

University of Southern Queensland
Faculty of Health, Engineering and Sciences

**Modelling Water Allocation Increases
Using Climate Predictions**

A dissertation submitted by

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ABSTRACT

Water allocations in Australia often commence at the start of the year with less than 100% supply and rely on seasonal streamflows into dams throughout the year to meet demand. Therefore more than ever, water allocation models are used with forward planning in order to effectively manage water supply. This dissertation focuses on developing a water allocation model incorporating climate forecasts for Cressbrook Dam, a major water supplier for the regional town of Toowoomba.

After determining the best climate index of ENSO, the methodology focussed on identifying a relationship between streamflow and SOI on a monthly and seasonal scale and the creation of the water balance model. To apply the findings of these results, the use of three water management scenarios were then run through the water balance model using an extended streamflow sequence.

This analysis indicated that there was a significant correlation in the months of December to March which was further strengthened when looking at a seasonal scale. A consistently positive SOI observed in November suggested that there was a 100% chance that the dam level will substantially increase and this to develop alternative water management scenarios that raised restrictions when this SOI phase was observed.

By raising restrictions early, these management scenarios achieved a reduction of around 280 days from level 5 water restrictions which would have relieved the residents of Toowoomba during a major drought period. However, the raising of restrictions also resulted in lowering the dam level to a critical low volume.

This unexpected response in dam level storage was identified due to a short streamflow record available. The development of the water management scenarios were based off a limited range of historical climate variability, therefore recognising that a large streamflow record is crucial to developing water management strategies which incorporate decisions based off climate events on the past.

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CERTIFICATION

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Nomenclature and Acronyms

ENSO	-	El Niño Southern Oscillation
MJO	-	Madden-Julian Oscillation
BOM	-	Bureau of Meteorology
SOI	-	Southern Oscillation Index
ECL	-	East Coast Lows
IOD	-	Indian Ocean Dipole
SST	-	Sea Surface Temperature
DMI	-	Dipole Mode Index
IPO	-	Inter-Decadal Pacific Oscillation
PDO	-	Pacific Decadal Oscillation
SAM	-	Southern Annular Mode
EOF	-	Empirical Orthogonal Functions
EMO	-	ENSO Modoki Index
DNRM	-	Department of Natural Resources and Mining
ML	-	Megalitres
RAP	-	River Analysis Package

CHAPTER 1 INTRODUCTION

1.1 Background

Australia has an extremely variable climate which can change from prolonged drought to flash flooding within a short period of time. Therefore it is important that water allocation models can accurately predict when water usage needs to be tightened and relaxed. While there are numerous literature regarding the changing climate of the earth, there is little in the way of how this knowledge can be applied to solving real world problems. The use of seasonal climatic data to aid in predicting short-term water allocations is one such problem that can be addressed. This proposal suggests a possible case study for developing a water allocation model for Cressbrook Dam, which is the major water supplier to the regional town of Toowoomba.

As Australia's second largest inland city, the expanding city of Toowoomba faces the challenge of finding more water resources to keep up with increasing demand. As a regional city, rainfall varies significantly within the Darling Downs from season to season. Due to this variability, Toowoomba receives much lower annual rainfall totals than other coastal south-east Queensland cities such as Brisbane, Sunshine Coast and Gold Coast. A rainfall comparison between Toowoomba (mean = 720.3 mm) and Brisbane (mean = 1011.7 mm) shows that on average the capital city receives nearly half a metre more in annual rainfall (BOM, 2013).

This difference in annual rainfalls may seem insignificant, but it has been shown recently in the past that Toowoomba is vulnerable to major drought. The past decade from 2000 to 2010 saw one of the worst droughts to affect Australia (Boyd, 2012). Toowoomba especially suffered from this drought as the combined dam level storage in the region dropped below 10% total. This resulted in major implications for the residents of the region which included:

- Harsh level 5 water restrictions
- The proposal to use recycled water for drinking purposes
- The eventual construction of the pipeline from Wivenhoe Dam to Cressbrook Dam

After the 2011 January floods and all of Toowoomba's dams were refilled to capacity, the Toowoomba Regional Council (TRC) decided to keep the region on permanent conservation water restrictions. Being one of the only places throughout Australia to use such permanent conservation water measures means that it has been identified that water availability will be an ongoing issue for the region in the future.

1.2 Aim and Objectives

Therefore there was an opportunity to investigate whether climate indices can help water managers in their forward planning and decision-making in regards to future streamflow forecasts. With this in mind, the primary aim of this research project is to provide a functioning water allocation model that can predict with short-term accuracy the likely increases and shortfalls in water availability for Cressbrook Dam using an appropriate climate indicator. In order to achieve this primary aim, three key objectives were identified and are listed below:

- Find a significant relationship between the most influential climate index and streamflow
- Incorporate climate-streamflow relationships into a working water balance model
- Develop a water allocation model that can make decisions about water restrictions based on climate indices

1.3 Justification of Project

The severe drought from 2000 to 2010 resulted in Toowoomba facing a water supply emergency with the combined dam level dropping to an all-time low of 7.8% in February 2010. This affected the livelihoods of many residents of the region in regards to water usage including myself. For the water supply systems in the area to get that critically low, it raised many questions as to why this occurred. Was it purely due to a major drought event, or could the management of the urban water supplies have been better managed so that there was not as much pressure placed on the community with its water consumption. It's for this reason that the use of climate indices were investigated to determine whether forecasting could have helped in the past and can be used in the future.

1.4 Dissertation Outline

There are 6 main chapters in this dissertation including the introduction. A short outline for each chapter is detailed below:

Chapter 2 – Literature Review

The literature review discusses why historical statistical approaches are used in the dissertation, reviews and assesses the best climate driver which affects the streamflows of Cressbrook Creek and discusses the risks associated with urban water supply management.

Chapter 3 – Methodology

The methodology talks about the development of the relationships that exist between the best climate index and streamflow, the development of the water balance model, and combining these two elements into a model which runs

three different water management scenarios, where water restrictions are based off the relationships found between streamflow and climate indices.

Chapter 4 – Results for Statistical Streamflow Forecast Model

This chapter shows the results on the best linear relationships between streamflow and climate indices and uses these results to develop cumulative probability distribution graphs for a range of different starting dam levels.

Chapter 5 – Results for Water Management Scenario Analysis

This chapter explains how the extended streamflow sequence was created and validated as well as the key results found from running the three different scenarios through the water balance model.

Chapter 6 - Conclusion

This chapter summarises the key findings in the results and whether the key objectives and primary aim have been met. It gives a recommendation on the appropriate timing that climate indices should be used to help in water management as well a number of different paths that could be utilised for further work.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This review will discuss the use of statistical models which use the concept of stationarity to link historical streamflow data to associated climate indices to provide an adequate water allocation model. An investigation into the relationship between streamflow data and climate predictions will then be examined in the aim to determine a climate index that will have the largest impact on the Cressbrook Creek catchment area. Lastly a discussion will review the risk management of urban water supplies and water resource managers' approaches towards urban water supply.

2.2 Statistical Predictions for Water Allocation Increases

Any type of prediction model can be produced from either complex dynamic numerical approaches or based on historical statistical data. While dynamic models are the preferred choice in today's world due to climate change, historical statistical data for predicting future rainfall events are still widely used through Australia. However there are some research papers in the past have which have looked at using climate models for streamflow forecasting within Australia (Chiew et.al 1998, Everingham et.al 2008). These papers make use of statistical approaches, where climate and streamflow events of the past are used as the basis for future predictions (Baillie & Brodie, 2011).

As explained by Baillie & Brodie (2011), the same concept of 'stationarity' is used within this investigation, but focuses on modelling an urban water supply rather than previous studies that have applied water allocation models to irrigation water supply. Statistical approaches have some obvious limitations which are reasons to believe that forecasts are better predicting by dynamic numerical modelling. The accuracy of statistical modelling is

dependent on the length and quality of historical streamflow and SOI data. The assumption of statistical stationarity also poses the problem of current and future conditions falling outside the limits of historical data range where both the risk and accuracy of forecasting is unknown. However, statistical approaches have the advantage of finding a direct relationship between streamflow and large climate drivers and its relative ease of use means that such approaches are well developed around Australia (Baillie & Brodie, 2011). Therefore statistical approaches is seen to be appropriate to use throughout this study.

2.3 Climate Indices

Variability of rainfall throughout Australia as a whole has been well documented compared to other places in the world. Inter-annual variability in Queensland rainfall is affected by a number of different climate systems. With Queensland covering a very large area of Australia, its variability in rainfall can be affected by tropical influences such as ENSO, MJO, IPO, tropical cyclones and IOD in the Pacific Ocean (Figure 1). The extratropical regions of the state (southern regions) have been shown to be affected by climate systems such as the Southern Annular Mode and atmospheric blocking (Risbey et.al, 2009). These climate indices will all be closely examined and investigated to determine which index will likely have the greatest influence over the Darling Downs region where Cressbrook Dam is located.

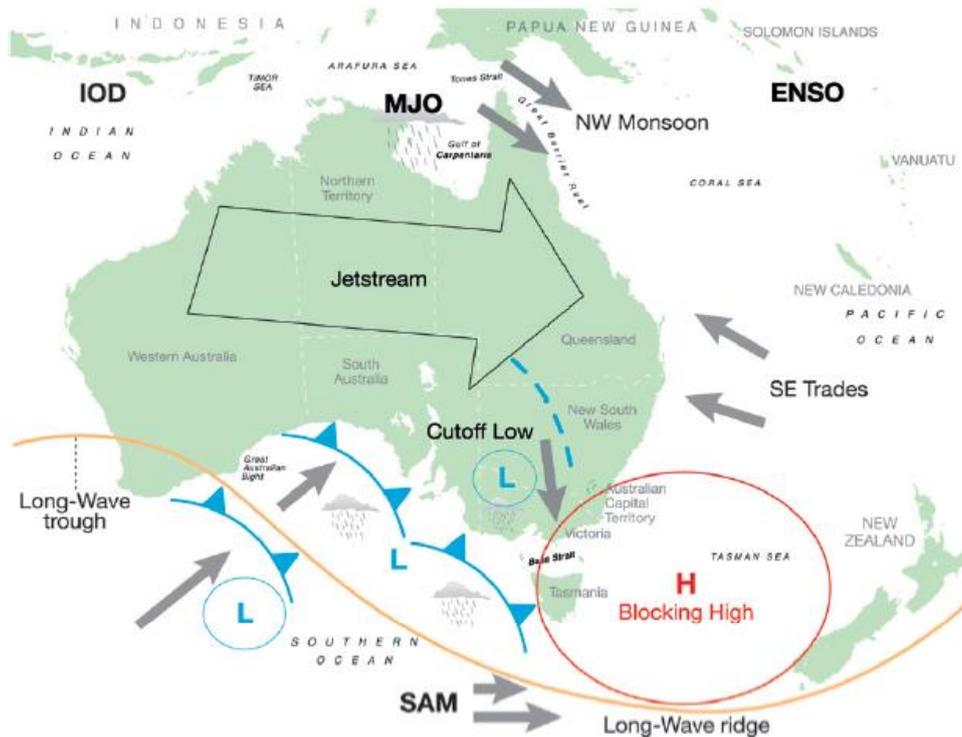


Figure 1: The Main Climate Indices Driving Rainfall Variability in Australia (Risbey et.al, 2009)

2.3.1 Madden-Julian Oscillation (MJO)

The Madden-Julian Oscillation (MJO) is a large scale climate phenomenon that has eastward propagating wave disturbances in both tropical and extratropical climates that effects parts of the world in the equatorial latitudes. The MJO is an important component of the intraseasonal variability in the tropical atmosphere which typically lasts from 30-90 days. The MJO is known for its large scale signals in the atmospheric circulation, deep convection and other clearly defined variables and signals, which are all propagating eastwards with a slow velocity of 5 metres per second through the warm equatorial sea surface waters of the Indian and Pacific Oceans. The MJO is constantly interacting with the underlying ocean and influences many weather and climate systems causing variations in tropical and subtropical locations within Australia (Zhang, 2013).

Zhang (2005) explains that the effects that the MJO has on Australia's weather, particularly in Queensland depends on the state or phase of other known climate phenomena's such as ENSO and their combined effects can result in significant weather events. The simplest observations made about the MJO is that the event features a large scale eastward moving centre of strong deep convection which is representative of an active stage of the event. The inactive stage is where both and east and west regions are diverted by weak convection and precipitation. Both of these phases of the MJO are linked by air circulations that occur vertically through the lower atmosphere. In the troposphere where all weather events occur, strong westerly and easterly winds coincide with their direction with a large-scale convective centre in the middle of the system. Once in the upper troposphere, the circulation of air will cause the winds to reverse directions. The connection between large air circulation and convective centre propagating slowly eastward at an average of 5 metres per second is essential to the characteristics of the MJO.

The MJO system can be recognised from just the observation of increased precipitation without the need for further analysis. The prominent period of the MJO system in precipitation and zonal winds spreads over the range between approximately 30-90 days. Its highest peak within this range is variable for a number of different reasons. Firstly, the MJO system is recognised as an oscillation but its propagation speeds and intervals between consecutive events are highly irregular. Secondly the MJO has interannual variability, particularly in zonal wind activity. The inter-annual variability of the MJO appears to have a possible weak relationship itself and ENSO in the Pacific Ocean regions, but is more likely to driven by atmospheric characteristics. Lastly, the MJO goes through a strong seasonal cycle in both latitudinal locations and its intensity. Its main peak season occurs during summer and in autumn when the strongest MJO signals are immediately south of the equator, coinciding with the Australian summer monsoon. Also it is known that there is a stronger seasonal migration in the western Pacific Ocean than in the Indian Ocean. Other basic characteristics that the MJO system has

is a geographic preference and a distinguishable multiscale structure (Zhang, 2005).

According to Risbey et.al (2009), the MJO is split into eight unique phases based on the different patterns of variability of convection and zonal winds within the system at latitudes close to the equator (Figure 2). These different patterns are used to describe the current location of the MJO and can be analysed for future predictions of the system. As claimed by Risbey et.al (2009), statistical and historical data analysis has shown that the strongest association that the MJO has with the Australian climate is in the northern part of Australia. As highlighted by Figure 1, the location of the MJO in phases 5 and 6 coincide with strong rainfall events occurring across the northern tropics of Australia during the monsoon season. Wheeler et.al (2009) suggests that weekly rainfall in northern Australia can increase more than three times with the convectively active MJO phase compared to its suppressed phase. There is also studies conducting which have shown that MJO can be influenced and can interact with ENSO. Wet MJO-related events are seen to have comparable characteristics to La Niña and vice versa with El Niño weather events. However overall analysis of the analysis between the two climate indices shows that ENSO is the dominant climate index and that the relationship between rainfall and ENSO is dependent on the activities of the MJO.

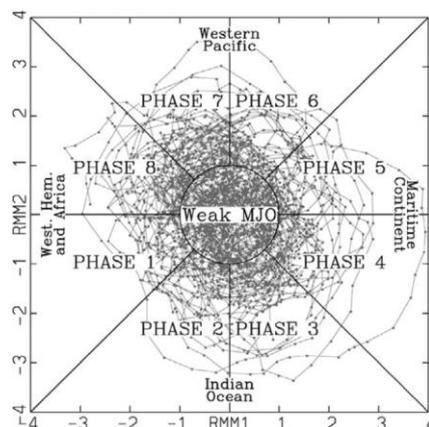


Figure 2: The Eight Different Phases and Locations of the MJO (Zhang, 2013)

Studies from Wheeler et.al (2009) analyse the possible impacts that the MJO has on Australia rainfall in extratropical regions and other locations other than the northern tropics and also whether its impacts vary with different seasons. Findings were shown that a winter season rainfall response to the MJO was evident along the Queensland coast, caused by the systems trade winds. However in all other places in different places, the MJO's effect is inconsistent and only found to have minimal correlation in localised areas. Although it is suggested that these responses are due to continental circulation, it is more likely that southern blocking may have a stronger presence in influencing extratropical regions such as the Darling Downs area.

2.3.2 Tropical Cyclones

According to Klingaman (2012), an average of four tropical cyclones per year form off the Queensland coast in the Coral Sea during the season between January to March. Further historical analyses from Klingaman (2012) indicates that on average at least one or two of these tropical cyclones will impact make landfall and impact the Queensland coast each year. Inter-annual variability is also shown to exist between the number of land falling cyclones with many years having no land falling cyclones and other years having up to three. Importantly, there is evidence from Lough (1991) to suggest that there is a positive correlation showing that years with above average annual mean rainfall coincide with years where there was a greater number of land falling tropical cyclones. These studies have complementary findings to back up what is already thought to be known, there is a higher chance of more extreme rainfall events occurring when there is an increase in the number of land falling cyclones within the Queensland region.

Variability in the amount of cyclones formed off the east coast of Australia has been frequently related to the ENSO climate system. During the El Niño phase in Australia, warm ocean temperatures are found in the central Pacific, therefore shifting the generation of tropical cyclones eastwards away from the

coastline of Queensland. The opposite effect is experienced during the La Niña where the spawn of tropical cyclones are closer to the Queensland coast, therefore increasing the chances of cyclones having an effect on rainfall anomalies. Variation of the strength and locations of tropical cyclone have also been attributed to the behaviour of the monsoon trough. The monsoon trough also works in unison with the ENSO climate, but affecting the generation of cyclones through differences in zonal winds (Klingaman, 2012).

Importantly, the impact of rainfall variability from tropical cyclones is mostly associated with affecting tropical parts of the country. Extratropical regions such as the focus region of the Darling Downs seldom has tropical cyclone influence. The last time that a tropical cyclone had a major impact on the Darling Downs region was in 1974 when Tropical Cyclone Wanda which crossed the coast near Maryborough (Office of Economic and Statistical Research, 2009). As the region of focus is inland, tropical cyclones are more likely to affect the Darling Downs as a rain depression rather than a cyclone. As explained by the Bureau of Meteorology (n.d.), tropical cyclones have a tendency to follow the Queensland coastline before moving safely away from the continent into the Pacific Ocean (as shown in Figure 3). Therefore cyclone activity if any, has a greater impact on coastal cities within south-east Queensland such as Brisbane then in the Toowoomba region.

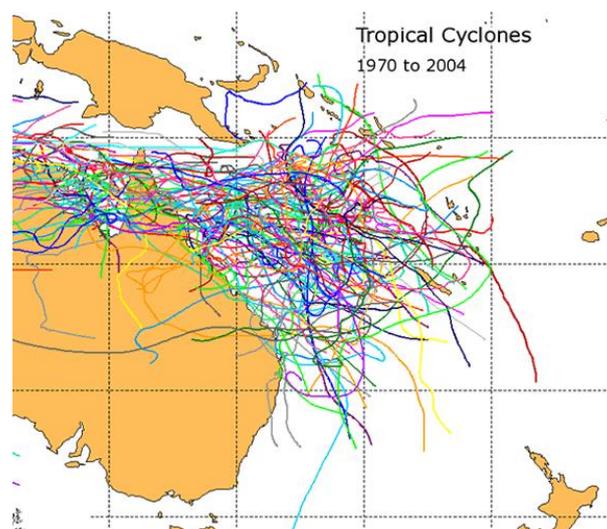


Figure 3: East Queensland Tropical Cyclones from 1970 to 2004 (BOM, n.d.)

2.3.3 Atmospheric Blocking

It is now well recognised that atmospheric blocking is an important climate driver for both southern and eastern parts of Australia. Blocking is often associated with blocking ‘anticyclones’ which are areas of slow moving high pressure systems that form due to the presence of atmospheric longwave patterns. The formation of these anticyclones occur most frequently in the Tasman Sea and the Southern Ocean with the most frequent occurrence being in the southeast of Australia during winter. Blocking can occur at any time of the year, however blocks form mostly between the months of April to August. The cause of atmospheric blocking is linked with the splitting of upper atmospheric westerly winds into two distinguishable states. The degree of this splitting in the atmosphere is represented by the BOM by a simple blocking index. An expression is used to calculate a monthly blocking index at a constant longitude of 140°E. The BOM uses this longitude value as it is found to be a common location where blocking occurs and affects the weather in Australia (Risbey et.al, 2009).

As claimed by Risbey et.al (2009), when blocking occurs the upper atmospheric westerly winds tend to recurve around the blocking high. This causes approaching synoptic features such as cold fronts to weaken and distort, as they move in an eastward-moving direction which avoids southeast Australia. Therefore blocking is often associated with dry weather conditions in southeast Queensland. However Klingaman (2009) also supports that there is evidence to believe that blocking can lead to increased rainfall along the southeast parts of Australia. This is due to studies which have found that blocking increases the chances of developing cut-off lows. These lows are often formed between the months of May-October which is consistent with frequent blocking in that period. Depending on the location of block, the response to rainfall in Australia will be different. When blocking occurs in the Great Australian Bight, rainfall is seen to occur mostly in Western Australia, whereas blocking in the Tasman Sea favours rainfall in the south-

eastern part of Australia. Figure 4 shows that there is a positive correlation between the blocking index (using 140°E) and Australian rainfall for all seasons except for summer.

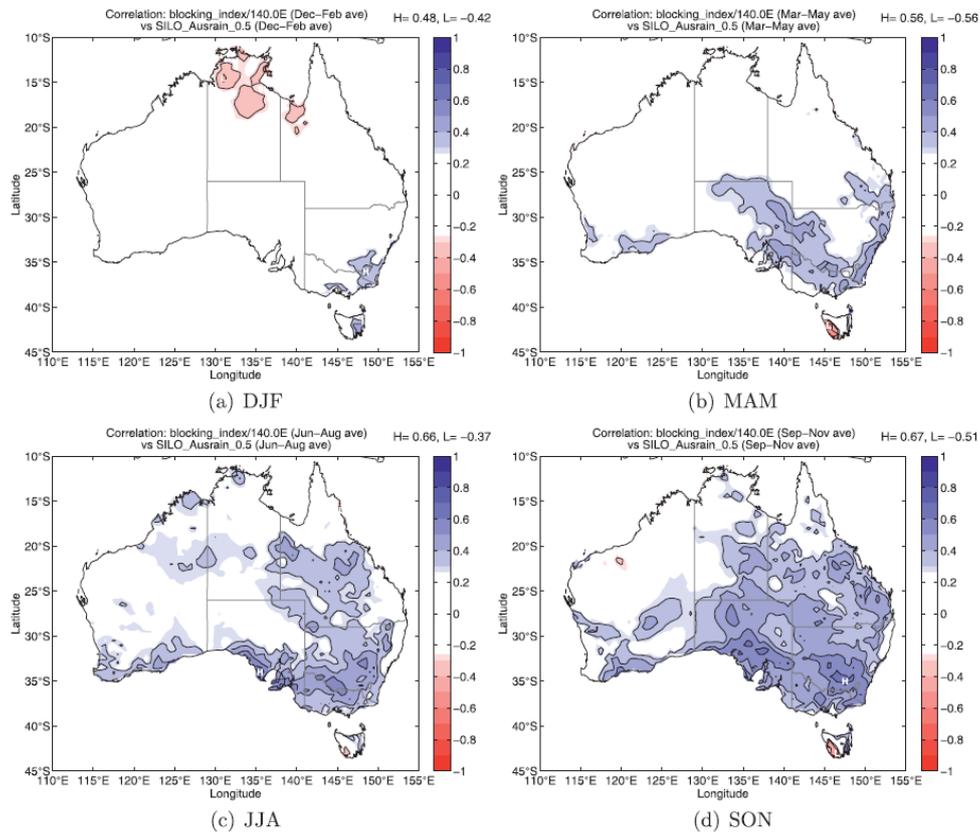


Figure 4: Correlation between Blocking and Rainfall in Different Australian Seasons (Risbey et.al, 2009)

According to Risbey et.al (2009), blocking in the Australia varies in both its location and intensity through each season and throughout each year. Variability within the blocking system is also associated with a present correlation with the climate system of ENSO. With a positive correlation between the blocking index and SOI, blocking in southeast Australia is more likely during the La Niña phase than the El Niño phase. However when the effect of ENSO is removed from the analysis, there still remains a consistent positive correlation over Southern Australia which suggests that the interaction between the two are still mainly unknown.

Atmospheric blocking and cut-off lows affect the rainfall variability in the Darling Downs region from the months of June to November, with a noticeably apparent positive correlation shown in Figure 4. For south-eastern Queensland, atmospheric blocking is considered to be the dominant remote driver of spring rainfall over other climate drivers including the SOI, IOD and the SAM. However the examination of the link between blocking and rainfall variability within Queensland has not been extensively researched compared to other states such as New South Wales and Victoria where blocking has the greatest impact (Klingaman, 2012).

