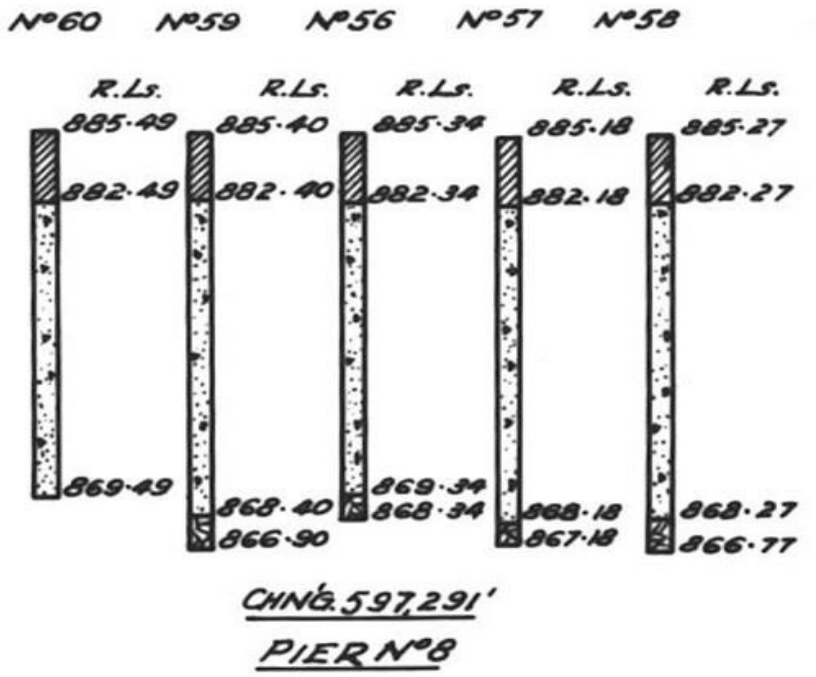

Figure 6.6: Bore logs (in feet) at the deepest pier at the centre of riverbed under road bridge at Bonnie Doon (with the 5 bore logs along the direction of flow).

Suggested possible weir sites are represented by the red lines shown in Figure 6.7 below, where abutments can be within a mix of shale, siltstone, and sandstone.

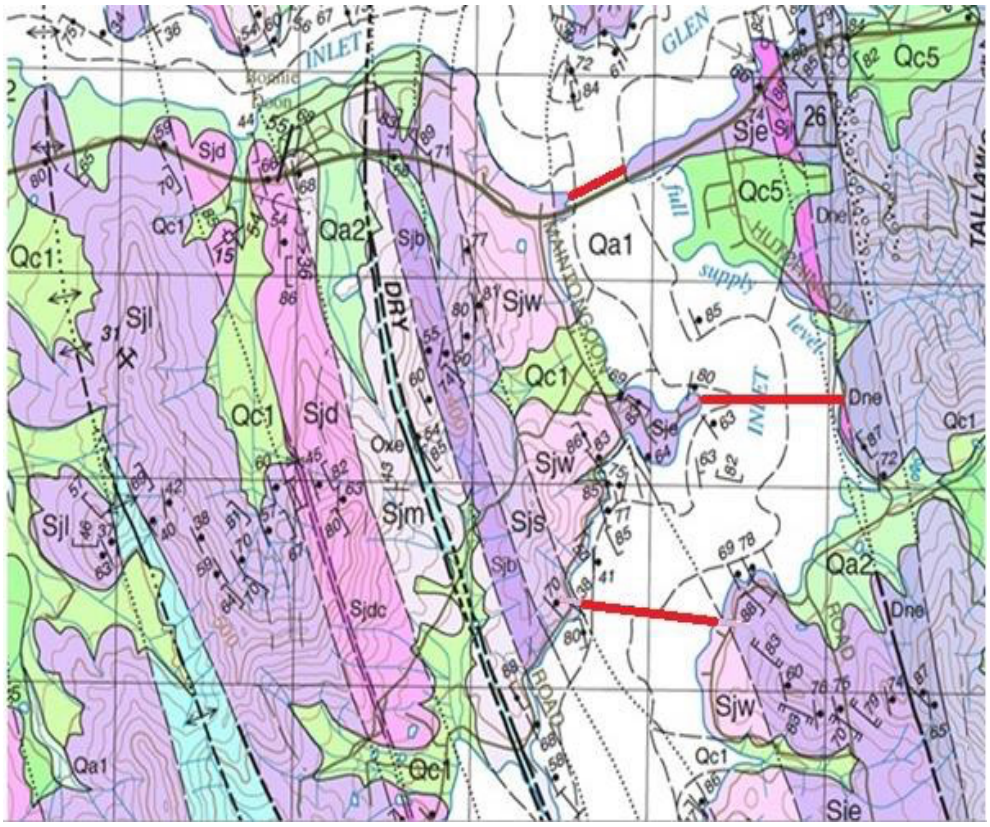

Figure 6.7: Geology at Lake Eildon weir sites.
Source: (Victorian/Eildon) Geological Map Series.
Scale 1cm=130m (approximate)

There are minor changes in bedrock between the three sites at Lake Eildon.

- Site #1 indicates Sjw – siltstone/minor sandstone on the western side with Sje – sandstone/siltstone on the eastern side.
- Site #2 indicates Sje – sandstone/siltstone (western) and Dne – siltstone/ sandstone/minor shale (eastern)
- Site #3 indicates Sjs – sandstone/siltstone (western) and Sje – sandstone/ siltstone (eastern)

Qa1 as seen in the map Figure 6.7 is within the lakebed, being sedimentary material from the Quaternary period, consisting of gravel, sand silt, and generally unconsolidated alluvial deposits as indicated in the Bore legend Figure 6.4.

Below Qa1 are igneous rocks form the Licola volcanic group.

The depth of Qa1 at weir sites is not specifically known, but the bridge footings give an indication that depth to bedrock at sites 2 and 3 could be between 2 and 5 metres.

This information suggests that an exceptionally deep cut off would not be required, unlike at the Narrows site on Lake Hume. This has a significant impact on construction cost.

Looking at the foundation for the Narrows weir, SMEC noted that "the alluvial aquifer is typically 20m to 50m thick along the flood plain of the river. Depth to bedrock at the centre of the river channel appears to be approximately 40m, reducing in depth closer to the abutments." This compares with a possible maximum depth of 5 metres to rock within Lake Eildon.

6.4.2. Structural considerations and access to materials

The type of structure differs between Site #1 and Sites #2 & #3.

- Site #1, being within 50 metres of the bridges, requires a weir with a small footprint to avoid compromising the bridges' pylons. It would require a concrete or cut stone wall, not rockfill or earth & rockfill structures.
- Sites #2 and #3 on the other hand can be the same in structure as each is in open water, with apparent similar geology. Locations allow for a wide footprint, as needed.
- The type of weir to propose must recognise that regular overtopping in both directions requires materials resistant to being eroded, as could happen if it was just rock and earth filled. Each batter might need an extensive rip-rap finish to maintain stability and minimise erosion.

- Access to general rock and earth materials locally would need to be surveyed. Creating a suitable quarry in the nearby hills is preferable, to minimise cartage and traffic disruption.

The type of infrastructure needed, and its footprint size and degree of batter slopes are dependent upon the geology at the site and the streamflow passing over the weir's crest. The stability of the Narrows weir is subject to overtopping by the Mitta Mitta River, a fast-flowing small river, which can deliver between 10,000 ML/day (normal), to 100,000 ML/day (major flood). SMEC considered four structural options but ruled out two for reasons of prohibitive cost.

Their two recommended options were: -

1. Rock filled structure with a core cut-off. SMEC described it as "a weir with rockfill shoulders and a nominally centrally located low permeability core and cut-off extending into the foundations" (see Figure 6.8 below).
2. A zoned earth and rockfill structure with a core cut-off (see Figure 6.9 below).

Two additional weir design options included (a) twin walled sheet pile with plunge pool, and (b) a concrete weir.

Because of the generally high cost of the (a) and (b) structures and the associated depth to bedrock, both of those options were discarded.

Both weir options were designed for overtopping by the fast-flowing Mitta Mitta River, hence the wide footprint / low angle batters.

Analysis of data showed that there were just six days (in 14,610 days/40 years) when the Brankeet Creek daily discharge exceeded 1,000 ML. When extrapolated with estimates for the three other creeks, the highest daily discharge is 19,683 ML.

In only 20 of the 480 months did the monthly flows exceed 10,000 ML, whilst that is the normal 'daily' flow for the Mitta Mitta River. The average monthly flow for the 20 months was 15,012 ML, giving a mean of 484 ML against the Mitta Mitta's daily 10,000 ML delivery.

Despite the infrequency of significant flood flow from the northern creeks, any weir must be designed to withstand the pressures of the volume passing above crest height of a proposed 5m wide broad-crested weir.

Two weir designs were chosen for the Narrows Project are shown in Figure 6.8 & 6.9 below.

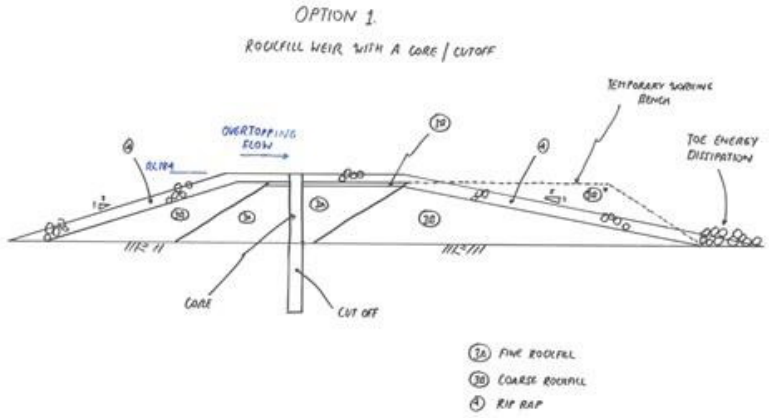

Figure 6.8: Weir Option 1.
(Source: SMEC Report, 2015)

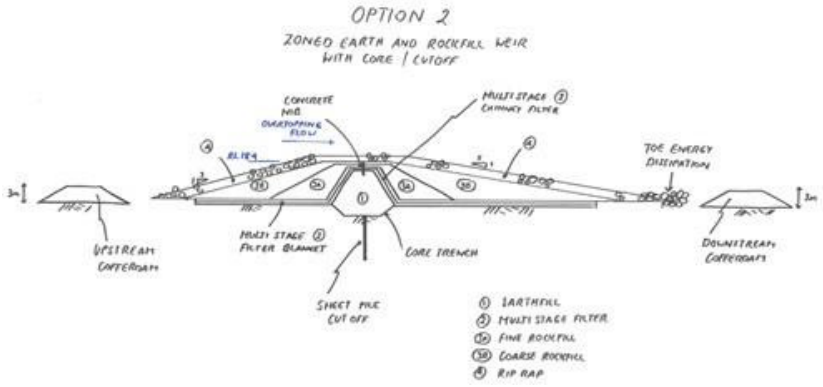

Figure 6.9: Weir Option 2.
(Source: SMEC Report, 2015)

6.4.3. Economics

Rough, simplified cost estimates for a Lake Eildon weir are based on a simple material volume extrapolation of those for a weir in The Narrows. Economic benefits are identified but placing a value on them is well outside the scope of this thesis. It should be noted however that the benefits of a weir at Lake Eildon would exceed those within Lake Hume. The CBA for a Lake Eildon weir would exceed '1', and also noting that had a discount rate of 4% been applied to The Narrows project, instead of the 7% imposed, it too would have met the criteria needed to have been positive for CBA.

