MODELLING THE WATER BALANCE AND HYDROLOGIC DYNAMICS OF A FARM DAM

Imogen Cescato

Master of Environmental Management

College of Humanities, Arts and Social Sciences

Flinders University

Flinders UNIVERSITY

Date of submission of thesis: 4th June 2018

Contents

List of Figures

List of Tables

Summary

This study modelled the components of the water balance of a farm dam in Willunga, South Australia. It is hoped that a small intensive study on a single site would eliminate influences from confounding factors that are present in literature models of farm dam impacts. This is important as understanding the dynamics behind a single dam can be extrapolated into entire catchments, which can be utilised to understand how a network of farm dams influence the hydrologic dynamics of the larger catchment.

A main aim of this study was to identify and gain understanding of the processes that influence the water balance of a farm dam. The main drivers affecting the water balance of the dam identified in this study were rainfall, streamflow, evaporation, transpiration and infiltration. Other factors that were considered but not included in the water balance calculations were overland run-off and overflow from the dam.

Several limitations arose from the processes undertaken in this study. Another aim in this project was to successfully collate data from several sources or several estimation methods into a water balance equation. There were gaps in some essential data such as water levels which presented difficulties in achieving this. Data gaps were overcome by splitting results into periods where the most important data was available and estimating missing parameters; open water evaporation was estimated through atmospheric conditions where pan evaporation data was not available, and water uptake by trees around the dam was estimated through literature values.

Several recommendations for improvements on data collection and processing were made for future research, including the installation of streamflow gauges upstream and downstream of the dam, for quantifiable values on streamflow contributing to the dam, and any flow spilling over the dam in wet months. Developing and utilising a rainfall-run-off model for the sub catchment of the dam would facilitate determining the proportion of inflow coming from streamflow versus overland run-off. Having an evaporation pan properly placed and monitored all year round would provide more accurate estimates of evaporation from the surface of the dam. A more accurate estimate of water uptake from the trees surrounding the dam could be achieved through recording sap flow data. Properly testing the soil found at the bottom of the dam to determine a k-value would yield more

precise estimates of infiltration from the dam. The addition of these processes would improve the overall reliability of the water balance.

It is hoped that a similar study to this could be extrapolated and provide the basis for a model of a larger catchment, which can more dependably deliver estimates of the impacts of farm dams, which in turn can advise decision making on farm dam and water resources management to ensure responsible and equitable allocation of resources to meet individual, industry wide, and environmental needs.

DECLARATION

I certify that this thesis does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Signed...

Date............04/06/2018...

Acknowledgements

First and foremost, I would like to thank my supervisors Okke Batelaan and Margaret Shanafield for their invaluable guidance and expertise working with me on this project. I am extremely grateful for being given the opportunity to work on this project with them, and for their constant patience and guidance. A special thank you must go to Michael Teubner for letting me study the dam on his property, and for always being happy to show me around or offer advice. I would also like to thank Vincent Post and Rob Keane for their assistance with navigating the enormous load of data I dealt with during this study.

A large thankyou goes to my parents, Mark and Mandy, for always offering me love and support with everything I do, and to my sister Mia for her constant encouragement and inspiration. There are far too many supportive friends and colleagues to thank everyone, but special mentions must go out to Carla, Breanne, George, Georgie, Amy and Emily for the endless volumes of support through difficult times as well as their valuable love and encouragement. I am grateful to all of you for helping me through the duration of this project.

1. Introduction and Literature Review

1.1 Introduction

Water is a highly valued natural resource in Australia, and water resources management is a key component of current environmental management discourse. Australia has over 2 million farm dams with an estimated storage of over 8 million ML combined (Land and Water Australia, 2008). Farm dams provide essential sources of water for irrigation schemes for all components of the agricultural industry from livestock farming to viticulture. Many irrigation schemes are reliant on farm dams as their primary source of water, however most use this water storage to allow more flexibility and security in their water management (Government of South Australia, 2011).

Farm dams either intercept water from watercourses or overland flow which would otherwise contribute to the downstream catchment, or in some cases pumps water from surface water or groundwater resources for storage. Removing this water can have adverse effects on both hydrological and ecological processes downstream (Habets et al. 2014). Environmental flow regimes are essential for water dependant ecosystems to function and thrive. Habitats can also be affected by the physical barrier that a farm dam creates.

Neal et al. (2015) assert that there is a large body of anecdotal evidence of the impact of farm dams on stream flows, however few studies provide accurate information on quantifying what these effects are and their magnitude. This is further reinforced by Nathan and Lowe (2012) and Schreider et al. (2002). Furthermore, there is little understanding of the dynamics that affect the water balances of farm dams, and long-term data is difficult to come by. There are often large gaps in data due to inconsistent monitoring and funding constraints. Moreover, it can be difficult to isolate changes caused downstream by farm dams when there are several other factors that may be contributing to changes in the flow regime such as climate change or land use changes (Beavis et al. 1997). This presents a difficulty in isolating changes caused by farm dam development over a whole catchment. Most current literature is orientated around a whole catchment and not individual dams. Determining the water balance of a catchment and farm dams was a limitation and presented several difficulties for many studies outlined in the literature review in the following section (Callow and Smettem, 2009; Habets et al. 2014; Neal et al. 2000). This challenge associated with creating an accurate water balance was mainly due to a lack of accessible data on farm dam capacities, inflows, outflows from spillage or irrigation demands and volumes over time. A lack of meaningful data makes results of catchment wide simulations questionable.

This study will provide an overview of the hydrology of a farm dam in Willunga, specifically determining components of the dam's water balance, to gain quantifiable information on its hydrological patterns. It is hoped that by focusing on a single site and single farm dam that the chances of confounding factors influencing results will be negated. Another aim is to understand further the mechanisms and physical drivers behind the water balance of the dam, which in turn can lead to improved understanding of the catchment as a whole. There are both significant and small gaps in the data available on the dam itself and so several methods will be explored to account for missing or incorrect information. For example, there is no continuous data set for the water levels in the dam, data varies from 2013 to late 2016 with large gaps and several different loggers used for measurements. Overcoming data gaps and comparing data from different sources is a key component to the research in this project, and also generally in this field of study. The aim of this project in particular is to use multiple lines of evidence to illustrate the water balance of the dam and compare and contrast results based on the different data sets and methods used. What factors influence the water balance of the dam will be determined in order to understand the role that the dam plays in its immediate sub-catchment. This can then give an indication of how a network of farm dams influence the hydrological dynamics in their shared catchment. An accurate water balance model of a farm dam would serve to make the results of larger models such as TEDI (Nathan and Lowe, 2000, Neal et al. 2000) more accurate. More accurate results from catchment or state-wide simulations can more accurately inform decision making processes regarding farm dam development and water allocation as water security becomes a more important concern.

1.2 Literature review

This literature review aims to give a thorough review of current and up to date literature regarding the impact of farm dams on water resources and the environment. Firstly, an overview of Farm Dams in Australia will be presented including a review of current policies and legislation regarding to farm dam development and allocation in Australia. Finally, literature on the hydrologic and environmental impacts of farm dams will be reviewed.

1.2.1 Farm Dams in Australia

Rory Nathan and Lisa Lowe stress the importance of farm dams in Australian agriculture in *The Hydrological Impacts of farm Dams,* (2012). Agriculture uses approximately 70% of the Earth's freshwater resources, and within that, irrigation accounts for 66% of water withdrawals (Tingey-Holyoak, 2014). Because of this, agricultural water allocations are a current and relevant issue, especially with stress from the growing population, climate change and water security fears. According to the Food and Agriculture Organization, food production will have to increase by 70% globally to meet the demand for food as global population and wealth increases (Meijer et al. 2013). The needs of agriculture and society need to be balanced with the needs of the environment.

Farm dams are essentially built to store captured run-off or rainfall when it is available for later usage. Such dams can be small, only storing a few megalitres or larger, storing water used for irrigation. Both small and large farm dams can play a vital role in agriculture and can increase productivity and therefore the profit of an agricultural operation (Nathan and Lowe, 2012). Increased productivity of local farmers and agricultural businesses is significant for the local and state-wide economy, as well as social well-being for rural communities. Other, less common purposes of farm dams may include aesthetics, flood control or erosion control (Nathan and Lowe, 2012). Farm dams can be generally classified as either on-stream or off-stream dams (Government of South Australia, 2011). On-stream dams, as the name suggests are constructed on a water course or drainage pathway to capture and store the natural flow from the water course or drainage pathway. Off-stream dams are not located on a waterway, and capture and store water that has been intentionally diverted from a waterway or surface run-off. Off-stream dams can often only capture a limited supply of water.

Before 2000, it was estimated that there were over 80, 000 farm dams in Victoria (Neal et al. 2000). Other estimates nationwide have approximated that there are currently over 2 million farm dams in Australia, storing in excess of 8 million megalitres (Land and Water Australia, 2008). Teoh, (2003) noted that the Onkaparinga catchment, from 1987 to 1999 saw a rise in farm dam development of 75 ML per year, a total of approximately 900 ML of farm dam volume. Between 1996-1999, the rate of development of 150 ML per year of farm dam storage. Over half of the total 900 ML increase from 1987-1999 came from this three-year period alone (Teoh, 2003). This illustrates the rate at which farm dams are being developed as a water storage option for agriculture.

Recently, the Murray Darling Basin Commission has attempted to identify quantity and size of farm dams across the Basin (Nathan and Lowe, 2012). Quantifying the number and magnitude of farm dams in a catchment or area is a large issue as there are no official records of the location or volume of most farm dams. Topographic maps combined with satellite imagery and aerial photography is a common approach used to estimate the location and number of farm dams in an area, however this approach is most suited to looking at small catchments or areas. For large areas or catchments this can be extremely time consuming and expensive. It is also hard to determine when development of farm dams has occurred, as the best quality aerial photographs may be years or decade apart.

According to Nathan and Lowe, within the Murray Darling Basin, the estimated capacity of farm dams is 2164 gigalitres. 162 catchments in the Basin were investigated, approximately 25% of the whole Basin, and the average density of farm dams was 3.9 ML/km^2. This density is higher than 10 ML/km^2 in approximately 16% of these catchments. The highest density levels occur in the Kiewa, South Australian, Goulburn-Broken and Namoi/Peel basins, while the lowest density (less than 3 ML/km^2) was found in the Upper Murray, Lachlan, and Wimmera catchments. The Onkaparinga and South Para catchments in South Australia were found to have densities of 13.7 ML/km^2 and 8.8 ML/km^2 respectively (Nathan and Lowe, 2012).

Figure 1 shows the characteristics in size and volume of farm dams across the Murray Darling Basin (Nathan and Lowe, 2012). Most farm dams are classified as “small” being less than 5 megalitres (ML). However, while these small dams account for close to 90% of the total number of dams, the account for less than half of the total volume of farm dams. On the contrary, less than 1% of the total number of dams are large dams, over 40 ML yet they account for nearly a quarter of the total volume. Using aerial photography, Nathan and Lowe estimate that in the Murray Darling Basin, the number of farm dams has increased by 37% between 2000-2010. With this increase in numbers there is a corresponding increase in aggregate volume of 48%. It is noted that these numbers are only estimates based on extrapolation from small areas of the Murray Darling Basin, however they seem to be consistent with other estimates reported in specific catchments in the Basin.

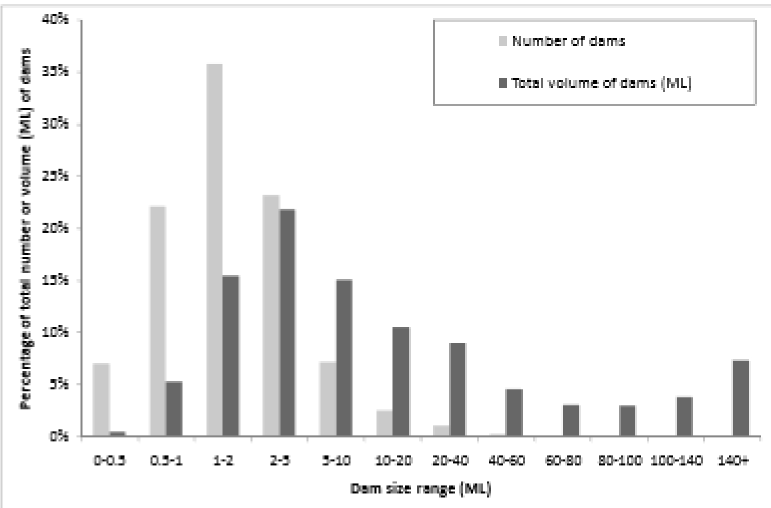

Figure 1: Distribution of farm dams in 162 catchments in the Murray Darling Basin (Nathan and Lowe, 2012)

There has been a general growth in the number of farm dams being utilised for irrigation instead of domestic or stock consumption, and construction appears to be trending towards larger dams (Nathan and Lowe, 2012). Callow and Smettem (2009) assert that a significant factor driving the increase in development of farm dams and water diverting structures in the south of Western

Australia is the decrease in rainfall. Around the Kent River catchment, there has been a 15% decrease in annual rainfall levels since the 1970s, which is pushing farmers to secure and retain on-farm water supplies as protection. Callow and Smettem (2009) also found that over all catchments they studied, there was an average increase in the number of dams per sub-catchment from 2.6 to 5.4, and that the number of dams per hectare doubled from 1.4 to 2.8.

It is clear that there has been a marked growth in farm dam development across Australia in recent decades. As development of farm dams increase, the cumulative effects of all the dams across a catchment increases. This increase is placing pressure on the hydrologic and ecologic processes in catchments in Australia where surface water resources are already a declining natural resource. In the next section, policy and legislation on farm dams in Australia will be discussed to gain an insight into development and allocation regulations.

Beavis et al. (1997) briefly discuss current policy related to farm dams and water allocation, in relation to the increasing development of farm dams in the article "*Impacts and Implications of Farm Dams on Catchment Hydrology: Methods and Application to Chaffey Catchment"*. The current policy structure for farm dams involves many levels of legislation at a local, state and national government. In addition to this, within each state there are several Acts and policies that relate to farm dams, and multiple agencies in charge of implementation and application. This makes administration and monitoring farm dams challenging. Adding to this challenge, Beavis et al. (1997) assert that there is a general lack of statutory requirements on which approvals for dam development are made. There is also, often lack of reliable weather and streamflow data to base decisions on. The Murray Darling Basin Commission Water Audit (1995) recognized the need to balance environmental needs and river health with consumptive water needs of agriculture and industry. This prompted responses at a state level to develop new water management strategies, including flow management schemes and caps on consumptive water usage (Beavis et al. 1997). Farm dams are a concern in these strategies due to their nature of diverting water before it enters a watercourse that water allocations are drawn from. If a dam was not present, water would contribute to streams and the catchment downstream and be counted in formal water allocations. This means some farmers are receiving extra water on top of their allocations. Water is a limited resource and several bodies are competing for its usage, such as agriculture, industry and the environment, and farm dams obviously support farming practices while potentially taking water away from other users. Overall, current policy does not adequately address the environmental impacts of farm dams and dam development, or have appropriate measures in place to create, monitor and enforce suitable water allocations (Beavis et al. 1997). This is in part due to a lack of scientific foundation to base policy on.

Despite these concerns, most government policy supports the development of farm dams through tax incentives, drought investment allowances and tax rebates if the damn is part of a land care project (Beavis et al. 1997). This creates conflict with policy at state and local level, where policies are concerned about allocation of water resources in farm dam development. The authors conclude that the present systems and policies are mismatched and cumbersome. Further policy development needs to address the divide between policy for agricultural allocations and policy for the needs of the environment and be based on credible scientific monitoring and investigation. Tingey-Holyoak, (2014) also confirms that policy response in Australia has been disjointed by governments and governing bodies at national, state and regional levels in her research article "Water sharing risk in agriculture: perceptions of farm dam management accountability in Australia". There is also a disconnect between policy and practice, and a lack of monitoring to ensure regulations are followed. Currently there is an onus on the owner of the dam to manage their dam and ensure they are compliant with current standards, however relying on owner responsibility does not adequately protect downstream users of water.

1.2.2 Hydrologic Impacts of Farm Dams

Several studies have attempted to present quantifiable evidence on the hydrological effects of farm dams. The studies to be examined in this review include; "The Hydrological Impacts of Farm Dams" (Nathan and Lowe, 2012), "Impacts and implications of farm dams on catchment hydrology: Methods and application to Chaffey catchment" (Beavis et al. 1997), "The effect of farm dams and constructed banks on hydrologic connectivity and run-off estimation in agricultural landscapes" (Callow and Smettem, 2009), and "The effect of catchment farm dams on stream flows - Victorian case studies" (Neal et al. 2000).

Nathan and Lowe (2012) provide a comprehensive literature review on the nature of farm dam impacts. They confirm that in most cases, individual dams have a relatively small impact on hydrological processes, however it is the collective effect of numerous farm dams in a catchment that can significantly affect stream flow. The issue is essentially that farm dams capture and store water from rainfall and run-off, preventing it from reaching waterways, reducing flows and water availability downstream. The magnitude of impacts depends on several different factors, most obviously, a greater impact in a catchment will be seen with a greater total volume of farm dams. The volume of extraction demands will also alter the impacts downstream. Higher rates of extraction from farm dams decreases their storage volumes which increases the opportunity for the dam to intercept run-off. The seasonal pattern of irrigation demands heavily influences the timing of water extractions, which in turn influences how much water is intercepted by dams. Figure 2 (Nathan and Lowe, 2012) shows an average seasonal pattern of irrigation demands in a typical south-eastern Australian catchment. Demands for irrigation are the highest from November to March, when rainfall and streamflow is low, and temperatures are high. This demand increases extraction in the summer months and leaves dams at their lowest level or sometimes empty by autumn. The more water that is extracted from dams during this period, the more water the dam will be able to acquire during wetter months. Around the end of autumn, the depleted storages of farm dams are filled by increased rainfall and run-off and this is when the largest impacts on stream flows occurs, and these impacts are lessened by the end of winter when dam storages are full again (Nathan and Lowe, 2012). Rates of evaporation will also influence the volume of farm dam storage, and consequently how much it is able to harvest in wetter months. The amount of evaporation from dams depends on meteorological conditions, which vary significantly across Australia, and the surface area that is exposed to evaporation. Dams with large surface areas will experience more evaporation than dams with small surface areas, regardless of volume (Nathan and Lowe, 2012).

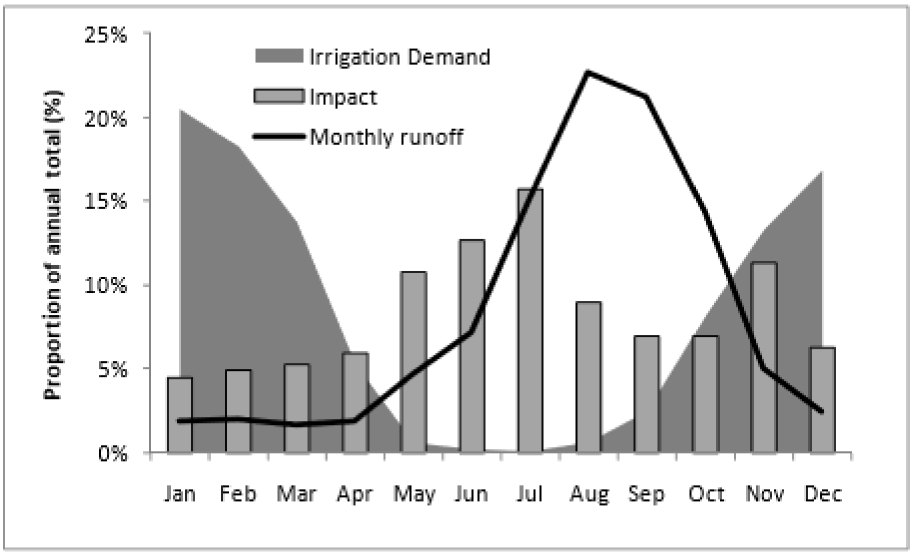

Figure 2: Average pattern of irrigation demands for a south-eastern Australian catchment (Nathan and Lowe, 2012)

A simulation model, TEDI (Tool for Estimating Dam Impacts) has been developed as a means to estimate the impacts of farm dams over large areas. The TEDI model uses evaporation rates, rainfall and run-off data and the volume of water used to estimate how much water is being captured by farm dams. Nathan and Lowe summarise data from the application of TEDI to catchments in Victoria in the Murray Darling Basin. Results of the model suggest that farm dams in Victoria are reducing annual flows by 5% on average, however some simulations have resulted in annual flow reductions of up to 30%. For 90% of the catchments modelled, it was shown that for every megalitre of farm dam storage, there was a reduction in average annual flows of 0.3 to 1.1 ML. The most probable correct reduction is around the median of these two extremes. The impact reduction on average summer flows was almost double the impact on average annual flows. This is likely due to dams being low in storage or nearly empty in summer months and so are intercepting more flows, as discussed previously. As the impacts of climate change are felt, the impacts of farm dams may be exacerbated. A simulation in Campaspe River, Victoria showed that farm dams are currently capturing 8% of flows that would otherwise contribute to Lake Eppalock, but under climate change scenarios it was estimated this could increase to over 25% (Nathan and Lowe, 2012).

Nathan and Lowe present a thorough review on the impact of farm dams, and the use of the TEDI model. The authors are careful in explaining each parameter and limitations of the TEDI model, for example noting the simulation has not produced accurate results in very highly developed catchments. The most accurate results are produced when detailed meteorological, streamflow and farm dam data is readily available, which is often not the case and instead calculated estimates are used, based on characteristics of the region (Nathan and Lowe, 2012). It is acknowledged that the largest knowledge gap is the demand supplied by farm dams, how much of irrigation and stock watering is supplied by these dams, and how much is delivered per unit volume of dam. Better estimates of this is needed before more accurate results can be produced. More quantified and specific results could have been presented by Nathan and Lowe, especially with the use of the TEDI model, however the authors note that this is a difficult task and suggest this for future research. The potential environmental impacts of farm dams are also reviewed in this paper and are discussed in the section "*Environmental Impacts*". Associated limitations regarding environmental impacts are briefly discussed, again with the suggestion for quantifiable studies for future research. There was slight bias towards environmental needs in the conclusions drawn by Nathan and Lowe, clearly stating that further development of farm dams needs to be mitigated, and even current policies are not adequately meeting the needs of the environment. Despite this, they acknowledge water resources must be properly shared to balance social, individual and economic needs with that of the environment.

Beavis et al. (1997) modelled water balances in Chaffey Catchment with a "before and after" approach to development of farm dams to assess the impacts farm dams are having downstream, particularly in periods of low flows. This study is part of a larger project to study 25 catchments within the Basin that have seen a substantial increase in dam development. The investigation of Chaffey Catchment is an initial study outlining the methodology and framework for modelling the water balance in catchments and provides some preliminary results, which could serve as indicators of what further studies may produce. As discussed in the previous section, there is not adequate policy surrounding farm dam development with respect to the environment and water sharing, and this is in part due to a lack of scientific monitoring and analysis. This project will hopefully have positive implications for future research and ongoing policy development (Beavis et al. 1997).