2.3.4 East Coast Lows

East coast lows (ECLs) are areas of closed circulation that form low pressure systems near the eastern coast of Australia and move parallel along the coastline (Figure 5). Although east coast lows can form at any time of the year, its most significant impact on Queensland is during the winter. During this time period, ECLs can produce heavy rainfall events when it associates with high pressure systems which are found to be at the most northern position (Pepler et.al, 2014).

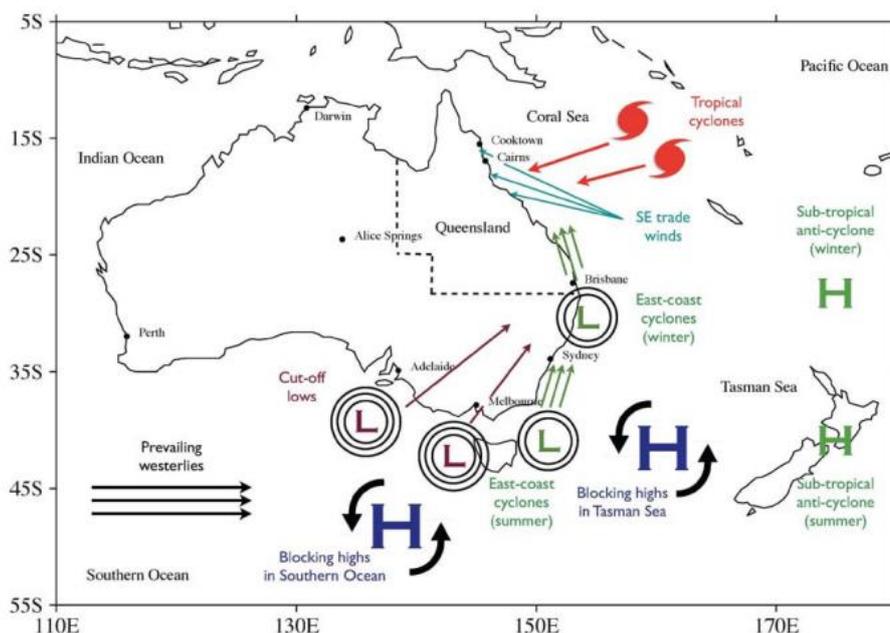


Figure 5: East Coast Lows (green) move up the coastline of NSW (Klingaman, 2012)

Klingaman (2012) further explains that substantial inter-annual variability exists in the number of ECLs that affect Queensland with range between 0 and 5 ECLs occurring each year. It also been found that there is no significant correlation that exists between ECLs and SOI phases. However there was a detection of correlation between ECLs and ENSO transition phases with a shift from El Niño to La Niña resulting in more ECLs and vice versa. There is no evidence however to connect the physical mechanism between ENSO shifts and ECLs. Overall ECLs are only responsible for rainfall between 3 to 5 days each year during the winter period, with its impact on rainfall variability mostly examined to be in the states of New South Wales and Victoria.

2.3.5 Indian Ocean Dipole

The Indian Ocean Dipole (IOD) is major climate driver for countries within the boundary of the Indian Ocean. The IOD is known to be a major component of sea surface temperature (SST) variability in the Indian Ocean near the equator. It is thought that the sea surface temperatures in the equatorial Indian Ocean co-varies with that in the tropical Pacific Ocean during ENSO and has a major impact on rainfall variability within Australia. Variations of SSTs in the Indian Ocean, are responsible for playing a primary role in rainfall variability in the southern regions during austral winter and early spring (Cai et.al, 2011).

According to Taschetto et.al (2011), the IOD is characterised by irregular east-west SST gradient along the tropical Indian Ocean. This is also combined with anomalous surface pressures and rainfall distribution, which produces air circulation changes and rainfall conditions over the southern parts of Australia. The IOD and ENSO can occur and work together in such a way as to reinforce each other, but various sources describe that the an independent or dependent relationship between ENSO and IOD being debatable with limited findings.

A measure of the IOD is the dipole mode index (DMI), which is the difference in SST's between the equatorial western Indian Ocean and the equatorial south-eastern Indian Ocean. As Figure 5a shows there is statistically significant correlation between Australian rainfall and the DMI for the peak IOD period between the months of June to October across mainly the southern part of Australia, but also effect parts of Queensland. However when the effect of ENSO is removed from the IOD, its independency shows that there is near to zero correlation between the IOD and rainfall in Queensland (Figure 5b). Studies as explained by Klingaman (2012), also suggest that there is no important correlation between Indian Ocean SSTs and rainfall within south-east Queensland. Therefore the IOD has little to no impact on the rainfall variability of the Darling Downs region.

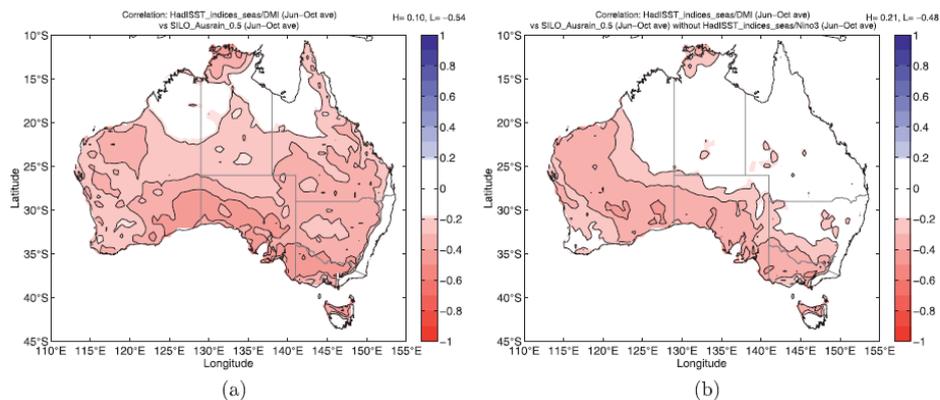


Figure 6: a) IOD correlation to rainfall with the presence of ENSO b) IOD correlation to rainfall without the presence of ENSO (Risbey et.al, 2009)

2.3.6 Inter-Decadal Pacific Oscillation (IPO)

Inter-annual climate variability has thought to been heavily dominated by the ENSO over Pacific regions. This is mainly due to the strongest SST signals between both the central and eastern Pacific Oceans. However recently, there has been a distinction made that similar ENSO features have occurred in a climate system that acts upon the much larger timescales of decadal and multi-decadal time periods. The Pacific Decadal Oscillation (PDO) may

explain lower frequency SST variability and are part of a larger system described as the Inter-decadal Pacific Oscillation (IPO). During the twentieth century there has been three phases of IPO that have been identified: a positive phase from 1922 to 1944, a negative phase from 1946 to 1977 and another positive phase from 1978 to 1998. During these phases it is thought that the IPO has a role in modulating inter-annual ENSO related climate rainfall variability over Australia. Through the use of teleconnection analysis, relationships with ENSO are seen to be varied with areas such as New Zealand showing strong teleconnections for positive IPO periods whereas in some Pacific areas showing weaker teleconnections (Power et.al, 1999).

As explained by Klingaman (2012), during the positive IPO phase of 1922 to 1944, both ENSO and Queensland became uncorrelated. The positive phase of the IPO, SSTs are found to be warmer in the Eastern Pacific and cooler in the extratropical West Pacific Ocean. Within this time period it was discovered that Queensland rainfall became less variable and spatially coherent. Salinger et.al (2001) claimed findings that suggested that the positive IPO phase was the result of a weakening in the ENSO Australian rainfall variability. This means that when positive IPO is currently present, modelling of the ENSO signal appears to be much more difficult and unpredictable. Therefore there is a limited understanding of the mechanisms that produce a weakening of the ENSO related rainfall variability in Queensland during positive IPO phases and also little knowledge besides its influence of the ENSO climate driver.

2.3.7 Southern Annular Mode (SAM)

According to Meneghini et.al (2007), the Southern Annular Mode (SAM) is a major climate system which drives the greatest amount of rainfall variability in extratropical areas within the Southern Hemisphere on inter-annual timescales. The SAM system has both a negative and positive phase which differ in atmospheric circulations. The positive SAM phase has pressures and

zonal winds that are higher than usual in the mid-latitudes and lower than usual in the high-latitudes and vice versa for the negative SAM phase. There is also been evidence to suggest that there is a link between SAM variability and the synoptic behaviour of Australia.

A way of defining the SAM climate system is using the difference between monthly zonal mean sea level pressures at 40 and 65°S latitude to form the SAM index. Using station pressures dating back to 1957, the SAM index is calculated on projecting daily 700 hPa heights onto empirical orthogonal functions (EOFs) of monthly mean 700 hPa heights. When correlating the index with rainfall variability in Australia, it was found that the SAM system only accounts for around 15% of weekly rain variance in only the south-western and south-eastern parts of Australia (Hendon et.al, 2007). Risbey et.al (2009) further explains that the positive phase of SAM has been linked to a reduction of rainfall in southern Australia particularly in winter months. However in spring, positive SAM is associated with increased rainfall mostly on the southeast coast of New South Wales but also in the southwest of Western Australia (Figure 7).

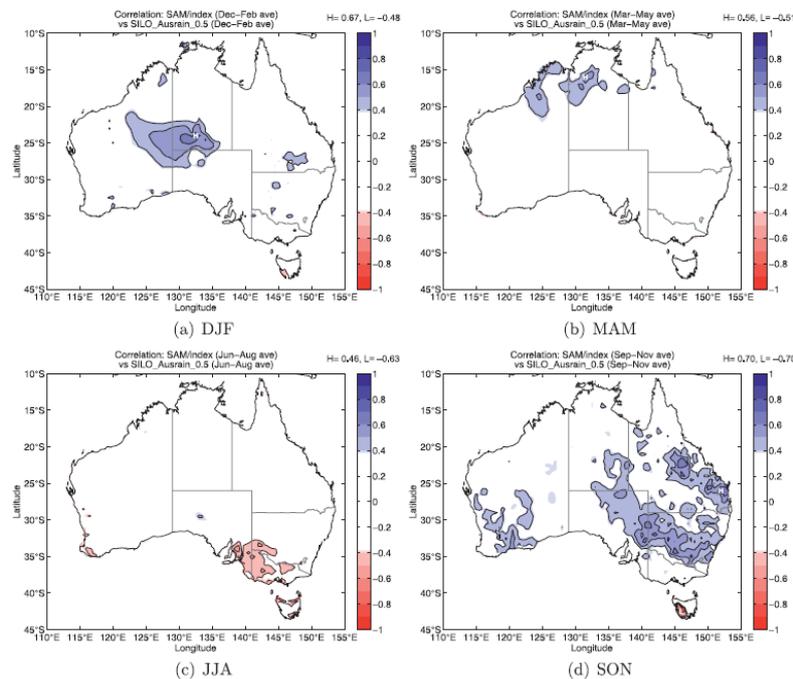


Figure 7: Correlation between SAM and rainfall throughout Australia in different seasons (Risbey et.al, 2009)

Overall there are only very weak relationships between the SAM system and rainfall within south-eastern Queensland. As from Figure 7, spring appears to be the season with the most correlation, but this correlation shows to have a greater impact in New South Wales than Queensland. The correlation between SAM and rainfall in spring is most likely explained by the presence of an enhanced onshore flow that occurs during that time period (Klingaman, 2012).

2.3.8 El-Nino Southern Oscillation (ENSO)

Bureau of Meteorology (2015) describes Australia's variable climate mainly due to the atmospheric phenomenon called the Southern Oscillation. As the name suggests, air pressure and rainfall patterns between the Australian and Indonesian regions of the eastern Pacific oscillate back and forwards. Depending on the temperature of the ocean and the SOI there are two possible events that can occur. The first event is termed as El Nino where sea surface temperatures are significantly cooler than usual and these results in a negative SOI reading. Cold water flow that usually occurs along the South American coast weakens and temperatures become as warm as the western Pacific which draws moisture away from Eastern Australia. Air circulation also plays an important role in determining the current SOI. During El Nino events, easterly trade winds which bring moist air towards Australia weaken and provide decreased amounts in rainfall. Therefore it is well established that El Nino events are associated with an increased risk of dry conditions and drought across Australia. El Nino also has a strong influence on temperatures with warmer daytime temperature usually experienced and cooler night time temperatures leading to more widespread and severe frosts. The opposite phase to El Nino is La Nina which brings wet conditions to eastern Australia and has a highly positive SOI value. Sea surface temperatures around Australia and Indonesia are particularly warm and associated easterly winds provide increased rain and flooding. Temperatures during La Nina events

tend to be below average and rainfall patterns are more widespread than that of El Niño.

Advancements in ENSO relationships have seen the development of computer models which can be used to forecast the behaviour of El Niño and La Niña in upcoming months. The Bureau of Meteorology's National Climate Centre has been producing climate outlooks since 1989 and provides details about rainfall and temperature every three months. Daily information is assimilated into computer models by many buoys that are placed through the Pacific Ocean which read surface and air temperatures and winds (Bureau of Meteorology, 2005). These seasonal forecasts of rainfall, streamflow and drought conditions are vital to management of water resources, particular in Australia where variability is greater than anywhere else in the world (Chiew et.al, 1998). The measurement of this oscillation is measured by an Index called the Southern Oscillation Index (SOI) which relates to distinct changes in the temperature of the Pacific Ocean. The SOI index is measured by the difference between pressures between Tahiti and Darwin which are taken by the Bureau of Meteorology. Figure 8 shows the SOI values in Australia over the past seven years and depicts both El Niño and La Niña phases. ENSO can also be characterised by the indices of Niño-3, Niño-3.4, Niño-4 which are SST based related and the ENSO Modoki Index (EMI), but these indices are rarely used compared to the SOI. This is mainly due to the fact that SOI has the strongest relationship between itself and rainfall through the country and can be monitored at a high confidence level (Risbey et.al, 2009).

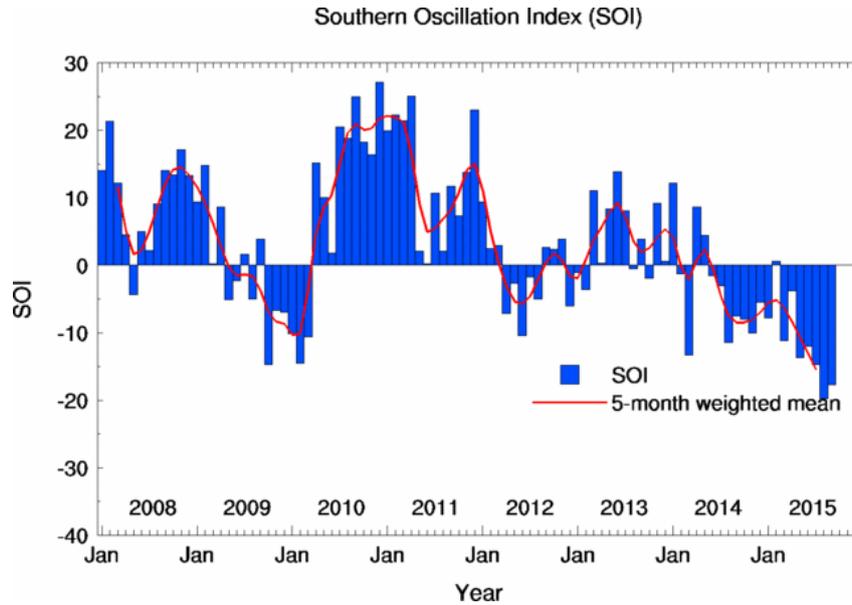


Figure 8: SOI readings in Australia in the past seven years (BOM, 2015)

The Bureau of Meteorology and Long Paddock (operated by the Science Delivery Division of the Department of Science, Information Technology and Innovation (DSITI) and provided by the Queensland Government) have SOI recordings dating from 1876 to present. In Figure 9 below, Risbey et.al (2009) use SOI data ranging from 1889 to 2006 with correlation to rainfall over the four different seasons of the year.

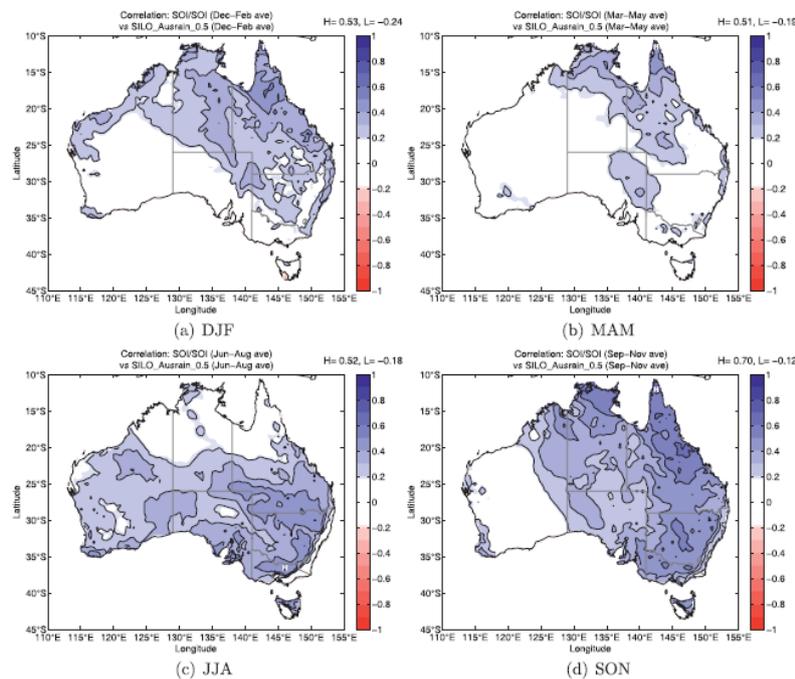


Figure 9: ENSO correlation between SOI and rainfall within Australia over four seasons (Risbey et.al, 2009)

From above it seen that there is a clear correlation between ENSO and rainfall in the eastern and north-eastern parts of Australia particularly during winter and spring. This supports claims by Klingaman (2012) that tropic rainfall in Australia is linked to SSTs and that ENSO is responsible for much of the inter-annual rainfall variance the in the extratropics. Studies suggest that the strongest SOI correlation with rainfall in Queensland occur during the spring months of October and November. Very few regions in Queensland however are shown to have a statistically insignificant relationship between rainfall and SOI. ENSO is known by many sources (Klingaman, 2012; McBride & Nicholls, 1983) to be weak and incoherent throughout the autumn season and is referred to as the ENSO “predictability barrier”.

Due to the ENSOs dominance in driving the climate of eastern Australia, it has been explained by previous climate index sections above that ENSO can modulate rainfall variability on synoptic and sub-seasonal scales, as well having effects on other climate drivers such as the generation of tropical cyclones, MJO, IOD and blocking. ENSO also remains to be seen as the dominant climate driver in Queensland due to the system which can act over many different timescales. While Klingaman (2012) explains that ENSO has the greatest impact on Queensland rainfall at the seasonal or inter-annual level, there is also evidence provided by Risbey et.al (2009) that claim that ENSO causes considerable multi-decadal variability in Australia rainfall patterns.

A few studies have also explored the possibility of a direct relationship between the ENSO climate and streamflow data. A study from Verdon et.al (2004) found that there is a relationship evident when the La Niña phase of the ENSO is in effect with a significant increase in streamflow totals. A total of 152 streamflow stations across eastern Australia where used in the investigation with findings showing that most stations displayed a streamflow increase of more than 100% during La Niña events. Looking at a multi-decadal timescale, it will also discovered that the IPO modulates the impact of ENSO and therefore the streamflow regime of eastern Australia. Another study by (*Chiew et.al, 1998*) show that streamflows are generally higher when

the SOI is a positive value and sea surface temperatures in the Pacific Ocean are lower than average (and vice versa). In terms of accuracy, a lag correlation analysis is shown to have the most potential in forecasting future events. Indicators of ENSO can be used to successfully forecast rainfall throughout eastern Australia in the spring months and summer months in north-eastern Australia.

With so many climate patterns and systems that exist and interact with each other on varying timescales, applying these climate drivers to real life situations becomes very complex. However the Bureau of Meteorology (2016), uses a number of different climate and synoptic drivers such as SOI, SSTs, trade winds, cloudiness near the dateline and the IOD to deliver a seasonal forecast for the next couple of months. In the seasonal outlook, the Bureau still regards ENSO as the core driver of climate for Australia.

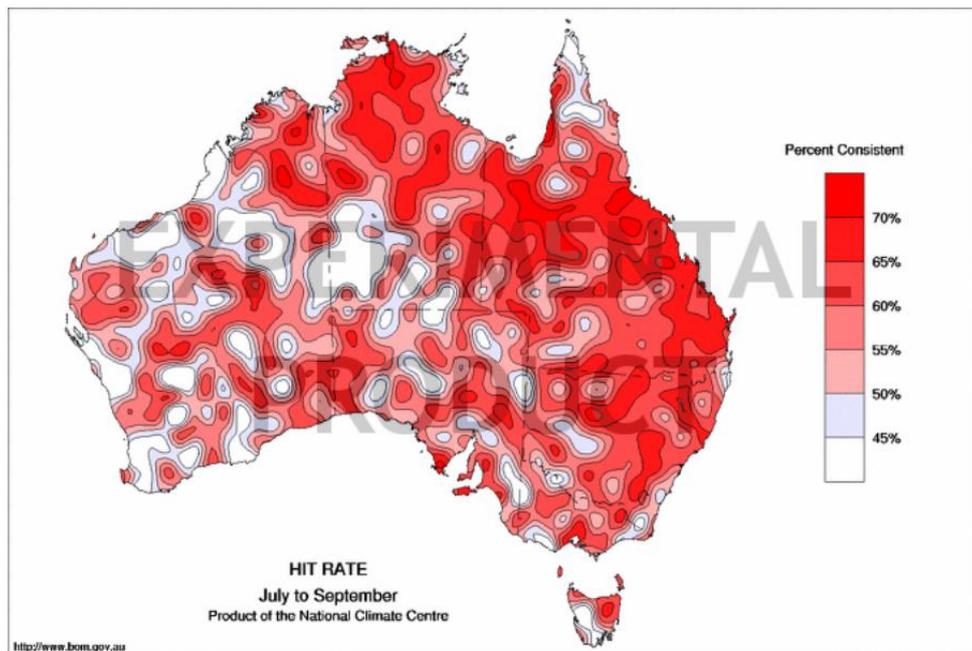


Figure 10: Forecast Hit Rate for the SOI Index since 2000 (Stone, 2011)

Figure 10 above explains the use of forecast hit rates using the SOI index from 2000. From this figure it is seen that the forecast success rate (recognised consistent ENSO rainfall relationships) in Queensland are mainly above 50%. The forecast skill of the ENSO is produced by the ‘SOI phase system’ which is applied to many agricultural and urban water supply situations which will be explained in the following sections.

2.3.9 Summary of Key Findings

A number of different climate indices were investigated in order to determine which index has the most influential effect on the Darling Downs region. The following Table (Table 1) summarises the key findings by listing the climate index that has the greatest impact on the region in each individual season of a year.

Table 1: Climate Index to be used in the analysis for each season

Season	Climate Index to be Used
Summer (December-January-February)	ENSO
Autumn (March-April-May)	ENSO
Winter (June-July-August)	ENSO
Spring (September-October-November)	ENSO

Each climate index investigated is found to have some impact on the Darling Downs area. From the findings above, climate indices such as the MJO, tropical cyclones and the IOD are more likely to affect the northern parts of Queensland as their origins are found to be near the equator. However the effects of the climate index of ENSO is seen to be the dominant index over the entire eastern coast of Australia. As explained by Risbey et.al (2009), SOI

has the strongest relationship between itself and rainfall and can be forecasting with the highest confidence levels in both the major seasons of winter and summer.

The most dominant climate index in the transitional seasons of autumn and spring are more unclear with ENSO have its weakest influence in autumn. However there is no other clear climate index that dominates the season of autumn and therefore ENSO was also chosen for this season. For spring there is reason to believe that atmospheric blocking is the most dominant influencer on climate. However Klingaman (2012) also explains that the relationship between rainfall and atmospheric blocking in Queensland has not been extensively researched and cannot be ascertained with high confidence. Therefore overall the climate index of ENSO was used within this investigation.

2.4 Urban Water Storage Management – Risk

One of the most important dimensions of water resources is the management of water supply risk (Griffin & Mjelde, 2000). The management of urban water supplies has always had the most conservative path with practices especially when Australia has strong relations to drought. Controlling urban water supplies traditionally has involved little to no risk with the developments of large water supplies such as dams to minimise the probability of any future shortfall. Water operations are handled by managers whose performance is gauged with the ability to provide water at any time regardless of the climate conditions (Griffin & Mjelde, 2000). Risk management of water supplies takes into account a number of supply uncertainties such as droughts and floods and demand uncertainties such as population growth, water consumption trends and environmental requirements (Victorian Government, 2011). Decisions based around water supplies are therefore conservative with water managers aware that maintaining a ‘safe yield’ is needed to minimise the chance of running out of

water. Therefore the constitution of conservative decision-making for urban water managers equates to decisions that are made after streamflow has already occurred in storage. This investigation however strives to look at how decision-making can be applied before the streamflow actually occurs, therefore removing the time barrier.