Cost estimates have been made for a weir at either Site #2 or #3 with the following assumptions:

Lake Eildon weir options

(A.1) Weir site #2

- A maximum weir height of 11m at elevation 275 mAHD
- Embankment length 233m
- A rockfill weir – see Option 1, see Figure 6.8 above
- An earth and rockfill weir – see Option 2, see Figure 6.9 above
- G-MW might insist on inclusion of a concrete lined steel 2m diameter pipe with a hydraulically actuated 2m x 2m vertical lift gate, for emptying the weir in exceptional circumstances. This might be done to meet dam safety emergency drawdown requirements. No additional cost has been included for this.
- A road bridge and a fishway are excluded from the cost estimates.

(A.2) Weir site #3

- A maximum weir height of 12m for Weir #3 and elevation 272 mAHD.
- Embankment length 257m
- A rockfill weir – see Option 1, see Figure 6.8 above
- An earth and rockfill weir – see Option 2, see Figure 6.9 above
- G-MW might insist on inclusion of a concrete lined steel 2m diameter pipe with a hydraulically actuated 2m x 2m vertical lift gate, for emptying the weir in exceptional circumstances.
- A road bridge and a fishway are excluded from the cost estimates.

Relevant cost parameters: -

- In both (A.1) and (A.2), there is a shorter embankment length than at The Narrows.
- Cost inflation index adopted is 2% per annum.
- Cost estimates are in 2022 dollars.
- Allowance for concrete cut off is 5m, compared with 8m for Narrows.
- Compared with The Narrows, additional heights in Lake Eildon weirs are 3m (to 11m) for (A.1) and 4m (to 12m) for (A.2).

Costs estimated for the Narrows Project were included in the GHD Report for Towong Shire Council, Phase 2, February 2017, to include: -

Narrows Option 1, a rockfill weir

- Weir only – AUD $64.7 million, including a contingency of AUD $16.8 million.

Narrows Option 2, a zoned earth and rockfill weir

- Weir only – AUD $52.7 million, including a contingency of AUD $13.7 million.

Narrows – Additional project options

- Road bridge AUD $25.2 million.
- Fishway AUD $5.0 million.

The Narrows embankment length was estimated at 400m with a crest height of 8m.

Additional costs would also be a price placed upon the increase in evaporation.

This would require the project to buy shares in water trading to offset this cost.

A simple extrapolation of costs from The Narrows to Lake Eildon has been based on the change in volumes of material for all sites.

These calculations are shown in Appendix C. Section D.

Lake Eildon Weir #2 estimated cost: -

- Option 1, a rockfill weir - $76.2 million.
- Option 2, an earth & rockfill weir - $64.2 million (cheapest)

Lake Eildon Weir #3 estimated cost: -

- Option 1, a rockfill weir - $98.9 million.
- Option 2, an earth & rockfill weir - $83.6 million.

The Narrows consultants' recommendation was for the project not to proceed. It was considered that the capital cost of infrastructure, ongoing maintenance cost and cost of loss to evaporation were more than the value placed on benefits, such that a CBA > 1.0 could not be achieved, where '1' was required for the project to proceed. This

was achievable with an internal rate of return of 4% and a demand level by tourists/lake users of 3 (highest). The state Department of Finance and Treasury required a discount rate of 7% for such projects, which gave a CBA closer to 0.5 and therefore not considered viable.

In recent years in Australia, interest rates have fallen dramatically, and they are forecast by the Reserve Bank to remain relatively low for considerable time ahead. This would suggest that the discount rate of 7% applied by DELWP is excessive and that the 4% which made the project viable would have been more appropriate.

In addition, Lake Eildon is Victoria's largest freshwater destination for boating and is within a 2-hour drive from many of Melbourne suburbs. Using historical visitor numbers and projecting a significant increase arising from a permanent water storage, the benefits in any CBA calculation might be much greater than existed for The Narrows project.

In estimating cost of the weir options for Lake Eildon, simple fractional extrapolation of The Narrows costs has been made, for changes in embankment length, depth of cut-off, crest height and timing of construction, and with more contemporary rates of return on capital charges.

6.5. Other considerations

6.5.1. Water quality

An assessment would be needed to determine whether there are different issues arising from the different depths for weirs at heights of 272 to 275 mAHD. The larger the surface area, the better the outcome for Goulburn Valley Water with respect to water drawn for treatment. Water contamination from gasoline-driven boating would be reduced with greater surface area and increased water depth, making treatment less complex.

6.5.2. Environmental issues

As part of an environmental impact statement, consideration might be given to whether, in conjunction with the construction of a weir, a new wetland might be constructed where the Brankeet Creek meets Lake Eildon. This could have significant importance for local and migratory birds and fish nursery. With current emphasis upon the environmental threats to the platypus species, a wetland may be an important feeding and breeding ground for this semiaquatic monotreme (egg laying) animal. Wetland visits might also add significant tourist dollars to the region. Planning processes will also need to be defined to address requirements of the Environmental Protection Agency and other relevant authorities.

6.5.3. The Water Act

The Water Act 1989 - Victorian legislation (Act number 80/1989) covers access to water across all of Victoria. This includes the operation of Lake Eildon for storage and release of water for irrigation, townships, and the environment. An amendment to the Act would be needed to allow a weir within Lake Eildon to separately control and store water not designated under the Act.

6.5.4. Planning Permit Requirements

Permit requirements would need to be assessed for development of a weir within the lake, road perimeter access for the build, any drilling investigations and for disposal of excess material.

6.5.5. Native title requirements

These would be observed and referred to, but may not create an issue, since the proposed weir sits within an area previously assessed.

6.5.6. Social impact

A local focus group might be formed at Lake Eildon to feed into any feasibility study the opinion, concerns and queries arising from stakeholders.

6.5.7. Traffic impact assessment

Changes in traffic conditions could arise from two sources: (a) increased activity by trucks carting machinery and materials to the weir site, and (b) post-construction increase in users of the new weir for recreation or viewing.

6.5.8. Heritage and cultural assessments

Legislation associated with cultural heritage is included in any of: -

- Heritage Act 1995
- Aboriginal Heritage Act 2006
- Aboriginal Heritage Regulations 2007

6.5.9. Management Plan

An overall management plan would be developed to oversee all aspects of the project.

These would include adherence to legislative requirements, management of all contractors, and keeping stakeholders and the public informed of progress.

6.5.10. Wetlands

If, beyond this thesis, an all-inclusive investigation beyond hydrologic elements was made, a survey would be needed of the area where the Brankeet Creek enters Lake Eildon, to identify a suitable wetland location.

This would determine the size possible for a wetland and enable overlays to be prepared for a small, gated barrage and adjacent wetland. Its location would be above the FSL of the main Lake Eildon.

The design may have Brankeet Creek flowing to a small barrage. This could impound a pondage to hold back any flood waters or adjust their release time into Lake Eildon. If the weir built near Bonnie Doon is submerged, no withholding of flood water would be necessary to protect the weir structure.

Constructed at right angles to the wetland's barrage could be a wall running the length of the wetland. The wall's height would be less than that of the barrage, so that by closing any gates it could take this pondage to its FSL, and water could flood over the adjacent wall into the wetland. This would create the wetland swamp and periodically repeat flooding would be made to assist in maintaining the wetland health. A boardwalk could run throughout the wetland for the benefit of tourists viewing the wetland.

Chapter 7: Outcomes, conclusions, and recommendations

7.1. Summary

When this thesis commenced, little was known or understood about the implications the main dam could have on a weir in the vicinity of Bonnie Doon. With the weir's principal purpose being the creation of a permanent water storage at the lake's northern end, it was hoped that evidence would exist for water levels to be topped up periodically by the main dam's overtopping of the weir. Those events would guarantee the success of the project.

However, when the impact of climate change was introduced with potentially severe projections (year 2060 at 90-percentile) for decreases in streamflows and precipitation whilst evaporation increased, a positive outcome for the weir was speculated as doubtful. Modelling from historical data through to climate change projections has allayed those doubts.

7.2. Outcomes

7.2.1. Main dam impact on weirs if historical data is applied.

(i) In applying historical data for main dam storage levels and discharges as reported by G-MW, weirs at all three sites performed well.

(ii) Overtopping by the main dam from downstream to upstream of the weirs failed to occur: -

- For 186 of 480 months for crest elevation 272 mAHD with just 12, 8, & 26 of those 186 months when water did not pass downstream from Weirs #1 to #3 respectively.
- For 216 of 480 months for crest elevation 275 mAHD with just 19, 22, & 34 of those 216 months when water did not pass downstream from Weirs #1 to #3 respectively.

- When FSL level behind the weirs was not sustained, water levels generally remained higher than 95% (at 272 mAHD).

(iii) It should be noted that the Millennium Drought caused most months in which no overtopping occurred.

7.2.2. Main dam impact on weirs if climate change projections were applied.

(i) Despite expectations that the weirs might not perform well with year 2065 projections applied for climate change, the range of outcomes from modelling was very satisfactory for their performance.

(ii) From Table 5.5, when a 50-percentile model was used with a weir crest elevation of 272 mAHD, with streamflows down 13.7% and main dam discharge reduced 15.9%: -

- Weirs at crest elevation 272 mAHD were not overtopped by the main dam for 184 (38.3%) of the 480 months (across the three weirs), and
- Were below weir FSL for 14, 21 and 30 months, but still at levels no more than a 15.2% decrease.

(iii) When a 90-percentile model was used, with streamflows down 41.9% and main dam discharge reduced 43%: -

- All three weirs at crest elevation 272 mAHD were not overtopped by the main dam for 211 (44%) of the 480 months, and
- Were below weir FSL 22, 34 and 53 months, but with water levels remaining high.

(iv) From Table 5.6 when a 50-percentile model was used with a weir crest elevation of 275 mAHD, with streamflows down 13.7% and main dam discharge reduced 15.9%: -

- Weirs at crest elevation 275 mAHD were not overtopped by the main dam for 211 (44%) of the 480 months (from Site #1 to Site #3), and
- Were below weir FSL between 23, 28, and 41 months when levels fell below FSL but still with storage above 90%.

(v) When a 90-percentile model was used with a weir crest elevation of 275 mAHD, with streamflows down 41.9% and main dam discharge reduced 43%: -

- Weirs at crest elevation 275 mAHD were not overtopped by the main dam for 287 (60%) of the 480 months.
- All weirs often maintained FSL, with 38, 50 and 83 months below FSL, but still with around 95% storage.

It should be noted that the climate change adverse parameters were being modelled on historical data that included the worst drought period on record.

Significant reductions in discharge from the main dam are applied to models, to avoid the dam becoming empty at any point, but the impact upon M-GW deliveries from the Goulburn River with such reductions are not addressed here in detail. It is assumed that G-MW will have modelled severe river reductions forecast by DELWP and considered the strategies needed to meet core activities around irrigation, town supplies and environmental flows.

7.2.3. Modelling a weir in the presumed absence of a main dam

This model (CC-17) assumed that the main dam did not exist, so no overtopping from downstream to upstream was included. The model only considered flows from the weir going downstream, with water delivered by the four northern creeks. The model was applied to Weir #3 as an example, at crest elevation 275 mAHD with 90-percentile climate change projections.