The Chaffey Catchment is located within the Naomi Basin in the north of New South Wales. The catchment has a total area of 420 km^2. The development of farm dams was quantified using aerial photography, dating back to the earliest streamflow records. The aerial photography is used for initial assessment to determine numbers and spatial distribution of farm dams, which was to be followed up by more detailed analyses such as estimates of volumes in each dam. The water balance of the catchment was modelled using a modified version of the IHACRES model with daily streamflow data from gauging station 419045 in the Chaffey Catchment. (Beavis et al. 1997). Factors of average relative parameter error, Bias and Efficiency (seen in equations 2 and 3 of the article) were used to assess the performance of the final model. Their results are mostly consistent with the work of other studies, overall seeing a reduced streamflow with increased farm dam development. There was a period in the 1970s where the water yield downstream actually increased substantially, which is unexpected considering the trend of farm dam development was increasing during that period. The authors suggest that this is due to a logging project being carried out upstream which has increased surface run-off and therefore increased water yield. The decrease in water yield modelled in the 1980s was attributed to both the increase in farm dam development, and the regrowth of forested areas that were previously logged (Beavis et al. 1997).

The authors note limitations within their study, for example, complex land use changes within the catchment and land management strategies, as well as other contributing issues such as climate change can become confounding factors in monitoring and analysis, which presents a difficulty in isolating changes caused by farm dam development. It is noted that future research should attempt to investigate the consequence of several different variables that affect streamflow responses. Unlike the article by Callow and Smettem, the authors do not note the limitations presented by manually quantifying farm dams through aerial photography, nor do they suggest an alternative method for future research. The authors were careful to outline specific steps in their processes and limitations of their work, this critical analysis adds weight to the credibility of their results and conclusions. Their study is also supported by a comprehensive catalogue of credible and relevant literature previously written on the subject. Their modelling validation was carefully detailed to the reader, assessing performance of their model with three separate parameters; average relative parameter error, Bias and Efficiency. This adds further reliability to the accuracy of their results and therefore conclusions.

Callow and Smettem (2009) modelled the influence of “water collection infrastructure” such as farm dams and earth banks that divert water on hydrologic connectivity in “The effect of farm dams and constructed banks on hydrologic connectivity and run-off estimation in agricultural landscapes”. Hydrologic connectivity is the flow of water (and sediment) through catchments and landscapes, controlled by system coupling and connectivity of the landscape. It is essential for ecological processes and the geological integrity of the landscape (Callow and Smettem, 2009). Within previous studies of changes in hydrologic connectivity, anthropogenic influences are rarely considered. Most investigations and discourse on this subject is focused on geomorphic processes over large time periods; hundreds to thousands of years. Callow and Smettem undertook this research to ascertain if human activity, in particular the development of farm dams and water diversion such as earth banks can significantly affect hillslope coupling and hydrologic connectivity, and if these changes can be accurately simulated by manually modifying a digital elevation model. Twelve small (0.5 – 4 km^2) sub-catchments were selected for investigation within the upper Kent River catchment, Western Australia. Corrected aerial photographs were used to identify and quantify farm dams and banks, comparable to the method discussed previously in Beavis et al. (1997). A digital elevation model (DEM) generated for a previous project was utilised to model the characteristics of each sub catchment. The catchments were modelled in what would be their “natural” state, with no man-made structures such as dams or constructed banks, and then in their “modified” state, which considers all man-made structures. The “modified” DEM was modelled by manual editing of the “natural” model to include numerous dams and banks, and the changes they make to the flow regime (Callow and Smettem, 2009). To ascertain any potential changes from decoupling the natural landscape with farm dams and constructed banks, several parameters were tested to represent hydrological processes in the sub-catchments. Cumulative area distribution, instantaneous unit hydrograph, simplified width function and hypsometric curve were used as these have been largely accepted as representations of hydrologic processes (Hancock, 2005).

Callow and Smettem found that over all catchments, there was an average increase in the number of dams per sub-catchment from 2.6 to 5.4, and that the number of dams per hectare doubled from 1.4 to 2.8. Catchment ii, as they authors named it, produced a good example of the impacts of dams and banks between its natural and modified simulation. An additional two dams and nearly 1km of banks disconnected a large area of the upper catchment from the catchment outlet. The banks route water into dams where the water is stored but also increase residence time in the catchment as water is forced to take less than optimal paths before discharging in the catchment outlet. Over the twelve study areas, it was clear that dam and bank construction causes reductions in effective catchment area, with an average reduction of 39.5% compared to the natural conditions. This translates into

39.5% of the area that maintains a hydrologic connection with the catchment outlet being lost (Callow and Smettem, 2009). It appears the number of dams and length of earth banks had little correlation to this dramatic reduction, but instead the location and landscape position of the dams and banks was the leading factor. Dams and banks that were constructed in the lower, concave areas of the catchment lead to the largest reduction in effective catchment area. For example, catchment iv had an area of $0.97km^2$ and the highest dam density, with 5 dams at 5.15 dams per hectare, and 2.77 km of banks, and had a large reduction in effective catchment area, while catchment vi had the largest number of dams (14) and the third highest density, yet the dams were located in high landscape positions (not concave areas) and had an effective catchment area reduction of 35%, which is less than average (Callow and Smettem, 2009). Catchments I, ii and iv were selected for further investigation of hydrological processes. All three basins showed insignificant changes in cumulative area distribution and hypsometric curves between natural and modified states. However, the simplified width function and the instantaneous unit hydrograph (IUH) were both affected by the construction of dams and banks, and therefore the reduction in effective catchment area. For catchment ii, both functions showed an increased residence time. Catchment I showed a 22% reduction in peak discharge, however the IUH had no significant difference between the natural and modified state, likely because dams were constructed in the upper catchment. A similar effect was seen in Basin iv, with a 29% reduction in peak discharge and a reduced rising limb of the IUH, due to dams being located lower in the landscape (Callow and Smettem, 2009). It is concluded that water diverting structures such as farm dams and earth banks are having a significant effect on hydrological processes in catchments.

Callow and Smettem ultimately conclude that manually altering a DEM can replicate hydrological processes in catchments modified by the construction of farm dams and earth banks, and this DEM can be used reasonably accurately to model flow scenarios. The authors note a limitation within their research was manual quantification of farm dams and banks based on aerial photography, which could have produced slightly inaccurate results. This also meant it was difficult to quantify volumes in dams. They suggest integrating this result with automated classification methods to increase the accuracy of classification of farm dams and earth banks (Callow and Smettem, 2009). This article has laid solid foundations for further research in this subject, asserting that anthropogenic activities can have a significant effect on hydrologic processes over a short time period. Their research methods were supported by extensive research from relevant and up-to date literature. There appears to be little bias in their results and conclusions, with attempts to isolate confounding factors (such as number of dams versus dam location) and proper discussion of their own limitations.

Neal, Shepard, Austin and Nathan, (2000) summarise a number of case studies undertaken in Victoria in "The effect of catchment farm dams on stream flows - Victorian case studies". The studies were done to specifically address the hydrologic effects of farm dams on downstream flows. This evidence is hoped to address water security and supply concerns as farm dam development continues to increase. Many surface water resources in Victorian catchments are already fully allocated, however water licences are not required for farm dams and so this water is not being allocated or monitored (Neal et al. 2000). The TEDI model previously discussed (Nathan and Lowe, 2012) was used in these case studies and applied to five catchments with varying streamflow and rainfall conditions. The key inputs into the model were streamflow data from gauging stations in the catchment, rainfall and evaporation data, estimations of demands from farm dams and quantification of dam numbers, volumes, and distribution from aerial photographs. Catchment outflows were estimated by subtracting licenced demands from streamflow and rainfall data and then performing adjustments based on the characteristics of each catchment. The study sites were selected based on availability of reliable streamflow records, representation of a variety of atmospheric and hydrologic conditions, the catchment having high numbers of farm dams, reliable available information on properties of the farm dams and a manageable catchment size (ideally <200km^2). Woori Yallock Creek catchment was the largest catchment studied, with an area of 322km^2 and a volume of farm dams of 678 ML, while Ten Mile Creek catchment was the smallest, with a total area of 45km^2 and a farm dam volume of 26ML. Mean annual flows in the catchments ranged from 8, 000 and 10, 000 ML/year in Ten Mile Creek and Arthurs Creek to 94, 000 ML/year in Woori Yallock Creek (Neal et al. 2000).

The results from the TEDI simulation show that the presence of farm dams affects both the timing on and magnitude of downstream flows. Overall, the simulation indicates that one megalitre of dam storage can reduce downstream flows by 1 to 3 megalitres annually, dependant on location, rainfall-run-off characteristics of the catchment and evaporative losses. Arthur's creek catchment was the most affected. For every ML of farm dam volume in the catchment, the annual streamflow was reduced by just over 2.5ML. Four out of the five catchments saw reductions of over 2ML per ML of farm dam volume, the only exception being Mt Cole Creek which had an average reduction of 1.9ML (Neal et al. 2000). Percentage reductions in total annual flows ranged from 0.6% in Running Creek to 4.4% in Mt Cole Creek. The differences in flow reductions in each catchment can be attributed to factors such as evaporation and topographic differences influencing the flow characteristics of each catchment. In Mt Cole Creek, the reduction in total annual flows was the lowest, while the average reduction per ML of farm dam volume was the lowest. This is because farm dams affect the timing of flows not just their magnitude. In Mt Cole Creek, the majority of inflow into the catchment is during winter and spring from high rainfall events, impacting average flows for the year. The average annual reduction per ML of farm dams in Running Creek catchment is relatively low due to the relatively low evaporation rate throughout the year. The simulation was run to compare the effects of farm dams on low, median and high flows. It is generally accepted that farm dams have the largest effect on low flows, as during medium to high flows, dams will be closer to capacity and therefore divert less water (Neal et al. 2000). The results of simulations in all five catchments found the percentage reduction of monthly flows due to dam presence during high flow periods was negligible. It was also shown that the percentage reduction in monthly flows for low flows was on average, greater than the percentage reduction for median flows. For example, Woori Yallock Creek, during low flows was experiencing a percentage reduction in monthly flows of around 6.5%, while the percentage reduction for median flows was only around 3%. Mount Cole Creek catchment however, showed a larger percentage reduction in monthly flows during median flows rather than low flows. This was attributed to the rainfall and hydrologic patterns of the area. In the catchment, low flows occur at the start of summer, when there is still a significant amount of storage in dams from winter and spring rainfall, and median flows occur around late autumn, when storage in the dams is heavily reduced after the dry summer and so the dams have a greater capacity to capture water (Neal et al. 2000). These patterns align with the theories presented in Nathan and Lowe (2012).

Overall this study managed to produce tangible results relating to the effects of farm dams on stream flows. Five different catchments were analysed, and this was important to see a range of conditions simulated. The simulations run considered annual, monthly and periods of low, median and high flows in an attempt to gain a more thorough understanding of how and when the impacts from farm dams occur. Confounding factors such as evaporation rates and different topographies of each catchment were accounted for in the discussion and analysis of the simulation results. This study has consistent findings with Nathan and Lowe (2012), who also utilised the TEDI model, although Nathan and Lowe went to greater extents to describe the limitations and methods of their model building. This study also had similar results in percentage reduction of annual flows due to farm dam influence as the study conducted by Habets et al. (2014) although Habets and the other authors did not make a comparison of the average ML reduction in downstream flows per ML of farm dam storage. Habets et al. (2000) also acknowledged limitations in building their model more so than Neal, Shepard, Austin and Nathan. Neal et al. (2000) briefly discussed limitations regarding inputs into the TEDI model and suggest further study could focus on refinement of the water balance used in the model. All three studies carefully considered discrepancies in their results and attempted to account for these in their discussions and conclusions.

1.2.3 Environmental Impacts of Farm Dams

Australian climate is very variable and so are its rivers and waterways. Australian watercourses are some of the most variable across the world (Walker, 2002). Environmental flows in Australia provide critical contributions to ecosystem health (Dyson et al. 2003). Especially in southern Australia, periods of no, low, moderate and heavy flow and when they occur during the year are essential in maintaining important ecosystem processes and services. The pattern of environmental flows in Southern Australia is usually low or no flows during summer and part of autumn, coinciding with low rainfall periods, and high flows in winter and spring accompanying periods of the highest rainfall. This pattern is significant for supporting native flora and fauna and their breeding and feeding patterns (Thoms et al. 2000). Environmental flows also support river health and also ensures social and economic benefits. Previous literature discussed in Section 1.2.3 "Hydrologic Impacts of Farm Dams" confirms that the addition of farm dams to an otherwise "natural" catchment has an effect on both the timing and magnitude of environmental flows downstream. Failure to meet the requirements of environmental flows can have disastrous impacts for habitats and ecosystems downstream (Dyson et al. 2003). The aquatic and water dependant ecosystems in and near rivers and streams are maintained by the environmental flow regimes and flora and fauna that inhabit these ecosystems are dependent on the flows to continue to function at optimal levels (McMurray, 2006). This is especially important in Australia and southern Australia where ecosystems are already fragile. Despite acknowledgement of this fact, there has been few studies focused on the ecological and environmental impacts of farm dams and their increased development. Two studies will be examined on this topic; "Temporal variations in water quality of farm dams: impacts of land use and water sources" (Brainwood et al. 2009), and "Effect of small catchment dams on downstream vegetation of a seasonal river in semi-arid African Savannah" (O'Connor, 2001).

Beavis et al. (1997) argues briefly for the positive environmental impacts of farm dams, in that they act as sediment traps and prevent erosion. The dams themselves also provide a habitat for small communities. This contrasts with the assumption that farm dams have a negative ecological effect. Brainwood and Burgin, (2009) further this argument for the positive ecological impacts of farm dams in "Hotspots of biodiversity or homogeneous landscapes: Farm dams as biodiversity reserves in Australia". Brainwood and Burgin compared the diversity of macroinvertebrates in farm dams with natural aquatic systems close by in New South Wales and argue that farm dams should not be decommissioned without consideration of their advantages as biodiversity reserves. Biodiversity is an important indicator of the general health of the ecosystem, and biodiversity and species richness is linked to important ecosystem processes such as primary productivity (Brainwood and Burgin, 2009). The authors assert that there is a fundamental lack of literature available on the role farm dams play as a biodiversity resource, and the literature that is available is unfocused and as such it is difficult to present meaningful conclusions or comparisons. Of the literature on biodiversity of farm dams, few studies have compared biodiversity samples with those of nearby natural habitats (Brainwood and Burgin, 2009). It is important to accumulate and collaborate knowledge from all sides of an issue to ensure an accurate representation is conveyed.

Brainwood and Burgin conducted studies in two separate sites over a year in similar agricultural settings in New South Wales. Three dams were surveyed in Raglan, while six stream sites were sampled in Cadia. Mean diversity values for each dam and stream were compared using ANOVA statistical analysis and ANOSIM analysis was used to recognize communities that were present in each water body (Brainwood and Burgin, 2009). Of the 10km of stream site surveyed, there was overall a larger number of species in the natural environments than in all three of the farm dams, although the difference was not significantly higher. Also, the stream sites also showed a lower average diversity and total diversity per site than in the three dams. Each dam was observed to be supporting discrete communities of macroinvertebrates, despite being relatively close to each other. 74 taxa were recorded at stream sites, and of these, 46% were single occurrences, compared to 0.08% of the 59 taxa recorded in the dams being single occurrences. Species were more consistently reported in the dams (Brainwood and Burgin, 2009).

This study showed that farm dams can provide a sustainable biodiversity reserve within their catchment with a variety of species, in contrast to the present common view. In fact, Brainwood and Burgin recorded some species that had not been previously recorded in a farm dam. The authors conclude that the microhabitats within farm dams have the ability to support the same degree of species richness as many natural systems. Farm dams can also provide habitat for aquatic vertebrates, birds and frogs. It is also possible that farm dams could act as a bridge between natural and modified habitats, somewhat preventing the fragmentation that agricultural practices cause (Brainwood and Burgin, 2009).

In addition to the impact on flows, the construction of farm dams can also have a negative ecological impact, especially if the farm is located on wetlands or a waterway. This coincides with the conclusion made by Callow and Smettem (2009) that the location of farm dams and water diversions is the leading factor in hydrologic impacts, not the number or volume of dams. The impact of farm dams on wetlands was studied in Wimmera and it was found that over 55% of all the wetlands in the area were anthropogenically altered to some extent from 1994 to 2004 (Nathan and Lowe, 2012). Construction of farm dams was the main modification. However, the authors note that farm dams can offer important habitat and ecosystem services, an even be a small ecosystem within themselves (Nathan and Lowe, 2012) and this reiterates the findings from Brainwood and Burgin (2009).

O'Connor, (2002) investigated the effects of several small farm dams in the Limpopo river in "Effect of small catchment dams on downstream vegetation of a seasonal river in semi-arid African Savannah". The effects of reducing or altering the natural pattern of stream flows on riparian vegetation was modelled. According to O'Connor, effects of farm dams have been investigated in systems in the Northern Hemisphere, but semi-arid regions of Africa have not been studied. Furthermore, most studies have focused on the impacts of large structures such as reservoirs in large river systems. Farm dams and their increased development in Africa have altered flow and flooding patterns in catchments and this has resulted in declines of riparian vegetation as seeding establishment is disrupted by the altered flow and flooding patterns (O'Connor, 2002). The riparian vegetation in semi-arid savannah regions in Africa is an integral part of habitats for both wildlife and livestock. The Kolope-Setkoni sub catchment of the Limpopo River in the Northern Province, South Africa. The catchment is prone to water stress during years or periods of low rainfall, being located within a semi-arid savannah. Firstly, an existing hydrological model was used to summarise present and past flow patterns. The number of farm dams and their volumes were estimated using aerial photography. Vegetation in the riparian zone of waterways was examined for dieback, population structure and mortality of four tree species, *Combretum imberbe* or leadwood, *Faidherbia albida* or ana tree, *Schotia brachypetala* or weeping boer-bean and *Xanthocercis zambeziaca* or nyala berry (O'Connor, 2002). These species are all long-lived, exclusive to riparian catchments, and have different water requirements, and so were appropriate to select for this study. This data was related back to water availability and hydrological patterns of the area. The results were also compared with the same tree populations in the Greefswald catchment (also in the Limpopo River) which has a more dependable water source and greater annual flow.

Based on the results of distribution in elevation above and distance from the river, the rank of water requirements for the four species from largest to smallest was determined to be: *Faidherbia albida, Schotia brachypetala, Xanthocercis zambeziaca, Combretum imberbe*. No statistically significant relationship between the mortality or canopy dieback and water requirements of the species (O'Connor, 2002). *F. albida* and *C. imberbe* experienced considerable mortality and dieback yet were the two species that required the largest and least amount of water respectively. Of the *F. albida* trees, 29% were dead and those left alive had experienced an average of 31% canopy dieback. *C. imberbe* had a 10% mortality rate, and the remaining 90% had lost canopy volume of 8%. Canopy dieback and mortality of the two species in the middle of the rank of water requirements, *S.*

brachypetala and *X. zambeziaca* was negligible (O'Connor, 2002). It seems that water requirements was not the influencing factor in mortality and dieback, but instead factors including tree size and the availability of water. Dead *C. imberbe* trees were located at a greater elevation or distance from the river, where waster was less available to them. The likelihood of *C. imberbe* experiencing canopy dieback was greater at higher elevations and greater distances from the river in large trees, whereas the chance of *F. albida* experiencing canopy dieback was only greater at higher elevations above the river in large trees (O'Connor, 2002). The population structures of all species differed. The structures of *S. brachypetala* and *X. zambeziaca* suggest their environmental needs have been met, enabling successful seeding establishment and continuation of adult life. *C. imberbe* showed a concerning population structure. High banks by the river mostly held dead or declining old trees, while the lowest terrace next to the river supports healthy adolescent and young adult trees with minimal canopy dieback. This suggests environmental flow conditions are insufficient for supporting the continual growth of *C. imberbe* individuals to adulthood. *F. albida*, which showed the greatest mortality rate, experienced a substantial loss of adult individuals, with recruitment of juveniles still being present, again suggesting environmental needs for adult individuals are not being sufficiently met due to altered flow regimes (O'Connor, 2002).

O'Connor concludes firmly that small farm dams are influencing ecological processes in semi-arid environments due to their alteration of timing, intensity and duration of flooding periods. This is affecting riparian vegetation in semi-arid Africa resulting in evidence of increased dieback and mortality of species that require significant amount of water, and in individuals growing at greater distances and high elevations from the river at their limit of water availability. However, an issue to consider in these results and analyses is potential confounding factors such as livestock grazing. Grazing of livestock also decreases vegetation cover, and compounds topsoil, which leads to reduced infiltration of water and increased surface run-off and erosion. O'Connor acknowledges this potential confounding factor and concedes the decline in vegetation could be a result of the altered flow from farm dams, or livestock grazing, or both, the likely answer being a combination of both. Other sources of potential error were carefully identified by O'Connor and analysed. For example, he noted limitations associated with quantifying numbers and capacities of farm dams using aerial photography. Limitations of using a nuanced parameter such as elevation above or distance from was also considered.

From the review of literature presented, it is clear that there is available credible literature on the hydrologic and environmental impacts of farm dams on catchments, but there are still large information gaps that need to be filled in order to inform decisions regarding sustainable water consumption and farm dam development in the future. Most literature discussed in this review focuses on multiple catchments, or large catchments with many dams. This presented challenges regarding obtaining data on farm dam characteristics and catchment characteristics, as well as the presence of confounding factors making it difficult to separate effects caused by farm dams from effects of land use changes or changes in climatic conditions. As previously stated, it is hoped that by focusing on specifics of a single farm dam that the chances of confounding factors influencing results will be negated. Furthermore, as only a single site is being investigated, accurate data regarding dam capacity, water levels over time and meteorological conditions are accessible, improving the accuracy of the water balance model. A more accurate water balance for farm dams would improve the accuracy of models simulating the effects of farm dams on downstream flows. In turn this more reliable information can be used to inform decision making on future farm dam development and current allocations as water security becomes increasingly uncertain.

2. Methodology

2.1 Data Collection

To calculate a water balance for a dam, several components of data are required. Figure 3 shows a simplified diagram of the water balance of a farm dam. Inputs into the dam's storage include precipitation directly on the dam, and overland flow (including stream flow and surface water run-off). Losses from dam storage include open water evaporation, transpiration or water uptake from vegetation and infiltration into the groundwater. Infiltration is a large loss in the specific dam studied in this research as it is unlined.