CHAPTER 3 METHODOLOGY

3.1 Introduction

This chapter details the importance of dam storages, and the relationships between its draft, storage, yield and reliability. It will then discuss the development of a water balance model for Cressbrook Dam which includes the inputs of streamflow and rainfall, and the outputs of evaporation, infiltration, water demand, spill over the top of the dam and water releases downstream. The next stage describes the linear regression analysis used to determine the best relationship and lag increase between SOI and streamflow data for Cressbrook Dam on both a monthly and seasonal scale. Lastly combining ENSO into the water balance model the development of three different water management scenarios will be discussed along with how the extended streamflow sequence was developed for the water balance model.

3.2 Hydrologic Analysis of Water Supply Systems

Estimations of volume runoff from a catchment are often required for civil engineers for a number of different applications. One of the most important reasons is for the design of containment systems, in particular dams which are able to store water over a relatively long periods of time. In today's modern world the demand for a city's water supply is an essential part of establishing a functional community. In order to meet the water demand of the city, water volumes of surface runoff are needed for the assessment of dam storages and urban water supply management so that the required amount can be delivered to urban, agricultural and industrial water users (Brodie, 2015).

According to Brodie (2015), runoff volumes or streamflow figures are calculated over various timescales which usually ranges from daily to

annually totals. The timescale used depends on the application and is expressed as a water volume over a certain time period. There are a number of ways that runoff volumes can be determined which mostly depends on the availability of measured streamflow data. One of the procedures used involves uses a water balance model when there is limited or no streamflow records or gauging stations available, however there would be less confidence in the accuracy of the predicted flow volumes made. There are also other runoff volume calculations that can be used for a variety of different timescales such as the average annual runoff produced from a catchment for a broader water resources approach as well as a runoff volumes for an individual storm event which is calculated using the volumetric runoff coefficient.

However within this investigation modelled streamflow data in the form of ML/day was obtained by the Department of Natural Resources and Mining (DNRM) over a number of years. Once large datasets of streamflow data are recorded over a long period of time such as TRC's, other important hydrological values can be assessed using storage behaviour analysis. Toowoomba's water supply from Cressbrook, Perseverance and Cooby Dam are designed to increase the amount of water available, store water when flows and demand are sufficiently large and be able to provide water when streamflows into the dams are sufficiently low. If streamflows into the reservoir are large, they may be sufficient enough to fill the reservoir causing it to spill the uncontrolled flow of water over the top of the reservoir spillway.

Characteristics of reservoirs include unregulated and regulated systems, carry over storages and yearly storages. Depending on the needs and capacity of the community, a city's urban water supply will be delivered by a regulated or unregulated system. Unregulated systems are designed for much smaller water demands as these systems rely on the natural streamflows of rivers which are then pumped and supplied to the users. These systems usually have yearly storages that will both fill and spill to balance the differences of streamflow throughout different seasons. With a regulated system, the water

is contained and controlled with engineering structures such as dams and reservoirs which are needed to provide water to satisfy the large demands of agricultural, industrial and domestic needs over a large area. These systems are often associated with having carry over storages where water can be held over many seasons so that there is supply available when streamflows coming into the reservoir are below average. Cressbrook Dam is therefore seen to be a regulated system that uses carry-over storages to satisfy water demands and this will be known throughout the analysis of the report (Lough, 2008).

As explained by Linsley & Franzini (1964), another aspect of reservoirs is the minimum operating level which is taken into consideration in its design which ensures that it will never go completely dry. The minimum operating level is usually calculated by a certain volume of water that remains at the bottom of the reservoir with any volume taken below this level known as the dead storage. While the dead storage takes water from below operating level, the active storage is the volume in a reservoir that is used during normal operations. The active storage is any amount of water that is between the full supply and the minimum operating level of the reservoir.

Three important terms that are commonly associated with water supply and storage are a dam's yield, draft and reliability. Both yield and draft are used interchangeably and refer to the average volume of water that is supplied by the dam to satisfy water demand needs over a certain period of time. The yield of a dam is also often set to meet water demands at a specified level of reliability (Linsley & Franzini, 1964). As discussed by Brodie (2015), the reliability of a dam is the proportion of time that a target demand can be met and is expressed by the following equation.

$$R(\%) = \frac{N_s}{N_t} \times 100$$

Where

N_s = the number of time periods that the target demand was supplied

And N_t = the total number of time periods

Therefore as expected, the calculation of yield and in turn reliability depends on a number of factors such as streamflow regimes, water demand patterns, water supply system characteristics, evaporation from reservoirs and most importantly the possible factor of climate changes which is being investigated in this report. As claimed by Lough, (2008) It is clear that there is a link between storage, yield and reliability and that a relationship can be derived between the three. This is best explained by the difference between a regulated and unregulated system. If an unregulated system harvests water from an uncontrolled stream then the reliability and water supply will be relatively low and if a flood occurs, the yield will be relatively high for a short period of time. In a regulated system however, the presence of a storage capacity will increase both the yield and reliability. Therefore the three terms can be formed into the following equations to represent the relationship between each other and described by Figure 11.

$$\alpha = \frac{D}{\bar{Q}} \quad \text{and} \quad S^* = \frac{S}{\bar{Q}}$$

Where

α = Draft ratio (%)

D = Draft (ML)

\bar{Q} = Mean annual flow (ML)

S^* = Storage ratio

S = Storage capacity (ML)

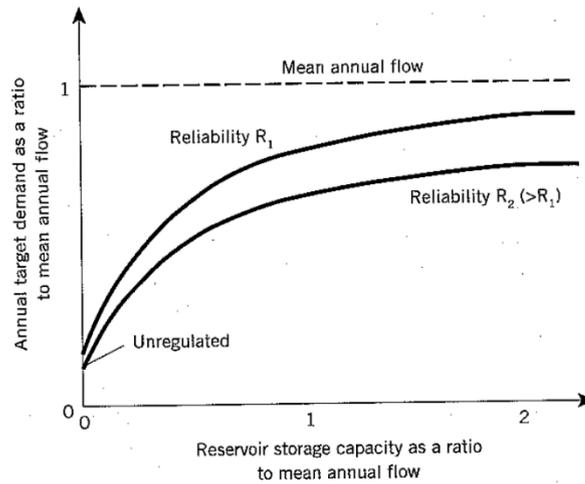


Figure 11: Relationship between storage, yield and reliability (Lough, 2008)

From this graph, it is shown that the storage capacity ratio is plotted on the x-axis against the draft ratio in the y-axis. The two different lines represent both a regulated and unregulated system with differing reliabilities. It is seen that as the storage ratio increases (a function of storage capacity over the mean annual flow) the draft ratio (a function of yield over the mean annual flow) also increases at a decreasing rate. For a given storage capacity of a dam, it is seen that as the reliability increases, the yield decreases due to less water being harvested (Lough, 2008).

3.3 Water Balance Model

The highly variable climate of Australia is the major reasoning behind the use of regulated systems such as dams and reservoirs. Taking water directly from natural streams are seen by many engineers and hydrologists as too unreliable, as natural streamflows are highly variable from season to season. The storage of water can improve reliability as explained previously, however it also brings forward many other important problems. Of these problems, the most important is the prediction of likely increases and shortfalls in water availability and supplying the water demand needed accordingly which is the main aim of the report.

3.3.1 Behaviour Analysis

As suggested by Brodie (2015), in a storage behaviour analysis the application of a water balance equation are used to determine both the dam yield and reliability. At its simplest form, the change in storage volume in a reservoir is equal to the difference between the inflow and outflow of the system which is consistent with the conservation of mass. However a proper and complex water balance model accounts for a number of different parameter as seen in Figure 12 below.

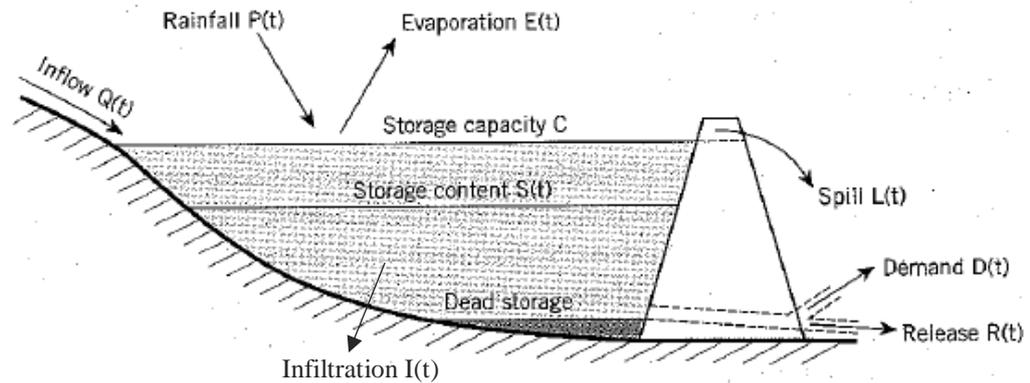


Figure 12: Inflows and Outflows from a Reservoir (Lough, 2008)

From this diagram, the following water balance equation can be formed:

$$S_t = S_{t-1} + Q_t + P_t - E_t - I_t - D_t - L_t - R_t$$

Where

S_t = Storage volume on day t (ML)

S_{t-1} = Storage volume at the end of the previous day t-1 (ML)

Q_t = Volume of stream inflow on day t (ML)

P_t = Volume of rainfall that falls directly onto the dam on day t (ML)

E_t = Volume of water evaporated from the dam on day t (ML)

I_t = Volume of water infiltrated through seepage on day t (ML)

D_t = Volume of water drafted from the dam on day t (ML)

L_t = Volume of water spilt on day t (ML)

R_t = Volume of water released on day t (ML)

According to Lough (2008), the water balance equation shows that there are two main sources of inflow into the dam which are the natural streamflows and the direct rainfall on the dam site as well as the storage that is already present from the previous day. The outputs of the water balance equation include evaporation, infiltration, water draft, the spillage over the top of the dam and the environmental releases from the dam. The determination of each of these parameters will be further discussed in the sections below as well as how the surface area of the water held by the dam can affect the overall volume of the storage.

3.3.2 Storage volume at the end of the previous day (S_{t-1})

To calculate the current storage volume of Cressbrook Dam on day t, the storage volume of the dam must be known from the previous day. Therefore there must be a known storage volume of the dam from the very beginning of the time, so that the model can then calculate the storage volume of the next day and continue the loop of equations until a certain time period is reached. Information regarding the storage volume of Cressbrook Dam was provided by the Toowoomba Regional Council to have a maximum capacity of 81842 ML. Therefore starting storage volumes of 90%, 75%, 50% and 25% of the maximum storage capacity were used to run various water balance models to give a percentage likelihood of the dam reaching a certain volume.

3.3.3 Volume of stream inflow on day t (Q_t)

The volume of streamflow running into the dam site is the main source of storage volume increase. Streamflow data from Cressbrook Creek was sourced from DNRM, with volumes in the form of ML/day taken to determine the inflow and increase of the storage dam volume. Although not ideal, the only streamflow data from DNRM is from a closed gauging station with records lasting from 1965 to 1981 and providing 16 years of usable data.

3.3.4 Volume of direct rainfall onto the dam on day t (P_t)

While the volume of streamflow running into the dam accounts for the rainfall runoff from the entire Cressbrook catchment area of 320 km² into Cressbrook Creek, the parameter of R_t accounts for the precipitation that falls directly onto Cressbrook Dam during a daily period. Daily precipitation values are given from the Bureau of Meteorology (2016), with the station site of Cressbrook Dam providing daily precipitation values in mm. The average value of precipitation for each month (mm/month) was taken (as shown in Table 2) and used for the water balance model by dividing these values by the number of days in each month to create a constant daily rainfall value (mm/day). These daily rainfall values were then multiplied by the surface storage area to provide a volume of rainfall in ML/day. It is expected that the volume of rainfall added to system is dependent on the surface storage area at that certain point in time.

Table 2: Monthly average rainfall for Cressbrook Dam

Month	Average Monthly Rainfall (mm/month)
January	121.3
February	121.9
March	70.1
April	38.5
May	56.6
June	34.7
July	25.3
August	26.1
September	36.6
October	57.6
November	74.2
December	107.4

3.3.5 Volume of water evaporated from the dam on day t (E_t)

As claimed by Wong (1999), for large water storage areas such as dams or reservoirs, the estimation of evaporation is commonly used using nearby measurements of pan evaporation. A class A evaporation pan is used which is made from galvanised iron, measurements of 122 cm diameter and 25.4 cm deep and supported on a timber frame for air circulation. The process involves filling this pan with water to a depth of 20 cm and is continually refilled after the depth has fallen to 18 cm. To calculate the evaporation, the difference between the observed levels are taken and adjusted for the addition of any rainfall that is measured in a standard rain gauge. Average annual pan evaporations varies from location to location but generally in the south-east region of Queensland, an average is estimated to be around 1800 mm. McJannet et.al (2013) however suggests that the pan evaporation has to be multiplied by a pan coefficient to derive a value which accurately represents evaporation of a large open water storage area. While there are limitations to this approach, it is still considered the most common and widely used technique for calculating evaporation over a large open water area due to its

simplistic nature and the requirement of only small amounts of data. Monthly pan factors have been computed for 29 stations located throughout Queensland. The closest station to Cressbrook Dam is Gatton as explained by Queensland Government (2008), which gives average monthly values in mm which was then converted into equivalent daily evaporation values as shown in Table 3 below.

Table 3: Monthly Pan Evaporation for Cressbrook Dam

Month	Monthly Pan Evaporation (mm/month)
January	201
February	163
March	163
April	130
May	96
June	84
July	92
August	116
September	152
October	182
November	197
December	213

3.3.6 Volume of water infiltrated through seepage on day t (I_t)

This value was also constant throughout the entire water balance model. The infiltration rate due to the seepage is dependent on the type of soil over which the dam holds the water. Depending on the permeability of the soil a constant rate loss will be applied to the model. The value that was used is based from the Queensland Government (2008) which claims that a value of 25mm/month is used in all of their modelling of Cressbrook Dam.

3.3.7 Volume of water drafted from the dam on day t (D_t)

Toowoomba's main three urban water suppliers are from Cooby Dam, Perseverance Dam (upstream) and Cressbrook Dam (downstream). The volume of water that is drafted from each of these dams depends on a number of different factors. These factors include population, water restrictions, and the size capacity of the dam itself. Cressbrook Dam is the largest supplier of urban water with a maximum capacity of 81842 ML. Currently, water restrictions within Toowoomba are a part of permanent conservation measures. As explained by Toowoomba City Council (2006), the average consumption under these measures is 250 L/p/d and is used as the base volume of water drafted in the water balance model. The current population according to Boyd (2014) is 135,000 people. Therefore multiplying the water consumption by the population gives the total demand required for Toowoomba each day. However taking into consideration that water is drafted from all three dam sources, it was determined that Cressbrook Dam (as the largest supplier) accounts for approximately 60% of the daily demand (Toowoomba City Council, 2006). Therefore applying a factor of 0.6 to the total daily demand a draft value of 20.25 ML was used for the water balance model.

3.3.8 Volume of water spilt on day t (L_t)

At every time step of the model, the overall storage volume will increase or decrease by a net or gain loss. Comparing the inflows of the dam which are the stream inflow into the dam and the direct rainfall onto the dam, and the outflows of the dam which include evaporation, infiltration, water draft and water spill. If the inflows into the dam are higher than the outflows, the storage volume will increase compared to the previous day and vice versa. If the new storage volume is between its dead storage and maximum capacity level, then there will be no water spilt on that day. If the new storage volume is above its maximum capacity level, then there will be a volume of water

spilt over the top of the spillway of Cressbrook Dam. A simplified equation can be seen as follows:

$$\text{Airspace at the end of Day } t \text{ (ML)} = \\ (\text{Full supply volume} - \text{current storage volume}) + \text{Outflows} - \text{Inflows}$$

From this equation the resulting airspace can mean two different scenarios. If the airspace value ends out to be negative at the end of the day, then this means that there will be a spill over the top of the dam which is equal to the negative value. If the airspace at the end of the day is positive, then there will be no spill.

3.3.9 Volume of Water Released from the Dam on Day t (R_t)

The Queensland Government (2014) explain a number of complex rules and criteria that need to be met to release a certain amount of water downstream of Cressbrook Dam. Since Cressbrook Dam's catchment is upstream of the Brisbane River catchment, it is the responsibility of the TRC to make sure that a certain amount of water is released downstream to support this catchment. The criteria given within the report are too complex to incorporate into the water balance model created in excel spreadsheet. Therefore a daily release volume of 2 ML was assigned based on the report from Queensland Government (2014), which states that release flow has to be less than 3 ML per day for Cressbrook Creek.

3.3.10 Surface Storage Area

The impact of the water balance parameters of rainfall, evaporation and infiltration all depend on the surface area that dam supply holds on each day. The parameters listed above have to be converted from water depth in mm/day into a volume loss or gain in the units of ML/day. Therefore as shown in Table 4 below, the Queensland Government's report (2008) shows the area occupied by the water storage when a certain volume of water is held. This table was used within the water balance model at the start of each new daily time step to determine through interpolate the area occupied by the water storage.

Table 4: Surface Area of Cressbrook Dam depending on storage volume

Volume (ML)	Surface Area (m²)
1136	32000
2139	50000
3691	75000
5885	101000
8742	128000
12254	153000
16480	187000
21597	223000
28954	270000
36267	314000
54125	404000
64839	454000
76764	499000
81842	517000

3.4 Streamflow and ENSO Relationships

In this part of the analysis, the point in which the streamflows running into Cressbrook Dam, known as Q_t in the water balance equation, was further explored to find a potential relationship between itself and climate indices.

3.4.1 Monthly Streamflow and ENSO Relationships

The first stage of the analysis involves using monthly historic streamflow data from Cressbrook Dam. All available streamflow data was downloaded from DNRM (1/11/1965 to 1/05/1981), and placed alongside with the corresponding SOI value from that month. Sorting the streamflow data by month, each month could then be individually assessed against SOI using an r-squared linear regression analysis. The r-squared (or ordinary least squares) method is a common and simple way to determine whether there is a relationship between two different variables. An r-squared value is a fraction between 0 and 1 with no units, with values closer to 1 indicating that there is a better relationship between the dependent and independent variables (Graph Pad, n.d.). Within this analysis, it was determined whether there is a significant linear relationship which describes that streamflow is dependent on SOI.

For each month, there was five different r-squared values that were determined. The first r-squared value as explained was between streamflows values and their corresponding SOI values for those months. The other four r-squared values were determined by bringing all SOI values in the dataset forward by a continual one month so that there is a lag increase between streamflow and SOI. This was repeated until there is a five month lag difference between streamflow and SOI. As explained by Chiew et.al (2002), this technique is “*a simple, direct and consistent measure for exploring the potential for forecasting streamflow several months ahead*”. Therefore this lag factor was used to identify the strongest correlation between SOI and lagged monthly streamflows.

3.4.2 Seasonal Streamflow and ENSO Relationships

Once significant monthly relationships were found, the next step was to increase the temporal scale from monthly to seasonal to determine if the relationship was improved. Monthly streamflow totals were added together according to their season, and were firstly checked to see what proportion of streamflow occurs in which season throughout the year. Then a continual one month lag was once again applied to SOI values until a five month lag was reached. Seasonal graphs with five lines of best fit and five r-squared values was then used to determine the best seasonal relationship, with the best lag increase determining how far out this best seasonal relationship can be made.

3.4.3 Seasonal Cumulative Probability Distributions

The final stage of the analysis focused on developing a cumulative probability distribution of the streamflow that showed the best seasonal relationship. From this point forward in the analysis, SOI values were substituted for SOI phases. SOI phases have been identified by Stone (2011) as a simpler way to quantify ENSO which can be used for practical applications and future seasonal forecasting. SOI phases are identified by categorising SOI values into one of five different phases depending on the immediate SOI value and the month preceding it. The five categories are:

1 – Consistently Negative

2 – Consistently Positive

3 – Rapidly Falling

4 – Rapidly Rising

5 – Near Zero

The approach to developing a cumulative probability distribution was similar to that used by Stone (1996), which plots the rainfall data of more than 70 years from different places around the world on the x-axis against probability

on the y-axis. Similarly in this analysis, the x-axis contained the streamflow total from the best particular season and the y-axis contained a percentage exceedance or probability scale from 0% to 100%. The graph contained six different probability lines consisting of the five SOI phases shown above and a sixth line which combines all five SOI phases into one. These six different SOI phases depicted the percentage chance that when the SOI is a certain phase, the total streamflow will be a certain amount within a certain season.

3.5 Combined Water Balance Model with ENSO Relationships

Once a definitive relationship was formed between streamflow and SOI, its findings were applied to the water balance model to create a water allocation tool that can be used to explore water management scenarios. Depending on the best seasonal relationship, a water balance model was run for the best seasonal time each year from 1965 to 1981 with fifteen seasons in total. Out of these fifteen seasons, there was a certain amount seasons that fall under each of the SOI phases according to the best lag increase. Therefore the end result from running 15 different water balance models gave a certain total storage volume held within Cressbrook Dam. To see whether certain SOI phases resulted in the total storage volume being higher or lower, a cumulative probability distribution similar to the process explained in the section above was used. In this case, the y-axis will still be a probability of exceedance from 0% to 100% but the x-axis showed the different end level storage volumes of Cressbrook Dam.

The starting storage volume for Cressbrook Dam was expected to impact on the final end storage volumes and this was also shown by the cumulative probability distribution. Therefore variations of the water allocation graph will show differences between:

- A starting volume of 90% (73657.8 ML)
- A starting volume of 75% (61381.5 ML)
- A starting volume of 50% (40921 ML)
- A starting volume of 25% (20460.5 ML)

3.6 Scenarios

Once water allocation graphs were established for a range of starting volumes, it was important that their validities were investigated by exploring a range of alternative water management approaches based on their findings. To examine how the behaviour of Cressbrook Dam would have occurred by incorporating climate indices into decision-making, three different scenarios were run based on past historical streamflows. These three different scenarios were:

1. Normal water restrictions that are currently used by the TRC
2. Restrictions raised to level 2 from December to March when the SOI phase is observed to be consistently positive
3. Restrictions raised by one level from December to March when the SOI phase is observed to be consistently positive

3.6.1 Scenario 1

Until now, all water balance models have been using a flat rate of daily water demands of 20.25 ML which is equal to level 2 water restrictions (refer to Table 5) . In reality, this would not be the case as all authorities controlling urban water supplies would have a number of water restrictions that are applied when a certain percentage of the dam storage level is met. Table 5 below shows the restrictions that are in place by the Toowoomba Regional Council and are used to run scenario 1.

Table 5: Water Restrictions in Place by TRC

Restriction	Level 2 (Permanent Conservation)	Level 3	Level 4	Level 5
Useable Storage trigger point to introduce restrictions	100% to 40%	<40%	<30%	<20%
Useable storage trigger point to lift restrictions	50% to 100%	>50%	>40%	>30%
Water Consumption (L/p/d)	250	210	170	125

An important note to take away from Table 4 is the use of ‘useable storage’. The useable storage is the different from using the maximum storage of the dam from 0 to 81842 ML and is calculated using the following equation:

$$\begin{aligned}
 \text{Useable Storage (ML)} &= ((\text{Total dam storage} - \text{dead storage}) \\
 &\quad \times \text{Percentage of Dam Level Full}) + \text{dead storage}
 \end{aligned}$$

Where

Total dam storage = 81842 ML

And Dead storage = 2995 ML

Therefore according to the volume of the dam on the previous day, scenario 1 was run with a check on each individual day to see whether restrictions needed to be raised or lowered, which then affected the daily water draft used in the water balance model.

3.6.2 Scenario 2

Scenario 2 incorporates a new layer of decision-making processes, with this layer being the current SOI phase. As seen in Figure 13 below, if the SOI phase in November was viewed to be 2 (consistently positive) and the current water restriction was not level 2, then the model will raise the restrictions straight to level 2 for the period of December to March.