The following outcomes occurred: -

- It took streamflows from the northern creeks nine months to fill the weir to 11,185 ML from empty.
- There were 107 months when no overtopping downstream occurred and 373 months (78%) when water passed downstream over the weir.
- There were 106 months (22%) when the weir was below FSL, but still above 90% storage and often at 95% or more.

7.2.4. Impact of prolonged drought

The Millennium Drought commenced in 1996 and ended in 2010. Nothing of this magnitude had been recorded before, nor lasted so long. In all the modelling, this drought was responsible for most of the months where no overtopping from downstream to upstream was made by the main dam.

Despite the drought's severity, the model for Weir #3, in the absence of a dam, indicated that the northern creeks, even at reduced flows, sustained a viable weir.

7.3. Conclusions

Section 7.3.1 below considers the positive and negative impacts of each weir site.

The core impacts are those for recreational water use and local town water supply.

It also looks at economic benefits arising from a new weir, followed by possible ramifications of its construction. An overview of each weir site is concluded for primary elements including embankment length, surface area and type of weir.

7.3.1. Advantages/disadvantages of each weir site

Possible and actual positive impacts from a new weir: -

1. Improved water security for Bonnie Doon.
2. Increased water security for local recreational boating and fishing.

3. Expansion of local economy.
4. Increase in local employment.
5. Greater security for bookings at caravan park and motels.
6. Environmental benefits from water for fauna and flora.
7. Water guarantee for firefighting use.

Possible and actual negative impacts from a new weir: -

1. Low main dam water levels to enable construction – below elevation 260 mAHD (invert level).
2. Noise from construction.
3. Possible adverse impact upon air quality caused by dust.
4. Interruption to recreational boating during build.
5. Movement of large trucks on local roads.
6. Environmental impacts.
7. Increased risk from machines/trucks working at the site.
8. An overall increase in water lost to evaporation with the presence of both a weir and a dam. The summaries below, for the three weir sites considered, weigh the potential of each site, which lead to the recommendations in Section 7.

Weir site #1:

Advantages: –

- Shorter embankment length and lower crest height than other weirs,
- Concrete construction with smaller footprint; fastest to construct,
- With overall smaller dimensions, it may still be cheaper to build than other weirs, despite being of concrete material.

Disadvantages: –

- Small surface area for boating.
- Relatively shallow pondage prevents larger, faster boats accessing it, especially as too dangerous for water skiing due to number of fully or semi-submerged dead trees – suitable only for small, slow, tinny fishing boats.
- With relatively lower water levels, higher evaporation rates might occur.
- A risk of algal blooms with lower water depth and warmer water temperatures.
- Infrastructure for water extraction for town supply would need relocation.
- With the smaller surface areas this weir may have little appeal to many of the stakeholders.

Weir site #2:

Advantages: –

- Surface area is 1.9 times that of Weir #1 at 272 mAHD (37 to 72 ha), 1.5 times for 275mAHD (82 to 121 ha) reducing crowding of boating activities compared with Weir #1.
- Deeper water with no submerged trees below Weir #1 for 1.1km south of the bridges renders it suitable for all boating sizes and activity types.
- With lower weir heights, but similar embankment lengths to Weir #3 at 272 mAHD, it is cheaper to build at either structural option than Weir #3 at 272 mAHD.

Disadvantages: –

- Surface area (72 ha) is 46% of Weir #3 (for 272mAHD), and (121 ha) 54% at 275mAHD, so less boating space if traffic on the water is heavy at full season.

Weir site #3

Advantages –

- Maximizes surface area at 158 and 223 ha (272 v. 275 mAHD),
- Provides a deep body of water for boating and fishing,
- Extends the lake behind the weir 2.2km downstream from Weir #2,
- Cost of a Weir #3 option at 272 mAHD is more expensive than Weir #2 at 275 mAHD, but still below the $100 Million considered the maximum viable cost.

Disadvantages –

- Higher weir heights of 12 or 15 metres increases construction cost and higher ongoing costs with the annual charge for evaporation.

7.3.2. Operations of the main dam

This section looks at the impact upon the main dam from climate change forecasts.

Historical management reports for the main dam indicated continuously strong discharges for downstream irrigation and maintained positive storage levels across the forty years to 2019. Levels only fell for reasons of maintenance or during the Millennium Drought, but the dam was never seen as 'at risk' of approaching a state of 'empty'. This position changes, however, with the application of climate change projections. Unless discharges are reduced by greater than the reduction in stream flows, the main dam would be empty for considerable periods of time, an untenable situation.

It is outside the breadth of this thesis, but significantly reduced discharge is an issue to be addressed by G-MW, since less water delivered to irrigators has far-reaching implications for food production. It would also impact upon water available for downstream environmental flows and downstream towns' supply.

Some recognition has already been made of the need to use water differently, with switches from flood irrigation and broadcast sprays to drip systems, but more will be

needed to reduce losses from seepage and evaporation from water delivered by open channels.

7.3.3. Cost of construction

Cost of construction has been estimated, based upon historical forecast costs for the Narrows Project, and applying a current cost of capital index. Since no precise designs for the weirs (for concrete or rock and earth filled) has been undertaken, costing is roughly estimated.

It is also recognized that if flood mitigation of the northern creeks is achieved using a wetland pondage, the footprint of either weirs #2 or #3 might be slightly reduced, further reducing the cost of construction. In addition, local exploration of and access to rock supply has an impact on cost, especially for cartage costs.

7.3.4. Inclusion of a lock

When water levels for the main dam are below that of the weir, two lakes exist, and the question arises as to whether any opportunity could exist to navigate from one lake to the other. This has some relevance due to the presence, adjacent to the lake, at Bonnie Doon, of a hotel. A ‘boaties’ pub’ visit has been part of the daily ritual for lunches and dinner, with boat owners parking their vessel near an access point. This is dealt with in Recommendations 7.4.2.

7.3.5. Inclusion of a fishway

With four northern creeks feeding the weir, DEWLP and others with interests in fishing might expect a fishway to be included in the weir design, to allow movement of fish from the main dam, through the weir’s lake to hatchery sites within the creeks. This is dealt with in Recommendations 7.4.3.

7.3.6. Inclusion of a wetland

Inclusion of a wetland as part of the project is seen as having several benefits.

These include: -

1. Flood mitigation, where if the weir at Bonnie Doon is above the main dam water level it is subject to flood forces.
2. If severe flooding from the Brankeet Creek is partly controlled with a wetland pondage, the weir within the lake might not need as large a footprint as was designed for The Narrows project, significantly reducing construction cost. Flooding by the northern creeks is just a fraction of the magnitude of those at The Narrows, so a wetland might reduce the impact of flooding.
3. A wetland adds a new cohort of beneficiaries, not necessarily associated with boating, being tourists accessing a wetland boardwalk to observe the potentially large variety of flora and fauna within this new habitat.
4. The extension of the weir project to include a wetland would be relatively small additional cost for a large environmental value, thus making it easier to sell the overall project politically.
5. It greatly adds to the new aesthetic for the local area at Bonnie Doon, creating a 'must see' outcome.

7.4. Recommendations

Following on from the conclusions around each weir, this section recommends the best of the three weir sites, based on maximizing surface area for boating for a realistic construction cost.

7.4.1. Weir selection

Selecting Weir #1 as the option is seen as a quick fix for the problem, with little benefit for most stakeholders. Although possibly the cheapest solution, it fails to deliver significant benefits. It might fail a CBA economic test, as the benefits might not accrue at the level for weirs 2 & 3.

It is recommended that the final choice should be between weirs #2 and #3. Both weirs deliver benefits to all, with weir #3 amplifying those benefits. If construction costs vary significantly between the two options, political will might favor weir #2, which should deliver the project for under $100 million with a high level of economic benefit. However, Weir #3 at the lower 12 metre weir height for elevation 272 mAHD could be constructed for a figure close to the Weir #2 at the lower 11 metre weir height at 275 mAHD and would therefore provide a larger surface area. It is recognized though that any weir at 272 mAHD provides a small boating area north of the bridges (for fishing in tinny boats).

Weirs 2 & 3 both allow water pick up for the treatment plant, without any relocation needed for water pumping infrastructure. If weir #1 was adopted, relocation of infrastructure would be needed.

Any of the three weir sites meets the needs for water pick up for fire-fighting purposes.

7.4.2. Inclusion of a lock

It is recommended that a lock for boat transfer between lakes is excluded from the project.

For a significant percentage of time, any lock, if included, would be submerged and inactive. Conversely, there will be significant time periods when the main dam is well below the invert level of the weir and main dam water's presence could in fact be more than one kilometre further downstream. It is probable that a lock could only function with purpose for a very small period of time, and being periodically submerged, maintenance costs could be high. This renders it an unacceptable cost inclusion.

7.4.3. Inclusion of a fishway

It is recommended that a fishway between the two lakes be excluded from the project.

For reasons similar to exclusion of a lock, a fishway might not function if water in each lake is well separated. When the main dam surface exceeds the weir height, fish

can naturally travel within both water storages. If water levels are approximately the same for both lakes, but no overtopping occurs, a valve within the weir wall could be opened to allow fish exchange. For these reasons, no fishway would be expressly included in the design.

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Appendix A - Examples of weirs present in Australia

A.1 The Fitzroy River barrage

Only if the proposed weir at Bonnie Doon was to have a crest height equal to the main dam, would the barrage, shown in Figure 1, have any relevance as a construction type. Because of cost constraint, the proposed weir will be several metres below main dam FSL, therefore this type of weir would not be included for consideration.

Figure A.1: The Fitzroy River Barrage
(Source: Photo by Fitzroy River Water, 2020)

This barrage is an example of where water is impounded as a river meets a barrage of eighteen gates. Some 80,000 ML is held upstream of the barrage and all gates would normally only open in times of flood. The gates, when all are closed, also prevent tidal saltwater entering the upstream dam and mixing fresh and saltwater. This was the critical reason for its construction, to ensure town water was fresh, not salty.

A.2 Casey Weir

Casey Weir, in Central Victoria, seen in Figures 2 and 3, are examples of what could be built to meet the needs of the proposed weir.

It is constructed of cut stone blocks, stepped across its footprint for stability.

Its stepped design nature, seen when water levels in the main dam are below the weir's invert level, would of course add strong visible aesthetic.

Although suitable as a design type, cost might rule it out as a design option.

Figure A.2: Casey weir in flood
(Source: G-MW, 2020)

Casey Weir was constructed jointly by the Yarrawonga and Shepparton Waterworks Trusts in 1885. Casey Weir was the first major weir on the Broken River.

Figure A.3: Casey weir at lower flow showing fish ladder
(Source: G-MW 2020)

A.3 Pacific Hydro weir

Pacific Hydro is a relatively recent operator in the energy industry in Australia and was created to take advantage of existing potential to harness water flows from small streams, rivers, weirs, and dams. Their more recent overview, which follows, appears on their website 'pacifichydro.com'. One of their installations is seen within the pondage below the main dam at Lake Eildon, where water release is better controlled when released after electricity generation by the main dam. Release from the pondage offers further smaller generation of power. In 1995, the Eildon Pondage project was completed, and has been responsibly producing clean electricity ever since. Figure 4 shows an example of a suitable (Pacific Hydro) weir for this project if it falls within budget.