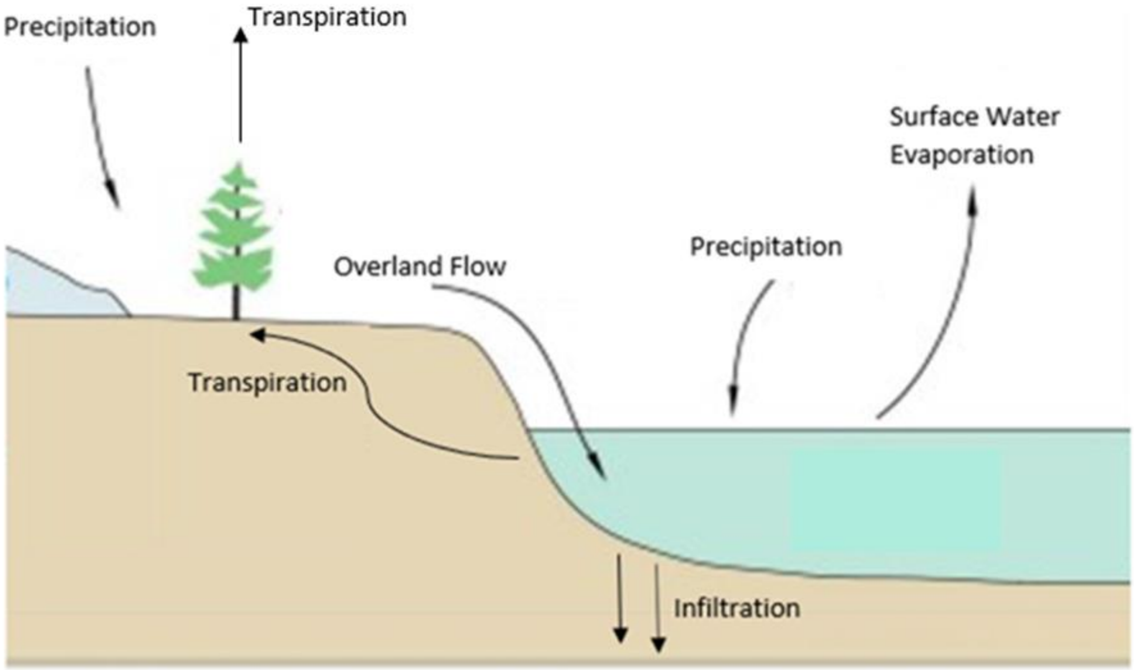

Figure 3: Water balance of a farm dam

This was a retrospective study and made use of existing data. There were several gaps in data, for several parameters, and there was no data available for some necessary parameters, and so a large portion of this study was dedicated to collecting and collating available data and determining appropriate methods to utilise this for a meaningful result. To approximate the losses from the dam's volume evaporation data was collected, and transpiration values were estimated. Water level data was also obtained, along with weather and atmospheric data from a nearby weather station, to determine inputs into the dam's storage. This data was collected over the longest time period available, for most of 2013 to early 2017, to gain a better understanding of any patterns and relationships. Multiple methods were used for processing different parameters, with the hope of comparisons between methods aiding in gaining a more accurate representation of conditions in the dam and its surrounding catchment.

2.1.1 Study Site

The dam which is investigated in this study is located on a property at 290 McMurtrie Road in Willunga, owned by Michael Teubner, an academic at the University of Adelaide and the National Centre for Groundwater Research and Training (Flinders University). The property is located in the Peddler Creek catchment, approximately 30km to the south of Adelaide, as can be seen in Figure 4 (Google Maps, 2018).

Figure 4: Study site in relation to Adelaide (Google Maps, 2018)

Michael's property is 300m by 300m (see Figure 5, Google Maps, 2018) and contains a small dam (a small farm dam is less than 5 mega litres according to Nathan and Lowe, 2012) with a capacity of approximately 1.8 mega litres (ML), surrounded by a perimeter of red gum trees. The dam is recharged mostly by an intermittent stream that flows during large rainfall events, as well as rainfall and run-off in the area. Most of the property is covered by trees and grassy vegetation, and the dam itself is surrounded by a perimeter of River Red Gum trees (*Eucalyptus camaldulensis*). A small vineyard and olive grove are also on the property. The dominant soil on the property is Bay of Biscay clay. The area around the study site is almost all agricultural, in particular viticultural, as McLaren Vale is one of South Australia's most prominent wine regions. Most farm dams in the area are used to provide security for farmers for livestock or irrigation. Michael does not utilise the water stored in the dam, and instead has been monitoring several parameters in and near the dam for several years.

As no water is being taken from the dam for use on Michael's property, this gives a solid insight of the dynamics of this particular dam and where and when its losses occur before losses due to usage on a farm is even a factor. There is a small jetty on the west side of the dam that has a reference marker on one of its posts (as seen in Appendix A, Figures A3 and A4). Almost all calculations were done to produce results that were in reference to this marker on the jetty. For example, water levels were presented after corrections as "metres below reference point". This was done as no absolute metres above sea level reference points were available and, they were not needed as all the data was referenced to each other.

Figure 5: Michael's Property (Google Maps, 2018)

2.1.2 Weather Data

The majority of weather and atmospheric data was collected from the McLaren Vale website (McLaren Vale, 2017). The site has a network of weather stations around the McLaren Vale and Willunga region, with data of several different meteorological parameters dating back to 2006. Although none of the stations were directly in the sub-catchment of Michael's dam, the decision was made to use the data from the station just off from the corner of Main Road and McMurtrie Road in McLaren Vale. This station can be seen in in Figure 6 (McLaren Vale, 2017). This decision was made based on the McLaren Vale station being the closest geographically to Michael's dam, at a distance of approximately 2.8km (the McLaren Flat station was over 3.5 km away with the Willunga station being over 4km away). Data for all available meteorological parameters was obtained from this website, both in daily readings and 15-minute readings. The 15-minute readings only included rainfall while the daily readings contained several other parameters including wind speed, solar radiation, dew point and temperature. Due to the weather station's distance away from Michael's property it should be noted that not all parameters will be a completely accurate representation of the atmospheric conditions at the dam site. For example, wind speed is likely to differ between the weather station and Michael's property, due to the presence of trees and foliage and also height differences at the measurement point. However, the McLaren Vale weather station is still the most reliable data set within a reasonable distance of the dam site, and so can be used as a reasonable estimate for the conditions at the site.

Data was also collected from a weather station on Michael's property for temperature and relative humidity from 10/01/2013 until 05/01/2014. This weather station data also included time series for rainfall and other atmospheric data, however it was found to be unreliable.

Figure 6: McLaren Vale and McLaren Flat weather stations

2.1.3 Water Level Data

There have been water level loggers in the dam at different times since 2013. Several sets of data for water levels in the dam were collected. Data from 6/6/2013 until 27/12/2013 were collected using Solinst Levelogger (Solinst, 2018). Data was also collected from 7/12/2013 until 13/2/2014 and then again from 25/7/2014 until 6/9/2014 using Druck submersible pressure sensors (General Electric Company, 2013). Finally, data was collected from 11/5/2016 until 25/1/2017 using Diver water level loggers (Eijkelkamp Soil and Water, 2016). All data from 2013 was measured every hour, the loggers in 2014 measured approximately every 6 minutes, and the diver water level loggers measured every half an hour. The water loggers measure the combined water pressure and atmospheric pressure exerted which was then corrected to a water level measurement. The loggers also record the water temperature, which was used in evaporation calculations as described in section 2.2.4, although it should be noted that this is the temperature in the well which would differ slightly from the exact water temperature at the surface. However, this is still the best available estimate of water temperature. Missing time periods in the water level data and collating and organising this data into meaningful sets were large challenges associated with this project.

2.1.4 Evaporation Data

Pan evaporation data was collected from a standard Class A pan from October 2013 until December 2014. The pan was positioned close to the dam (approximately 5 metres away) for the data to closer resemble the conditions in the dam. Data was taken daily between 6am and 8am. It should be noted that the data from the pan would differ slightly from standardised data from an official site such as the Bureau of Meteorology, as not all BOM specifications were met. For example, the pan was measured close to trees and this may have affected the results (Hydrological Services America, 2018). However, the pan evaporation data will still give a reasonable representation of what is happening in the dam. Furthermore, several methods are being used to calculate an approximation of evaporation, so pan evaporation data can be compared and contrasted to other methods to gain a more accurate understanding of the losses from the dam. There was not pan evaporation data for all the time periods water levels were collected for, and so in its absence the closest estimate was used. This is discussed further in Section 2.2.4.

2.2 Data Processing

2.2.1 Catchment Area

The sub-catchment area of the dam was determined using the Watershed tool in ArcMap. This tool delineates the area upstream that contributes flow to the dam, through rainfall or run-off. ArcMap was the preferred option of determining the catchment area of the dam as it is generally accurate and less time consuming than attempting the process manually. The results from this showing the boundary of the dam's sub-catchment can be seen in Figure 7, illustrating how the sub-catchment fits within the larger catchment, and Figure 8, illustrating a close up of the sub-catchment. The sub-catchment can be seen in opaque beige (named *Watershed* in the legend). The watershed tool gave a sub-catchment area for the dam of 663, 100 m^2, or 0.6631 km^2.

This watershed calculated by ArcMap appears accurate as it adheres to the rules for delineating catchment boundaries if it were to be done manually. This is; the watershed boundaries are perpendicular to contour lines when they meet, and that the boundary does not cross any waterways or water bodies (Bellette and Lee, 2003).

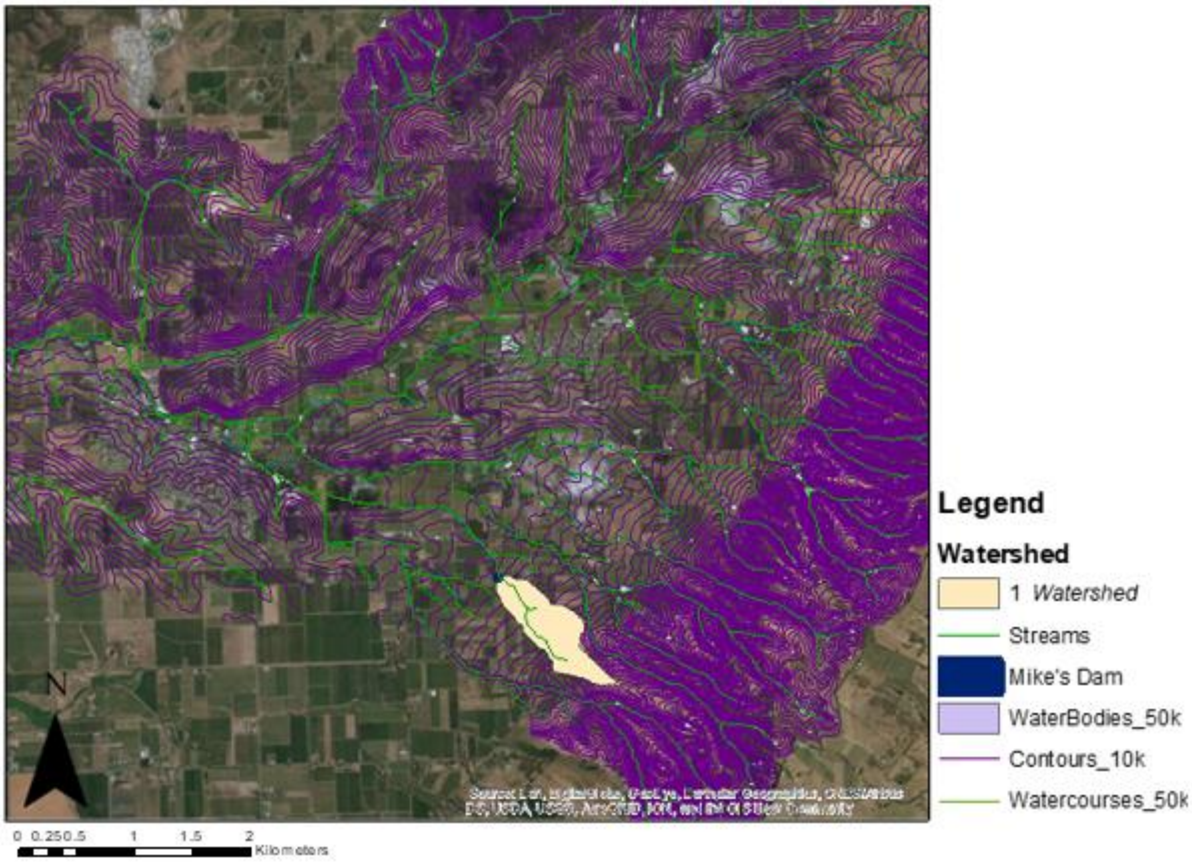

Figure 7: Delineated Sub-Catchment

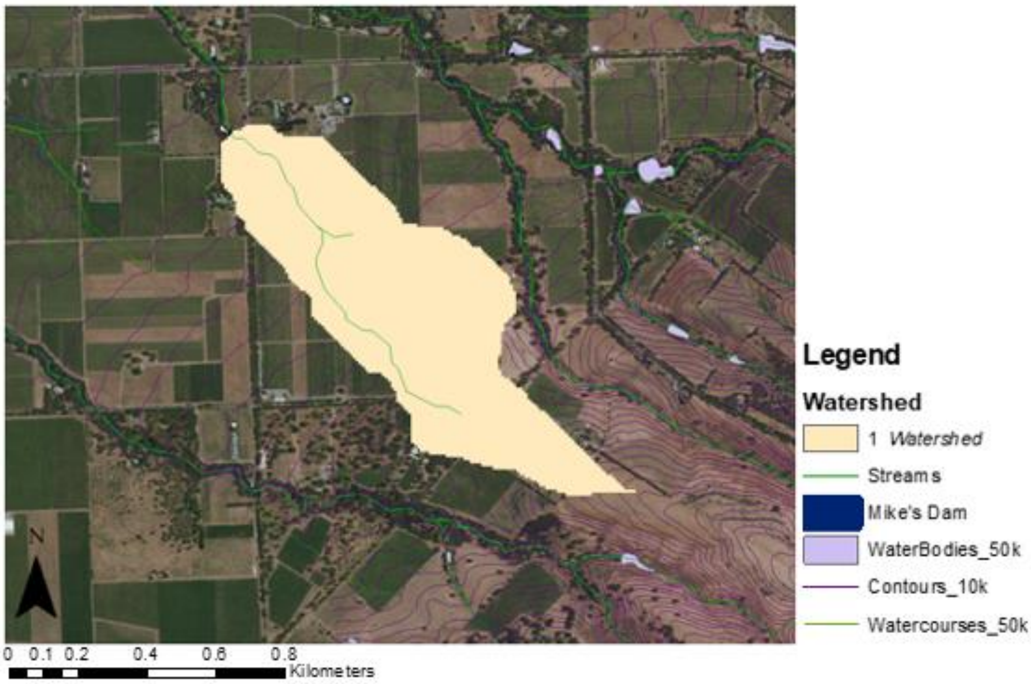

Figure 8: Delineated Sub-Catchment

2.2.2 Dam Dimensions

To determine the volume and surface area of the dam over time, the dimensions of the dam were needed. A bathymetric survey of the dam was carried out in 2014. This survey was used to plot around 50 points in the dam onto an x, y, z coordinate system with (0, 0, 0) being the reference marker on the jetty. X, y and z values were equivalent to metres away from the reference point. This system can be seen in 2D in Figure 9.

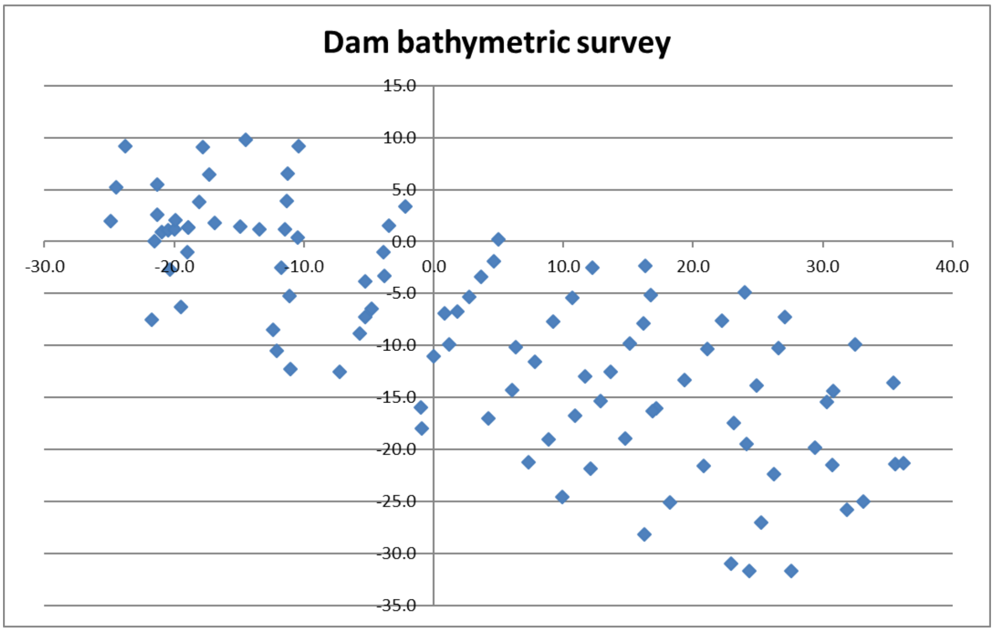

Figure 9: Dam dimensions in (x, y)

These points were entered into ArcMap and converted into a TIN using the "Create TIN" function. A TIN is a triangulated irregular network which was used to interpolate between the points given by the bathymetric survey to create a singular surface that represents the bottom surface of the dam. The output of the TIN can be seen in Figure 10. Elevation on the colour bar refers to metres below the reference point.

The TIN surface was used to calculate both the volume and surface area using the surface volume tool in the spatial analyst toolkit. The volume tool was set up to calculate the 2D surface area and volume of the dam below the reference plane every 5cm from a height of 0 to 2.7metres (the bottom of the dam). This series of volume and surface areas was plotted in excel with volume or surface area on the y axis and water level in metres below the reference point on the x axis. The trend line function in excel was used on both data sets to determine the water level-volume relationship and the water level-surface area relationship. These relationships can determine the volume in or the surface area of the dam on any given day from the measured water level.

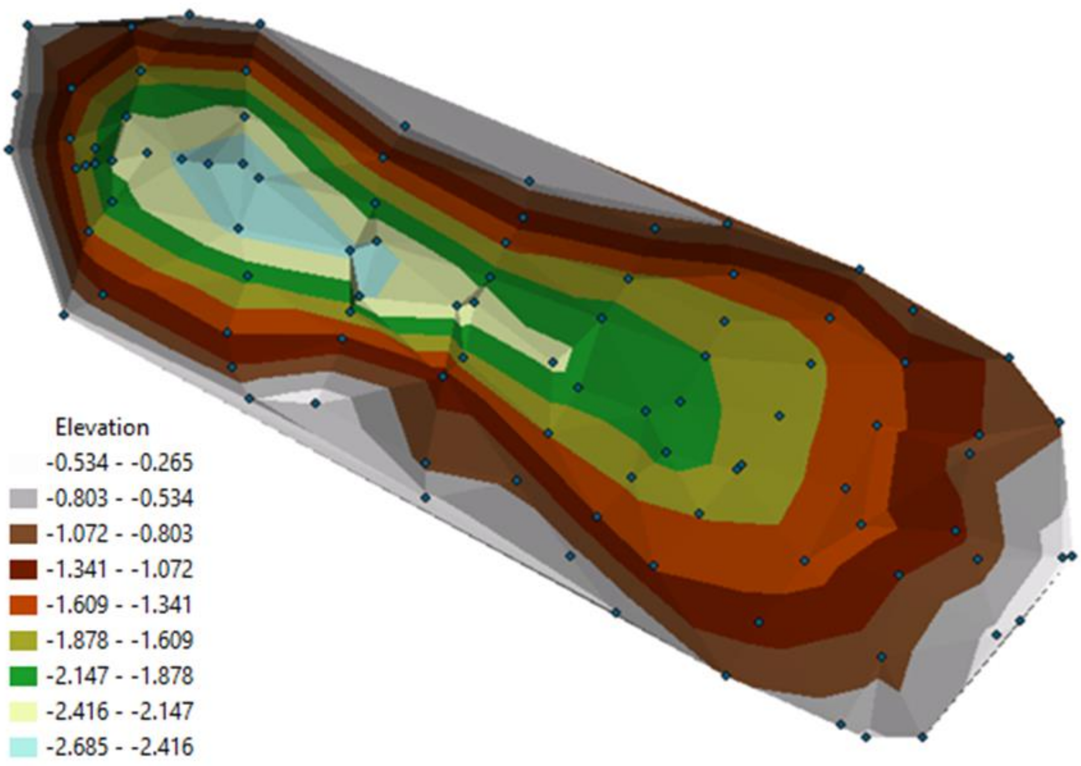

Figure 10: TIN surface

The water level-volume relationship and water level-surface area relationship graphs can be seen in Figure 11 and 12 respectively. The water level-volume relationship is illustrated in Equation 1 and the water level surface area relationship in Equation 2.