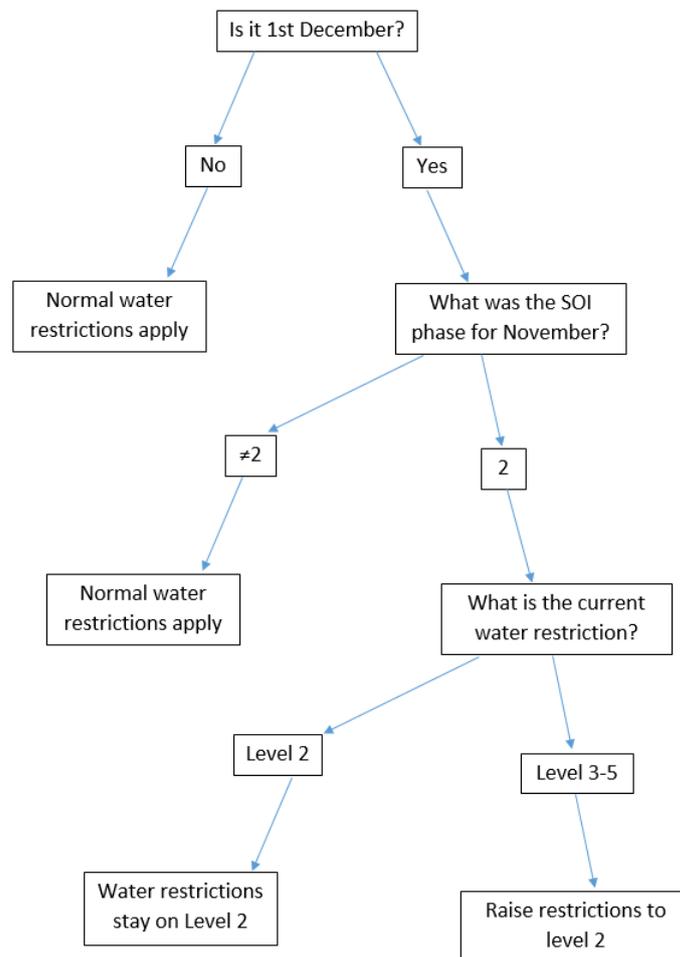


Figure 13: Scenario 2 Decision Tree

3.6.3 Scenario 3

The last scenario analyses the behaviour of Cressbrook Dam using a more conservative approach than scenario 2 but has still taken SOI into consideration. The decision-tree shown in Figure 14 shows that this approach has raised the water level restrictions by one level instead of straight to level 2, when the SOI was observed to be phase 2 in November.

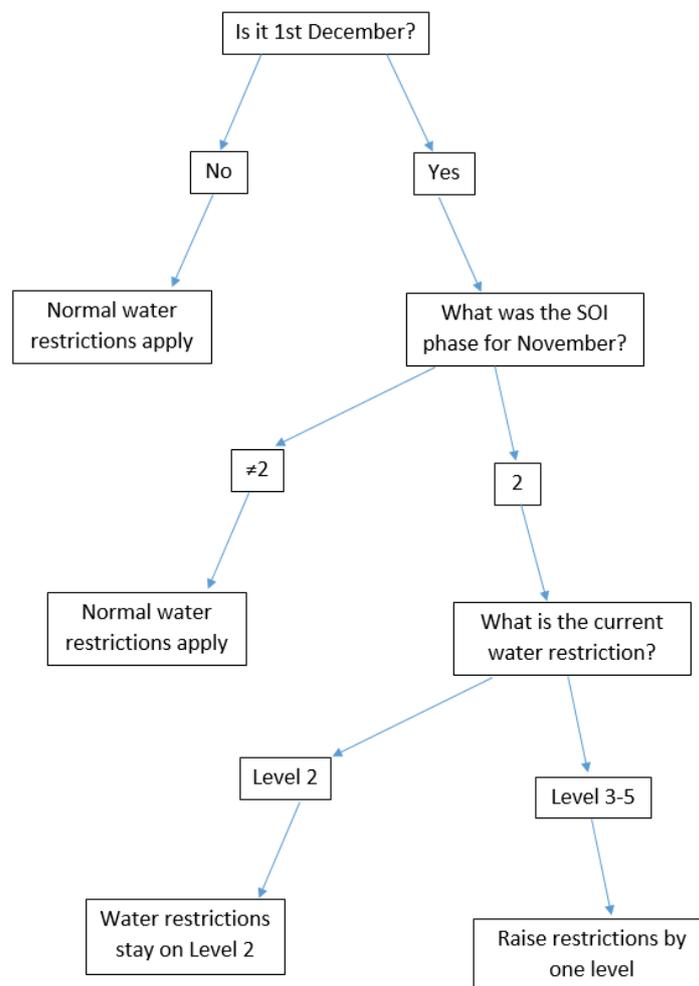


Figure 14: Scenario 3 Decision Tree

3.6.4 Development of Streamflows for Scenarios

The establishment of relationships between SOI and streamflow for the best months throughout the year and the best forecasting period were made from streamflow records that actually existed at the dam site itself. However when this record of 16 years of streamflow data were used to run the three various scenarios, the final result showed the storage level volume of the dam remained relatively high meaning that there was no difference between the different scenarios.

Therefore in order to make a comparable difference between the different scenarios other closed or open stream gauges that recorded flow from Cressbrook Creek were investigated. From the DNRM water monitoring panel, there are two other stream gauges that are found to record streamflow for Cressbrook Creek:

- 1) Cressbrook Creek at Tinton (downstream) – Available streamflow record from 1/10/1952 to 15/6/1986
- 2) Cressbrook Creek at Rosentretters Crossing (further downstream) – Available record from 20/8/1986 to now

To simulate streamflows that could be used for the dam site of Cressbrook, firstly the streamflow from Tinton was compared with the actual streamflow at Cressbrook Dam. Streamflow records from the dam site are available from 1/11/1965 to 12/5/1981 with an overlap of around 16 years of data between Tinton and the dam site. The streamflow from Tinton and the dam site were then run side by side using the same dates and sorted from lowest to highest. A scatter plot was then created between the two different streamflows for 12 out of the 16 years of data with any streamflows greater than 3000 ML not used. An equation for a linear relationship between the two was then formed, making sure that the intercept value was set to zero. Using this linear relationship a series of simulated streamflows were created using the four years of unused data. Using the streamflows that were above 3000 ML, a separate linear relationship was formed using an intercept that was not zero.

To compare the error between the two datasets, the simulated and actual dam site streamflows from the four years were summed so that a comparison could be made between the cumulative volumes of each dataset. Once the relative error between the two was less than 5%, then these streamflows were used to simulate streamflows from the dam site dating back to 1/10/1952.

Simulated streamflows for the dam site were also created from 1986 to the end of 2015 using streamflows available from Rosentretters Crossing. Using the relative difference between the catchment sizes of Rosentretters and Tinton, a scaling factor was applied to simulate streamflows at the dam site. It is noted that these methods used to simulate streamflow are not truly accurate as the isolation of rainfall events will determine the magnitude of streamflows depending on their location. However, the use of these simulated streamflows are only used for indicative purposes of changes of storage volume based on water restrictions and is therefore appropriate for this study. Therefore overall a full dataset of streamflows from 1/10/1952 to 31/12/2015 were used to run the water balance model with the three different scenarios.

CHAPTER 4 RESULTS FOR STATISTICAL STREAMFLOW FORECAST MODEL

4.1 Introduction

This chapter contains an in depth analysis of the results found from the relationship between ENSO and streamflow for Cressbrook Dam on a monthly and seasonal scale. From these relationships, cumulative probability distribution graphs for streamflows and storage levels were developed and discussed in detail.

4.2 Monthly Streamflow and ENSO Analysis

An assessment of the relationship between monthly SOI values and monthly streamflow totals for each month throughout the streamflow record were analysed. The resultant graphs from each of these months can be found in Appendix C which shows the r-squared values from zero month to a five month lag increase. To summarise the findings from these monthly SOI and streamflow relationship graphs, Table 6 below shows the average r-squared correlation for each month.

Table 6: Average Correlation Values for Each Month

Month	R-Squared Value
January	0.277
February	0.209
March	0.271
April	0.0332
May	0.194
June	0.0530
July	0.0222
August	0.0349
September	0.0520
October	0.0623
November	0.00613
December	0.249

From these results, average r-squared values for every month were not anywhere close to approaching a value of 1 which indicates a perfect linear relationship between. Automatically, months that had a correlation of less than 0.1 were discarded and were not further investigated as a relationship this low cannot be used as a justification for future predictions. However, there were certain months which showed a significant enough relationship to investigate further. The months of December, January, February, March and May all had correlation values above 0.1. A reasonable explanation as to why certain months had a better correlation than other months is shown by Table 7 below which shows the total monthly streamflow that occurred for each month throughout the streamflow record.

Table 7: Monthly Streamflow Totals

Month	Monthly Streamflow Total (ML/Month)
January	85076.75
February	94442.85
March	40668.01
April	14068.61
May	8059.1
June	36609.4
July	14966.67
August	9001.58
September	9037.72
October	9298.44
November	14082.82
December	15422.06

If the streamflow totals are compared with the correlation values for each month respectively, then it is seen that there is trend where the best correlated months are associated with the highest streamflow totals. The months of January, February and March have the three highest streamflow totals and also have correlations above 0.1. The month of May was viewed to be an anomaly in the data as it had a high correlation for a small streamflow total. The months above and below May were viewed to be have little to no correlation and therefore was why May was also removed as a month to further investigate.

4.3 Seasonal Streamflow and ENSO Analysis

The best correlated months of December, January, February and March were added together to give a seasonal streamflow total for each year within the streamflow dataset. These streamflows were then assessed for their correlation against monthly SOI values with increasing one month lags, the same analysis used previously. Whereas the monthly relationships helped to identify the best timeframe to make streamflow predictions based off SOI, the seasonal relationship was used to identify the forecasting period.

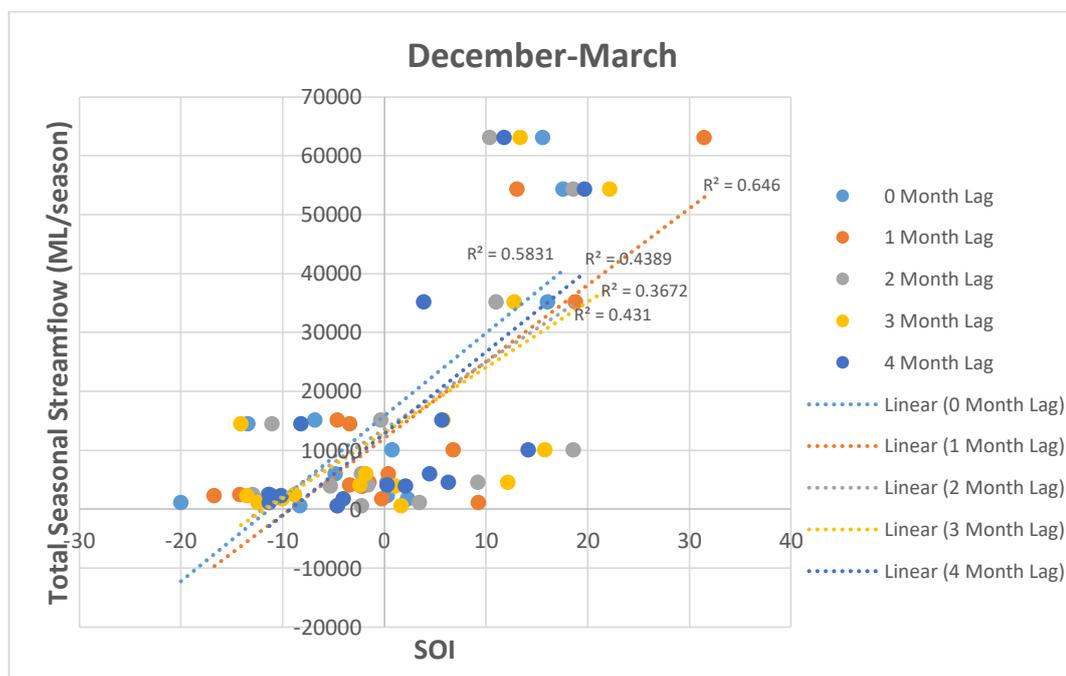


Figure 15: Seasonal Streamflow and SOI Relationships

Immediately from figure 15, the change in temporal scales from monthly to seasonal has resulted in correlations that are much higher than the monthly correlations. The lowest correlation is seen to be 0.431 for a lag of three months between streamflow and the SOI value observed in September. This correlation is higher than any average monthly r-squared value shown in Table 6 which coincides with the document produced by Klingaman (2012), which indicates that the effects ENSO are based on a seasonal to inter-annual temporal scale more so than a monthly temporal scale. The highest correlation between SOI and seasonal streamflow was for a one month lag period between the datasets with a value of 0.646. This indicates that the best forecasting period for the months of December to March are based on the SOI values that are observed in the month of November.

4.4 Seasonal Cumulative Probability Distribution Analysis

After identifying the prediction timeframe and the forecasting period, these elements were used to create a cumulative probability distribution graph based on streamflow. The basis of this graph was to obtain preliminary results and trends towards predictions of streamflow according to SOI values for certain probabilities. Since the best relationships between SOI and streamflow for Cressbrook Creek have been formed, the results now indicate forecasted streamflow based on SOI phases (as discussed in the methodology). In order to produce this cumulative probability distribution graph, the streamflow from each December to March season in the dataset were separated according to the SOI phase that was observed in the November month prior.

Table 8: Streamflow Totals According to SOI Phase in November

Season	Streamflow Total December-March (ML)	SOI phase November
65-66	2298.97	1
72-73	14468.76	1
77-78	2478.31	1
70-71	35187.83	2
71-72	10012.71	2
75-76	54312.4	2
74-75	4538.69	3
69-70	1685.27	4
73-74	63038.73	4
76-77	1113.5	4
66-67	5953.04	5
67-68	15103.31	5
68-69	4033.7	5
78-79	3886.15	5
79-80	568.59	5

Each different SOI phase was observed to occur in November throughout the streamflow record, ranging from one season where SOI phase 3 was observed (Rapid Falling) to five seasons where SOI phase 5 was observed (near zero). Therefore a percentile of 0%, 25%, 50%, 75% and 100% were calculated based off the streamflow ranges for each SOI phase. This culminated in the following cumulative probability distribution graph.

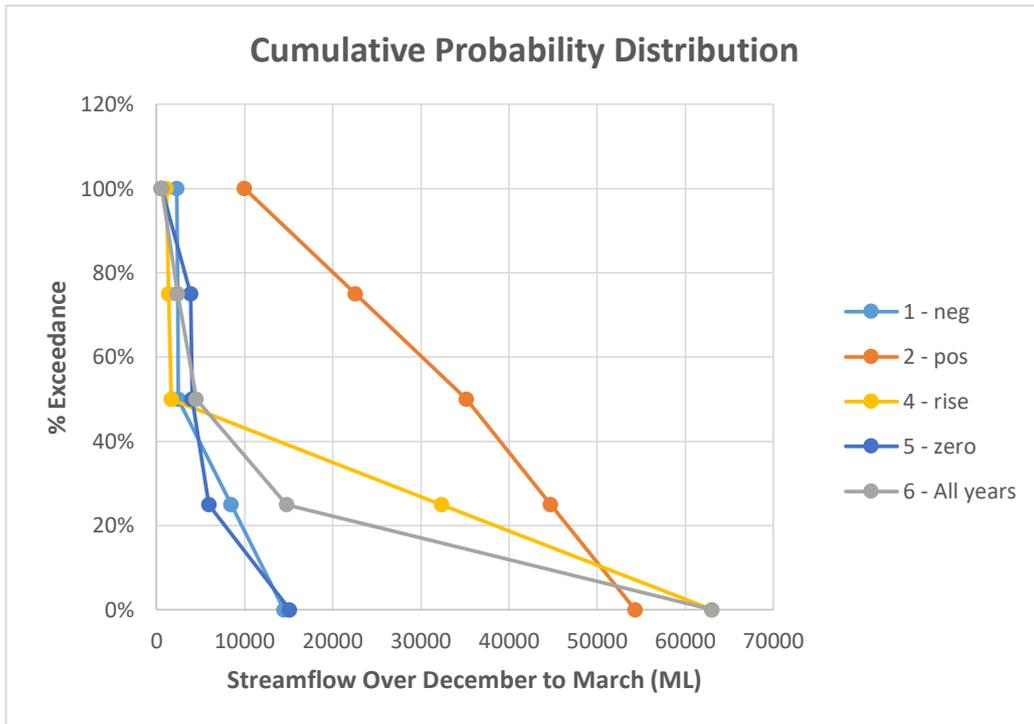


Figure 16: Cumulative Probability Distribution Graph for Cressbrook Creek

An example of how this graph could be utilised in decision-making, an assumed SOI phase of 4 (rapidly rising) is observed in the month of November. The decision maker can then be indicated on what amount of streamflow might run into Cressbrook Dam during the period of December to March according to and the probability chance that they choose. Therefore the decisions chosen on water supplies are still at the discretion of the user, and this is where other factors such political, social and sustainable issues may affect the overall decision of the percentage risk chosen by TRC. For example if TRC decided to take a 20% chance (very high risk) on the SOI phase 4, than the graph indicates that Cressbrook Dam will receive around 38000 ML into Cressbrook Dam between December to March. However as suggested in the literature review, urban water managers tend to be risk adverse in their decision-making and therefore would not be likely deviate from normal decisions unless there is a certain chance (100%) that SOI will have a significant impact on the streamflow of Cressbrook Dam.

Therefore there is one clear standout SOI phase which differentiates from the other SOI phases with this phase being SOI phase 2 (consistently positive). Figure 15 indicates that there is a 100% chance that there will be around 10000 ML of streamflow received by Cressbrook Dam between December to March. When comparing this against other SOI phases at 100% probability, a streamflow inflow of around 10000 ML indicates that the dam level could be significantly raised during this period, whereas all other phases indicate that only inflows of approximately 1000 ML could result in a drop in the dam level over this period of time. To know for sure, the next stage of the investigation determines cumulative probability distributions graphs which show the storage level behaviour of the dam according to different SOI phases.

Lastly, it may be noticed that the SOI phase of 3 (rapid falling) is missing from this distribution graph. This was due to there being only one season available in the dataset that had a phase of 3 in November. This was giving the graph an inaccurate straight vertical line and was therefore removed from any further results.

4.5 Cumulative Probability Distribution Analysis of End of Season Storage Levels

While preliminary results indicated a substantial increase in storage volume for a phase 2 observed in November, all other phases indicated that there would be hardly any increase in storage level if not less volume. To verify these initial results, cumulative probability distribution graphs were used to show the relationship between SOI phases, the storage level of the dam and the percentage chance when the starting levels of the dam were at 90%, 75%, 50% and 25%. The development of these distribution graphs were made by applying each of these starting water storage levels to the water balance model for Cressbrook Dam for every December to March season throughout the

streamflow record (refer to Appendix D). The end storage levels were then used to create each cumulative probability distribution graph shown below.

4.5.1 90% Starting Storage Capacity

Figure 17 below shows the cumulative probability distribution graph when Cressbrook Dam has a starting storage level volume of 73657.8 ML which is 90% capacity.

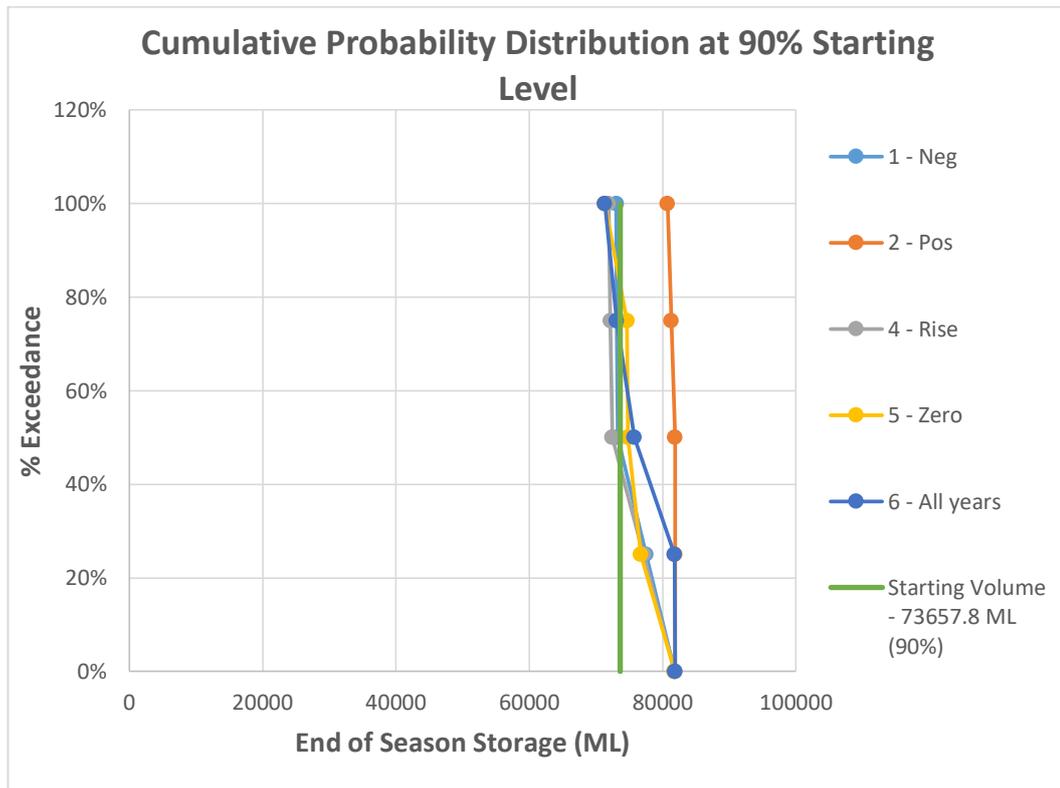


Figure 17: Cumulative Probability Distribution at 90% Starting Level

If the November SOI phase is seen to be consistently positive (phase 2) then it's shown from the figure above that there is nearly a 100% chance that the dam will be filled to 100% capacity by the end of March. It's also observed that the lines from all different phases are close to vertical, and this is due to the limiting factor of the available airspace in the reservoir. As there is only

a small amount of airspace available, this factor is seen to have the greatest effect on the distributions lines as they become more vertical and bunched.

4.5.2 75% Starting Storage Capacity

The following figure shows the cumulative probability distribution graph when the dam has a starting volume of 61381.5 ML which is 75% of its capacity.

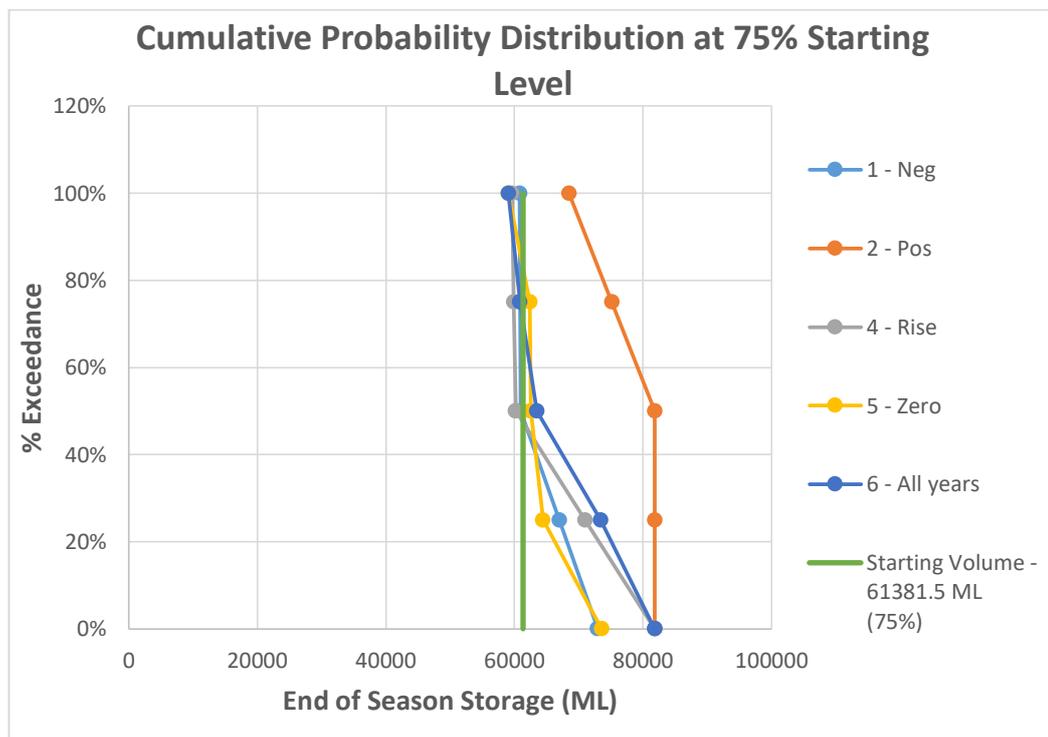


Figure 18: Cumulative Probability Distribution at 75% Starting Level

An analysis of this graph shows that a phase 2 in November results in the dam reaching a volume of around 68500 ML indicating an increase in volume of approximately 7000 ML over the four month period. For the other four phases, the graph shows that a substantial increase in storage level is highly unlikely. There is a very small chance that a phase 4 (rapidly rising) will increase the dam level to full capacity. Comparing this graph to the 90%

capacity, the lines are more spaced and less vertical due to there being more airspace available within the reservoir.