Figure A.4: A Pacific Hydro weir (Source: pacifichydro.com, 2020)

A.4 Concrete weir on the Broken River, Central Victoria

The concrete weir shown in Figure A.5 would be suitable for this project. Despite not having a wide footprint, it is not subject to extreme flood forces, as the main dam rise from below the weir is generally gradual, before overtopping the weir from downstream. Flood forces from the northern creeks are also suggested to be partly mitigated if a wetland is developed as part of the project, where the Brankeet Creek enters Lake Eildon, with a pondage of minimum 40ML include to receive flood flows.

Figure A.5: Typical overtopped concrete weir, Broken River, Shepparton Victoria
(Source: G-MW, 2020)

A.5 When things go wrong

Figures A.6 & A.7 illustrate what can happen to weir structures. Design and material type will be critical for this project, as the weir will be subject to regular overtopping in either direction and will often be submerged and might remain so for several months at a time.

Figure A.6: Todd Brook Reservoir, UK (2019)

(Source: damfailures.com, 2020)

Weirs and dams may slump or deteriorate with time, seepage or settlement from minor earthquakes or tremors. Sometimes the risk is hidden and does not materialise into potential disaster until some form of collapse occurs. This has happened with the Toddbrook Reservoir built 180 years ago, above Whaley Bridge in England's Derbyshire High Peak area. It was originally built as an earth dam with a puddled clay core, with concrete spillway panels added much later in its life.

When these panels were undermined and dislodged during heavy rain in late July 2019, there was a risk of collapse, threatening the local village.

Figure A.7: Toddbrook Reservoir

(Source: damfailures.com, 2020)

Appendix B - Extension of Chapter 3 data, tables, and graphs

Rainfall data for reporting stations in vicinity of Lake Eildon

B.1 Alexandra Rainfall, 40 years 1980 – 2019

Total rainfall over the 40-year reporting period was 25,144 mm.

No graph is recorded here**:** Annual Rainfall (mm) Alexandra Station as this reporting station is considered outside the area of influence on Lake Eildon.

B.2 Lake Eildon Rainfall, 40 years 1980 – 2019

Total rainfall over the 40-year reporting period was 18,443 mm.

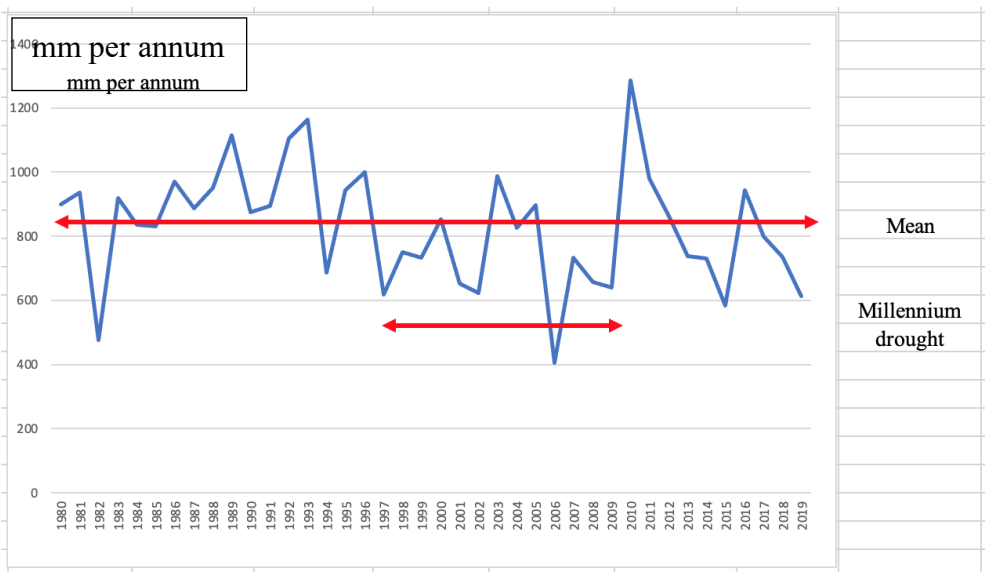


Figure B.1: Annual Rainfall (mm) Lake Eildon Station

(Source: BOM, 2020)

B.3 Mansfield Rainfall, 40 years 1980 – 2019

Total rainfall over the 40-year reporting period was 15,230 mm

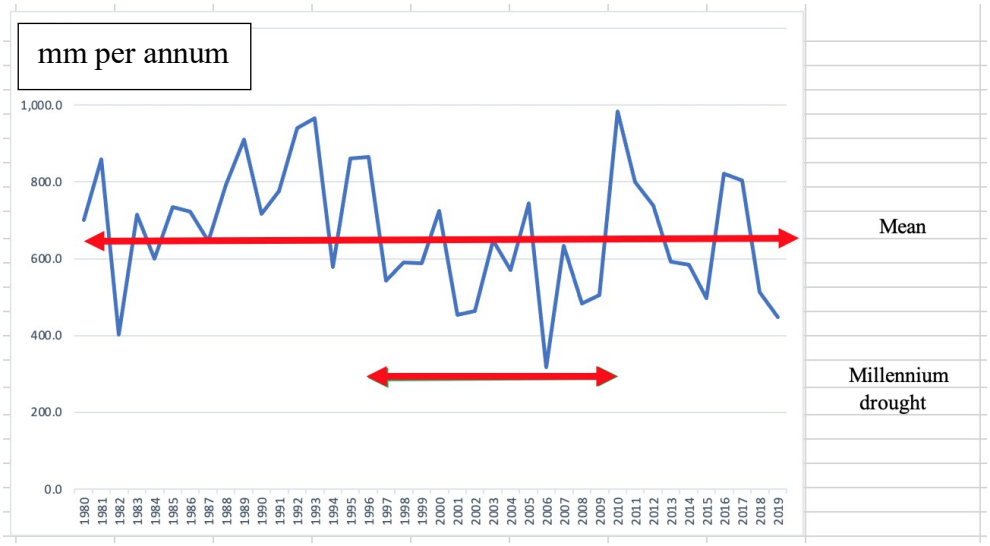


Figure B.2: Annual Rainfall (mm) Mansfield Station

(Source: BOM, 2020)

B.4 Strathbogie Rainfall, 40 years 1980 – 2019

Total rainfall over the 40-year reporting period was 21,290 mm.

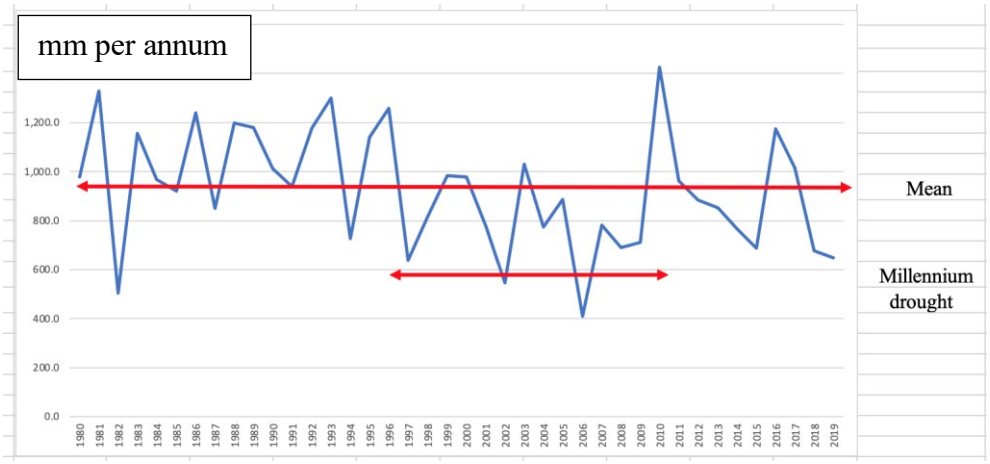


Figure B.3: Annual Rainfall (mm) Strathbogie Station

(Source: BOM, 2020)

B.5 Strathbogie North Rainfall, 40 years 1977 - 2017

Total rainfall over the 40-year reporting period was 40,476 mm.

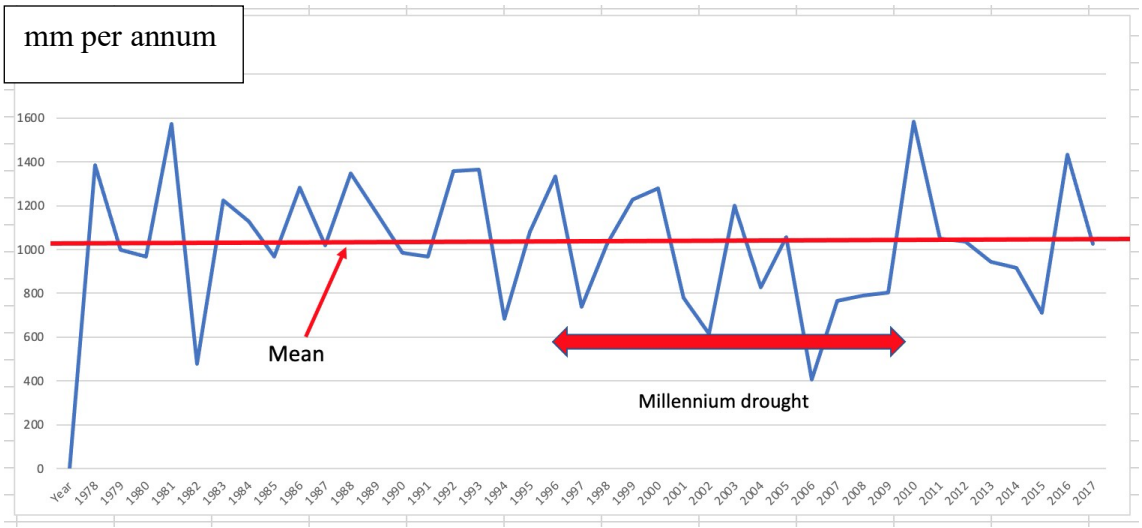


Figure B.4: Annual Rainfall (mm) Strathbogie North Station

(Source: BOM, 2020)

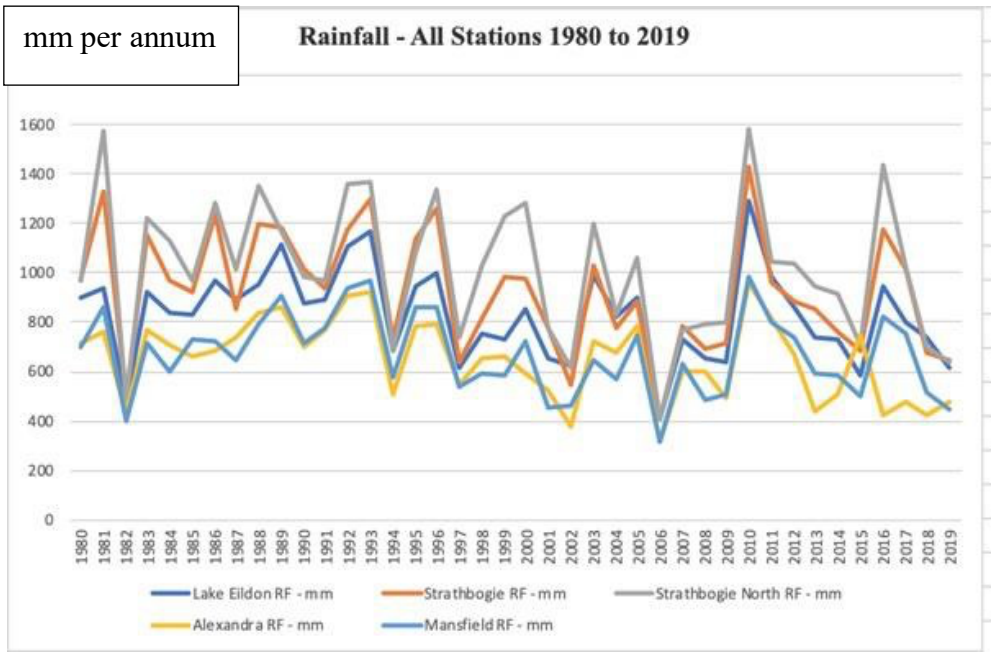


Figure B.5: Summary rainfall five reporting stations

(Source: BOM, 2020)