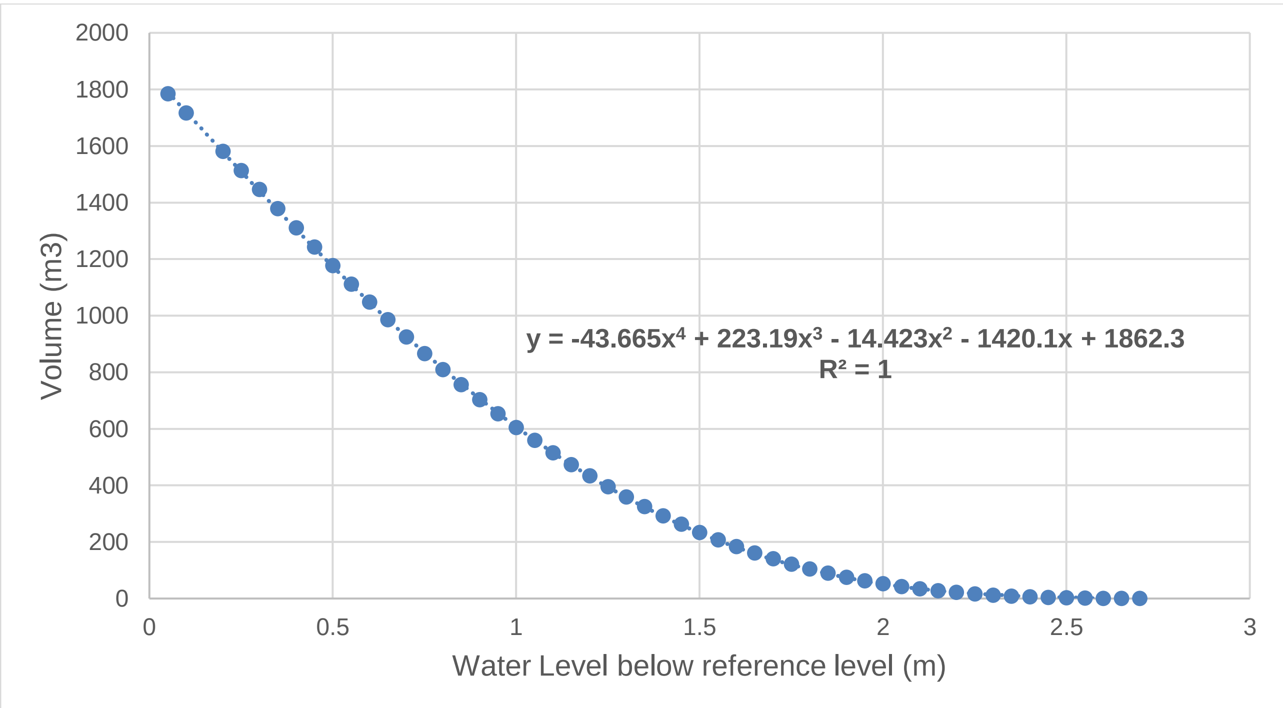

Figure 11: Water Level-Volume Relationship

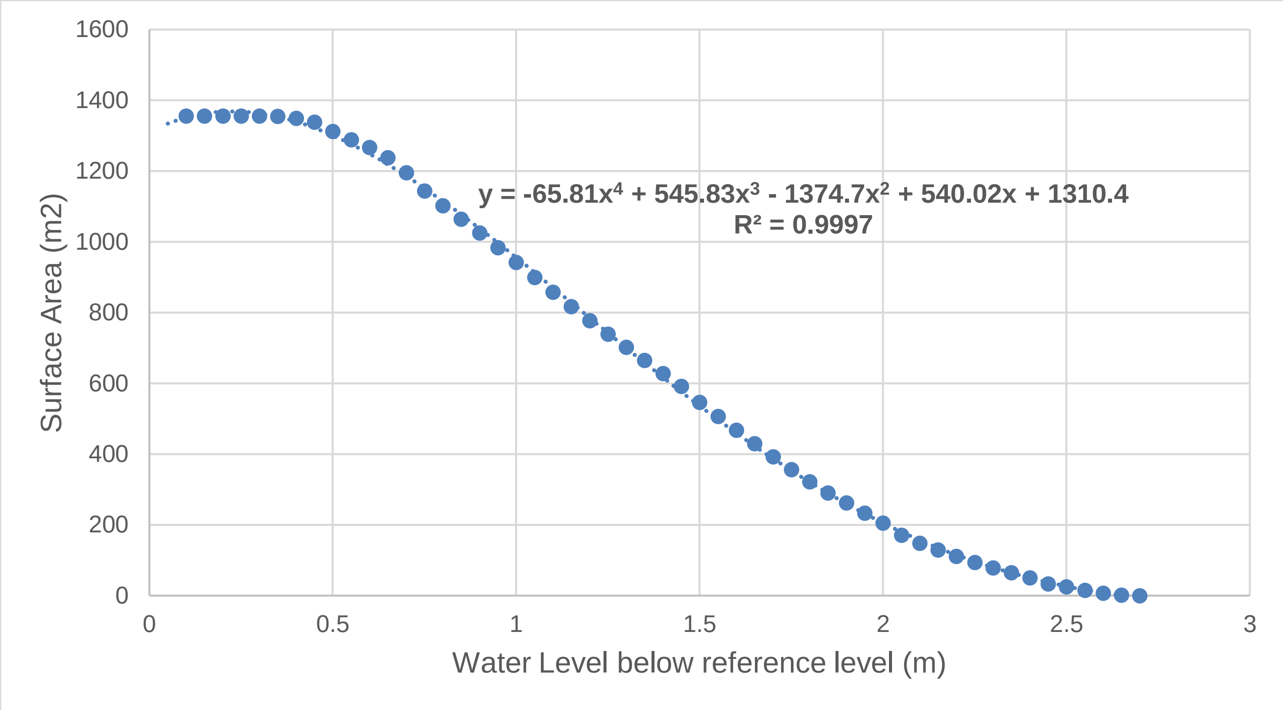

Figure 12: Water Level-Surface Area Relationship

Equation 1: Water Level – Volume Relationship

$$y = -43.7x^4 + 223.2x^3 - 14.4x^2 - 1420 + 1862.3 \quad \text{Equation 1}$$

Where x is the water level below the reference point in m and y is the volume of the dam in m^3.

Equation 2: Water Level – Surface Area Relationship

$$y = -65.81x^4 + 545.8x^3 - 1374.7x^2 + 540x + 1310.4 \quad \text{Equation 2}$$

Where x is the water level below the reference point in m and y is the surface area of the surface of the dam in m^2.

The trend line for each equation appears to have been fit extremely accurately, with an R^2 value of 1 for the water level-volume relationship and a value of 0.9997 for the water level-surface area relationship. Simpler trend lines with lesser degree polynomials could have been fit, however their R^2 values were not as high and there was potential for overestimation or underestimation of volume or surface area, which could lead to errors later in analysis. Therefore, it was decided that the equations presented in Equation 1 and 2 were the best representations of the trends in each graph respectively.

2.2.3 Water Levels and Dam Volume

Data from the water loggers was recorded as a pressure, the combined pressure of water and the atmosphere. To convert this into a meaningful value of water levels, the atmospheric pressure was subtracted. The resulting water level measurement in centimetres was adjusted to be in reference to the marker on the jetty. The marker on the jetty was measured to be 4 mm above the top of the well casing. The top of the casing is 153.4 cm from the top of the water logger (See well casing in Figure A4). So, the reference marker was a total 153.8cm above the top of the logger. Once the data was corrected to be in reference to metres below the marker on the jetty, daily averages of water levels were taken. The water level from 2013 was measured every hour, the loggers in 2014 measured approximately every 6 minutes, and the diver water level loggers in 2016 measured every half an hour. Most other parameters for the water balance are measured daily, so it was decided for ease of computation, the water level data would be converted to daily values instead of sub-daily values. This was done through averaging all the readings for a day, starting at midnight and ending at 11.59pm. It was decided that this was the most accurate way to convert the sub-daily readings into daily values. Average also reduces the effects of any potential random errors present from previous data processing.

2.2.4 Evaporation

Chapra, 2008 describes computations to estimate the daily losses due to evaporation from a water body. Equation 3 is used to convert daily pan evaporation data into the volume of water lost daily due to evaporation by the water body.

Equation 3 (Chapra, 2008):

$$Q_e = 0.01 k_p E_p A_s \qquad \text{Equation 3}$$

Where:

Q_e = evaporative water flow (m^3/day)

k_p = conversion constant (dimensionless)

E_p = pan evaporation rate (cm/day)

A_s = surface area (m2)

0.01 is included to convert from centimetres to metres.

The average value for k_p in the United States is 0.70, with a total range of 0.64 to 0.81 (Chapra, 2008) and so this value of 0.70 was used as an estimation in the absence of sufficient information from Australia. This is also in line with values from other literature (Winter, 1981; Rosenberry et al. 2007).

There were several days in the pan evaporation data where no measurement was taken. This meant that the measurement for the next day included evaporation for both that day and the previous day of no measurement. To account for this, the readings for days after days with no measurements were divided by the number of days consecutively that measurements were missed plus one (either one or two days were missing, this corresponded to averaging over two or three days respectively). This value was used for the missing days and the day immediately following.

There were large periods of time where no pan evaporation data was available at all. Evaporation is a key component of the water balance and another method was needed to determine the value. Two methods to achieve this were explored, from "*Surface Water-Quality Modelling*" (Chapra, 2008) where the equation for open water evaporation was obtained, and "*Applied Hydrology*" (Chow et al. 1988).

Equation 4 is used to estimate the volume of water lost daily due to evaporation by the water body based on meteorological conditions and the conditions of the water body.

Equation 4 (Chapra, 2008):

$$\boldsymbol{Q_e = 0.01\,\frac{f(U_w)(e_s - e_{air})}{L_e p_w}\,A_s} \qquad \text{Equation 4}$$

Where:

Q_e = evaporative water flow (m^3/day)

A_s = surface area (m2)

p_w = water density (g/cm^3)

$f(U_w)$ = a function of wind speed (see Equation 5)

L_e = Latent heat of vaporisation (cal/g) (see Equation 6)

e_s = vapour pressure corresponding to the water temperature (see Equation 7)

e_{air} = vapour pressure corresponding to the air temperature (see Equation 7)

0.01 is included to convert the final result to m^3/day

The wind function can be calculated using Equation 5 (Chapra, 2008):

$$f(U_w) = 19.0 + 0.95{U_w}^2$$ Equation 5

Where:

U_w = the wind speed (m/s) measured 7m above the water surface

The latent heat of vaporisation can be calculated using Equation 6 (Chapra, 2008):

$$L_e = 597.3 - 0.57T$$ Equation 6

Where:

T = Temperature (°C)

Both vapour pressures can be calculated using Equation 7 (Chapra, 2008):

$$e = 4.596e^{\frac{17.27T}{237.3+T}}$$ Equation 7

Where:

T = the surface water and dew point temperature to calculate e_s and e_{air} respectfully (°C)

Chow et al. (1998) also describe several methods for evaporation calculations in *Applied Hydrology*. The “energy balance method” is shown in Equation 8.

Equation 8 (Chow et al. 1998):

$$E_r = \frac{R_n}{l_v p_w}$$ Equation 8

Where:

E_r = evaporation rate (mm/day) (this then needs to be converted to volume of evaporative water flow from the water body per day)

R_n = net radiation (W/m^2)

l_v = latent heat of vaporisation kJ/kg (if using this method, l_v is calculated through equation 9)

p_w = water density (kg/m^3)

Equation 9, (Chow, 1998):

$$\boldsymbol{l_v = 2500 - 2.36T} \quad \text{Equation 9}$$

Where:

T = Temperature (^{o}C)

The radiation data from the weather station only gave values of total radiation for the day. This initially resulted in extremely large results for evaporation rate from Chow's equation. For a better estimate of net radiation, a calculation for extra-terrestrial radiation (Allen et al. 1998) was used. Extra-terrestrial radiation is the radiation received at the top of Earth's atmosphere. While this is not the exact net radiation (which is the difference between incoming and outgoing radiation) it was not possible to calculate the exact net radiation from the available parameters, so this is a much closer estimate than using the solar radiation from the weather station, which is the total radiation for the day, not accounting for any outgoing.

Equation 10, (Allen et al. 1998):

$$\boldsymbol{R_a = \left(\frac{24(60)}{\pi}\right) G_{SC} d_r [\omega_s \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\sin(\omega_s)]} \quad \text{Equation 10}$$

Where:

R_a = extra-terrestrial radiation (MJ/m^{2}day)

G_{SC} = solar constant = 0.0820 (MJ/m^{2}min)

d_r = inverse relative distance Earth-Sun (equation 11)

ω_s = sunset hour angle (radians) (Equation 12)

φ = latitude of location = -35.23 decimal degrees = -0.6149 radians (Google Maps, 2018)

δ = solar declination (radians) (Equation 13)

The inverse relative distance Earth-Sun is given in Equation 11.

Equation 11 (Allen et al. 1998):

$$\boldsymbol{d_r = 1 + 0.033\cos(\frac{2\pi}{365}J)} \qquad \text{Equation 11}$$

Where J is the number of the day in the year, between 1 and 365 or 366.

The sunset hour angle is given in Equation 12.

Equation 12 (Allen et al. 1998):

$$\boldsymbol{\omega_s = \arccos(-\tan(\varphi)\tan(\delta))} \qquad \text{Equation 12}$$

The solar declination is given in equation 13.

Equation 13 (Allen et al. 1998):

$$\boldsymbol{\delta = 0.0409\sin(\frac{2\pi}{365}J - 1.39)} \qquad \text{Equation 13}$$

Where J is as in Equation 11.

Once the evaporation rate E_r is calculated from Equation 9, this was converted to a volume of evaporation from the surface of the dam using Equation 3.

Most of the data required for these equations was obtained from the McLaren Vale weather station. The temperature of the day was estimated from the “average air temperature” value from the weather station. The average value was chosen instead of the minimum or maximum temperature to provide a more accurate representation of the weather conditions of the whole day, as often there could be a 10-20 degree difference between minimum and maximum temperature for the day. Using the maximum temperature could overestimate the evaporation rate and visa-versa with using the minimum temperature. This same reasoning was used in the dew point temperature, also taken from the weather station, from the “average dew point” value for the day. The value for wind speed was also taken from the wind speed measured at the weather station. An accurate value for wind speed on the property was not available, and so this was chosen as an appropriate estimate. It should be noted that the actual value for wind speed 7 metres above the dam will likely be different from the reading at the weather station, due to the station being located nearly 3km away from Michael's property. The dam is also surrounded by trees and vegetation which would affect wind speed. Water density was estimated as 1 g/cm^3 or 1000 kg/m^3 as in Chapra (2002). This is generally regarded as an accurate estimate of water density (Chapra, 2008; Chow et al. 1998) and so was used as such. Converting the water temperature into an accurate density for every day was not a feasible undertaking. The water temperature was taken from the water logger data. This temperature will likely differ slightly from the exact temperature of the surface of the water as this reading was taken in the wells not from the water's surface. The water temperatures were also measured every 6 minutes, and so this was converted into a daily average to align with the other data this has been done for.

It would be ideal to get all evaporation estimates using the pan evaporation data as the equation is much simpler, however the pan evaporation data is incomplete and does not span the entire study period. Therefore, Equation 4 or 8 will be needed to estimate evaporation losses in the dam during time periods where no pan evaporation data is available. Both methods will also be used to compare results each other and with the pan evaporation method. This is a useful process as it helps to gauge the reliability of the results; if both methods produce dramatically different results to the pan evaporation estimates this will suggest an error has been made in either the collection of the pan evaporation data or the meteorological data. One meteorological method may produce results that align closer with the pan evaporation data and this could suggest that it is the more reliable method. Multiple lines of evidence help to create a more accurate representation of the hydrology and dynamics of the dam and its surrounding catchment.

2.2.5 Transpiration

Transpiration from the vegetation around the dam is an important component of losses from the dam. The transpiration also represents horizontal seepage out of the dam in the water balance. Michael's dam is surrounded by River Red Gum trees (*Eucalyptus camaldulensis*) and so an estimation of their water uptake was needed. Marshall et al. (1997) estimated monthly average transpiration from four river red gum trees, both upstream and downstream of a dam using a heat-pulse technique in "Water uptake by two river red gum (*Eucalyptus camaldulensis)* clones in a discharge site plantation in the Western Australia wheatbelt". Their results for average monthly water uptake (as an average of the four trees) can be seen in Figure 13, where the filled bars are rainfall, the continuous line is water uptake and the dashed line is pan evaporation (Marshall et al. 1997). These results were compared with the reference evapotranspiration values for tall crops from the weather station, to see if monthly results were comparable. This comparison can be seen in Figure 15. The weather station records daily values for evapotranspiration, which were averaged into monthly values for two years for this comparison.

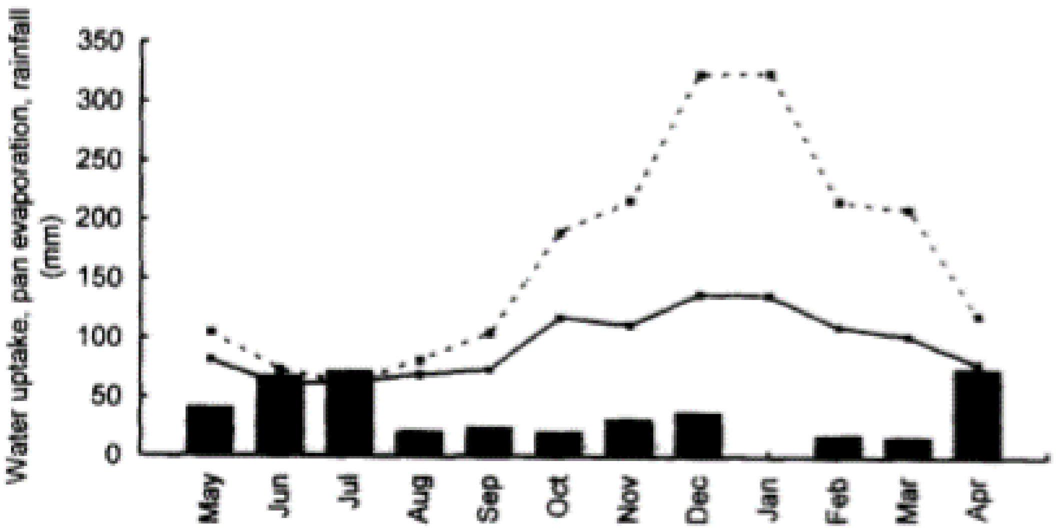

Figure 13: Average water uptake (continuous line) of river red gum trees compared to rainfall (filled bars) and pan evaporation (dashed line) (Marshall et al. 1997)

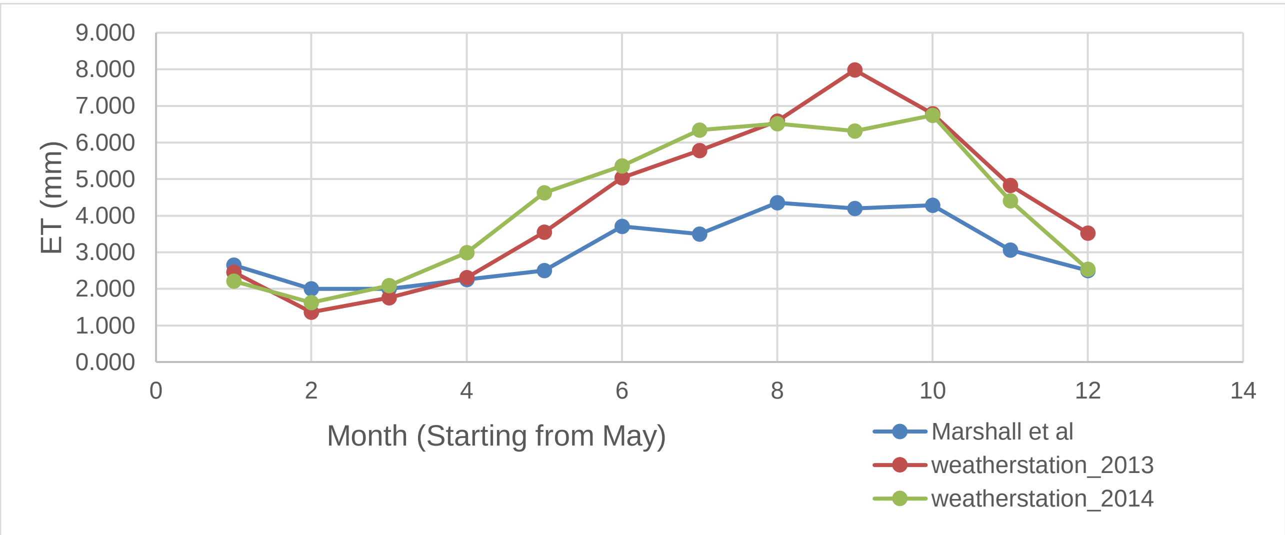

Figure 14: Comparing average monthly transpiration values from the weather stations to values from Marshall et al. (1997)

It can be seen from Figure 14 that both the transpiration values from Marshall et al. (1997) and from tall crops measured by the weather station follow the same overall trend, lower values in autumn and winter, with the highest values from December to January. The weather station values were mostly higher than those estimated by Marshall et al. with the highest error being nearly 4mm in January. However, there is large uncertainty surrounding the transpiration values from the weather station. It is unclear over what area these values were taken from, and the type of vegetation, the only information given was that it was taken from “tall” crops as opposed to “short” crops. For this reason, the values from Marshall et al. (1997) are to be used for further calculations, as they are from the same tree as the trees around Michael’s dam. However, the weather station values still provided a good comparison and show that the literature values follow the same overall trend. There will likely still be an error present in these values, due to differing climatic conditions, and different geographic locations influencing water uptake. Furthermore, Marshall et al. (1997) claim the heat pulse method has an accuracy of ± 10%. Nevertheless, these values still provide a reasonable estimate of transpiration rates of the red gum trees around the dam, and potential errors would likely be small and not have a significant effect on end results.

The monthly values from Marshall et al. (1997) were averaged into daily values per tree, seen in Table 1. It was assumed, through in person observations and aerial photography (Google Maps, 2018) that there were approximately 2.5 trees per metre of circumference of the dam. The circumference of the dam was calculated in ArcMap to be 160.6 metres. This was done by creating a polygon from the outer points in Figure 10 and determining the “shape length”. This gave an approximate area of trees around the dam of 266.5 m^2, which was multiplied by the daily water uptake in Table 1 to produce a daily time series of transpiration estimates.

Table 1: Water uptake from a single river red gum

Month	Total monthly water uptake (mm/tree)	Daily water uptake (mm per tree)
May	82	2.6
June	60	2.0
July	62	2.0
August	70	2.3
September	75	2.5
October	115	3.7
November	105	3.5
December	135	4.4
Jan	130	4.2
Feb	120	4.3
March	95	3.1
April	75	2.5

2.2.6 Infiltration

Vertical infiltration from the bottom of the dam into groundwater, was calculated using a modified version of Darcy's Law for flow rate through a medium, as shown in Equation 14. Any horizontal infiltration from the dam should be accounted for through the transpiration estimates.

$$\boldsymbol{q} = \mathrm{K}\ \frac{\boldsymbol{p_1} - \boldsymbol{p_2}}{\Delta \boldsymbol{L}} \qquad \textbf{Equation 14}$$

Where:

q = flux through the medium (cm/s)

K = hydraulic conductivity of the medium (cm/s)

p_1 = water level in the logger at the dam jetty (cm)

p_2 = water level in the piezometer in the dam (cm)

ΔL = vertical distance between where the two loggers measure (cm)

A value for hydraulic conductivity of the soil in the dam, K, was estimated based on the properties of the soil found on Michael's property, and the table shown in Appendix B, Figure B1, (Freeze and Cherry, 1979). Exact properties of the soil on Michael's property was unknown, and so two K-values were taken from this table to provide two sets of results that can be compared in the final result. K = 10^{-8} cm/s was chosen to represent clayey soils on the property with a smaller permeability, and K = 10^{-5} cm/s was chosen to represent more silty loams with an increased permeability.

ΔL was estimated from the difference between p_1 and p_2 in summer months when the soil was dry. For data from 2013-2014 this was approximately 50 cm. For the 2016 data, this was approximately 35 cm, a piezometer in a different well was used for the 2016 calculations.

For both time series, the average for each day was taken, as described in Section 2.2.3 with the water level data. For each day, the flow rate through the medium was multiplied by the surface area of the bottom of the dam on that day, to give a total volume of infiltration from the dam into the groundwater.

2.2.7 Water Balance

Estimating the water balance of the dam involved bringing all the separate components previously calculated together. The simplified equation for a water balance is shown in Equation 15.

$$\Delta \boldsymbol{S} = \boldsymbol{I} - \boldsymbol{O} \qquad \text{Equation 15}$$

Where ΔS refers to the change in storage per day, I is the volume of inputs into the dam's storage, and O is the volume of outputs from the dam.

Change in storage for the dam was calculated daily, based on the daily time series of dam volumes. Inputs to the dam volume are streamflow (SF), and rainfall (P) and run-off (RN). Outputs are evaporation from the surface of the dam (E), transpiration from the trees around the circumference of the dam (T) and any infiltration losses (IF).

There was an absence of reliable streamflow data, and so this is the major unknown in the water balance. Future studies could utilise a proper rainfall run-off model to more accurately estimate inflows into the dam, this was not done due to time and scope of this project, as well as lack of viable streamflow data. For ease of computation, the volume time series were separated, to represent periods where the dam was filling up, and periods where the dam was emptying or "wet" and "dry" periods respectfully.