4.5.3 50% Starting Storage Capacity

Figure 19 below shows the cumulative probability distribution graph when Cressbrook Dam has a starting storage level volume of 40921 ML which is 50% capacity.

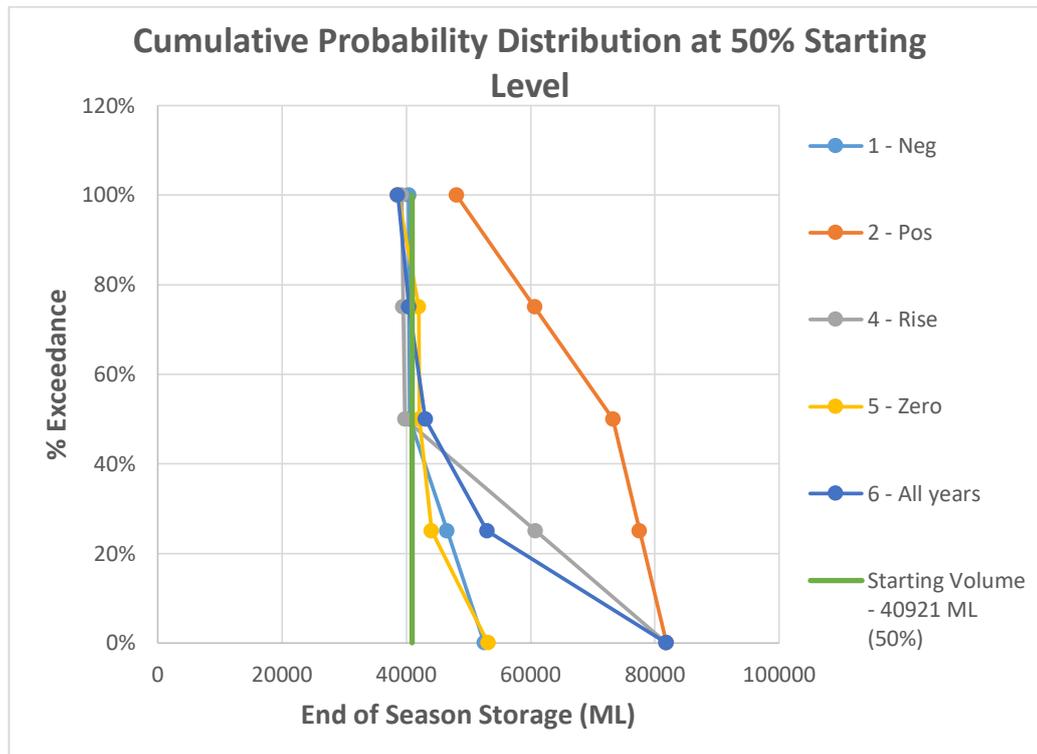


Figure 19: Cumulative Probability Distribution at 75% Starting Level

SOI phase 2 once again shows a substantial increase in storage level over the four month period whereas the other phases shows little to no significant increases in storage level for a high range of probabilities. The distribution lines continue to spread out as the starting volume of the dam drops, providing more airspace for streamflow to be captured.

4.5.4 25% Starting Storage Capacity

The following figure shows the cumulative probability distribution graph when the dam has a starting volume of 20460.5 ML which is 25% of its capacity.

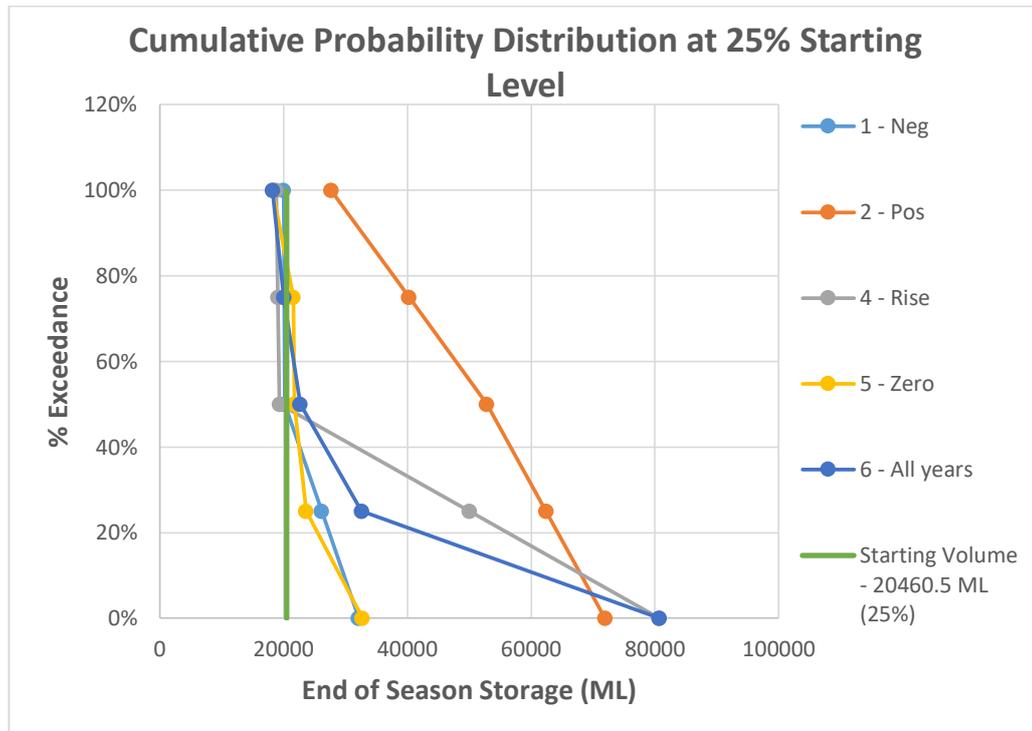


Figure 20: Cumulative Probability Distribution at 75% Starting Level

The trends of phase 2 in comparison to the other phases remains consistent with the other distribution graphs. There also seems to be wider range of end storage levels for different probabilities across all different SOI phases. An interesting observation from this graph was that at a very small probability a SOI phase of rapidly rising (phase 4) in November could result in filling the dam to capacity whereas a consistently positive SOI phase at the smallest percentage chance was shown to only reach a volume of around 70000 ML.

4.5.5 Summary of End of Season Storage Levels

A summary of the end of season storage levels are shown in Table 9 below which tabulates the dam volume's increase or decrease in size over December to March with different SOI phases for a probability of 100%, for all starting volumes investigated.

Table 9: Dam volume increases and decreases at 100% Probability

	1 - Neg	2 - Pos	4 - Rise	5 - Zero
25%	-482.03	7198.853	-1666.17	-2233.41
50%	-533.717	7149.291	-1718.23	-2285.87
75%	-575.856	7107.91	-1760.43	-2328.34
90%	-596.755	7087.952	-1781.5	-2349.58

This table justifies the preliminary findings and identifies that at a 100% probability there will be an increase in dam volume of approximately 7000 ML for a phase 2. The dam volume drops for the other four phases and this is indicated by the negative volumes ranging from around 500 to 2000 ML.

Table 9 also uncovers another important trend from the results of the cumulative probability distribution graph. By looking at the phase 2 column, it is seen that the volume increase is not the same, but actually decreases as the starting dam level increases. This is to do with the water balance model equation as the input of rainfall and the outputs of evaporation and infiltration are dependent on the surface area of the dam. For a starting dam level of 25% the dam's surface area will be significantly lower than if it was at 90%, therefore making the input and output factors have less of an impact and making the overall increase in storage volume greater.

CHAPTER 5 RESULTS FOR WATER MANAGEMENT SCENARIO ANALYSIS

5.1 Introduction

In this chapter the findings from the cumulative probability distribution analyses were used to apply different water management strategies. Firstly an extended sequence of streamflows were created and validated for Cressbrook Creek, before three different scenarios were run through the water balance model with different management strategies based on water restrictions, which was dependent on the climate events that occurred throughout the modelling period.

5.2 Extended Streamflow Sequence Development and Validation

An initial run of the model with the three different water management scenarios for the actual 16 years of recorded streamflow at the dam site resulted in no change in the storage behaviour of the dam at all. This was due to the dam being relatively full for the entire period of 1965 to 1981 and therefore water restrictions remained at the lowest level throughout this time period. Therefore there was a need to extend the streamflow record in order to clearly show how the implementation of these new water management practices (based off SOI phases) affected the storage level of the dam.

5.2.1 Relationship and Validation of Streamflows between Cressbrook Dam Site and Tinton

The first stage in the development of these extended streamflows was the relationship and validation of streamflows between the Cressbrook damsite streamgauge station and the Tinton streamgauge station. As explained in the

methodology, the Tinton station is located downstream of the dam site and has daily streamflow records dating from 1/10/1952 to 15/6/1986. As the dam site streamflow record dates from 1/11/1965 to 12/5/1981, it was identified that there was a 16 year overlap in daily streamflows between the two stations. Therefore this time period was used as the basis for developing a relationship between the two sites.

The process of the developing the relationship between the two stations was broken down into 6 different steps:

1. Streamflows from 1/11/1965 to 31/12/1967 were placed aside and was used later for validation
2. Streamflows from 1/1/1968 to 12/5/1981 were sorted from lowest to highest for Tinton along with the streamflows from the dam site
3. A scatter plot between Tinton and dam site streamflows were created for all streamflows in the period that were below 3000 ML
4. A linear regression line was added to the scatter plot and its equation was obtained by setting the intercept at zero
5. This equation was used to create simulated dam site streamflows for the validation period of 1/11/1965 to 31/12/1967 (as explained in Step 1)
6. The cumulative streamflow volumes between the actual dam site and the simulated dam site streamflows were compared by the percentage error between the two datasets

Therefore using this analysis, the scatterplot between Tinton and the dam site was developed below:

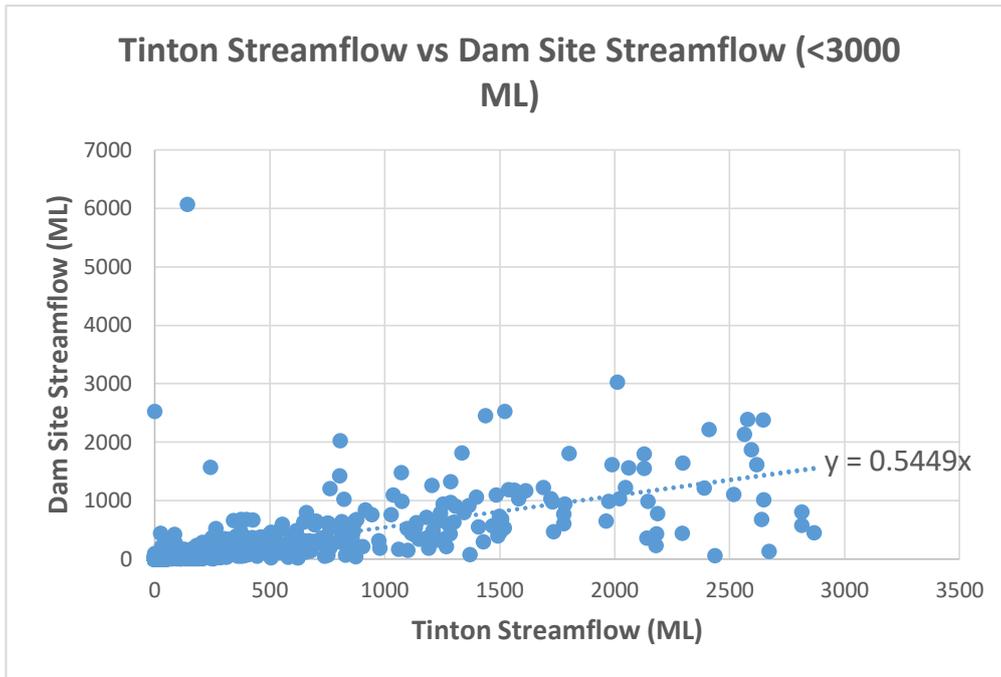


Figure 21: Tinton Streamflow vs Dam Site Streamflow (<3000 ML)

The line of best fit obtained from excel explains that the any Tinton streamflow that is below 3000 ML needs to be multiplied by a factor of 0.5449 to achieve a streamflow similar to the dam site. To validate how accurate this relationship is, the cumulative streamflow volumes between the two stations in the validation period resulted in the following calculation.

$$\% \text{ error} = \left(\frac{\text{Cum. volume}(\text{simulated}) - \text{Cum. volume}(\text{real})}{\text{Cum. volume}(\text{real})} \right) \times 100$$

Where

$$\text{Cum. volume}(\text{simulated}) = 49706.23 \text{ ML}$$

$$\text{Cum. volume}(\text{real}) = 51313.94 \text{ ML}$$

$$\% \text{ error} = \left(\frac{49706.23 - 51313.94}{51313.94} \right) \times 100$$

$$\% \text{ error} = -3.13 \%$$

A percentage error below 5% was deemed to be sufficient enough evidence to show that the streamflows had been validated. After this, the same analysis was performed using streamflows above 3000 ML. However when the linear regression line was added into the scatterplot, the intercept on the equation was not set to zero as this obtained a more accurate fit to the high streamflow data.

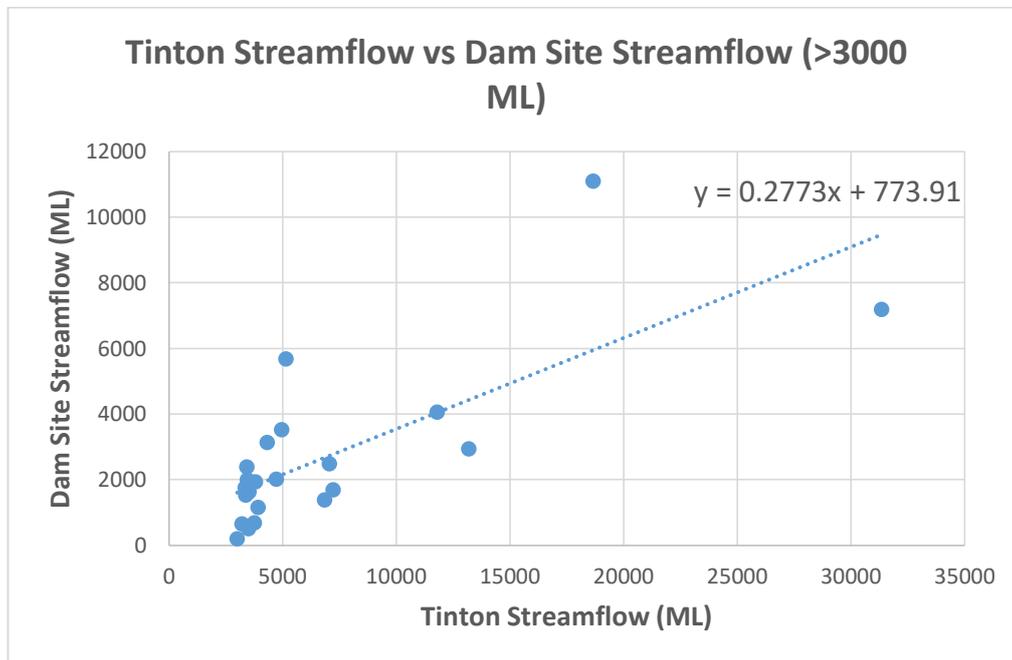


Figure 22: Tinton Streamflow vs Dam Site Streamflow (>3000 ML)

The line of best fit obtained from excel explains that the any Tinton streamflow that is above 3000 ML needs to be multiplied by a factor of 0.2773 + 773.91 to achieve a streamflow similar to the dam site. These large streamflows were not investigated by the percentage error as these are the only flows that are found throughout the whole dataset.

Combining these two different relationships based on the volume size, a set of simulated streamflows were created for the dam site which could add the dates of 1/10/1952 to 1/11/1965 to the streamflow record.

5.2.2 Relationship and Validation of Streamflows between Cressbrook Dam Site and Rosentretters Crossing

The Rosentretters Crossing streamgauge station is located a short distance downstream of the Tinton streamgauge station. As explained in the methodology, this streamgauge station has daily streamflow recordings from 20/8/1986 to the current day (although for this analysis the end date was set as 31/12/2015).

As there are no overlaps in streamflow records between Rosentretters and the dam site, there is no way to create streamflows for this time period that are accurate or validated. However for the purposes of the overall water balance model generated, the model is not trying to replicate the exact historical water storage behaviour of Cressbrook Dam in the past. The model being created will also use current water demands and current water restrictions as it is a model that is being used for future predictive purposes. Therefore it is important that the model still represents a similar response to what has happened in the past but it is not essential for streamflows to be pin-point accurate.

Keeping this important consideration in mind, the development of the dam site streamflows from Rosentretters Crossing used the following equation which converts the streamflows observed at Rosentretters into equivalent Tinton streamflows.

$$\text{Scaling factor} = 1 - \left(\frac{\text{Catchment Area}(\text{Ros}) - \text{Catchment Area}(\text{Tin})}{\text{Catchment Area}(\text{Ros})} \right)$$

Where

$$\text{Catchment Area}(\text{Ros}) = 447 \text{ km}^2$$

$$\text{Catchment Area}(\text{Tin}) = 422 \text{ km}^2$$

$$\text{Scaling factor} = 1 - \left(\frac{447 - 422}{447} \right)$$

$$\text{Scaling factor} = 0.9441$$

Therefore all daily streamflows from 20/8/1986 to 31/12/2015 were appropriately scaled to represent streamflow that occurred at Tinton. The relationships developed in the previous section between Tinton and the dam site were then used to create simulated streamflow at this site.

5.2.3 Extended Streamflow Gap Analysis

With simulated streamflow represented for around 13 years before and 29 years after the recorded streamflow at the dam site, the extended streamflow sequence was nearly completed. To complete this streamflow sequence an analysis had to be performed on the gaps or missing data found throughout the dataset. To identify these gaps in the record, the program River Analysis Package (RAP) was used, and also aided in filling some gaps by using its linear interpolation function. Table 10 below shows the summary of all the missing data gaps and the approach taken to fill these gaps.

Table 10: Missing Data Gaps Summary

Gap Date	Gap Length (days)	How Gap Was Filled
7/08/1979 – 12/10/1979	67	- From 7/08/1979 to 27/08/1979, streamflows linear interpolated from 6.24 to 0. - Streamflow of 0 given from 27/08/1979 to 4/10/1979 - Streamflow peak on 5/10/1979 given a value of 30.38 from 24.2 mm rainfall on that day - Gaps in between filled by linear interpolation
29/11/1980 – 7/01/1981	40	- Filled by Tinton relationship
3/08/1981 – 29/10/1981	88	- Filled by linear interpolation
18/01/1982 – 11/02/1982	25	- Streamflow peak on 20/01/1982 given a value of 1678.95 from 102.0 mm rainfall on that day - Rest of gaps filled by linear interpolation

25/3/1982 – 1/04/1982	8	- Streamflow peak on 31/03/1982 given a value of 278.25 based on 41.2 mm rainfall on that day - Gaps in between filled by linear interpolation
13/01/1983 – 4/02/1983	23	- Filled by linear interpolation as rainfall over gap period was 3 mm
9/05/1983 – 17/05/1983	9	- Filled by linear interpolation as rainfall over gap period was 0 mm
13/10/1983 – 3/11/1983	22	- Streamflow peak on 14/10/1983 given a value of 11.883 from 15.6 mm rainfall on that day - Streamflow peak on 21/10/1983 given a value of 7.45 from 8.0 mm rainfall on that day - Streamflow peak on 26/10/1983 given a value of 137.05 from 56.0 mm rainfall on that day - Filled by linear interpolation for the other days
30/12/1983 – 18/01/1984	20	- Streamflow peak on 17/01/1984 given a value of 65.65 from 46.2 mm rainfall on that day - Filled by linear interpolation for the other days
22/07/1985 – 13/08/1985	23	- A streamflow of 0 given on 13/08/1985 and the rest of the gap filled by linear interpolation
4/10/1985 – 15/10/1985	12	- Streamflows of zero given from 4/10/1985 to 12/10/1985 - Streamflow peak on 13/10/1985 given a value of 63.476 from 32.0 mm rainfall on that day - Gaps in between filled by linear interpolation
9/4/1986 – 20/08/1986	134	- Streamflow peak on 02/05/1986 given a value of 50.734 from 52.6 mm rainfall on that day - Streamflow peak on 10/05/1986 given a value of 31.22 from 41 mm rainfall on that day and returns to zero on 31/5/1986 - Streamflow peak on 03/07/1986 given a value of 1.12 from 5.0 mm rainfall on that day and returns to zero on 06/07/1986 - Streamflow peak on 17/07/1986 given a value of 2.65 from 7.0 mm rainfall on that day and returns to zero on 21/07/1986 - Streamflow peak on 04/08/1986 given a value of 2.70 from 8.4 mm rainfall on that day and returns to zero on 08/08/1986 - Gaps in between filled by linear interpolation
12/12/1991 – 15/01/1992	35	- Streamflow peak on 12/12/1991 given a value of 42.172 from 66.0 mm rainfall on that day - Streamflow peak on 01/01/1992 given a value of 33.738 from 46.0 mm rainfall on that day - Streamflow peak on 08/01/1992 given a value of 31.629 from 42.0 mm rainfall on that day - Rest of gaps filled by linear interpolation
14/01/1999 – 09/02/1999	27	- Streamflow on 08/02/1999 given a value of 798.875 from 65.2 mm rainfall on that day - Streamflow peak on 09/02/1999 given a value of 2794.4 from 156.0 mm rainfall on that day - Filled by linear interpolation for the other days

5.3 Water Management Scenarios

With the completion of the extended streamflow dataset, the water balance model was then used to describe the water storage behaviour of Cressbrook Dam from 1952 to the end of 2015 using the three different water management scenarios. A reminder of the three different scenarios that were investigated using this extended streamflow sequence are:

1. Normal water restrictions that are currently used by the TRC
2. Restrictions raised to level 2 from December to March when SOI phase is observed to be consistently positive
3. Restrictions raised by one level from December to March when SOI phase is observed to be consistently positive

By utilising the decision-trees discussed in the methodology section, the water balance model was modified so that the decision each day was based off the current time period, the current SOI phase and the current water restriction it is on, and adjusted the water restriction according to which water management scenario was being put into place. The result of running the water balance model with three different scenarios shows the following figure which has three different dam storage levels over time.

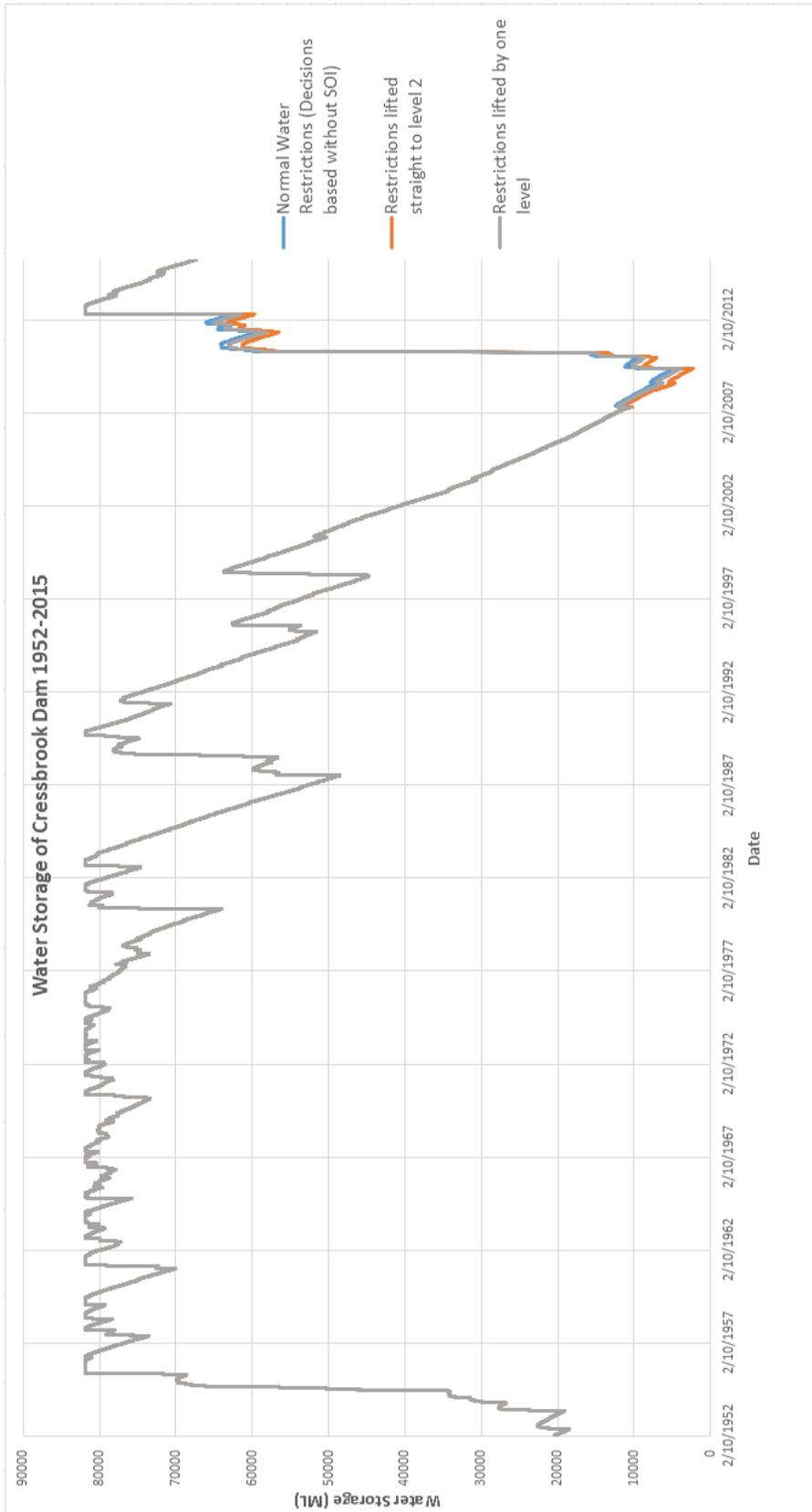


Figure 23: Water Storage of Cressbrook Dam 1952-2015 with Three Different Water Management Strategies

From this timeseries it is seen that the model was started at a volume of 25% of the storage capacity or 20460.5 ML. The starting volume of the dam ultimately did not matter because the dam quickly rose to full capacity just after the model started and had no effect on the different scenarios. For the first approximately 50 years of the model, the dam remains relatively close to its full capacity of 81842 ML. When the date reaches around the year 2000, the behaviour of the dam storage shows a sharp decline in the dam's volume. This behaviour would be expected throughout this time period, as it has been discussed that the years from 2000 to 2010 were part of a major drought for the city of Toowoomba. It is also seen that the dam is significantly raised from the January 2011 floods back up to near full capacity. Therefore the dam's broad responses to historical wet and dry periods means that the model has some validity behind its results (cannot be fully validated as the model is not a historical representation).