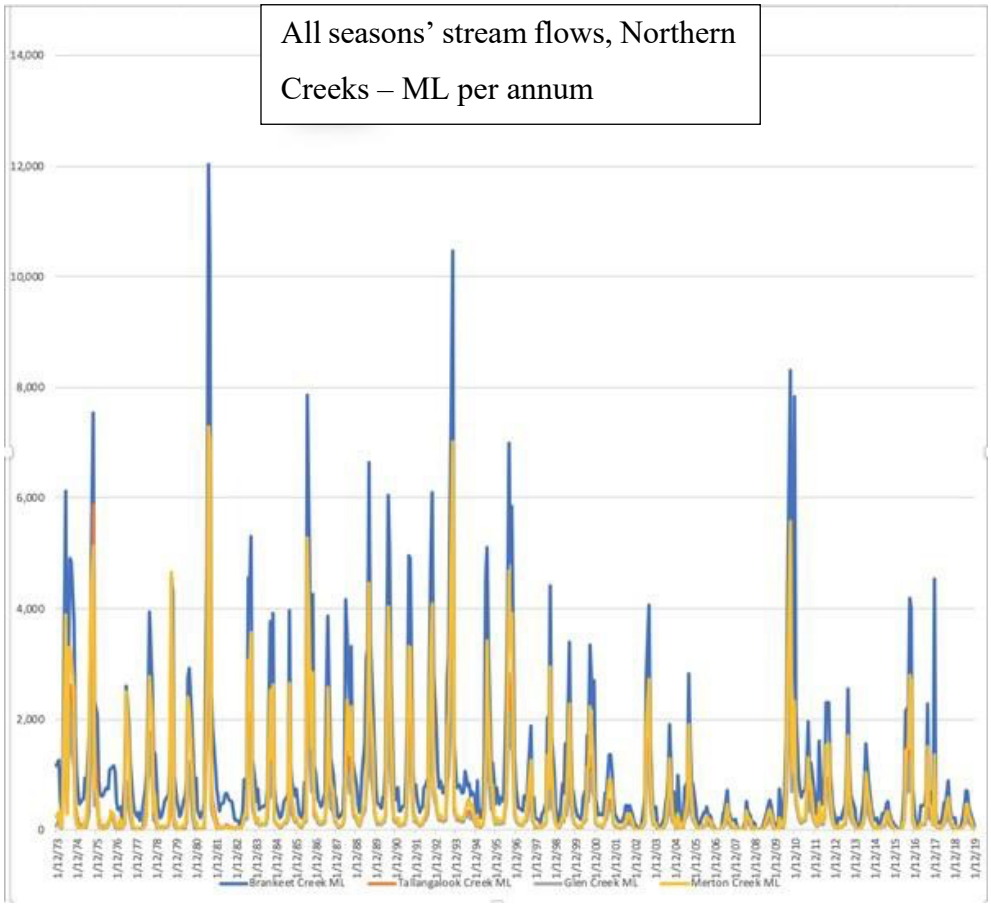


Figure B.6: All seasons combined creeks streamflows

(Source: DEECA, 2020)

Appendix C - Extension of Chapters 4, 5 & 6, data, tables, and graphs

C.1: Data from the other reporting stations

Data from the other reporting stations: Strathbogie, Lake Eildon, Alexandra, and Mansfield are shown below (Strathbogie North appears in Chapter 4, Figure 4.2).

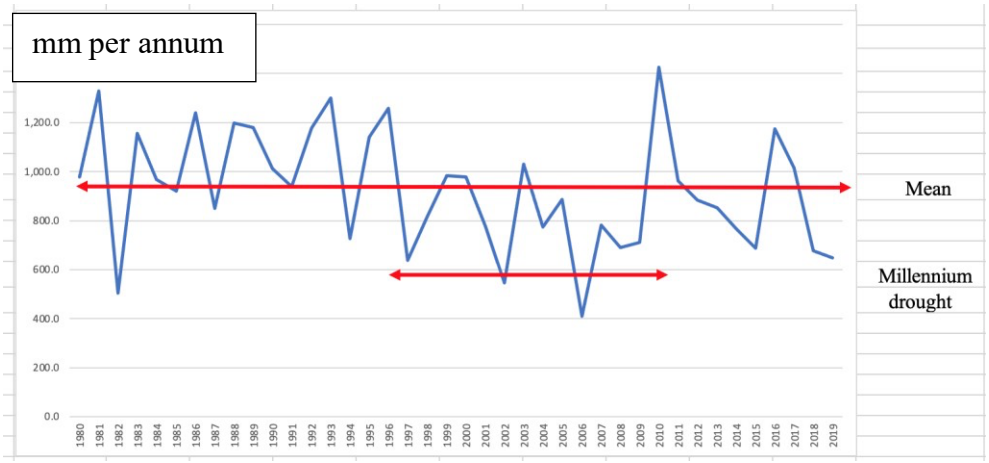


Figure C.1: Rainfall, 40 years to 2019, Strathbogie (Source: BOM, 2020)

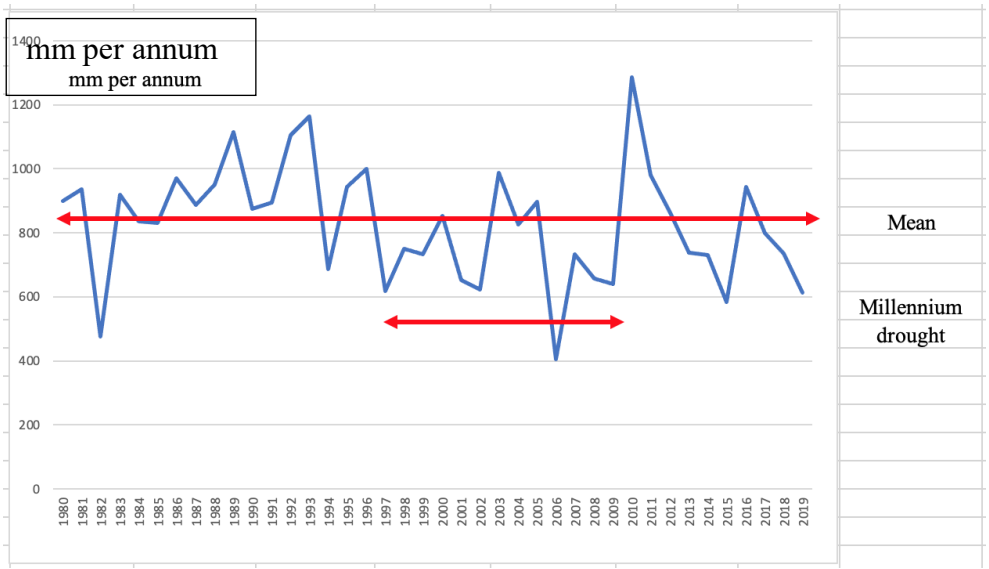
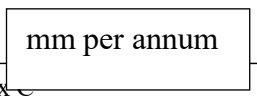


Figure C.2: Rainfall, 40 years to 2019, Lake Eildon. (Source: BOM, 2020)



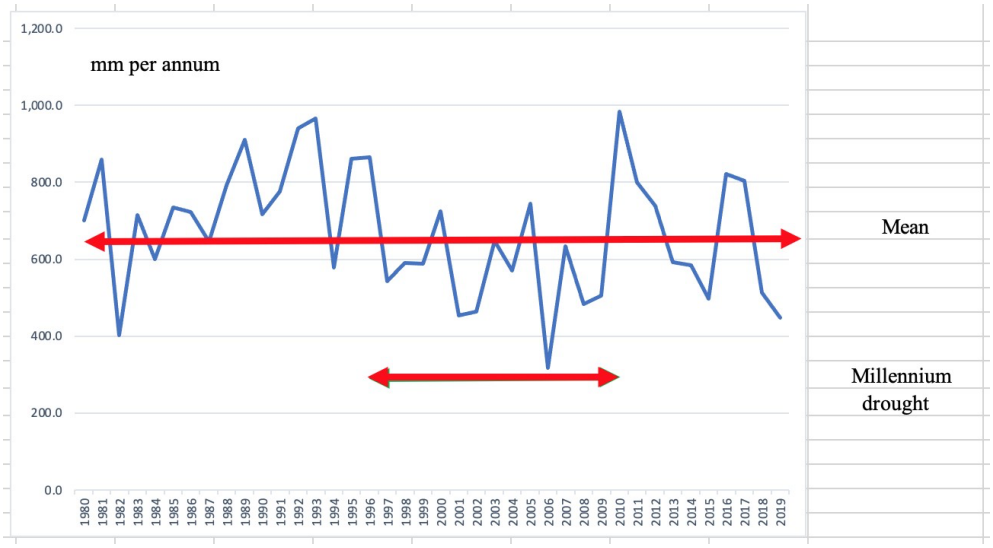


Figure C.3: Rainfall, 40 years to 2019, Mansfield PO
(Source: BOM, 2020)

C.2: Streamflow and discharge volumes by four creeks feeding the Brankeet Arm

Graphed discharge for Brankeet Creek is illustrated in (Figure 4.7) Chapter 4, along with a table for volumes discharged into Lake Eildon (Table 4.2).

The remaining three northern creeks are shown below with a graph and table for each.

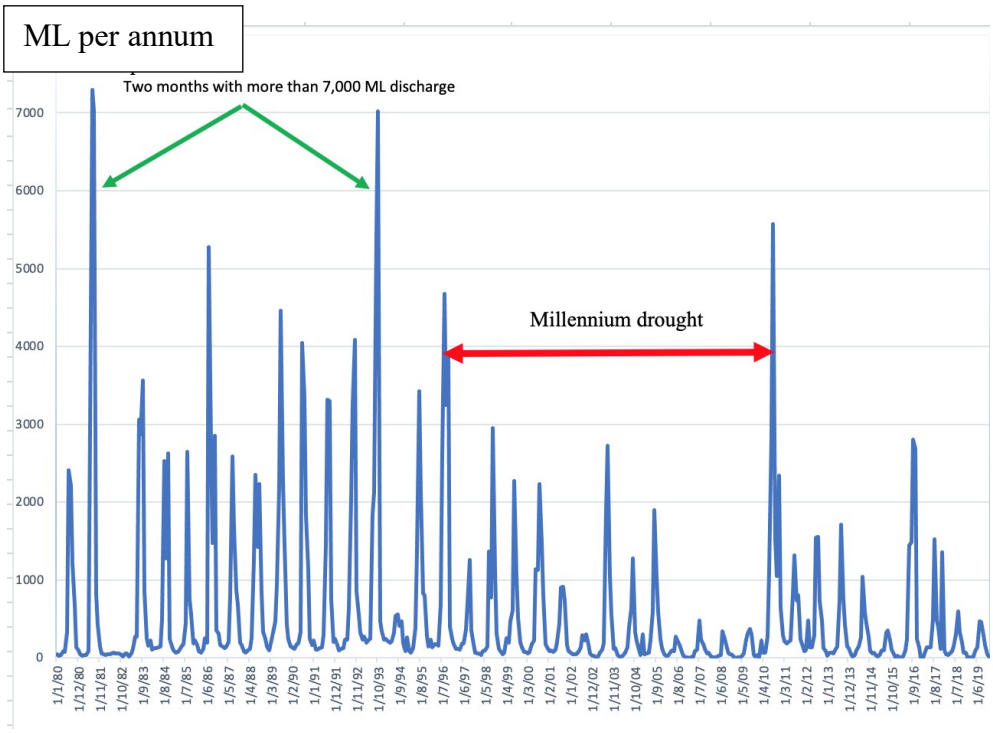


Figure C.4: Discharge, 40 years to 2019, Merton Creek
(Source: DELWP, 2020)

Table C.1: Discharge data for Merton Creek over 40 years

Five years to	5-Year total	Change outcome
1984	46,471	100.0
1989	49,533	106.6
1994	56,816	122.3
1999	43,310	93.2
2004	23,107	49.7
2009	9,934	21.4
2014	34,039	73.2
2019	19,081	41.1

Table C.1 indicates that Merton Creek has seen a 59% reduction in volume over the last 40 years, identical with Brankeet Creek.