"Wet" periods, where the dam was filling were from 6/6/2013 until 22/7/2013 and from 22/6/2016 until 2/9/2016. In 2013, the dam does not start filling considerably until the 29th of June, however there are periods of significant rainfall between the 6th of June and then, so this was still included as a "wet" time period. In 2016, from the 8th of July until September, there is not a clear increasing trend in the dam's storage, the volume of the dam stays roughly the same with a slight increasing trend. There is still significant rainfall during this period, and the overall trend was an increase, despite this increase being small, and so it was still included as a "wet" time period. "Dry" periods where the dam was emptying were from 23/7/2013 until 27/12/2013, from 7/12/13 until 13/2/14, from 25/7/14 until 6/9/2014 and 2/9/2016 until 22/12/2016. There was still intermittent rainfall until September or October in most years, however overall these can be classified as "dry" periods.

For periods where the dam is filling, and storage is increasing, or "wet periods" the soil has already been saturated and so losses due to infiltration can be assumed to be zero. This now makes the water balance equation:

$$\Delta \boldsymbol{S} = \boldsymbol{P} + \boldsymbol{OF} - \boldsymbol{E} - \boldsymbol{T} \quad \text{Equation 16}$$

Where precipitation is rain falling directly on the dam, and OF refers to the overland flow. This equation was solved for overland flow to estimate the daily inputs into the dam. Overland flow in this context includes stream flow and also any surface run-off, although surface run-off would be minimal compared to stream flow.

Precipitation falling directly on the dam's surface was calculated using two methods. Firstly, daily precipitation was multiplied by the surface area of the dam on that day. The second method assumed that all rainfall falling in the direct proximity of the dam would contribute to storage, as the soil is already saturated. This involved multiplying the daily rainfall by the maximum surface area of the dam, given from Figure 13 to be approximately 1350 m^2.

For periods where the dam is emptying, or "dry periods" it can be assumed that there is no overland flow, from streamflow or surface run-off. There were still some days of minimal rainfall during these periods, but the amount is small and not continuous enough to generate any run-off or stream flow as the creek runs completely dry during these periods. This now makes the water balance equation:

$$\Delta \boldsymbol{S} = \boldsymbol{P} + \boldsymbol{OF} - \boldsymbol{E} - \boldsymbol{T} - \boldsymbol{IF} \quad \text{Equation 17}$$

Where precipitation is rain falling directly on the dam. This could be assumed to be zero, as rainfall during these periods is minimal, however it was kept in as there were some days of rainfall. Precipitation for the day was calculated by multiplying the daily precipitation by the surface area of the dam on that day, so it was only including rain that falls directly on the water's surface of the dam. The second method of calculating precipitation for the day was not used for periods where the dam is emptying, as the soil is not saturated and rain that falls on bare ground would not run-off.

This equation was solved for infiltration, and also solved for change in storage with the calculated infiltration values, as discussed in Section 2.2.6, to compare and contrast results from the different methods, and find any sources of errors. Errors could have occurred while calculating the infiltration, calculating the other components of the water balance, or from another source of losses of storage that has not been considered, such as spillage.

3. Results

3.1 Dam Storage

After converting the water level measurements into daily volumes of the dam as described in Section 2.2.2 and 2.2.3, results were graphed to be compared and contrasted. Figure 15 shows the daily dam volume for the 2013 and 2016 data. Error bars derived from the standard error of each time series are depicted to account for errors in data collection and processing, and any errors from conversion of the data from a water level to a volume with the assumptions in Equation 1. These were the only water level data that were recorded at the same time of year, and as such the only data that is comparable between years. The general trend for both years appears the same, a steady volume until July, with a quick increase and then steady decrease over spring. The dam began to fil later in 2013 than in 2016, around the 30th of June, and was full by the 21st of July. From the 21st of July until late August, there is a slow but steady decrease in volume, followed by a large decrease from the beginning of September until the end of the year. 2016 follows a similar pattern, although the dam begins to fill sooner, in mid-June as opposed to late June, reaching a steady state around the 7th of July. The volume of the dam remains roughly the same, with a slight increasing trend for approximately a month, before starting to empty around the 7th of September.

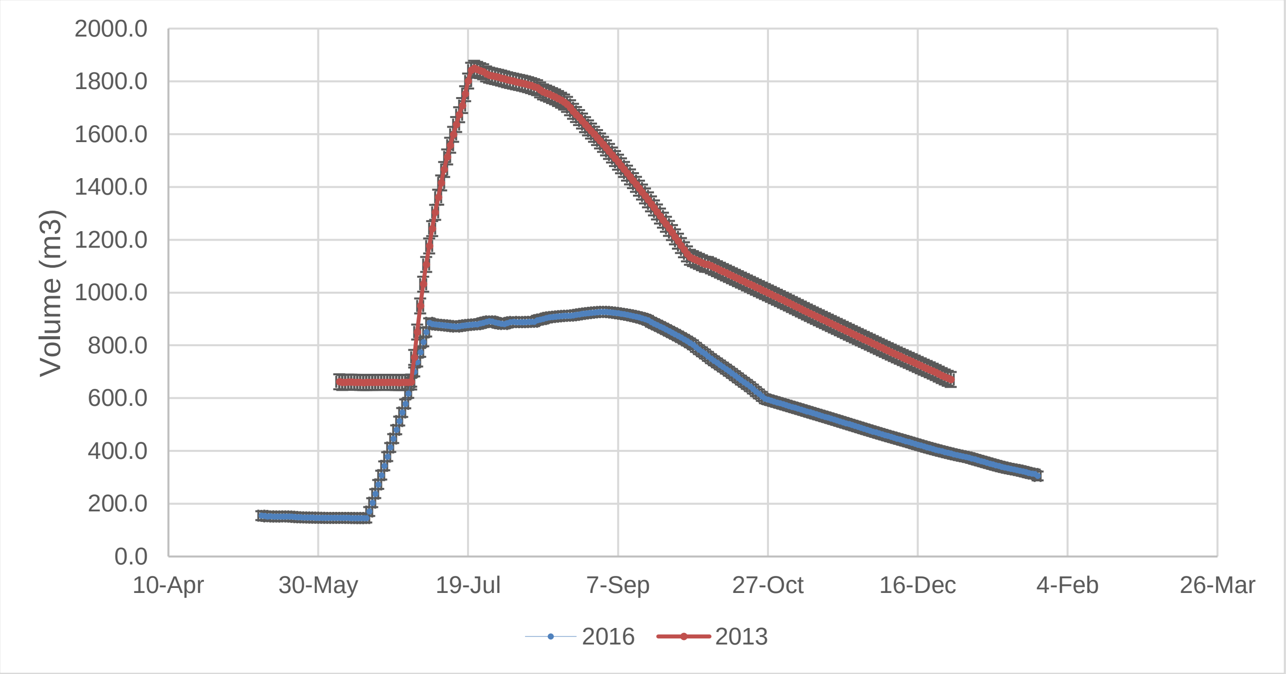

Figure 15: Comparing daily dam storage in 2013 and 2016

A large difference between the volumes of each year is that the volume in 2013 is significantly larger than in 2016. The 2016 time series seems to follow the same pattern as 2013, but with much lower values. At the start of winter in 2016, the dam volume was sitting around 150 m^3, while at the same time in 2013, the dam was at around 650 m^3. In 2013, the initial decline from around the 21st of July to the 21st of August was at a slope of approximately -4.4 m^3 per day, which increased significantly to a slope of approximately -14.5 m^3 per day in the steep period of decline from the 21st of August until the end of September, the fastest decline of any recorded time period. This decline lessened at the end of September, having a slope of approximately -5.7 m^3 per day for the rest of the year. By comparison, the 2016 volume only had two distinct periods of decline, a steep decline from mid-September at a slope of approximately -7.8 m^3 per day, before decreasing at the end of October to an approximate slope of -4.2 m^3 per day. Not only does 2013 have larger volume but also sees a much faster decline between August and September. From November onwards, both years see a comparable rate of decline 5.7 m^3 per day and 4.2 m^3 per day in 2013 and 2016 respectfully.

The daily rainfall from the McLaren Vale weather station for the time periods of 2013, 2014 and 2016 is shown in Figure 16 to help understand what may be causing this discrepancy in volumes between the two years. The weather station did not have data for the 2016 period until the 22nd of June, and so Figure 16 only shows rainfall from the 22nd of June in all years.

From Figure 16 and the descriptive statistics shown in Appendix D, Table D1, it can be seen that there was significantly more rainfall in 2016 than in 2013, which is not reflected in the results of the dam's volume. The average daily rainfall over this period for 2016 was nearly 1mm more than the average for 2013, and the maximum daily value (37.6 mm) was nearly double that for 2013 (21.4). In late June and early July, rainfall in 2016 was much higher than 2013, although days in 2013 around the middle and end of July showed a higher rainfall than 2016. Rainfall in 2013 also started to decline around mid-September while in 2016 there were periods of notable rainfall after then.

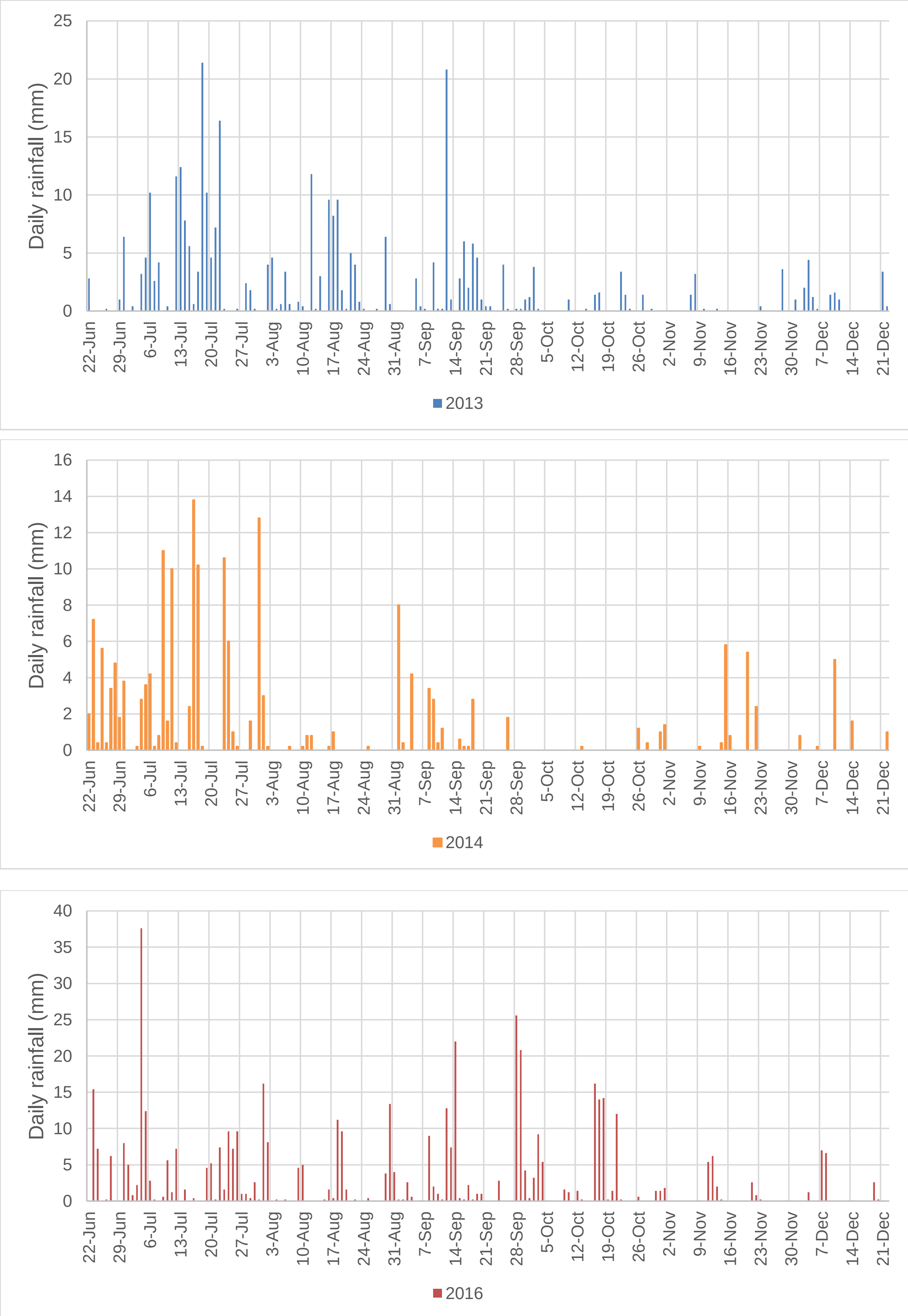

Figure 16A, B and C: Comparing daily rainfall in 2013, 2014 and 2016

Figures 17 and 18 show the daily volume of the dam in the summer of 2013 and 2014, and the spring of 2014 respectfully. Error bars on both time series represent the standard error. Both of these time series show a consistent decline that would be expected from data in Summer and Spring (Nathan and Lowe, 2012). The decline in the summer of 2013 and 2014 before plateauing off is at a slope of approximately -9.1 m^3 per day, compared to the approximation -5.8 m^3 per day for the same time period in Figure 15. Several days overlap in the data in 2013 (Figure 15) and the summer of 2013 and 2014 data. Comparing the dam volumes, the data from the Solinst loggers in 2013 gives much higher water levels, and therefore volumes than the data measured with Druck sensors in summer of 2013 and 2014. In December, volumes from the Solinst loggers are between 800 to 700 m^3, while the highest volume given from the Druck sensors is only 375 m^3. The 2016 data in December (ranging from approximately 450 to 350 m^3) is more consistent with the data in December measured with the Druck sensors.

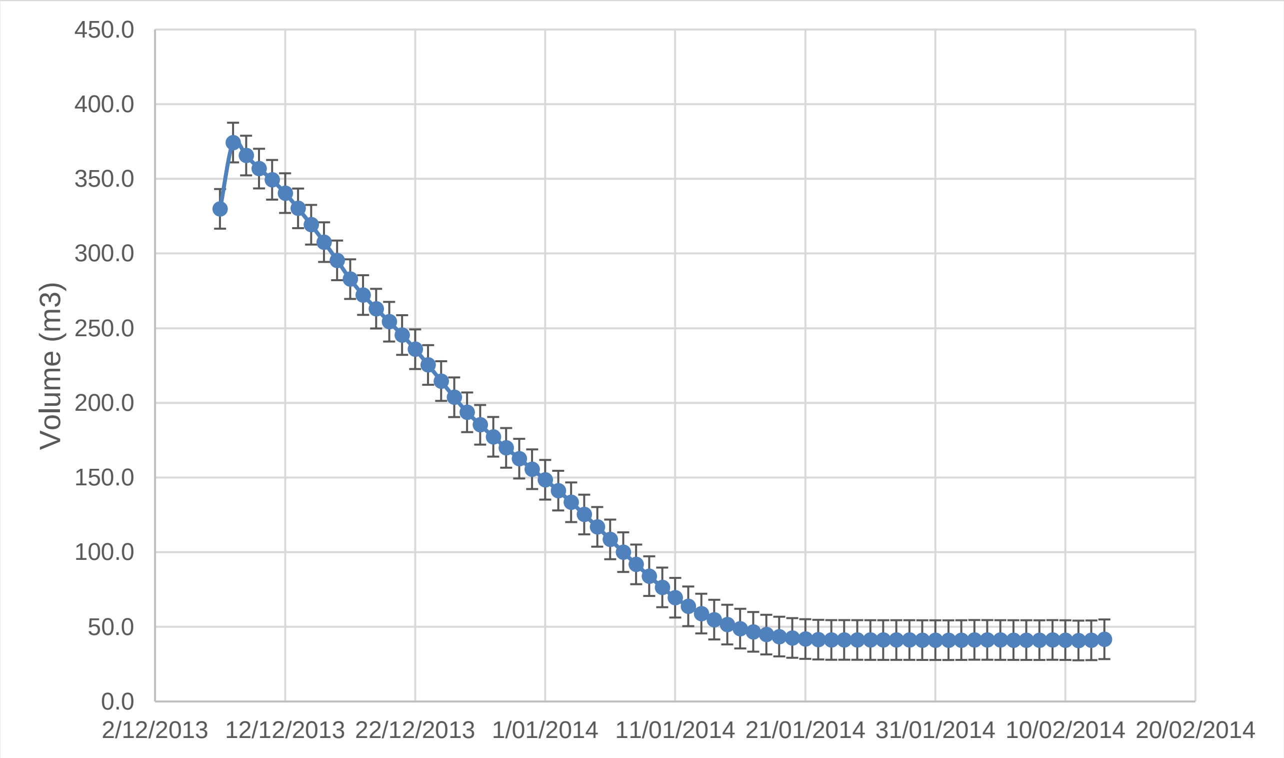

Figure 17: Daily dam storage in Summer of 2013 and 2014

The volume in the spring of 2014 (Figure 18) is lower than in the summer of 2013 and 2014. The 2014 data shows the dam is nearly empty (at around 35 m^3) by the start of September. The volume is declining with a slope of approximately -2.81 m^3 per day, the lowest decline of any of the time periods.

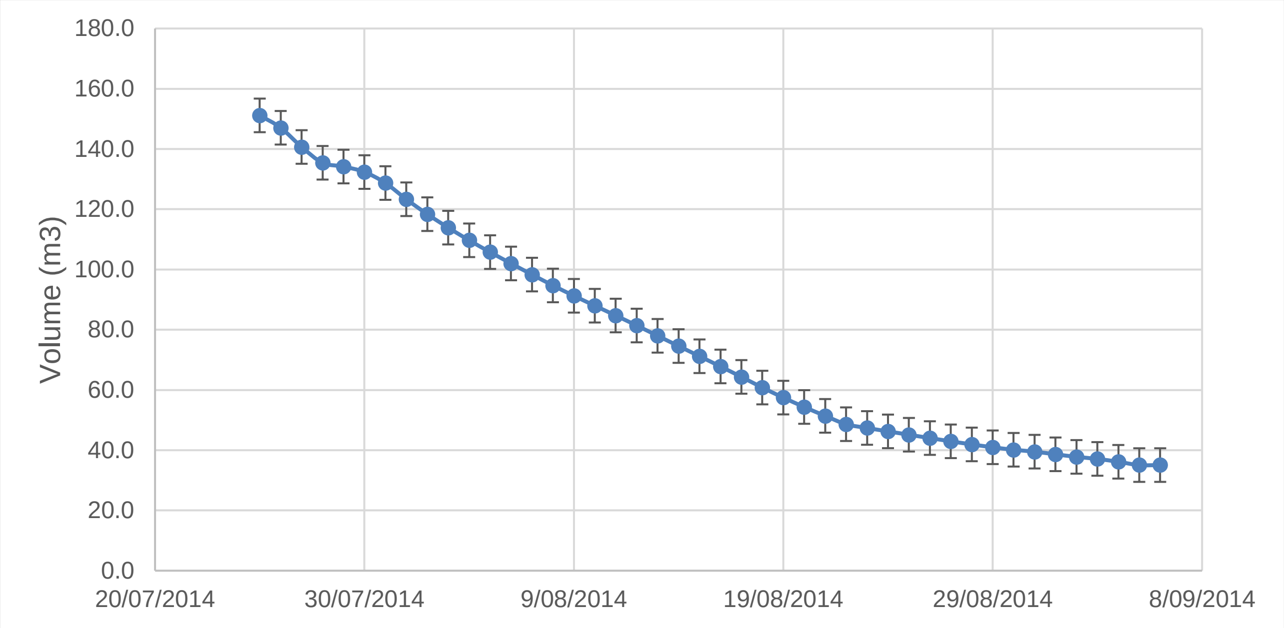

Figure 18: Daily dam storage in Spring 2014

3.2 Evaporation

Pan evaporation where available was calculated using Equation 3 as described in Section 2.2.4. Pan evaporation data was not available for most of the same time period as the 2013 water level data, or any of the 2016 period, and so, two alternative methods to estimate open water evaporation from the surface of the dam were used to find the closest approximation. Equation 4 (Chapra, 2008) and Equation 8 (Chow et al. 1998) describe these estimations. Both were calculated over all periods of time with streamflow data, to compare to each other and to the results from the pan evaporation, which would be the most accurate estimate. Figures 19, 20 and 21 show the results of the total evaporation from the surface of the dam from pan evaporation, estimation from Chapra and estimation from Chow over the time pan evaporation data was available in 2013, summer of 2013 and 2014 and spring of 2014. Figure 22 does not include pan evaporation data but illustrates the differences between the estimation based on Chapra's method and Chow's method. The error between the pan evaporation data and each method of estimation was calculated for each day, and descriptive statistics are shown for these errors in Table 2.

While the descriptive statistics in Table 2 show that the minimum and maximum error from the pan evaporation estimate are smaller using Chow's method, Figures 19, 20 and 21 show a major difference in trends between the estimate from pan evaporation and the estimate from Chow. The estimate of evaporation from the pan data fluctuates daily while the trends from Chow are constant. While there are differences between the estimate from the pan data and the estimate from Chapra, they both seem to follow similar trends in Figures 19 and 20, fluctuating daily and peaking and falling at the same times. In the end of 2013 the estimate from Chapra is generally giving a slightly lower value than the estimate from the pan, while in the summer of 2013 and 2014, the estimate from Chapra is almost always higher. The average error between the estimate from pan evaporation and the estimate from Chapra for all the time series is lower than the average error from Chow, and so is the total error.