This therefore means that the different scenario strategies did not need to be used for the first 50 or so years as water restrictions remained on the lowest level possible, resulting one timeseries line instead of three separate lines. However during the period of extreme drought, it is shown from Figure 23 that there is a change in dam storage behaviour and that the scenarios play a role in doing so. In order to get a clearer understanding of what happened in the drought period, figure 24 shows a zoomed in plot of the water storage behaviour of the dam from the start of 2006 to the end of 2015.

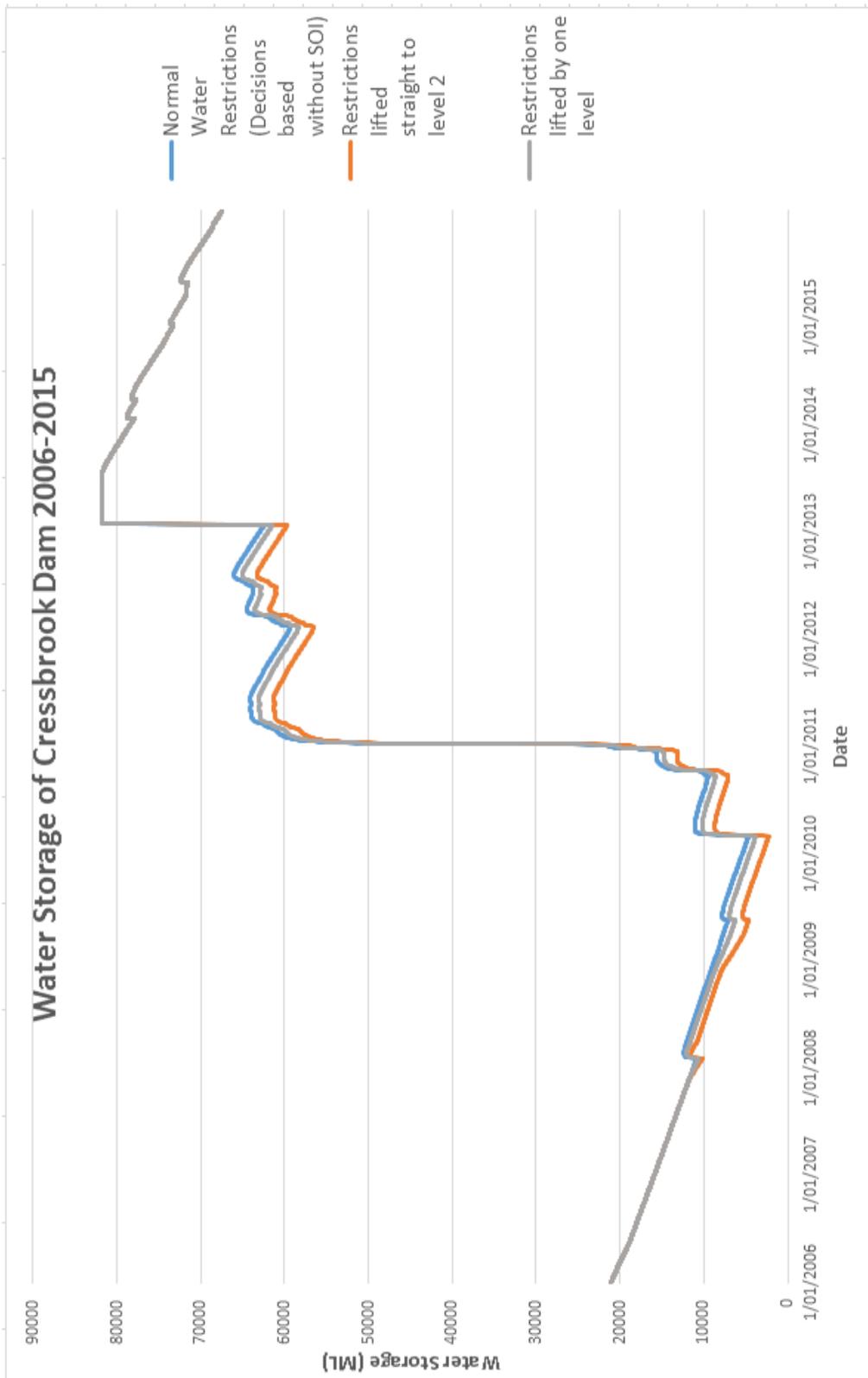


Figure 24: Water Storage of Cressbrook Dam 2006-2015 with Three Different Water Management Strategies

5.4 Discussion of Key Results

Figure 24 indicates that the three different scenarios did in fact have an influential role in changing the behaviour of the water storage level of Cressbrook Dam. The first time that a SOI phase of 2 (consistently positive) is viewed in November and the water restrictions levels are not on level 2 is in November 2007. Therefore from the start of December 2007 to the end of March 2008, restrictions were lifted from the existing water restriction at that time (level 5) to level 2 water restriction for scenario 2 (orange line) and level 4 water restrictions for scenario 3 (grey line). This resulted in the dam level being separated into three different timeseries lines with the scenario 1 (blue) decreasing at the highest dam level volume, scenario 2 (grey) decreasing at the lowest dam level volume and scenario 3 (orange) decreasing at the second lowest dam level volume.

The fact that the dam level showed a continual decrease in volume in the period of December 2007 to March 2008 indicates that although the phase in November was observed to be phase 2 (consistently positive), an insufficient amount of streamflow occurred during this period. This is contrary to the findings from the cumulative probability distribution graphs, which suggested that there was a 100% chance that a phase 2 in November would lead to around 10000 ML of streamflow and the dam volume would increase by around 7000 ML. Because of this reason, the relaxing of restrictions during this time period resulted in scenario 2 and 3 dropping the dam volume lower than it would have been if normal water restrictions were applied (scenario 1).

The next period where SOI phases were applied to determining the water restrictions was the following year from December 2008 to March 2009 based off a SOI phase 2 observed in November 2008. The consequences of raising restrictions from level 5 at that time to either level 2 (scenario 2) or level 4 (scenario 3) resulted in the same trend as identified previously. The dam

volume continued to drop, which is contrary to results found previously. Although the raising of restrictions in these four months would ease the Toowoomba community from harsh level 5 water restrictions, it has also resulted in worsening the dam's capacity to critically low volumes.

The last season that was influenced by the presence of a phase 2 in November was in the period of December 2010 to March 2011. During this period it was observed that a huge inflow of streamflow occurred which finally meant that the cumulative probability distribution graphs made a correct prediction. The amount of streamflow that was received by Cressbrook Dam in this time period was 50543.6 ML. Using Figure 15, this suggests that a streamflow total of this magnitude equates to a probability chance of less than 10%. During this period, the dam level was raised from a volume of 13166.2 ML at the start of December to an end volume of 60896.9 ML, therefore meaning that the dam increased in volume by 47730.7 ML over the period from December to March. This closely correlates to the response seen in Figure 19 for an SOI phase of 2 in November which suggests that the dam volume at the end of March reaches a value of around 60000 ML using a low chance probability. Therefore the key results from this successful prediction suggests that usage of SOI phases in water management strategies successfully relieved the residents of the region from 42 days of level 5 water restrictions in advance before restrictions were lifted back to level 2.

Overall the model of Cressbrook Dam from 1952 to 2016, identified that three seasons could be modified due to the knowledge of the SOI phase observed in November. This resulted in changing the water restrictions and water demand for 364 out of 23101 days in the whole modelling period. Although this sounds like an insignificant number of days, the 364 days were changed within a major drought in Toowoomba's history. Therefore the decisions made in this crucial time period would have had a significant impact on the residents of the region. To truly investigate the effects that these water management strategies had on the storage of the dam and the residents of

Toowoomba, Table 11 shows tabulates the key results from figures 21 and 22.

Table 11: Key Results from Water Management Analysis

Scenarios	Lowest Dam Level Percentage Reached (%)	Total Water Drafted in Critical Period (2006-2015) (ML)	Total No. of Days on Level 2 (1952-2015)	Total No. of Days on Level 3 (1952-2015)	Total No. of Days on Level 4 (1952-2015)	Total No. of Days on Level 5 (1952-2015)
Scenario 1 - Normal Restrictions	5.76	55885.95	19450	567	985	2099
Scenario 2 - Restrictions lifted to level 2	2.82	58792.2 (+2906.3)	19736 (+286)	568	986	1811 (-288)
Scenario 3 - Restrictions lifted by one level	4.70	56930.9 (+1045.0)	19541	568	1267 (+282)	1815 (-284)

During the critical drought period, it was identified that for both scenario 2 and scenario 3, unexpected responses based off phase 2 SOI's in November resulted in lowering the dam the level on both occasions. This resulted in dropping the dam volume to an extremely low level of 2.82% for scenario 2 and a volume of 4.70% for scenario 3 when compared to the normal water restrictions (scenario 1) which dropped to the lowest level of 5.70%. As a result of lowering the dam level, as expected the total water drafted from the dam during the period of 2006-2015 for scenario 2 and scenario 3 increased by volumes of 2906.3 ML and 1045.0 ML respectively.

Looking at the implications that the different scenarios had on the residents of the region, for scenario 2 it was identified that 288 days throughout the modelling period were removed from harsh level 5 water restrictions and that 286 days were added onto level 2 restrictions. For scenario 3 as expected, the number of days on level 5 water restrictions was dropped by 284 days and 282 days were added to level 4 water restrictions.

Overall the implementation of water restrictions based the SOI phase observed in November resulted in both positive and negative outcomes. The positive outcomes of implementing the SOI phases into the decision-making of future forecasts were that it was able to provide relief to the residents of the region during a critically dry period in time. As discussed the use of SOI phases for forecasting was also able to predict that restrictions could be relaxed from level 5 to level 2, 42 days in advance before the dam filled back up to near full capacity. The negative outcomes of incorporating SOI phases into decision-making were that unexpected responses that fell outside the range of climate variability investigated in SOI-streamflow relationships resulted in the dam level dropping in two of out the three seasons affected. This therefore resulted in the management strategies drafting more water and lowering the dam level to a critically low volume.

The reason as to why the alternative water management strategies resulted in the dam level dropping further was due to the lack of streamflow data in the formation of the cumulative probability distribution graphs. For the period in which the cumulative probability distribution graphs were developed, the accuracy would actually be quite high. However as these graphs were formed off only the 16 years of recorded streamflow data, it could not account for the climate variability that occurred outside this time period. For example if the seasons of 2008 and 2009 were added to the end of season storage level cumulative probability distribution graphs, then the SOI Phase 2 line would be significantly altered so that at 100% probability, the first point would be located in a position similar to the other four phases.

The most important outcome from this work was that the incorporation of SOI phases into future forecasting and decision-making resulted in accurately predicted that a substantial increase in the dam level would occur during the period of December 2010 to March 2011. This was proven to be true with substantial rainfall events occurring in Toowoomba throughout the summer months, especially the 2011 January floods. As claimed by the Toowoomba Regional Council (2016), the actual lowest water level that Cressbrook Dam got to was 7.5% which is around 2% higher than the modelled scenario using normal water restrictions. This would have been due to the use of water bores and the other dams being utilised more than Cressbrook Dam which would have been conserved the most. Therefore taking into consideration the usage of Toowoomba's other water supply systems, the decision to relax restrictions from level 5 to level 2 (scenario 2) or from level 5 to level 4 (scenario 3) could may have truly been implemented, which would have relieved the residents of the region 42 days in advance before the dam was filled back up to near full capacity.

CHAPTER 6 CONCLUSION AND FUTURE WORK

6.1 Introduction

The main aim of this research project was to create a water balance model that can accurately predict likely increases and shortfalls in water availability for Cressbrook Dam using an appropriate climate indicator. Therefore this investigation included an in depth literature review on the main climate drivers of Australia, which was used in order to identify which driver had the most influence over the streamflows of Cressbrook Creek. After this identification, the best relationship timeframe was identified between best climate index and streamflow as well as the best forecasting period. A water balance model was then used to describe the water storage behaviour of Cressbrook Dam using a number of different inputs and outputs. The incorporation of best climate driver and streamflow relationship with the water balance model resulted in the creation of a number of different cumulative probability distribution graphs according to the starting volume of the dam. Lastly the findings from the cumulative probability distribution graphs were used to create three different water management scenarios that were run through the water balance model with an extended streamflow sequence.

6.2 Achievements

After a thorough investigation of all climate drivers that effect Australia, the literature review identified the climate driver of ENSO to be the most influential index that would affect the streamflow of Cressbrook Creek. ENSO is quantified by the value of SOI and this value was used to develop relationships between itself and monthly streamflow totals. Using linear relationship between the two, the months of December, January, February and March were identified as the months that showed the best correlation. Therefore these months were combined together to investigate SOI against

seasonal streamflow totals and identified that the best forecasts of streamflow could be made one month in advance. Therefore with the knowledge that streamflows for the period from December to March can be made from the observed SOI phase in November cumulative probability distribution graphs were created in relation to streamflow totals and the dam level behaviour. Both type of distributions graphs clearly indicated that a phase 2 (consistently positive SOI) observed in November suggested a substantial streamflow total and a substantial raise in the dam's water level.

Applying the results from the SOI-streamflow relationships, three alternative water management strategies were used to see how the incorporation of SOI affected the decisions of water demands and restrictions. The three different scenarios were normal water restrictions, raising water restrictions straight to level 2 if the SOI phase was observed to be 2, and raising water restrictions by one level if the SOI phase was observed to be 2. These three scenarios were run through the water balance model with an extended streamflow sequence (validated to be within 5% error of the actual dam site streamflows) from 1952 to the end of 2015. The result of running this model with scenarios which base water restrictions off SOI phases, ended with three different seasons (2007, 2008 and 2010) or 364 days being affected.

The consequence of raising restrictions in the 2007 and 2008 periods resulted in dropping the dam volume below what it would have if normal water restrictions were in place. The raising of restrictions in 2010 however was beneficial for the community as it resulted in an earlier relief from the harsh level 5 water restrictions that would have been in place. It also proved to be correct in its prediction that the dam level would significantly be raised in this time period and therefore raised restrictions in advance by 42 days. Therefore it can be said that the use of these water allocation tools throughout the report was able to predict with some accuracy the likely increases in water availability (even with a limited range of climate variability) but was not able to predict the likely shortfalls in water availability.

6.3 Recommendations and Future Work

The verification of raising restrictions if the SOI phase in November was observed to be 2 (consistently positive) ended in two of the three seasons going against what was suggested by the cumulative probability distribution graphs. Due to the unavailability of streamflow data the cumulative probability distribution graphs were not able to account for a wide range of climate variability and this affected the outcomes of the water management strategies. Therefore future work may look obtaining more streamflow data to incorporate a wider range of climate variability in the cumulative probability distribution graphs for Cressbrook Creek.

The two alternative water management scenarios identified that there was always the chance that predictions based off SOI phases can be wrong, and this resulted in dropping the dam level storage to a further extent during a critically dry period in time. Due to this situation occurring, it is recommended that decisions based off SOI phases should not be used when current operations are on already of the highest water level restriction (level 5).

Due to the short range of climate variability in the development of the cumulative probability distribution graphs, there were no other SOI phases that showed a significant trend that could be used to justify the proposal to tighten water restrictions in advancement to the indication of a significant drought period ahead. Therefore future work could also investigate how SOI phases can be used to justify decisions which tighten water restrictions at earlier time periods.

CHAPTER 7 REFERENCES

Australian Transaction Reports and Analysis Centre 2006, *Risk Management*, viewed 25 October 2015

<http://www.austrac.gov.au/sites/default/files/documents/risk_management_tool.pdf>

Baillie, J & Brodie, I 2011, *Review of dynamic water allocation systems*, In: SEAg 2011: Diverse Challenges, Innovative Solutions, 29-30 Sep 2011, Gold Coast, Australia

Boyd, M 2012, *Toowoomba 2011 – From Drought to Flood*, Toowoomba Regional Council (TRC), viewed 26 October 2015

<http://www.wioa.org.au/conference_papers/2012_nsw/documents/Marcus_Boyd.pdf>

Boyd, M 2014, *Toowoomba Wastewater Infrastructure Project (TWIP)*, Toowoomba Regional Council (TRC), viewed 3 August 2016

Brodie, I 2015, *ENV3105 Hydrology: course notes*, University of Southern Queensland, Toowoomba

Bureau of Meteorology (BOM) 2005, *El Nino, La Nina and Australia's Climate*, viewed 29 October 2015

<<http://www.bom.gov.au/info/leaflets/nino-nina.pdf>>

Bureau of Meteorology (BOM) 2013, *Climate Data Online*, viewed 29 October 2015

<<http://www.bom.gov.au/climate/data/index.shtml>>

Bureau of Meteorology (BOM) 2016, *Daily Rainfall*, Cressbrook Dam, Climate Data Online, viewed 20 May 2016

<[http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136
&p_display_type=dailyDataFile&p_stn_num=040808&p_startYear](http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_stn_num=040808&p_startYear)>

Bureau of Meteorology (BOM) 2016, *ENSO Wrap-Up*, viewed 27 April 2016

<<http://www.bom.gov.au/climate/enso/index.shtml?link=1>>

Bureau of Meteorology (BOM) n.d., *Tropical Cyclones in Queensland*, viewed 19 April 2016.

<<http://www.bom.gov.au/cyclone/about/eastern.shtml>>

Cai, W, Van Rensch, P, Cowan, T & Hendon, HH, 2011, *Teleconnection pathways of ENSO and the IOD and the mechanisms for impacts on Australian rainfall*, *Journal of Climate*, 24(15), pp. 3910-3923.

Chiew, F & McMahon, T 2002, *Global ENSO-streamflow teleconnection, streamflow forecasting and interannual variability*, *Hydrological Sciences Journal*, 47(3), pp. 505-522.

Chiew, F, Piechota, T, Dracup, J, & McMahon, T 1998, *El Nino/Southern Oscillation and Australian rainfall, streamflow and drought: Links and potential for forecasting*, *Journal of Hydrology*, 204(1-4), pp. 138-149.

Everingham, Y, Baillie, C, Inman-Bamber, G & Baillie, J 2008, *Forecasting water allocations for Bundaberg sugarcane farmers*, *Climate Research*, 36(3), pp. 231-239.

Graph Pad Software n.d., *R squared*, viewed 5 September 2016

<http://www.graphpad.com/guides/prism/6/curvefitting/index.htm?reg_diagnosics_tab_7_2.htm>

Griffin, R & Mjelde, J, 2000, *Valuing water supply reliability*, *American Journal of Agricultural Economics*, 82(2), pp.414-426.

Hendon, HH, Thompson, DW & Wheeler, MC, 2007, *Australian rainfall and surface temperature variations associated with the Southern Hemisphere annular mode*, *Journal of Climate*, 20(11), pp. 2452-2467.

Hurlimann, A & Dolnicar, S 2010, *When Public Opposition Defeats Alternative Water Projects - the Case of Toowoomba*, Australia, *Water Research*, 44 (1), pp 287-297.

Klingaman, NP, 2012, *A literature survey of key rainfall drivers in Queensland, Australia: Rainfall variability and change*, QCCCE Research Report, Rainfall in Queensland, Part 1, Department of Environmental and Resource Management, Queensland Government, Brisbane, Australia, viewed 17 April 2016

<<https://www.longpaddock.qld.gov.au/about/publications/pdf/walker-report-part-1.pdf>>

Klingaman, NP, 2012, *Empirical orthogonal teleconnection analysis of interannual-variability in Queensland rainfall*, QCCCE Research Report, Rainfall in Queensland, Part 3, Department of Environment and Resource Management, Queensland Government, Brisbane, Australia, viewed 17 April 2016

<<https://www.longpaddock.qld.gov.au/about/publications/pdf/walker-report-part-3.pdf>>

Linsley, R & Franzini, J 1964, *Water-Resources Engineering*, McGraw Hill Inc., Sydney

Lough, A 2008, *Hydrology: an Australian introduction*, Oxford University Press, Melbourne, Victoria, pp. 291-296.

Lough, JM, 1991, *Rainfall variations in Queensland, Australia: 1891–1986*, *International Journal of Climatology*, 11(7), pp. 745-768.

McBride, JL & Nicholls, N, 1983, *Seasonal relationships between Australian rainfall and the Southern Oscillation*, Monthly Weather Review, *111*(10), pp. 1998-2004.

McJannet, DL, Cook, FJ & Burn, S 2013, *Comparison of techniques for estimating evaporation from an irrigation water storage*, Water Resources Research, *49*(3), pp. 1415-1428

Meneghini, B, Simmonds, I & Smith, IN, 2007, *Association between Australian rainfall and the southern annular mode*, International Journal of Climatology, *27*(1), pp. 109-121.

Brodie, I 2015, Study book notes, ENV3105, University of Southern Queensland, Toowoomba, viewed 10 May 2016

<<http://usqstudydesk.usq.edu.au>>

Office of Economic and Statistical Research, 2009, *Queensland Past and Present: 100 Years of Statistics, 1896–1996*, Queensland Government, *2*(2), pp. 29-51.

Pepler, A, Coutts-Smith, A & Timbal, B, 2014, *The role of East Coast Lows on rainfall patterns and inter-annual variability across the East Coast of Australia*, International Journal of Climatology, *34*(4), pp. 1011-1021.

Power, S, Casey, T, Folland, C, Colman, A & Mehta, V, 1999, *Inter-decadal modulation of the impact of ENSO on Australia*, Climate Dynamics, *15*(5), pp. 319-324.

Queensland Government 2008, *Reach 6b Flow Derivation Report 143000.PR/73*, Department of Natural Resources and Water (DNRM), viewed 25 July 2016

Queensland Government 2014, *Moreton Resource Operations Plan*, Department of Natural Resources and Mines (DNRM), viewed 3 August 2016

Risbey, JS, Pook, MJ, McIntosh, PC, Wheeler, MC & Hendon, HH, 2009, *On the remote drivers of rainfall variability in Australia*, Monthly Weather Review, 137(10), pp. 3233-3253.

Salinger, MJ, Renwick, JA, & Mullan, AB, 2001, *Interdecadal Pacific oscillation and south Pacific climate*, International Journal of Climatology, 21(14), pp. 1705-1721.

Stone, RC 2011, *Principles of short and medium term climate forecasting - what's driving our climate and how accurate have Northern Grains Region forecasts been in the last decade*, GRDC Advisor Updates, Goondiwindi, (11).

Stone, RC, Hammer, GL & Marcussen, T 1996, *Prediction of global rainfall probabilities using phases of the Southern Oscillation Index*. Nature, 384 (6606). pp. 252-255.