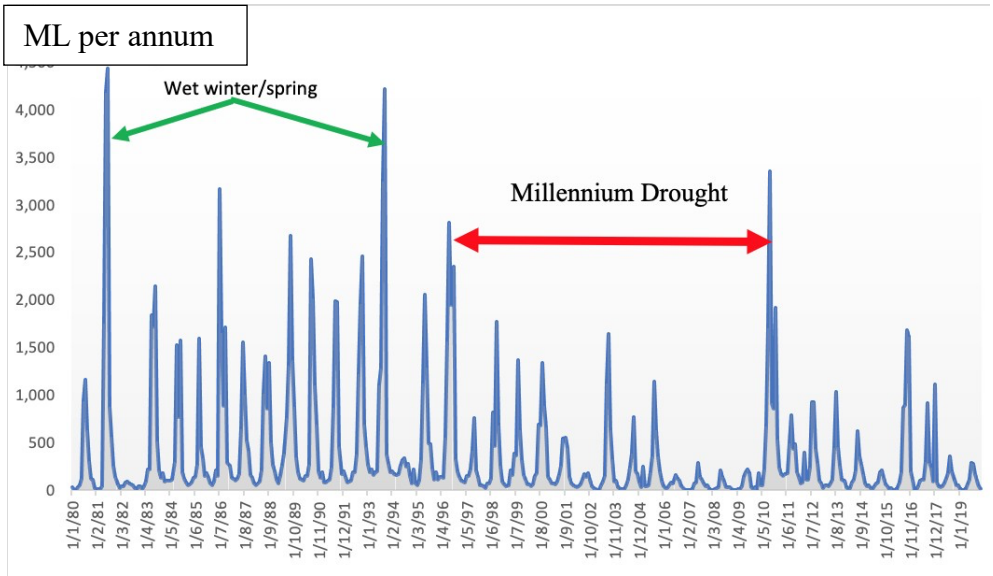


Figure C.5: Discharge, 40 years to 2019, Tallangalook Creek

(Source: DELWP, 2020)

Table C.2: Discharge data for Tallangalook Creek over 40 years

Five years to	5-Year total	Change outcome
1984	28,796	100.0
1989	31,917	110.8
1994	36,197	125.7
1999	27,864	96.8
2004	14,835	51.5
2009	6,431	22.3
2014	22,452	78.0
2019	12,345	42.9

Table C.2 indicates that Tallangalook Creek has seen a 57% overall reduction in discharge over the last 40 years, similar to Brankeet and Merton creeks.

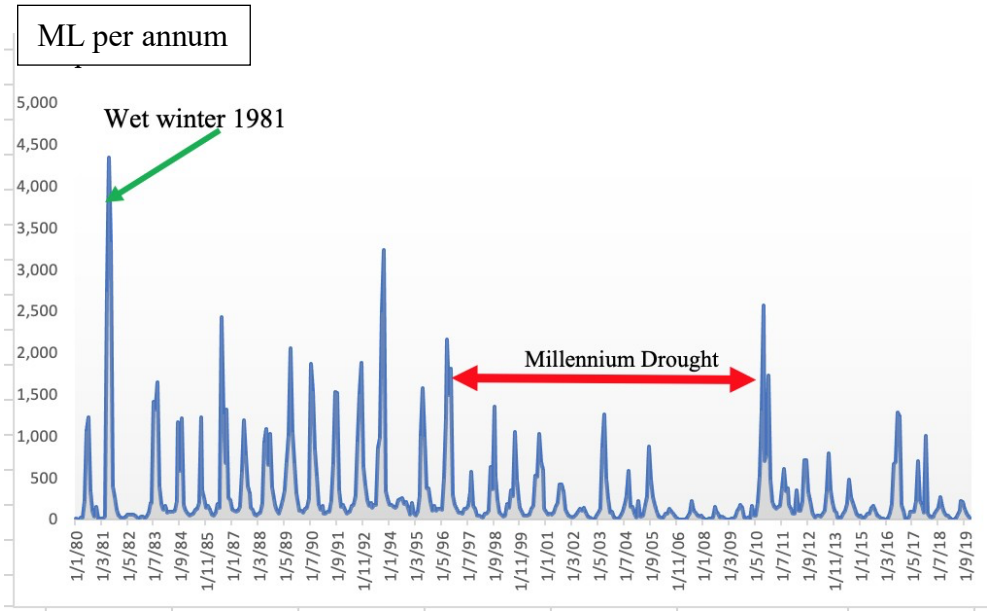


Figure C6: Discharge, 40 years to 2019, Glen Creek

(Source: DELWP, 2020)

Table C.3: Discharge data for Glen Creek over 40 years

Five years to	5-Year total	Change outcome
1984	24,732	100.0
1989	25,553	103.3
1994	28,783	116.4
1999	22,288	90.1
2004	11,851	47.9
2009	5,163	20.9
2014	18,221	73.7
2019	9,908	40.1

Table C.3 indicates that Glen Creek has seen a 60% reduction in volume over the last 40 years, similar to Brankeet, Merton and Tallangalook creeks.

C.3: Streamflow and discharge volumes by five major rivers feeding Lake Eildon

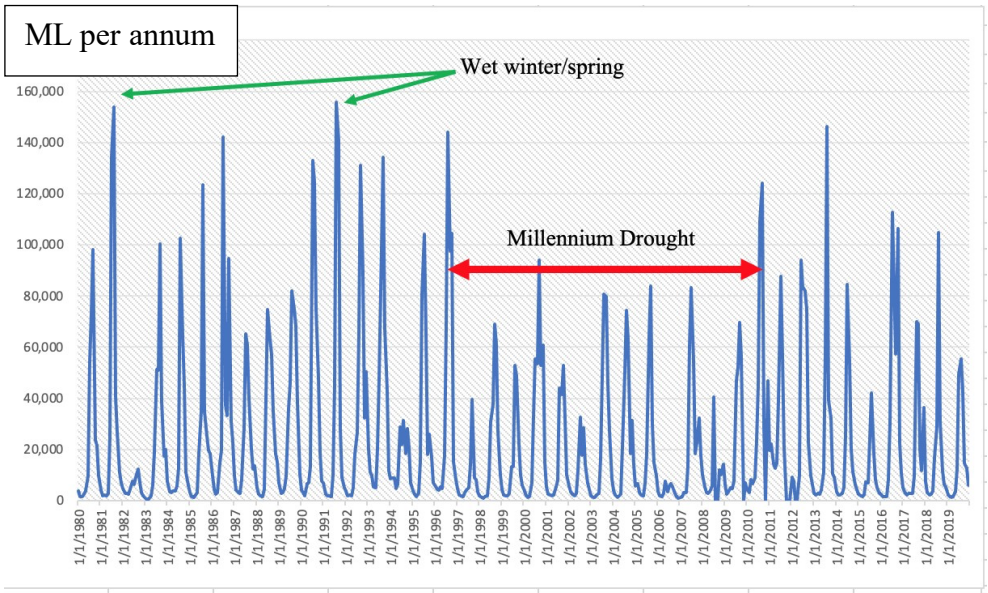


Figure C.7: Discharge, 40 years to 2019, Goulburn River

(Source: DELWP, 2020)

Table C.4: Discharge data for Goulburn River over 40 years

Five years to	5-Year total	% of 1984
1984	1,357,416	100.0
1989	1,674,429	123.4
1994	1,947,473	143.5
1999	1,354,148	99.8
2004	1,320,285	97.3
2009	975,221	71.8
2014	1,640,476	120.9
2019	1,227,155	90.4

Total discharge over 40 years was 11,496,603 ML, an average of 287,415 ML per annum and 23,951 ML per month, the most productive discharge of the five rivers feeding Lake Eildon.

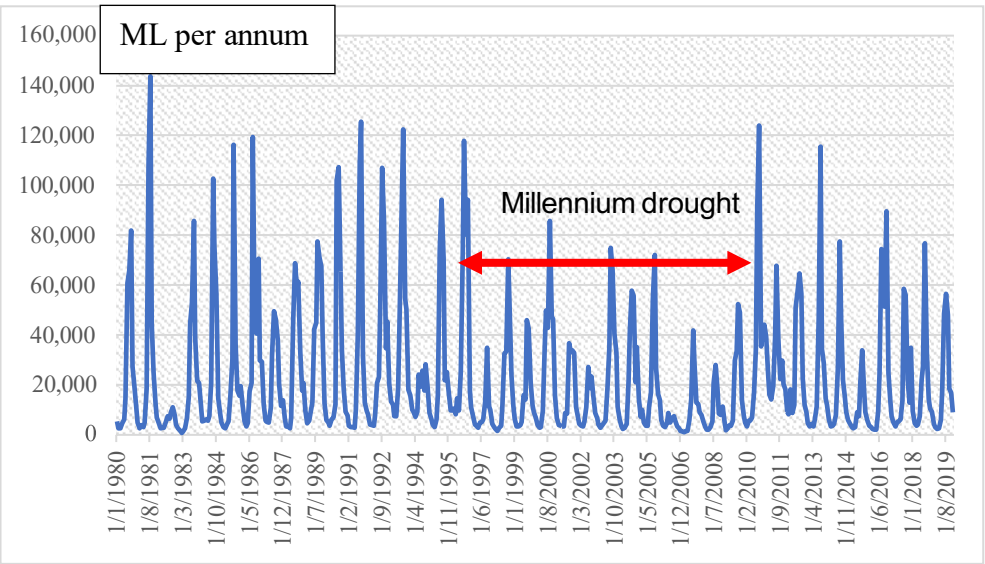


Figure C.8: Discharge, 40 years to 2019, Big River

(Source: DELWP, 2020)

Table C.5: Discharge data for Big River over 40 years

Five years to	5-Year total ML	% of 1984
1984	1,360,434	100.0
1989	2,020,156	148.5
1994	1,404,231	103.2
1999	1,363,706	100.2
2004	1,238,762	91.1
2009	765,216	56.2
2014	1,609,451	118.3
2019	1,174,605	86.3

Total discharge over 40 years was 10,936,561 ML, an average of 273,414 ML per annum and 22,785 ML per month.