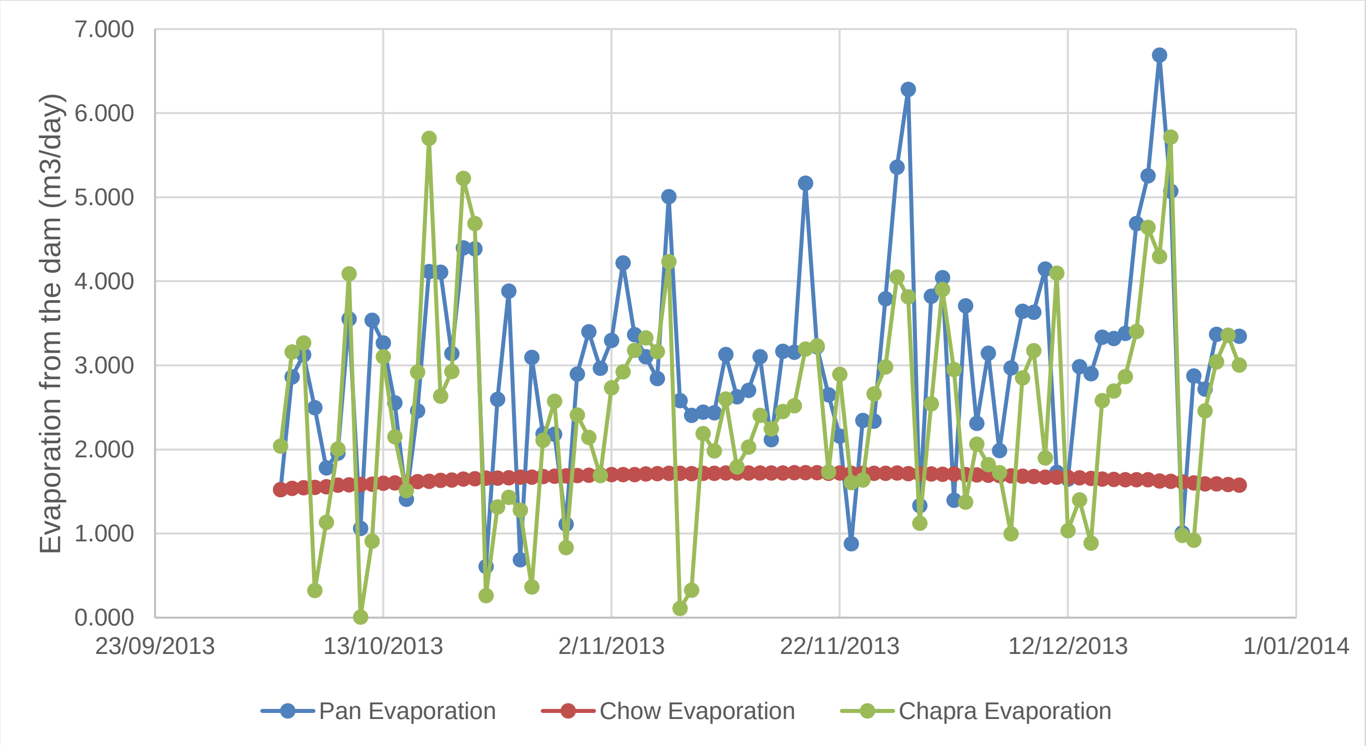

Figure 19: Evaporation estimates from 2013

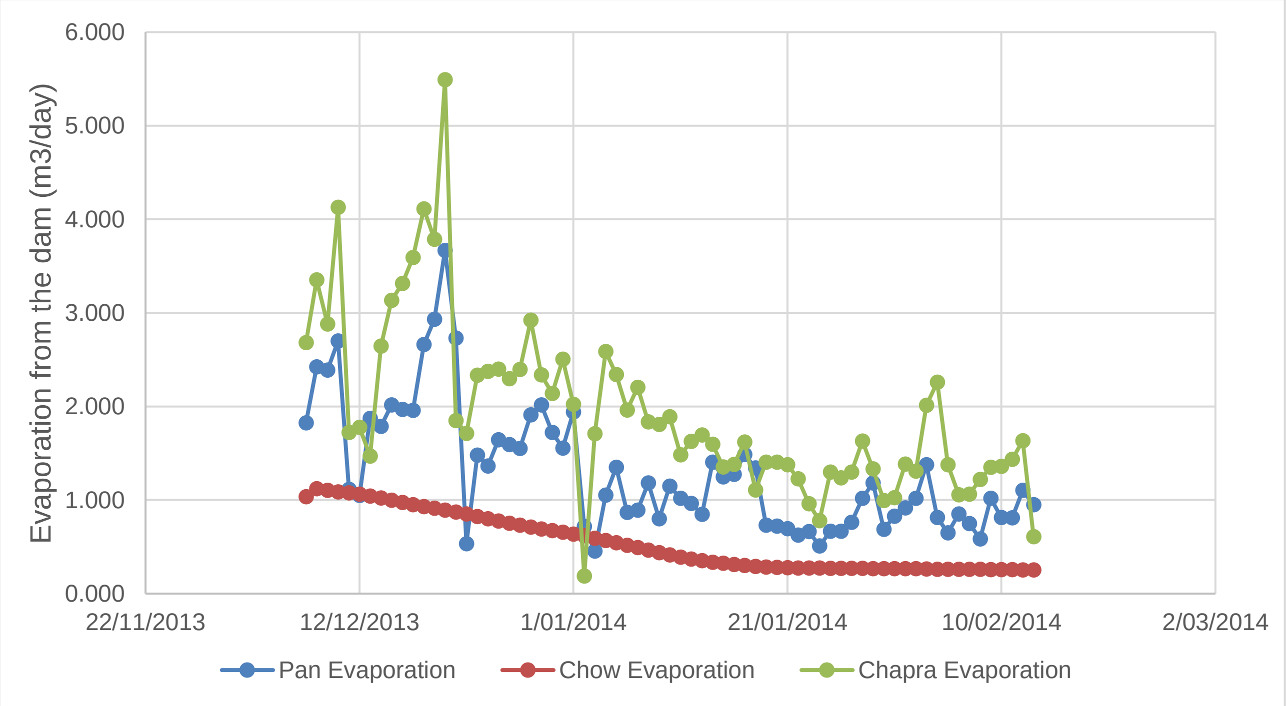

Figure 20: Evaporation estimates from summer of 2013 and 2014

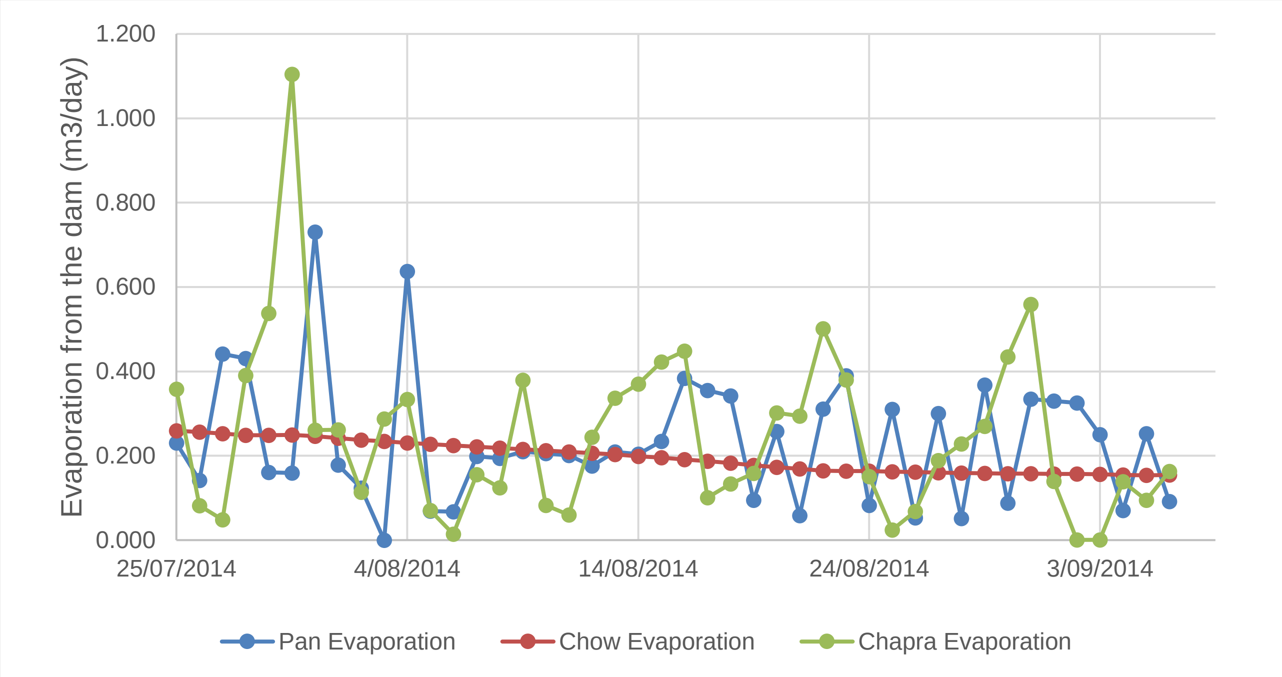

Figure 21: Evaporation estimates from spring of 2014

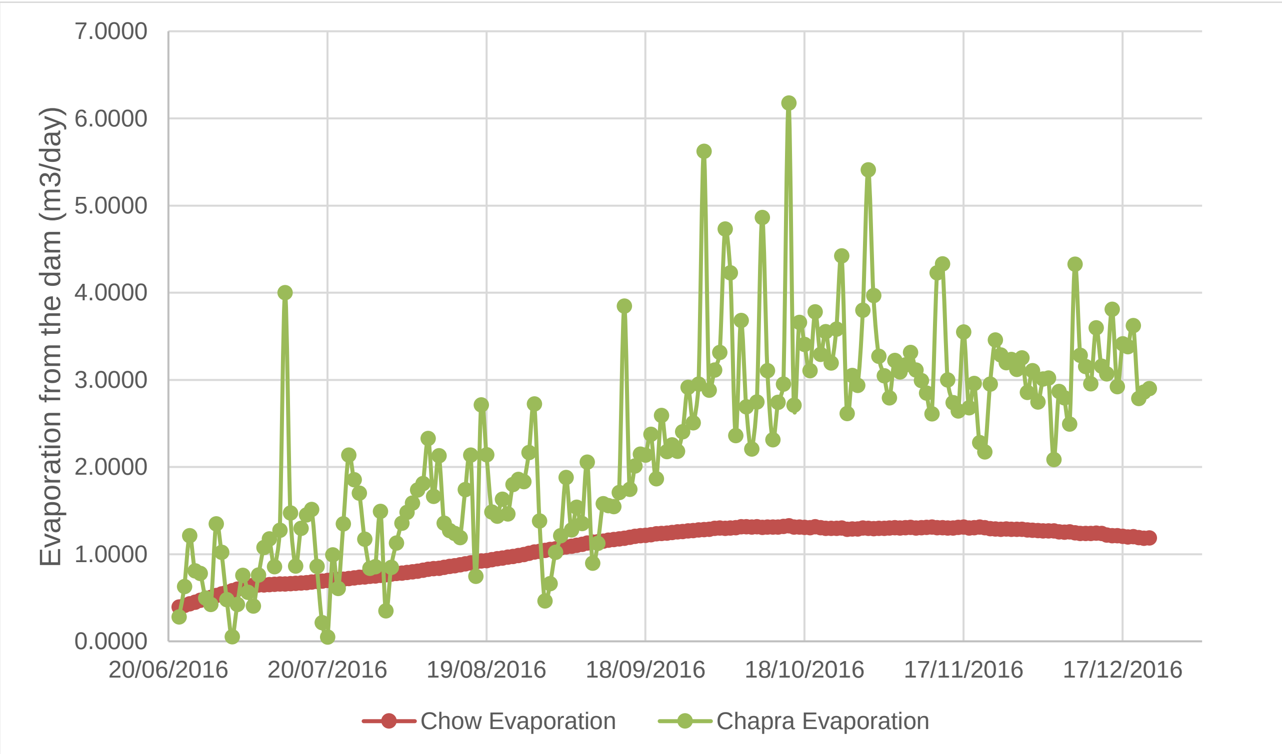

Figure 22: Evaporation estimates from 2016

In the spring of 2014, shown in Figure 21, the estimates from Chapra's method do not seem to follow the estimates from the pan evaporation as closely as in Figures 19 and 20. However there are still similar times of peaks and troughs and the estimate is much closer than the estimate from Chow's method. Figure 22 shows the estimates from Chow and Chapra in the 2016 time period. There is no pan evaporation data to compare either estimate to in this time, but it seems to be following similar trends to the three previous figures. The estimate from Chapra fluctuates with each day, while the estimate from Chow only shows a steady increasing pattern that plateaus from October to December. Based on the results shown in Figures 19, 20 and 21, it is more likely that the estimate from Chapra is closer to the estimate from the pan evaporation and is a more reasonable method to use in place of the missing pan data. Based on the results shown in Figures 19 to 22, and also Table 2, the decision was made to not proceed further with the estimates given by Chow's method, and to use estimates given by Chapra's method when the estimates from the pan evaporation data was missing. The estimates from pan evaporation are still the more desirable data and are to be used wherever possible.

Table 2: Descriptive statistics of the error between the pan evaporation estimate and the estimates calculated by Chow and Chapra

Chow Error (m^3)		***Chapra Error (m^3)***	
Mean	0.9	Mean	0.7
Standard Error	0.1	Standard Error	0.1
Median	0.7	Median	0.5
Standard Deviation	0.9	Standard Deviation	0.8
Minimum	0.0	Minimum	0.0
Maximum	5.1	Maximum	5.2
Sum	185.3	Sum	145.9
Count	198	Count	198
Confidence Level (95.0%)	0.1	Confidence Level (95.0%)	0.1

3.3 Transpiration

Transpiration rates were estimated from Marshall et al. (1997). Their estimates were for the total water uptake in a month, so this was averaged into a daily water uptake, which was then multiplied by the area of trees around the dam. Table 3 shows the results of this. These results show an expected pattern of transpiration, lower from winter until early spring, with the rate more than doubling in the summer months.

Table 3: Transpiration estimates

Month	Monthly water uptake (mm/tree)	Daily water uptake (mm per tree)	Daily water uptake from area around the dam (m3)
May	82	2.6	0.7
June	60	2.0	0.5
July	62	2.0	0.5
August	70	2.3	0.6
September	75	2.5	0.7
October	115	3.7	1.0
November	105	3.5	0.9
December	135	4.4	1.2
Jan	130	4.2	1.1
Feb	120	4.3	1.1
March	95	3.1	0.8
April	75	2.5	0.7

The value of the total daily water uptake from around the dam was applied to each day based on the respective month. An example of this can be seen in Figure 23, which shows the transpiration for the 2013 and 2016 time periods. Error bars represent potential errors occurring from the assumptions made by Marshall et al. (1997), as well as assumptions regarding the area of trees around the dam and averaging monthly values into daily values. There are potential errors up to ± 0.25 m^3 based on these error bars.

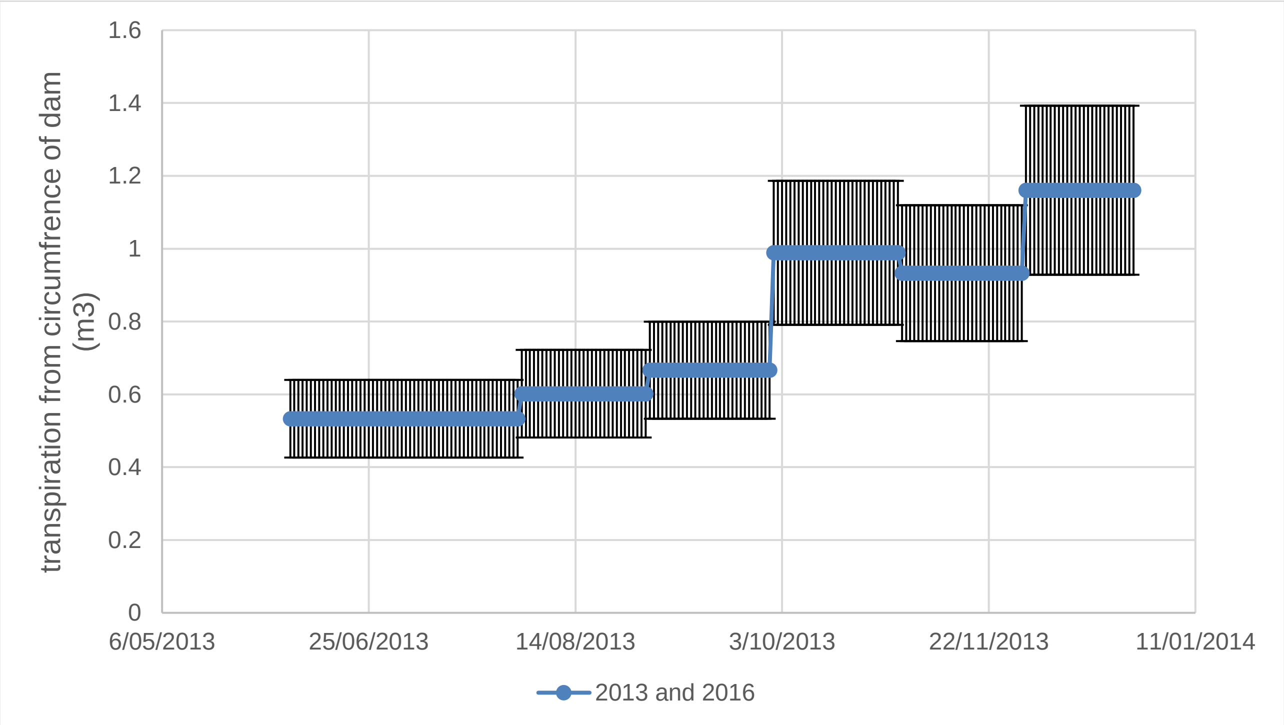

Figure 23: Transpiration estimates for 2013 and 2016

3.4 Water Balance

The results from the water balance are split into “wet” periods, or periods of time where the dam is filling, and “dry” periods, or periods of time where the dam is emptying, to estimate inflows and losses due to infiltration.

3.4.1 Inflows

The inflows into the dam were calculated during “wet” periods, or periods where the dam was filling. Inflows in this context refers to the flows coming into the dam from the stream, however it is likely that inflows from run-off are also contributing. In the absence of a rainfall-run-off model, only inflows from the stream were focused on, as they contribute significantly more to the dam’s volume than run-off. Figures 24 and 25 show the inflow estimated from the water balance for the wet periods in 2013 and 2016 respectfully. Both graphs compare the estimated inflow using two different inputs for rainfall contributing to the dam, one method, using a dynamic surface area, multiplies the daily rainfall by the surface area of the dam on that day, while the other assumes that all rainfall falling in direct proximity of the dam contributes to its storage, and so multiplies the daily rainfall by a constant maximum surface area, as described in Section 2.2.7. Error bars on both graphs represent the potential error cumulated by the assumptions made in the previous steps as components to the water balance. There were a couple of negative values for inflows; these were days in which the dam’s volume decreased instead of increasing. It was assumed any days which yielded a negative inflow meant that the stream was not flowing at all that day and inflows were zero.

The inflows for 2013 do not differ greatly depending on which method for contributing rainfall was used. The largest error was a difference of 5 m^3 on the 10th of June, and this was a day when the dam actually lost volume, and so the inflow would most probably be zero anyway. The first half of this graph shows very little inflow, corresponding to the same time period shown in the first part of Figure 15 when the volume is mostly constant. The dam does not start filling considerably until the 29th of June, however there are periods of significant rainfall between the 6th of June and then, so this was still included as a “wet” time period. The largest inflows occur in the first 6 days of July, with inflows from the stream of up to 100 m^3 in a day. These inflows begin dropping down to only 30 m^3 after the 11th of July, and going negative by the 21st, the same time the volume begins to sharply decrease in Figure 15. Comparing 2013 to 2016, the inflows for 2016 also do not differ significantly based on the method used to determine rainfall inputs, shown in Figure 25.