Taschetto, AS, Sen Gupta, A, Hendon, HH, Ummenhofer, CC & England, MH, 2011, *The contribution of Indian Ocean sea surface temperature anomalies on Australian summer rainfall during El Niño events*, Journal of Climate, 24(14), pp. 3734-3747.

Toowoomba City Council (TCC) 2006, *Water Futures*, viewed 8 August 2016

Toowoomba Regional Council 2016, *Toowoomba Region Water Supply – Dams and Bores*, viewed 27 October 2015

<<http://www.tr.qld.gov.au/environment-water-waste/water-supply-dams/dams-bores/788-toowoombas-dams>>

Verdon, DC, Wyatt, AM, Kiem, AS & Franks, SW, 2004, *Multidecadal variability of rainfall and streamflow: Eastern Australia*, Water Resources Research, 40(10).

Victorian Government Department of Sustainability and Environment 2011, *Guidelines for the Development of a Water Supply Demand Strategy*, viewed 28 August 2016

Wheeler, MC, Hendon, HH, Cleland, S, Meinke, H & Donald, A, 2009, *Impacts of the Madden-Julian oscillation on Australian rainfall and circulation*, *Journal of Climate*, 22(6), pp. 1482-1498.

Wong, W 1999, *Introduction to Hydrology*, Customer Service Managers Workshop 1999, State Water Projects, Brisbane.

Zhang, C, 2005, *Madden-Julian oscillation*, *Reviews of Geophysics*, 43(2).

Zhang, C, 2013, *Madden-Julian oscillation: Bridging weather and climate*, *Bulletin of the American Meteorological Society*, 94(12), pp. 1849-1870.

CHAPTER 8 APPENDICES

APPENDIX A – PROJECT SPECIFICATION

Appendix A

ENG4111/4112 Research Project

Project Specification

For: Daniel Verrall

Title: Modelling water allocation increases using climate predictions

Major: Civil Engineering

Supervisors: Justine Baillie

Enrolment: ENG4111 – ONC S1, 2016
ENG4112 – ONC S2, 2016

Project Aim: To provide a functioning water allocation model that can predict with short-term accuracy the likely increases and shortfalls in water availability for Cressbrook Dam using an appropriate climate indicator.

Programme: Issue A, 16th March 2016

1. Research the relationship between streamflow data and climate predictions and choose the most accurate climate index
2. Gather the important input data – including streamflow data, ENSO climate phases for the water allocation model
3. Gather the important information describing the water demand and water usage for the output of the water allocation model
4. Generating the water allocation model with all known data, conditions and boundaries
5. Validating that the model is correct with all formulation and equations and that the results are accurate and reliable
6. Applying the working model to different water seasons according to the appropriate ENSO situations
7. Comparing the results between different seasons and plotting ENSO relationships between climate conditions and the percentage chance that this water allocation will be given:

If time and resources permit:

8. Applying a number of different scenarios that can help assist for management strategies

APPENDIX C – MONTHLY STREAMFLOW AND SOI RELATIONSHIPS

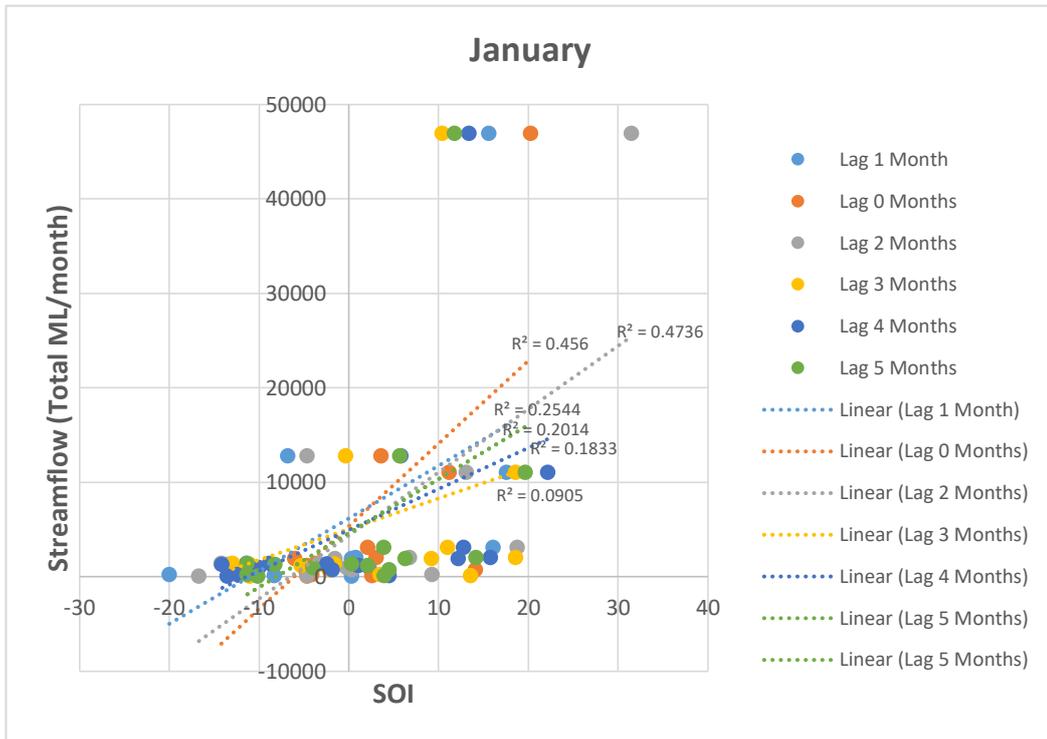


Figure 25: SOI and Streamflow Relationship for January

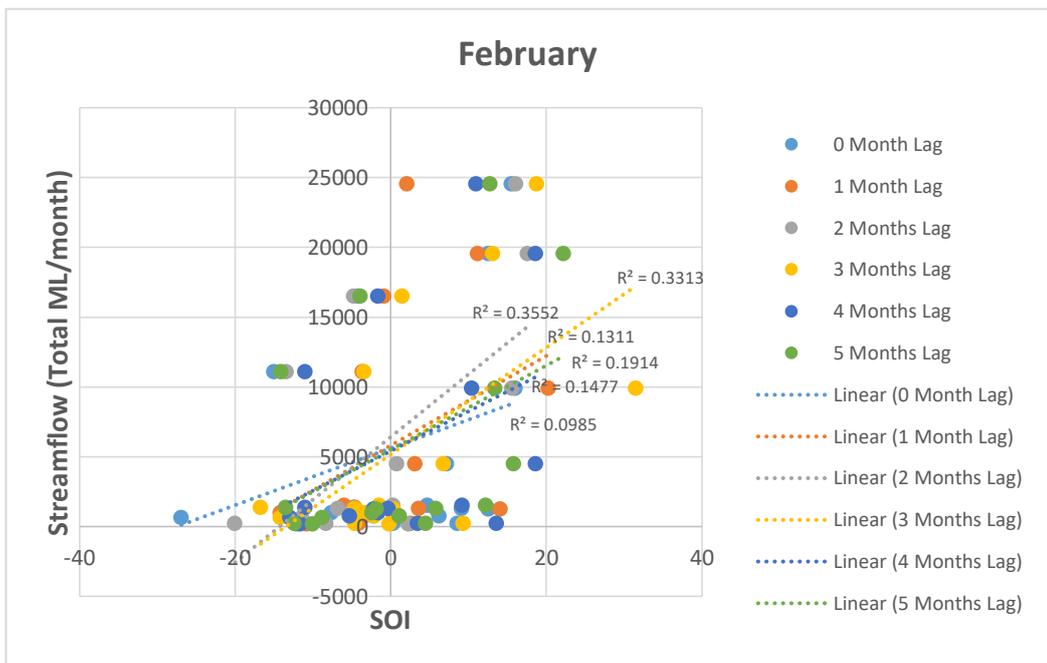


Figure 26: SOI and Streamflow Relationship for February

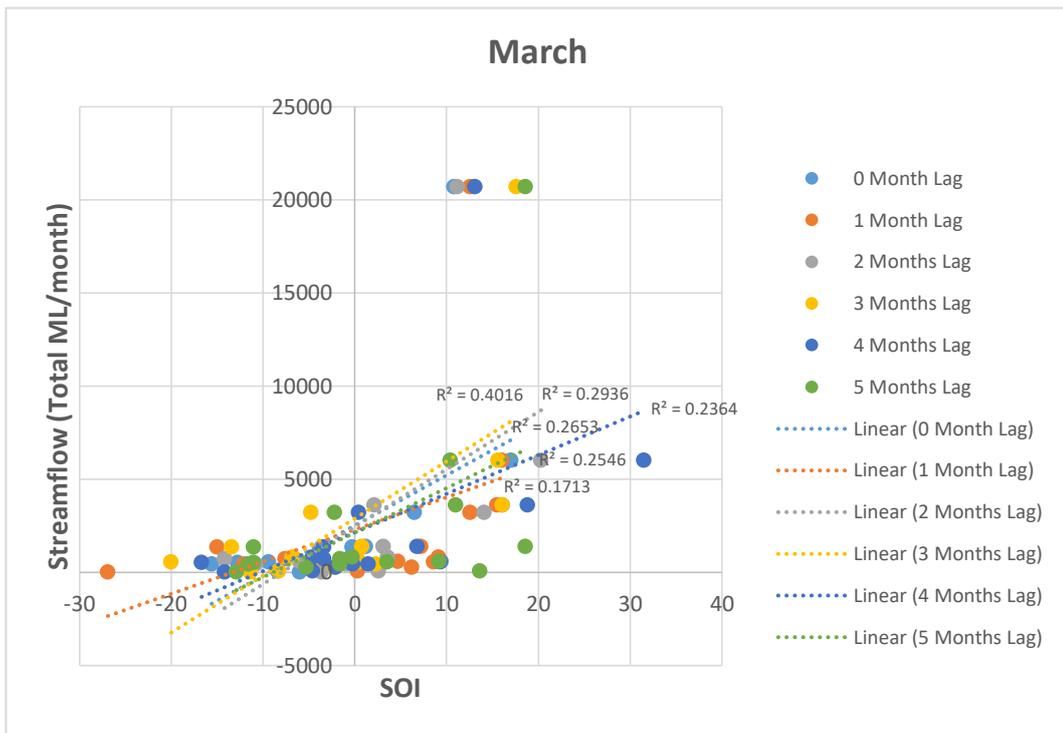


Figure 27: SOI and Streamflow Relationship for March

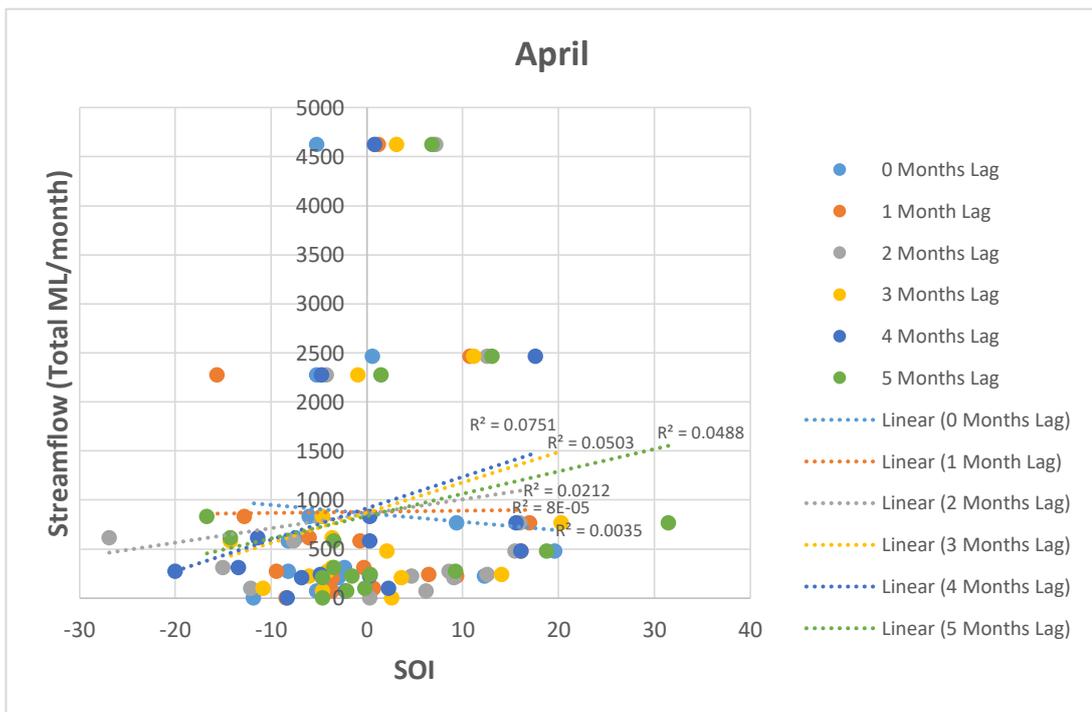


Figure 28: SOI and Streamflow Relationship for April

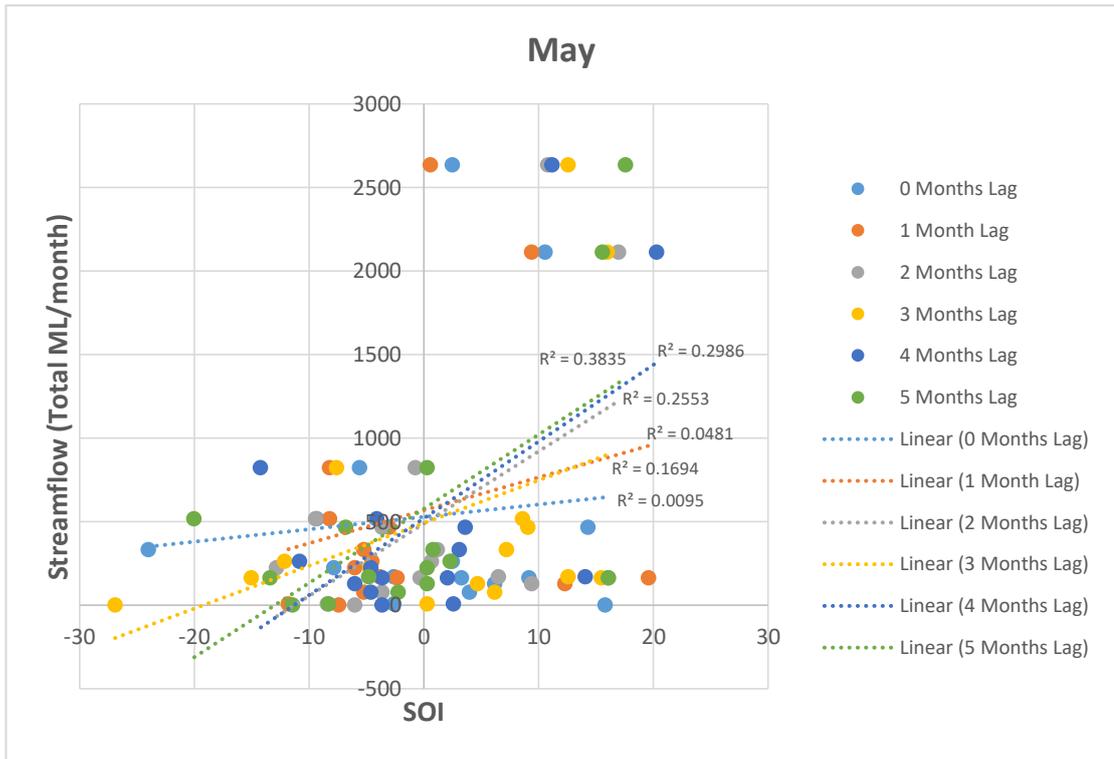


Figure 29: SOI and Streamflow Relationship for May

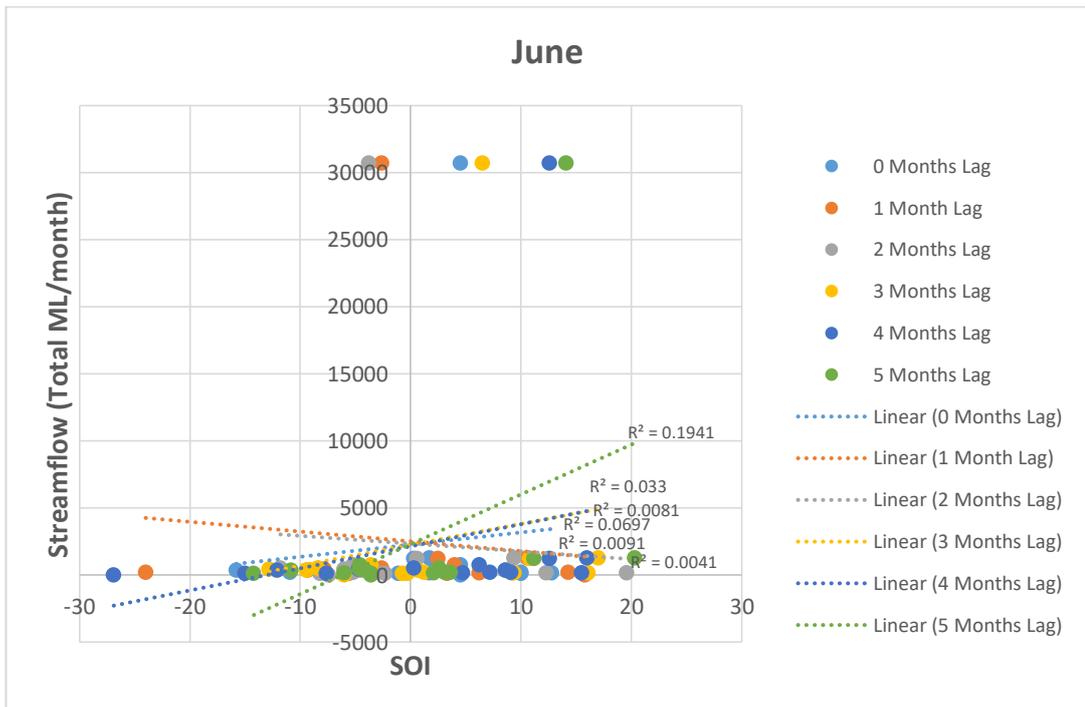


Figure 30: SOI and Streamflow Relationship for June

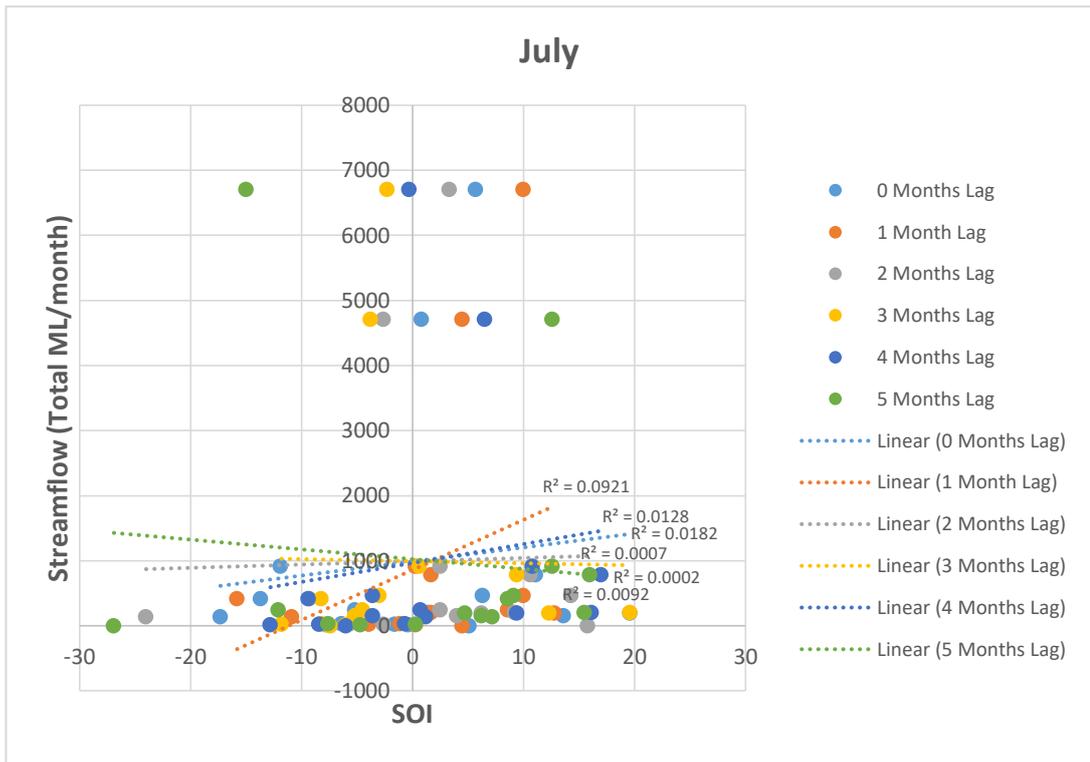


Figure 31: SOI and Streamflow Relationship for July

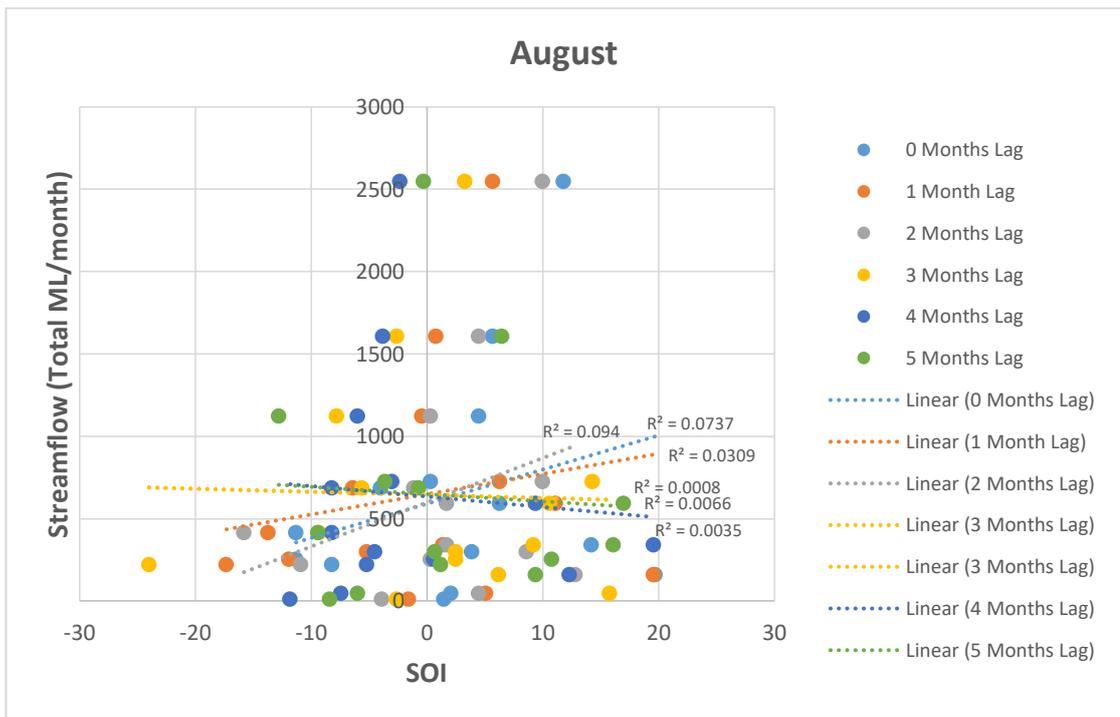


Figure 32: SOI and Streamflow Relationship for August

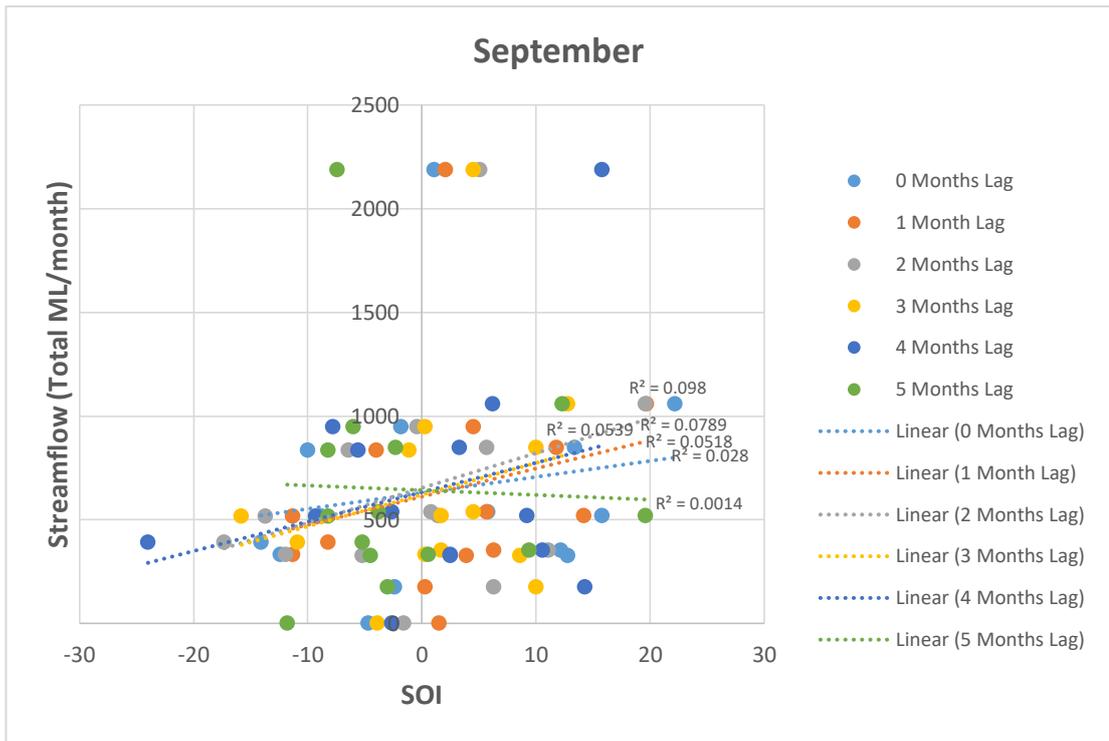


Figure 33: SOI and Streamflow Relationship for September

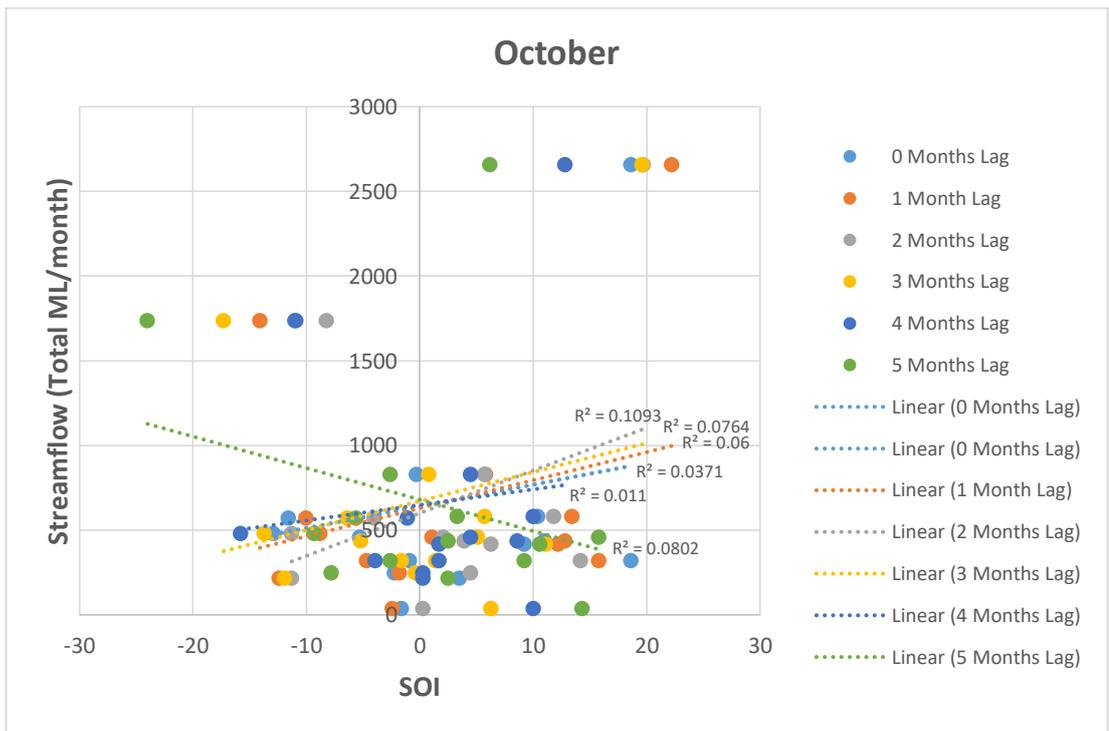


Figure 34: SOI and Streamflow Relationship for October

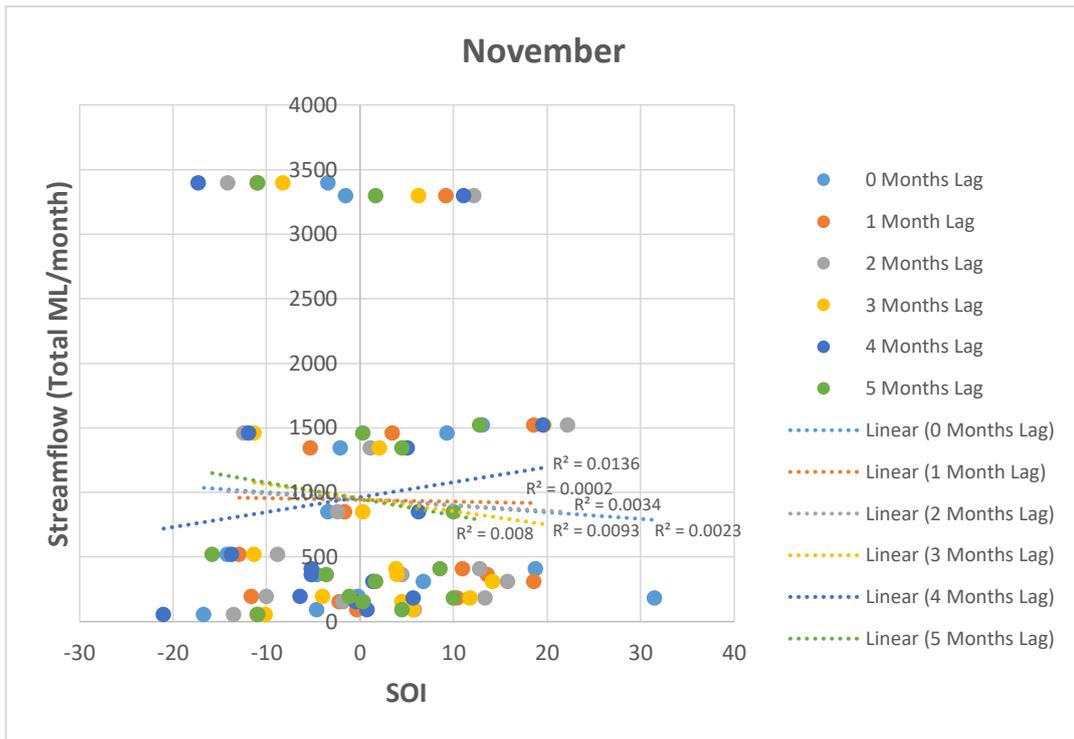


Figure 35: SOI and Streamflow Relationship for November

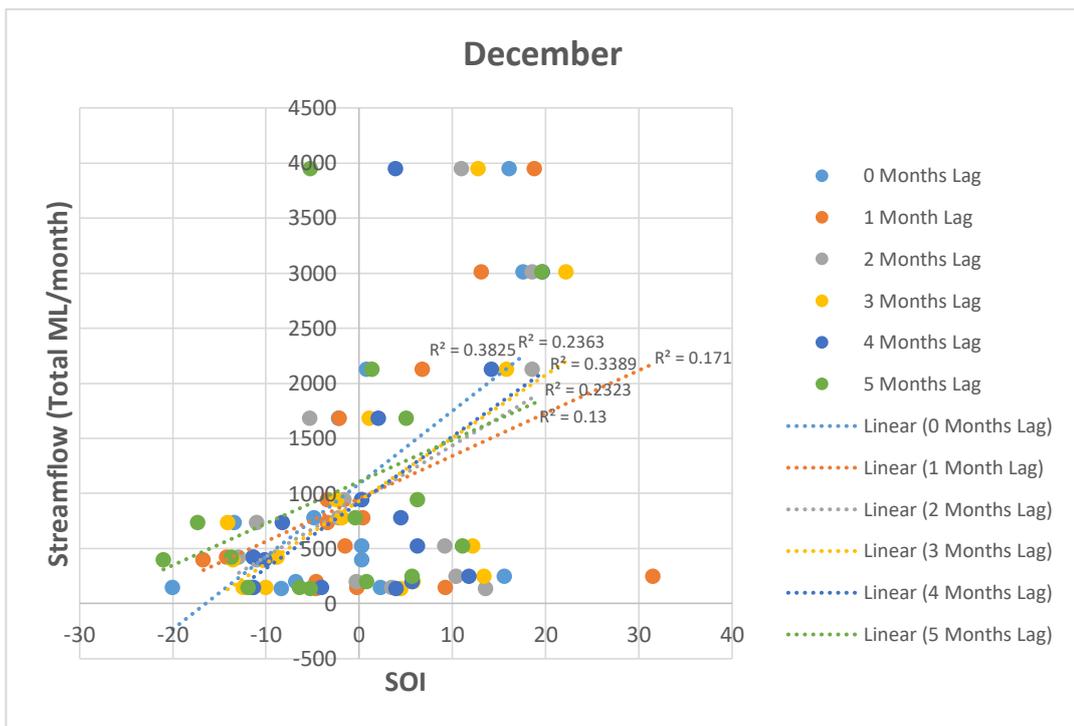


Figure 36: SOI and Streamflow Relationship for December

APPENDIX D – DAM STORAGE RESPONSES WITH VARIOUS STARTING LEVELS

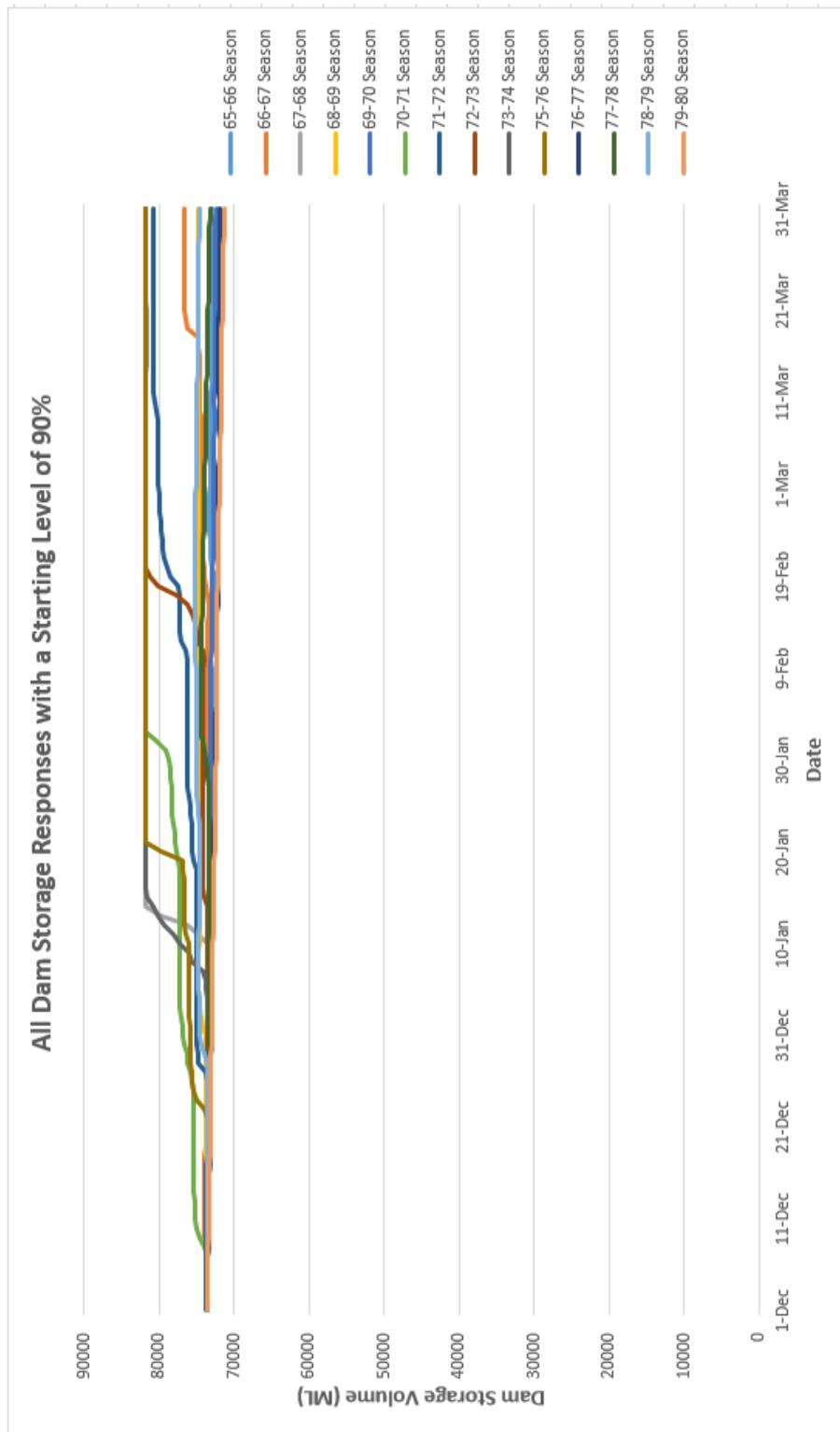


Figure 37: All Dam Storage Responses with a Starting level of 90%

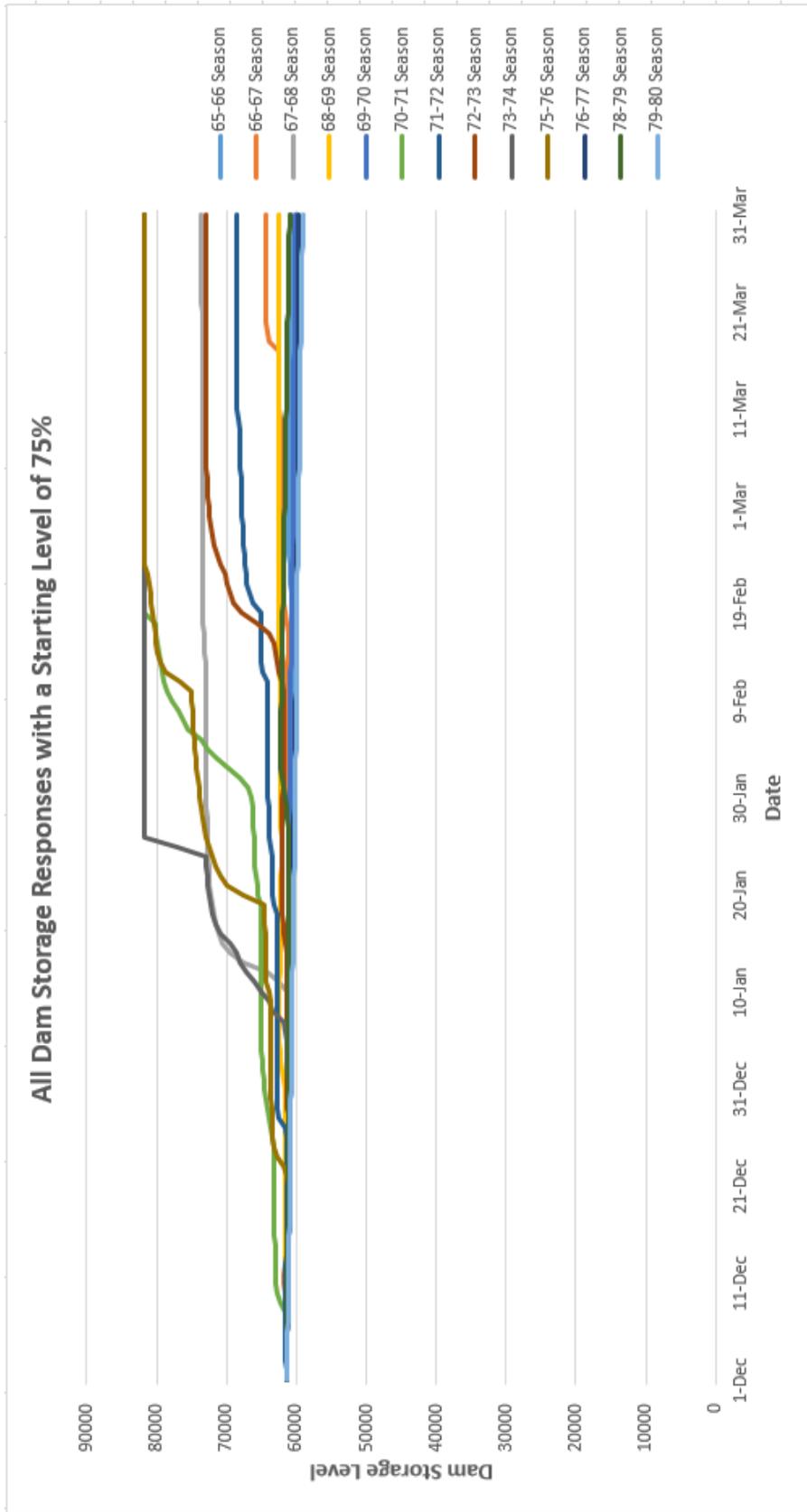


Figure 38: All Dam Storage Responses with a Starting level of 75%

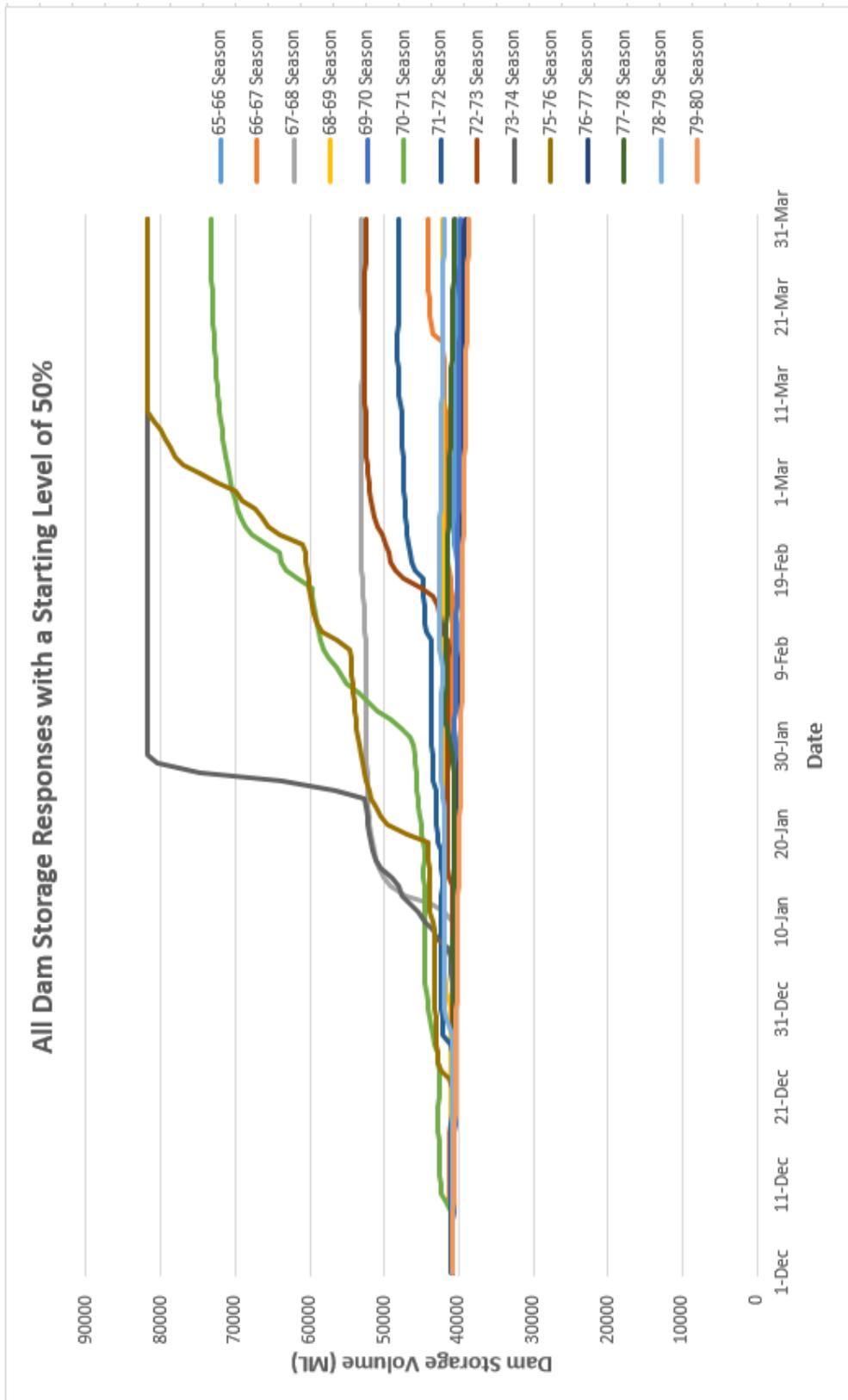


Figure 39: All Dam Storage Responses with a Starting level of 50%

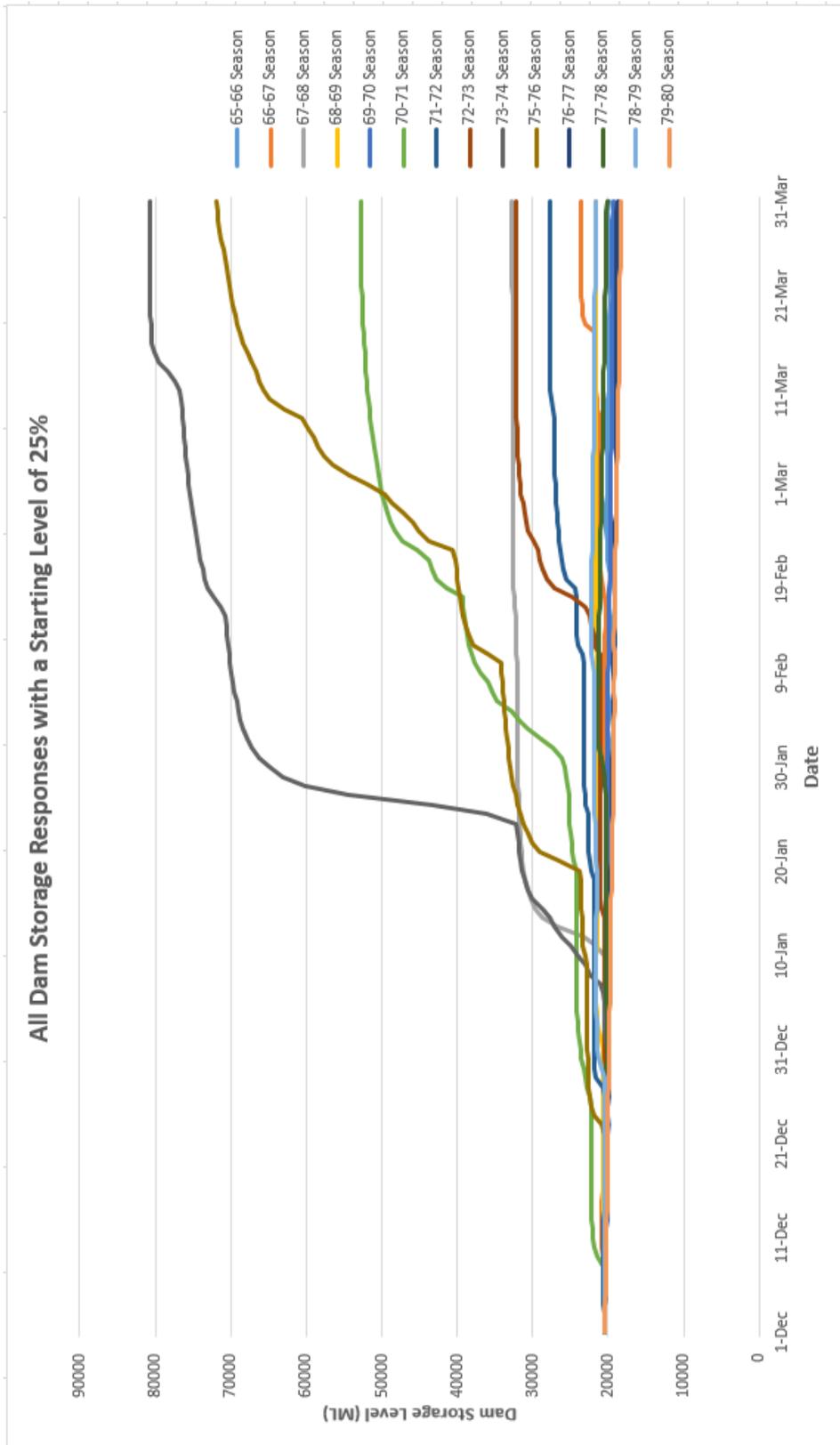


Figure 40: All Dam Storage Responses with a Starting level of 25%