Table C.5 indicates that Big River has seen a 14% reduction in volume over the last 40 years, despite early increases.

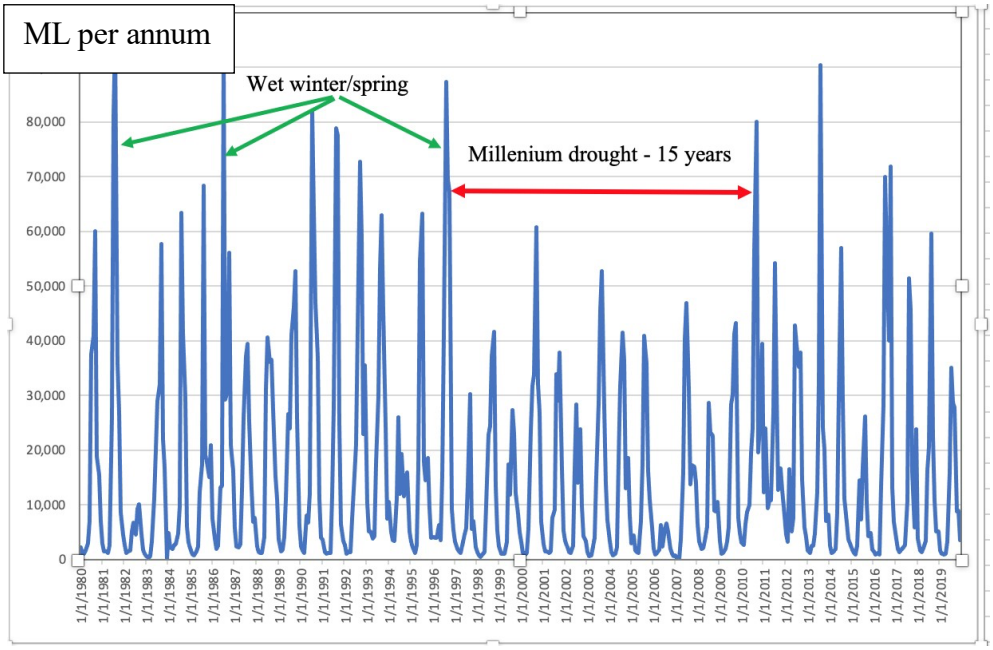


Figure C.9: Discharge, 40 years to 2019, Jamieson River

(Source: DELWP, 2020)

Table C.6: Discharge data for Jamieson River over 40 years

Five years to	5-Year total	% of 1984
1984	902,191	100.0
1989	1,103,126	122.3
1994	1,209,089	134.0
1999	879,769	97.5
2004	865,091	95.9
2009	682,357	75.6
2014	1,107,723	122.8
2019	856,417	94.9

Total discharge over 40 years was 7,605,764 ML, an average of 190,144 ML per annum and 15,845 ML per month.

Table C.6 indicates that Jamieson River has seen an overall 5% reduction in discharge over the last 40 years, despite early increases.

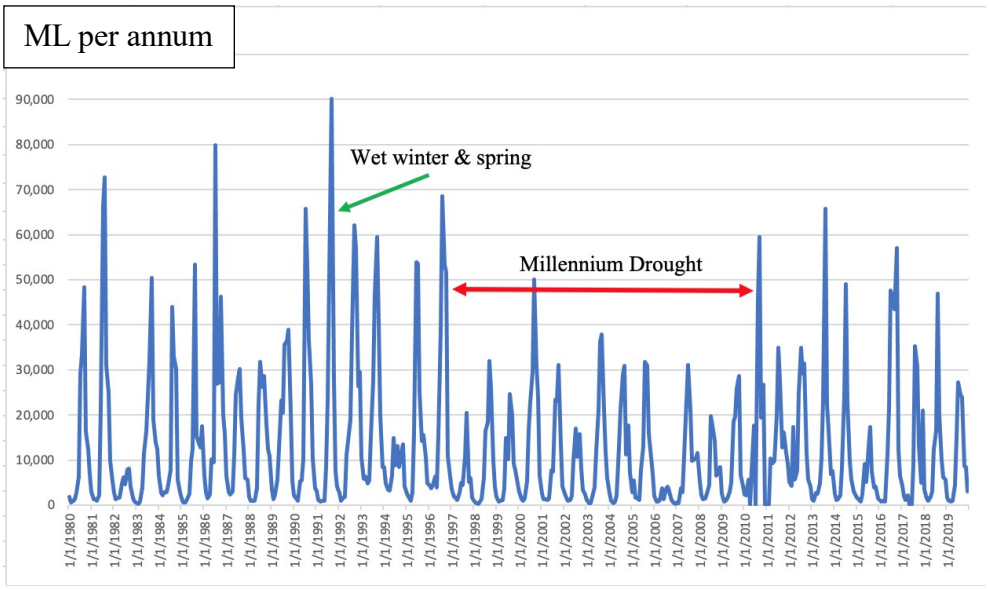


Figure C.10: Discharge, 40 years to 2019, Howqua River (Source: DELWP, 2020)

Total discharge over 40 years was 6,195,459 ML, an average of 154,886 ML per annum and 12,907 ML per month.

Table C.7 indicates that Howqua River has seen an 11% reduction in volume over the last 40 years, despite early increases.

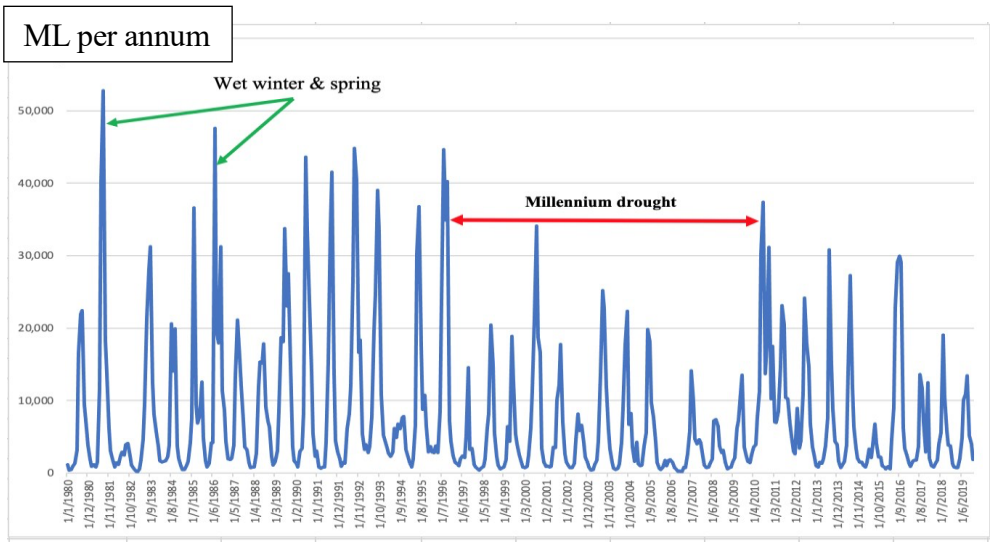


Figure C.11: Discharge, 40 years to 2019, Delatite River

(Source: DELWP, 2020)

Table C.7: Discharge data for Howqua River over 40 years

Five years to	5-Year total	% of 1984
1984	775,992	100.0
1989	907,996	117.0
1994	1,073,118	138.3
1999	749,927	96.6
2004	676,103	87.1
2009	497,634	64.1
2014	827,489	106.6
2019	687,201	88.6

Table C.8: Discharge data for Delatite River over 40 years

Five years to	5-Year total	% of 1984
1984	464,919	100.0
1989	578,651	124.5
1994	660,247	142.0
1999	468,292	100.7
2004	385,543	82.9
2009	232,310	50.0
2014	561,656	120.8
2019	343,055	73.8

Total discharge over 40 years was 3,694,672 ML, an average of 92,367 ML per annum and 7,697 ML per month.

Table C.8 indicates that Delatite River has seen an overall 26% reduction in discharge over the last 40 years, despite early increases.

C.4: Assumptions relevant to historical spreadsheet development – Chapter 4

1. Data was selected for forty years for spreadsheet development, in part due to what was historically readily available across dam volumes, discharge, rainfall and streamflows, but also because it was considered a wide enough time frame to create meaningful models.
2. This data was applied monthly, assumed to deliver greater accuracy for the dam's activity and its impact on weirs, as water levels behind the weirs can change monthly, whereas annual data might, through averaging over twelve months, miss the impact of weirs being at less than full supply levels.
3. It is also assumed that monthly data better reflects the significant changes in streamflows caused by wide variations in precipitation.
4. Since streamflows from the Northern Creeks have limited records for three of those four creeks, monthly data for what is available allows for a more accurate projection of estimates, based on Brankeet Creek's long records.
5. Withdrawal for town water supply is assumed to be constant, since long records are not available and the volumes applied are relatively small measured against other factors, so any error in monthly water removal has a very small impact on outcomes for the weirs' operations.
6. Historical monthly water levels for the main dam were provided by G-MW, so it was assumed that no further modelling was needed (unlike for climate change modelling) to measure the impact of streamflows, evaporation and precipitation. These levels allowed modelling to be made for the historical impact of the main dam upon weirs.

7. A Thiessen polygon was used to give percentage areas for rainfall reporting stations, and it was assumed that this provided sufficient accuracy when calculating rainfall within the spreadsheets for all weir options.

8. Lake open water evaporation (mm) was approximated by applying a coefficient of 0.67 to Class A pan evaporation, using the average monthly evaporation data form G-MW Lake Eildon site. With literature indicating a wide degree of conjecture around how to measure Pan evaporation, this coefficient was considered to be adequate and not delivering a high degree of error.

9. Net evaporation volumes (ML) were approximated by using the same areas for evaporation and rainfall. Although there is a small frequency of water levels slightly below FSL, resulting in reduced surface areas, this was ignored since it is assumed the impact on outcomes for evaporation causes minimal error.

C.5: Assumptions relevant to climate change spreadsheet development – Chapter 5

These assumptions are in addition to those outlined for Chapter 4, relevant to historical data.

1. In calculating evaporation for modelling the main dam, area was determined against prevailing volumes using the quadratic equation

   Area = (-0.000000001)*(Volumes)*(Volumes) + (0.0067)*(Volumes)+ 2549.6

   This might deliver a very small potential error, but not considered significant enough to impact outcomes.

2. The range of Class A Pan Evaporation figures were provided by Goulburn-Murray Water for each of the twelve months. The factors applied were increased to ‘0.75’ when modelling for climate change, as opposed to 0.67 used for historical records.

3. The projected seasonal reductions in precipitation and streamflows could shift expected data into different timelines, but this has not been modelled for such changes. The overall annual impact is the goal of this study. To derive outcomes monthly that accommodate seasonal changes would require a much more sophisticated modelling approach. Hence a simplified methodology has been adopted in this study.

4. Historical discharges by G-MW allow the main dam to maintain a reasonable volume (to meet needs of irrigation releases and sustain recreational boating) of water behind the dam, although across the forty-year period observed to 2019, during both the Millennium Drought and at times required to enable repairs of the dam wall, the main dam fell to as low as 5.3% storage in 2007. During the above exceptional circumstances, the storage generally ranged between 12 and 22 percent and then increased markedly when the drought ended.

   Whilst the above is outside the norm if long term data is viewed, assumptions were needed around discharge as modelling took account of climate change.