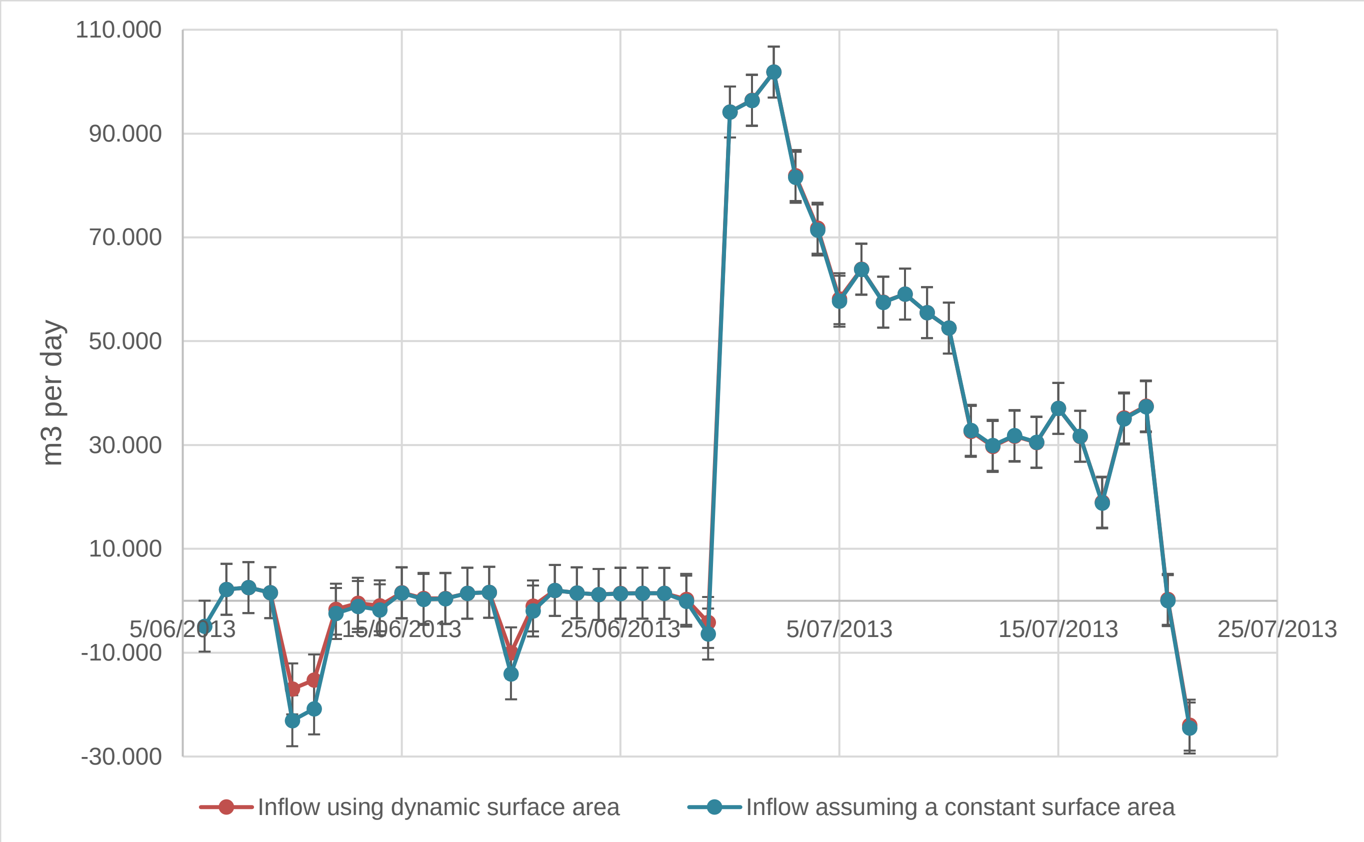

Figure 24: Estimated inflow from the water balance for the 2013 time period

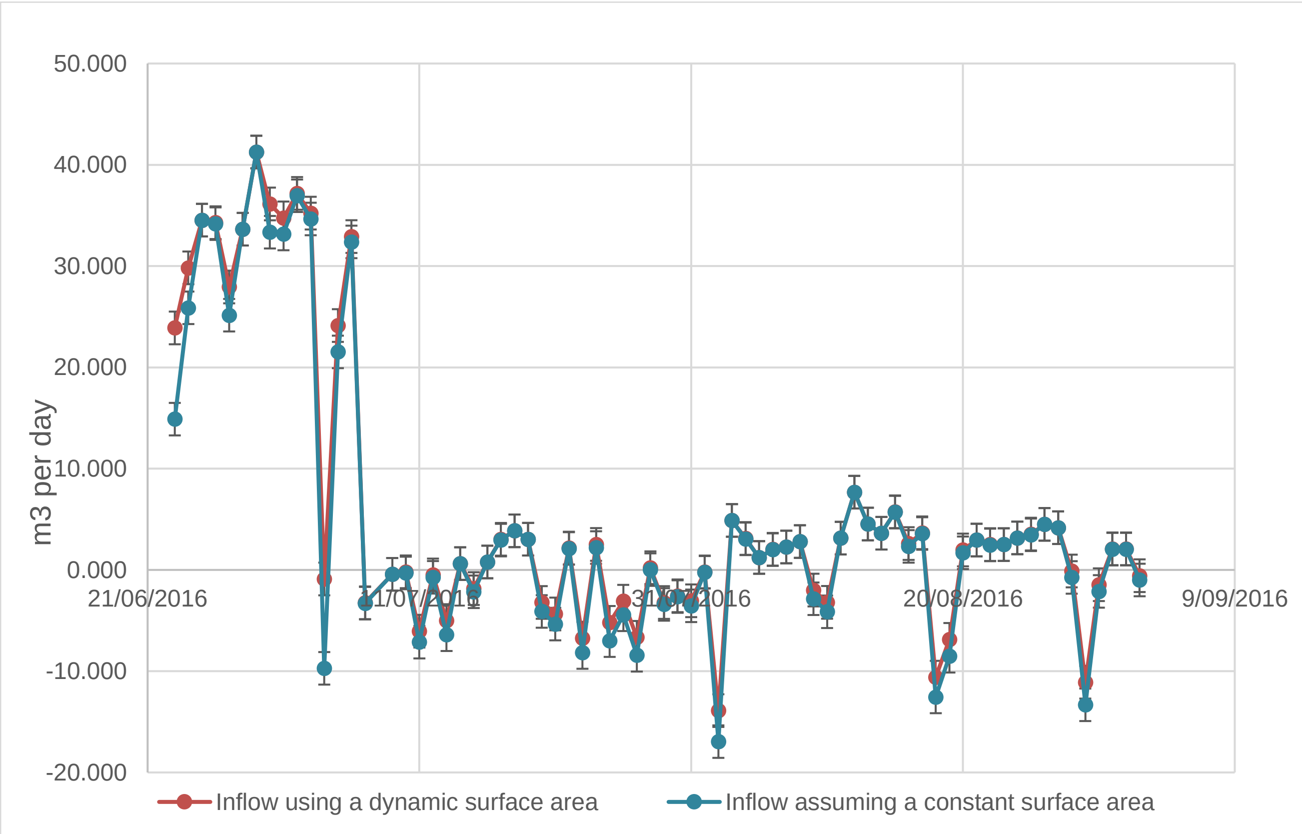

Figure 25: Estimated inflow from the water balance for the 2016 time period

3.4.2 Total Inflows

Figures 26 and 27 show the total inflows estimated from the water balance in 2013 and 2016 respectively. This represents the sum of rainfall falling directly on the dam, streamflow and run-off. Only the inflow calculated using the dynamic surface area was used, as it made no significant difference which rainfall method was used. The total inflows for both years follow the same patterns as the estimated inflow from streamflow shown in Figures 24 and 25. 2013 saw inflows as large as 100 m^3 at the start of July, while the major inflows in 2016 occurred at the end of June and early July and were only as large as 45 m^3. The inflows in 2013 were all very small, around 0 to 5 m^3 per day before extremely large inflows in the beginning of July. After the first 3 days of over 90 m^3 per day coming in, the trend of the inflows decreases, although there are still significant volumes coming into the dam. The wet period in 2013 saw an estimated total inflow of 1256 m^3, and an average daily estimate of 27.3 m^3 per day. The wet period for 2016 started slightly later than for 2013, and the inflows during the start of this period, from late June to early July were the largest, before this declined to inflows of between 0 and 10 m^3 in a day. Total for the wet period of 2016 was estimated to be 680 m^3, with an average of 9.7 m^3 per day.

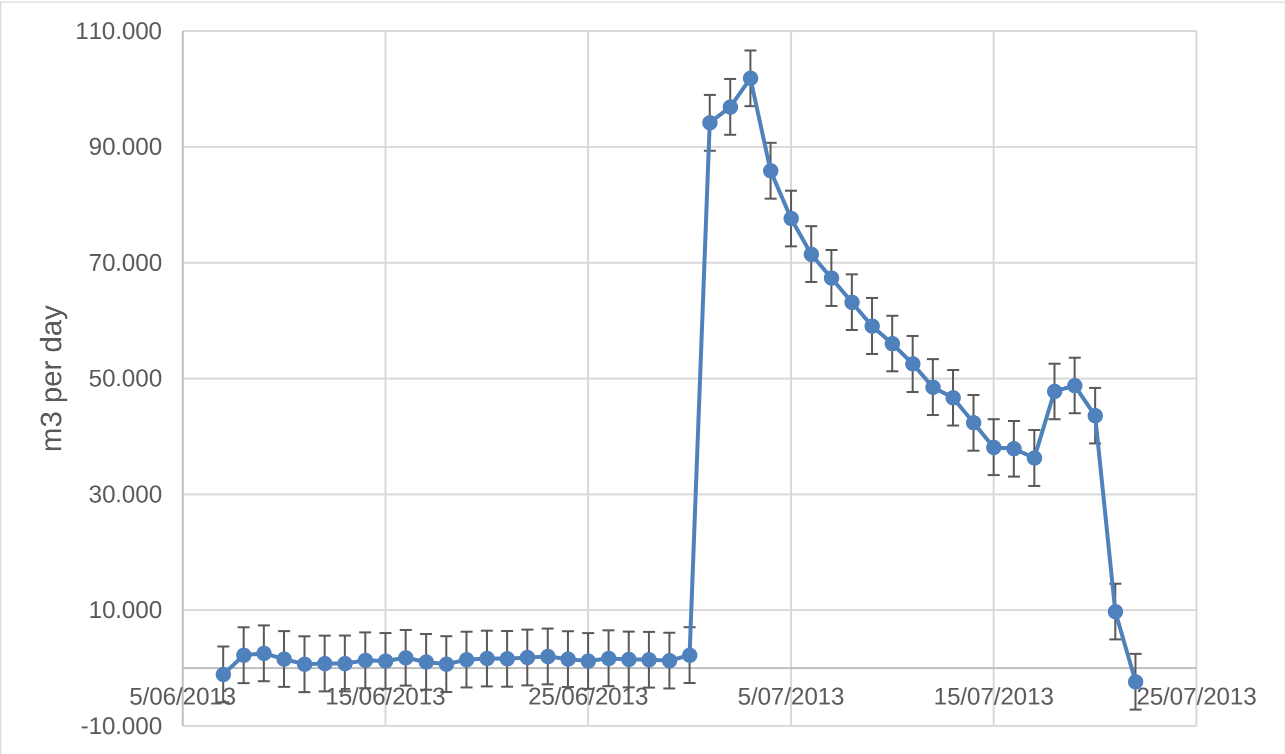

Figure 26: Total daily inflows in 2013

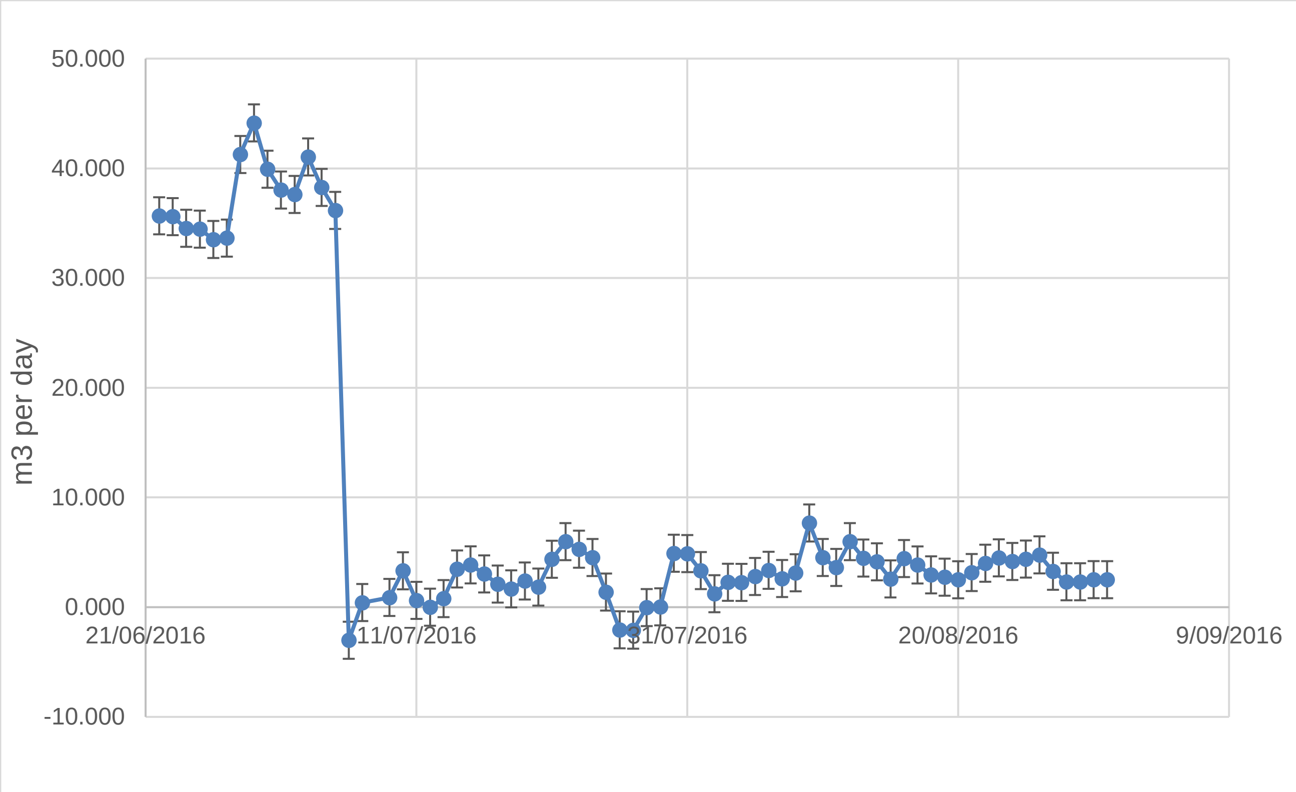

Figure 27: Total daily inflows for 2016

3.4.3 Infiltration

Figures 28, 29, 30 and 31 show the results from the water balance during dry time periods, or periods where the dam is emptying. The graphs show a comparison between the infiltration estimated by the water balance, and the infiltration estimated from the piezometers in the dam with k values of 10^{-8} cm/s and 10^{-5} cm/s. A negative infiltration corresponds to a positive change in storage that day, so the volume of the dam was increasing instead of decreasing. It is immediately noticeable from all four figures that there are major differences, both in magnitude and in general trends, between the infiltration estimated from the water balance and both the infiltrations estimated from the piezometers. The infiltration values estimated from the piezometers with a k value of 10^{-8} cm/s are considerably smaller than the infiltration estimated from the water balance and display a smoother trend rather than the larger variations day to day seen in the water balance estimations.

In 2013, seen in Figure 28, the estimate of infiltration from the water balance matches neither estimate with different k values. K = 10^{-8} cm/s is a very small number and as such the time series using this value does not appear significantly to vary day to day, or over time. Using a k value of 10^{-5} produces larger values with decreasing trend with values in July and August being larger than the values estimated from the water balance, before plateauing towards the start of summer, still with values mostly large than those from the water balance. The infiltration calculated using the water balance varies largely between days, increasing or decreasing as much as 25 m^3 in a day.

In the summer of 2013 and 2014, seen in Figure 29, both infiltrations estimated from the piezometers are consistently smaller than the infiltration from the water balance. Both the water balance estimates and the estimates with k = 10^{-5} cm/s follow a decreasing trend, although the water balance estimates are much larger and so have a larger decrease. Again, the k values using k = 10^{-8} cm/s are too small to see any significant trends or patterns. The infiltration from the water balance is also smaller than in Figure 28. There are similar patterns to the summer of 2013 and 2014 in spring of 2014, seen in Figure 29. Again, both infiltrations estimated from the piezometers are consistently smaller than the infiltration from the water balance, with the exception of two days in July and September where the infiltration from k = 10^{-5} cm/s is higher. Once again, the k values using k = 10^{-8} cm/s are too small to see any significant trends or patterns. The water balance infiltration varies significantly in the last week of July, before going to a steadier, but still slightly variable downwards trend. The water balance infiltration is at around 1 m^3 by the start of September. The infiltration from k = 10^{-5} cm/s follows a similar downward trend, although not as fluctuating, starting at around 3 m^3 over a day at the end of July, and ending at around 1.5 m^3 by September.