5. If discharge is reduced by less than the reduction in streamflows from the five main rivers, the main dam reaches a point where it is empty, an unacceptable and catastrophic situation (like the outcome on failed flows for the Darling River), given that discharge forms the Goulburn River, delivering water to towns and irrigators downstream, plus water for the environment. Even when discharge reduction matches streamflow reductions, the risk for an empty dam still exists, in part due to losses from evaporation exceeding input from precipitation.

6. The main dam discharge assumption applied is to have reduction at a higher percentage than streamflow reduction, so that a state of emptiness never occurs. Naturally, this reduction has significant ramifications for water delivered by the Goulburn River downstream, but that is not addressed in the thesis. Rather, it is for G-MW to process, should the adverse climate change projections be realised.

7. In the absence of any actual geotechnical analysis being undertaken at each weir site, an assumption was made as to the suitability and stability of the site geology based upon Victorian geological survey maps for the lake area. It was assumed

that the data found did not suggest a deep and expensive cut-off for a wall at each site. This was not the case for The Narrows Project on Lake Hume, where the cut-off core was particularly deep.

8. No allowances have been made to allow for potential water losses due to seepage.

C.6: Costing construction of four weir options at Sites # 2 and # 3

Calculating the cost of a weir at Lake Eildon

Shown below are costs estimated for weirs of two types at Lake Eildon Sites #2 and #3.

Cost estimates are based on a simplified method, not from detailed drawings of any proposed weirs.

It uses the volumes calculated for The Narrows project proposed weirs and their estimated costs and makes a simple extrapolation of costs based upon the volumes determined for Lake Eildon. Whilst this lacks a degree of accuracy, the error is considered small and acceptable for the purpose of creating a range of cost estimates for Lake Eildon.

Costing option C1 is for a weir at Site #2, Rockfill construction, at crest elevation 275 mAHD. The calculations for this costing option are presented in Table C9.

Costing option C2 is for a weir at Site #2, Earth & Rockfill construction, at crest elevation 275 mAHD. The calculations for this costing option are presented in Table C10.

Costing option C3 is for a weir at Site #3, Rockfill construction, at crest elevation 272 mAHD. The calculations for this costing option are presented in Table C11.

Costing option C4 is for a weir at Site #3, Earth & Rockfill construction, at crest elevation 272 mAHD. The calculations for this costing option are presented in Table C12.

Table C9: Costing option C1 – Rockfill construction at Site #2

Cost fundamental	**The Narrows weir**		**Lake Eildon weir at Site #2 / 275 mAHD**	
Weir height (metres)	8		11	
Upstream batter ratio	3:1		3:1	
Downstream batter ratio	5:1		5:1	
Crest width (metres)	5		5	
Concrete cut off (dimensions in m)	8 x 2 x 400		5 x 2 x 233	
Volumes (cubic metres)				
Upstream batter -	(24x8x400)/2	38,400	(33x11x233)/2	42,290
Downstream batter -	(40x8x400)/2	64,000	(55x11x233)/ 2	70,483
Weir centre -	(8 x 5 x 400)	16,000	(11 x 5 x 233)	12,815
Concrete cut off -	(8 x 2 x 400)	6,400	(5 x 2 x 233)	2,330
Total volume		124,800		127,918
The Narrows estimated cost (Yr. 2015)		$64,700,000		
Lake Eildon estimated cost (Yr. 2015)			(127,918 / 124,800) x 64,700,000	$66,316,463
Lake Eildon estimated cost (Yr. 2022) – using CPI of 2%				**$76,176,771**

Table C10: Costing option C2 – Earth and rockfill construction at Site #2

Cost fundamental	**The Narrows weir**		**Lake Eildon weir at Site #2 / 275 mAHD**	
Weir height (metres)	8		11	
Upstream batter ratio	3:1		3:1	
Downstream batter ratio	5:1		5:1	
Crest width (metres)	5		5	
Minor sheet pile cut off	N/A		N/A	
Volumes (cubic metres)				
Upstream batter -	(24x8x400)/2	38,400	(33x11x233)/2	42,290
Downstream batter -	(40x8x400)/2	64,000	(55x11x233)/ 2	70,483
Weir centre -	(8 x 5 x 400)	16,000	(11 x 5 x 233)	12,815
Minor sheet pile cut off	N/A		N/A	
Total volume		118,400		125,588
The Narrows estimated cost (Yr. 2015)		$52,700,000		
Lake Eildon estimated cost (Yr. 2015)			(125,588 / 118,400) x 52,700,000	$55,899,389
Lake Eildon estimated cost (Yr. 2022) – using CPI of 2%	**(Cheapest to build)**			**$64,210,827**

Table C11: Costing option C3 – Rockfill construction at Site #3

Cost fundamental	**The Narrows weir**		**Lake Eildon weir at Site #3 / 272 mAHD**	
Weir height (metres)	8		12	
Upstream batter ratio	3:1		3:1	
Downstream batter ratio	5:1		5:1	
Crest width (metres)	5		5	
Concrete cut off (dimensions in m)	8 x 2 x 400		5 x 2 x 257	
Volumes (cubic metres)				
Upstream batter -	(24 x 8 x 400)/2	38,400	(36x12x257)/2	55,512
Downstream batter -	(40 x 8 x 400)/2	64,000	(60x12x257)/2	92,520
Weir centre -	(8 x 5 x 400)	16,000	(12 x 5 x 257)	15,420
Concrete cut off -	(8 x 2 x 400)	6,400	(5 x 2 x 257)	2,570
Total volume		124,800		166,022
The Narrows estimated cost (Yr. 2015)		$64,700,000		
Lake Eildon estimated cost (Yr. 2015)			(166,022 / 124,800) x 64,700,000	$86,070,700
Lake Eildon estimated cost (Yr. 2022) – using CPI of 2%				**$98,868,180**

Table C12: Costing option C4 – Earth and rockfill construction at Site #3

Cost fundamental	**The Narrows weir**		**Lake Eildon weir at Site #3 / 272 mAHD**	
Weir height (metres)	8		12	
Upstream batter ratio	3:1		3:1	
Downstream batter ratio	5:1		5:1	
Crest width (metres)	5		5	
Minor sheet pile cut off	N/A		N/A	
Volumes (cubic metres)				
Upstream batter -	(24 x 8 x 400)/2	38,400	(36x12x257)/2	55,512
Downstream batter -	(40 x 8 x 400)/2	64,000	(60x12x257)/ 2	92,520
Weir centre -	(8 x 5 x 400)	16,000	(12 x 5 x 257)	15,420
Minor sheet pile cut off	N/A		N/A	
Total volume		118,400		163,452
The Narrows estimated cost (Yr. 2015)		$52,700,000		
Lake Eildon estimated cost (Yr. 2015)			(163,452 / 118,400) x 52,700,000	$72,752,706
Lake Eildon estimated cost (Yr. 2022)				**$83,569,991**

Based on the cost outcomes presented in the above tables, the construction costs, ranked from the cheapest are: -

1. Costing option C2 - $64.2 million, being an earth & rockfill weir at Site #2 at 275mAHD
2. Costing option C1 - $76.2 million, being a rockfill weir at Site #2 at 275mAHD
3. Costing option C4 - $83.6 million, being an earth & rockfill weir at Site #3 at 272mAHD
4. Costing option C3 - $98.9 million, being a rockfill weir at Site #3 at 272mAHD

C.7: Chapter 5 Models

All historical data models (HD) climate change (CC) models are available online via the following link:

https://www.dropbox.com/sh/umsy8odhmww34l0/AAD2A-Cun7prPIQ99EhTaAWda?dl=0

Historical models (HD – Historical Data) are also provided, referenced in Chapter 4.

HD – 1 Weir #1 at 272 mAHD

HD – 2 Weir #1 at 275 mAHD

HD – 3 Weir #2 at 272 mAHD

HD – 4 Weir #2 at 275 mAHD

HD – 5 Weir #3 at 272 mAHD

HD – 6 Weir #3 at 275 mAHD

The models below, for impact of climate change, are referenced in Chapter 5:

CC-1. - Weir #1 @ 272 mAHD - CC 50 %ile.xlsx

CC-2. - Weir #2 @ 272 mAHD- CC 50 %ile.xlsx

CC-3. -Weir #3- 272 mAHD-CC-50 %ile.xlsx

CC-4. - MAIN DAM-Inflows, Disch down 10% & CC 50 %ile.xlsx

CC-5. -Weir #1 at 272 mAHD CC-90 %ile.xlsx

CC-6. - Weir #2 at 272 mAHD CC-90 %ile.xlsx

CC-7. -Weir #3 at 272 mAHD CC-90 %ile.xlsx

CC-8. -New Dam levels-CC-90%ile-Discharge 41.9%.xlsx

CC-9. - Weir #1 @ 275 mAHD- CC 50 %ile.xlsx

CC-10. -Weir #2 @ 275 mAHD- CC 50 %ile.xlsx

CC-11. -Weir #3 @ 275 mAHD- CC 50 %ile.xlsx

CC-12. -Main dam – Disch. down 13%-40 yrs Inflows & rainfall-CC- 50%ile.xlsx

CC-13. -Weir#1- 275 mAHD-CC 90%ile.xlsx

CC-14. - Weir#2- 275 mAHD-CC 90%ile.xlsx

CC-15. -Weir#3- 275 mAHD-CC 90%ile.xlsx

CC-16.-Lake Eildon 40 yrs-CC- 90%ile.xlsx

CC-17- Weir #3 at 275 -CC-90%ile - 40 years. Starting empty.xlsx

A summary of all the climate change models is presented in Table C13.

Table C13. A summary of the climate change models

Model	CC percentile	mAHD	Weir number	Volume ML	Surface area-hectares
CC -1	50	272	1	457	37
CC -2	50	272	2	2180	83
CC -3	50	272	3	6510	142
CC -4	50	N/A	Dam	N/A	N/A
CC -5	90	272	1	457	37
CC -6	90	272	2	2180	83

CC -7	90	272	3	6510	142
CC -8	90	N/A	Dam	N/A	N/A
CC -9	50	275	1	2317	99
CC -10	50	275	2	5,450	135
CC -11	50	275	3	11,185	173
CC -12	50	N/A	Dam	N/A	N/A
CC -13	90	275	1	2317	99
CC -14	90	275	2	5,450	135
CC -15	90	275	3	11,185	173
CC -16	90	N/A	Dam	N/A	N/A

Model	Rainfall reduction-percentage	Streamflow reduction-percentage	Number of months with no overtopping weir	Evaporation increase-percentage	Main dam discharge reduced percentage
CC -1	4	13.7	170	8.2	16.5
CC -2	4	13.7	170	8.2	16.5
CC -3	4	13.7	170	8.2	16.5
CC -4	4	13.7	170	8.2	16.5
CC -5	20.7	41.9	226	11.4	43
CC -6	20.7	41.9	226	11.4	43
CC -7	20.7	41.9	226	11.4	43
CC -8	20.7	41.9	226	11.4	43
CC -9	4	13.7	199	8.2	16.5
CC -10	4	13.7	199	8.2	16.5
CC -11	4	13.7	199	8.2	16.5
CC -12	4	13.7	199	8.2	16.5
CC -13	20.7	41.9	278	11.4	43

CC -14	20.7	41.9	278	11.4	43
CC -15	20.7	41.9	278	11.4	43
CC -16	20.7	41.9	278	11.4	43