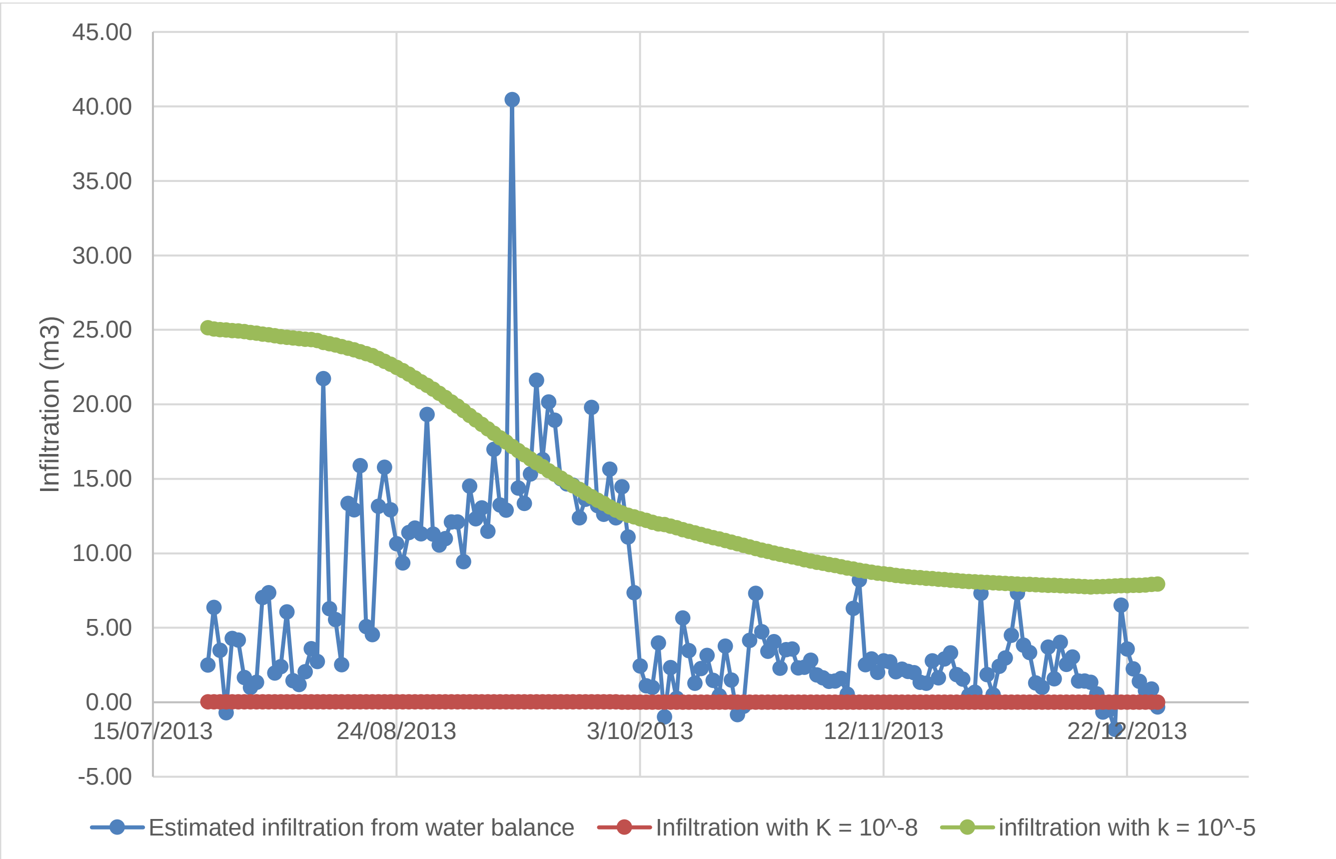

Figure 28: Infiltration comparisons in 2013

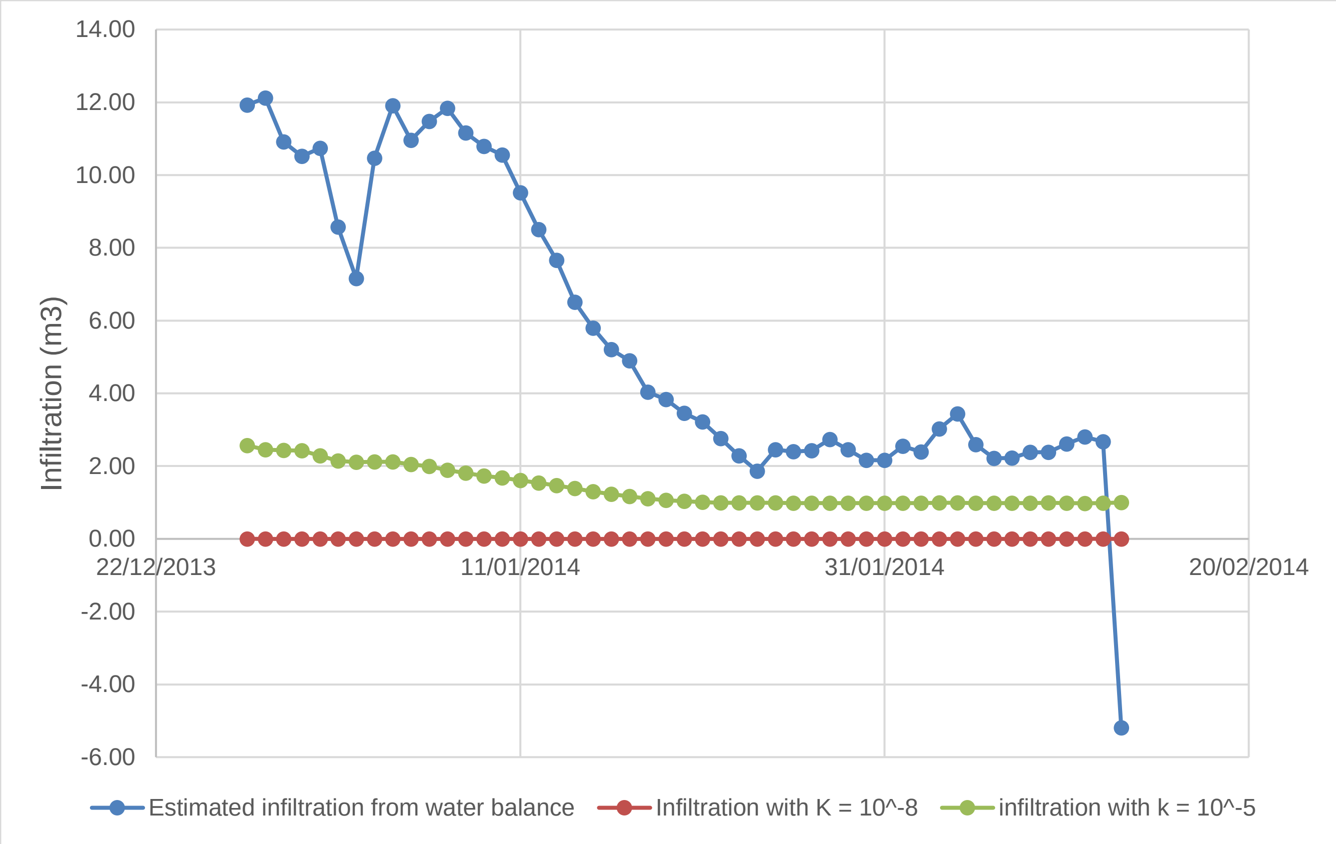

Figure 29: Infiltration comparisons in summer of 2013 and 2014

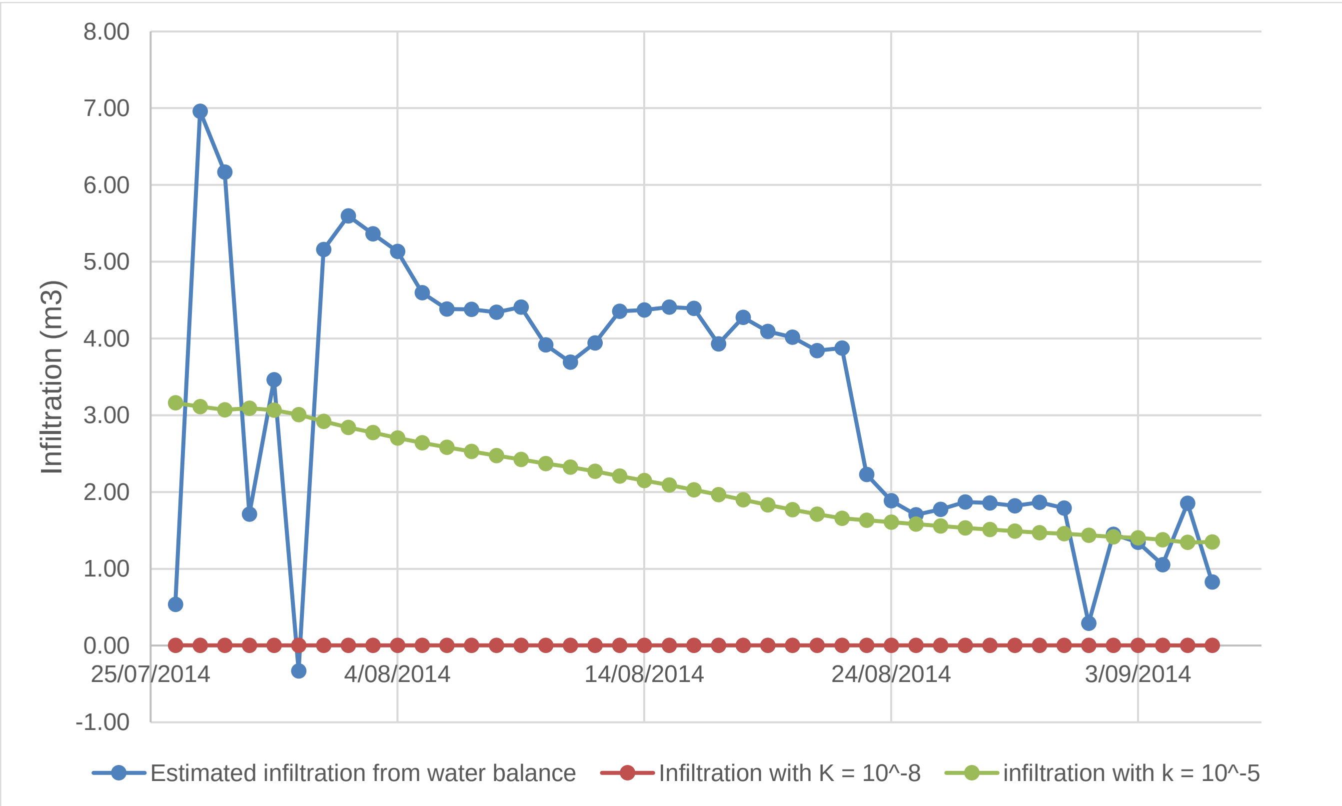

Figure 30: Infiltration comparisons in spring 2014

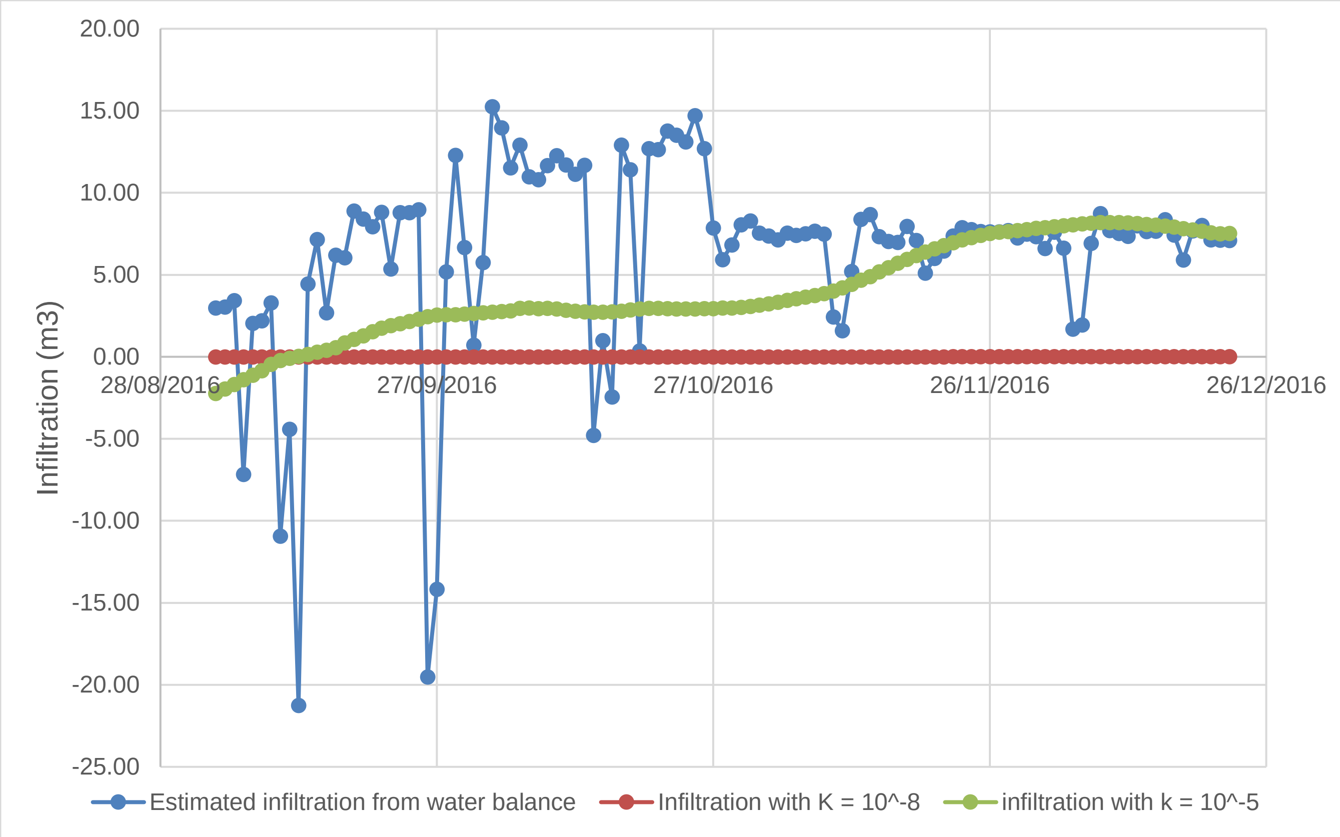

Figure 31: Infiltration comparisons in 2016

The water balance infiltration is considerably more variable in 2016, seen in Figure 31. The daily infiltration varies heavily, with several days of negative values and results up to 15 m^3, before steadying in mid-November with most values ranging from 6 to 7 m^3 until the end of the period. The infiltration from k = 10^{-5} cm/s showed a smooth increasing trend, starting at negative values (an increase in water level instead of decrease) and plateauing at around 6 to 7 m^3 at the end of November, with around the same results as from the water balance. Again, there is no discernible trend in the infiltration with k = 10^{-8} cm/s.

3.4.4 Change in Storage

Figures 32-35 show results from the calculated change in storage from the water levels compared to the change in storage estimated from the water balance, with different infiltration values, for periods of time where the dam volume is decreasing. This was another way of highlighting if one k- value appears to be more accurate. The change in storage was calculated by subtracting the volume on a day from the volume on the immediate next day, and so a positive value for change in storage represents a decline in volume, and a negative change in storage represents an increase in volume. Figure 32 compares the daily change in storages for the declining period in 2013. Neither estimate from the water balance appears to follow the same pattern as the estimate from the water level loggers. From the end of July until early October, the change in storage from the water levels has a slight increasing trend, meaning the magnitude of change is increasing so the volume is decreasing faster, (although with variations depending on the day) while both estimates from the water balance including infiltration appear to have more of a decreasing trend, that is the magnitude of the change in storage is decreasing. From early October onwards, the estimates from the water level plateaus at around 5 m^3 per day (consistent with the slope calculated from Figure 15 in Section 3.1) while both estimates including infiltration from the piezometers fluctuate at different values. Neither k value for infiltration appears to produce a time series closer to the estimate from the water levels than the other.

Figure 33 shows the same results for the summer of 2013 and 2014 time period. There is a clear decreasing trend in the change in storage from the water levels, while only a slight decreasing trend is seen in the series from the water balance with infiltration. As with the 2013 data, neither k value appears to produce a more accurate water balance than the other, with the estimates with k = 10^{-5} cm/s being closer to the water level change in storage initially, but then the estimates from k = 10^{-8} cm/s being closer from mid-January onwards.

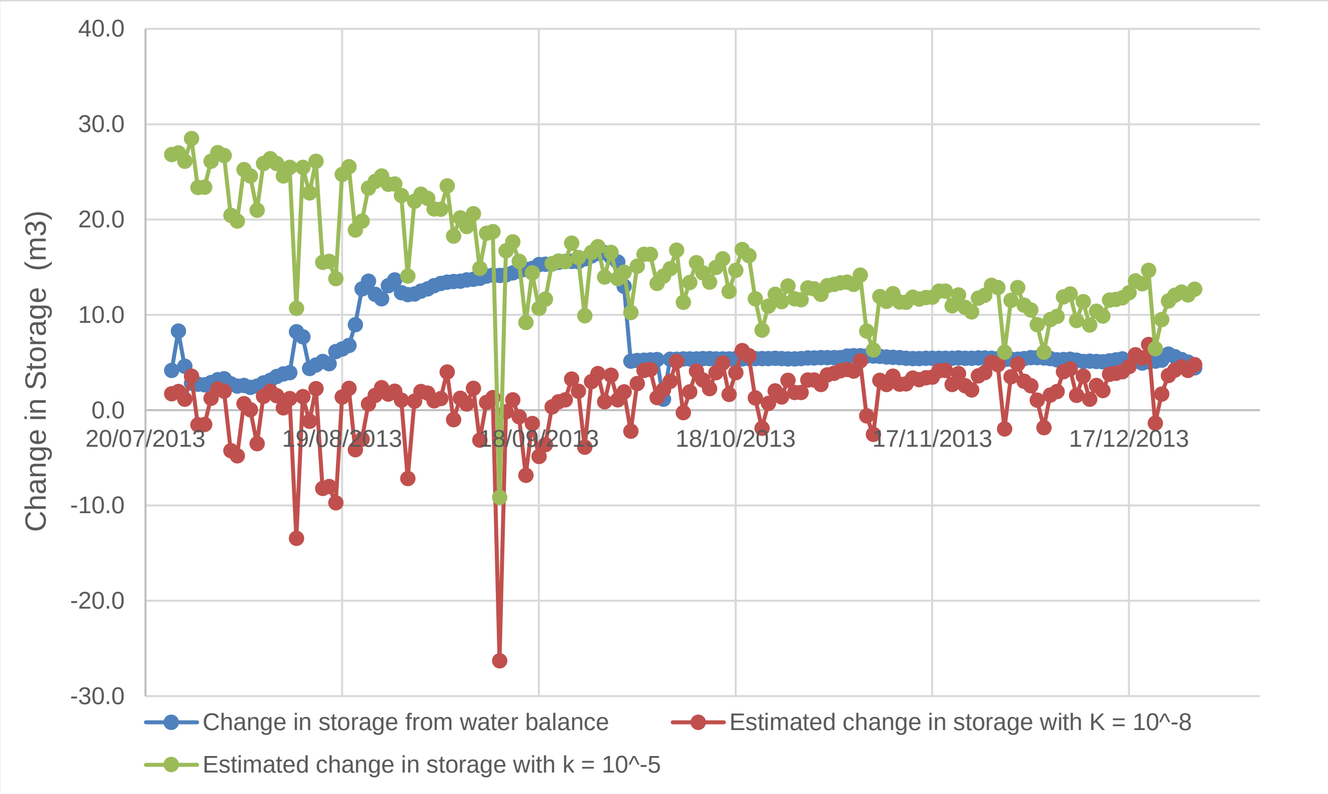

Figure 32: Daily change in storage comparisons for 2013

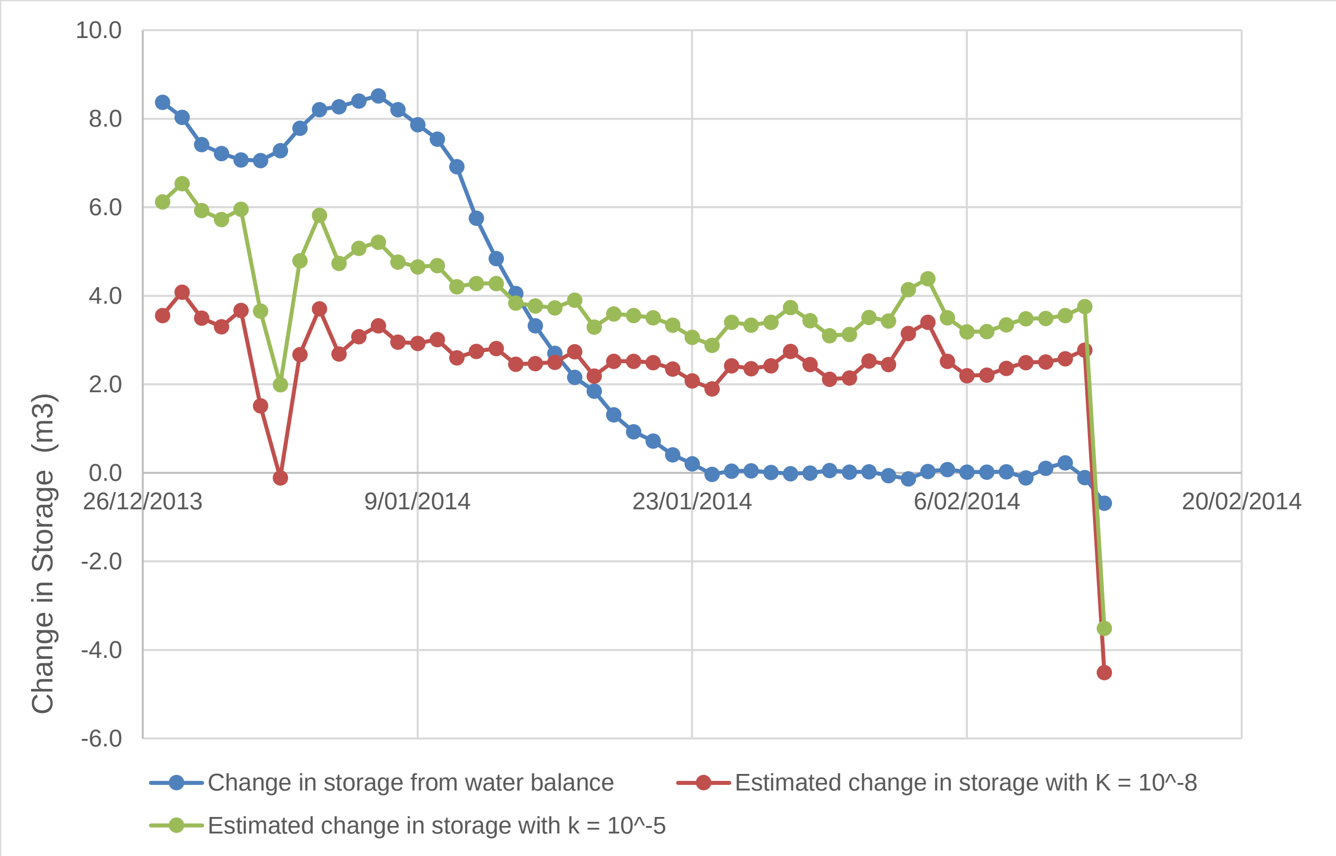

Figure 33: Daily change in storage comparisons for summer of 2013 and 2014

Figure 34 produces the most comparable results in spring of 2014. Both estimates follow the same decreasing trend while dipping and rising on the same days. For this time period, the estimate with k = 10^{-5} cm/s produces closer values to the estimate from the water levels for the majority of the graph, but from late August to early September the estimates with k = 10^{-8} cm/s give the closer values.

Figure 35 shows the results from the declining period in 2016. Both estimations from the water balance seem to initially follow the increasing trend from the water levels, although there are several days where the water balance estimates produce largely negative values up to -25 m^3 while the estimates from the water levels remain positive and increasing. From late October until the end of December, the estimation with k = 10^{-8} cm/s appears to be more accurate, sitting at around the same values as the estimates from the water levels. As with the infiltration results, these Figures also provide no tangible clarity on which k value was the more accurate.

Table 4 shows the descriptive statistics of the errors between the initial change in storage calculated and the estimated change in storages. Despite k = 10^{-5} cm/s looking to be the more accurate result in Figures 27 to 29, Table 4 shows a lower average and minimum error with k = 10^{-8} cm/s, and also a lower total sum of the errors. However, the maximum error is double that of the results using k = 10^{-5} cm/s. This provides no real clarity on which k value was the more accurate.

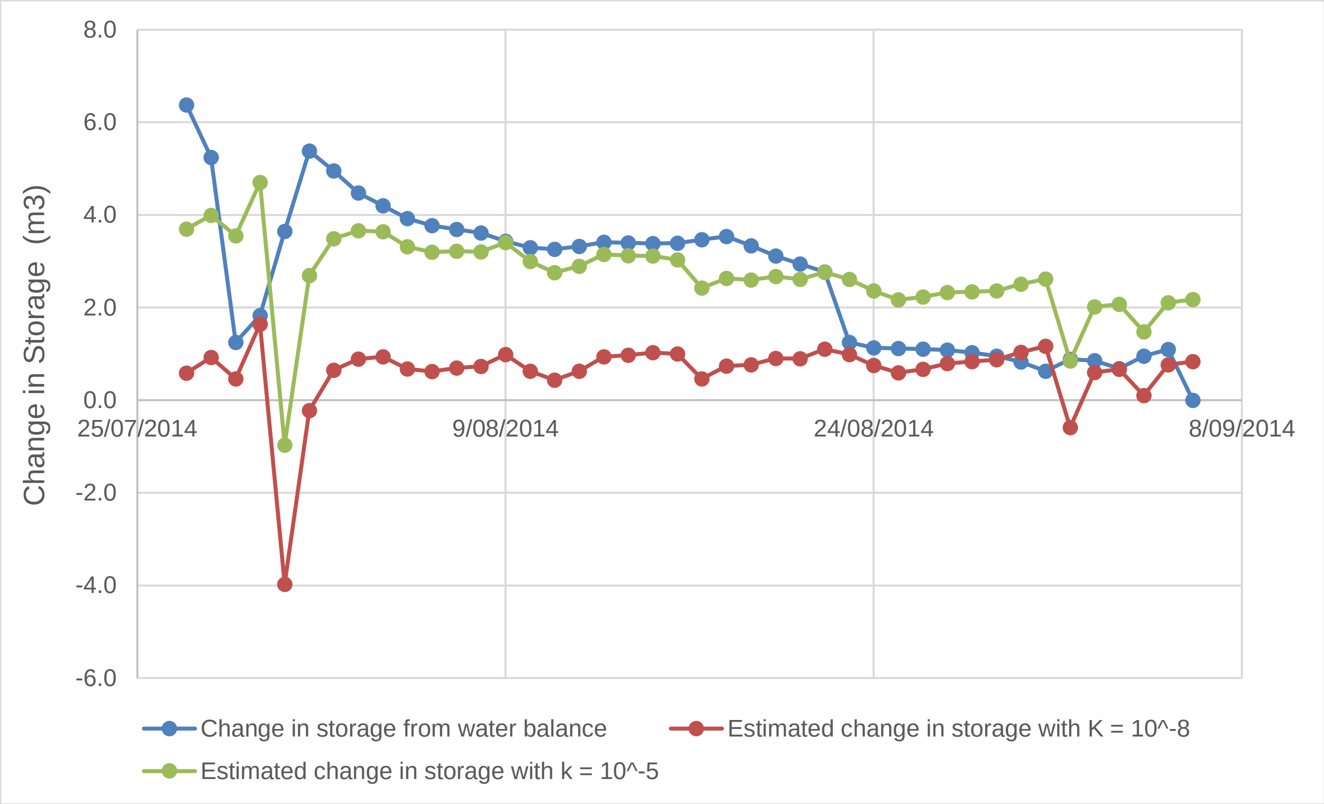

Figure 34: Daily change in storage comparisons for spring of 2014

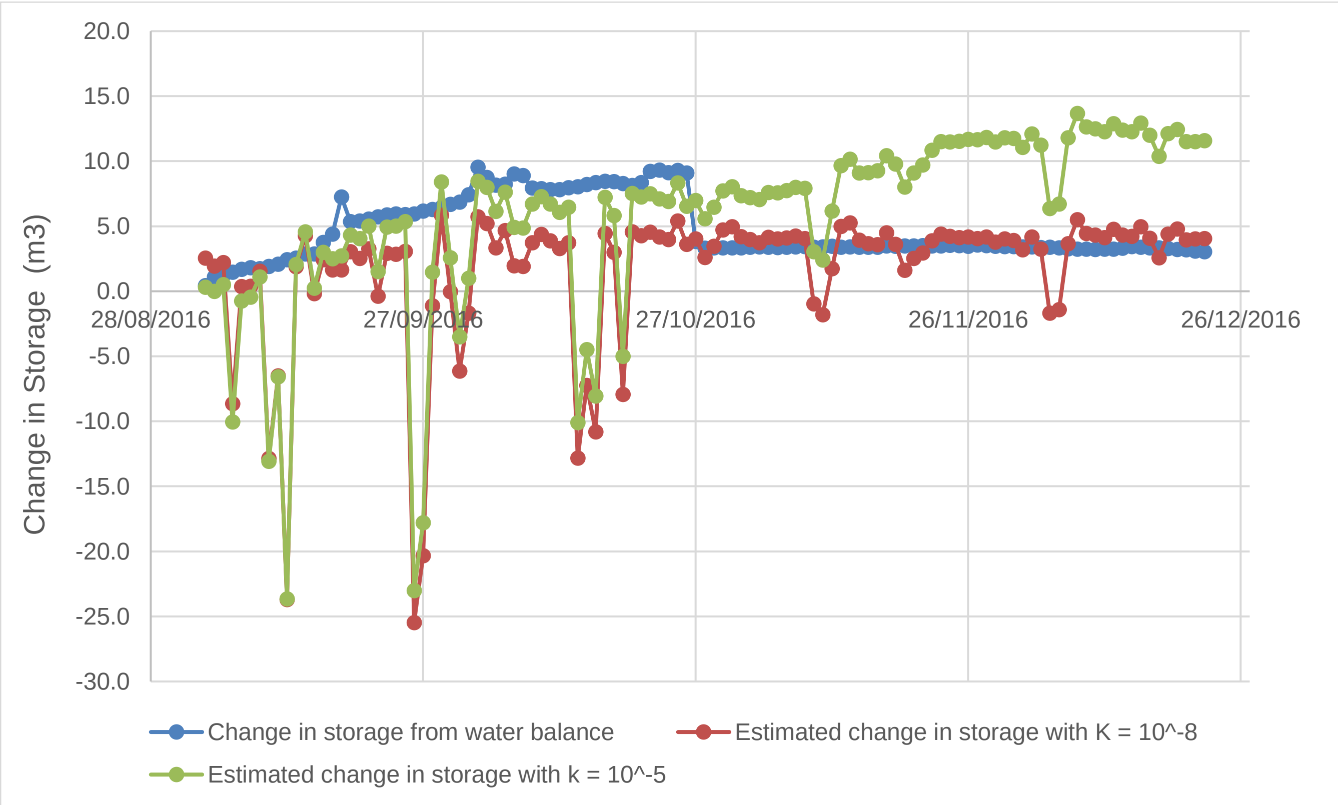

Figure 35: Daily change in storage comparisons for 2016

Table 4: Descriptive statistics of the total error for all years between the actual change in dam volume and the estimated change in dam volume

Error with k = 10^{-8} cm/s (m^3)		*Error with k = 10^{-5} cm/s (m^3)*	
Mean	4.5	Mean	6.0
Standard Error	0.29	Standard Error	0.3
Median	2.5	Median	4.6
Standard Deviation	5.4	Standard Deviation	5.7
Minimum	0.0	Minimum	0.0
Maximum	40.4	Maximum	28.9
Sum	1638.1	Sum	2177.3
Count	361	Count	361
Largest (1)	40.4	Largest (1)	28.9
Smallest (1)	0.01	Smallest (1)	0.01
Confidence Level (95.0%)	0.6	Confidence Level (95.0%)	0.6

3.4.5 Total losses

The total of all the losses from the dam during the dry periods was calculated from the water balance and is shown in Figures 36 – 39. The losses include evaporation, transpiration and infiltration. These were estimated using the infiltration estimated from the water balance, not the infiltration from the water levels, for consistency with the results from the total inflows. This also accounts for any other potential losses from the dam that were not included, such as overflow. Evaporation was estimated from the pan where available, and from the method by Chapra where there was no pan data. Error bars are based on the standard error of the series.

2013, seen in Figure 36, shows a similar trend to the change in storage estimated from the water levels. Until the start of October, there is a general increasing trend, although with daily fluctuations, before decreasing to a steady loss between 5 and 10 m^3 per day until the end of the time period. The largest loss was in September, at 42 m^2 in a day. The total loss for this period was estimated to be 1455.6 m^3, with an average of 9.27 m^3 per day.

Figure 37 shows the total losses for the summer of 2013 and 2014.The graph shows the same declining trend as the change in storage from the water balance during this time, although at slightly higher volumes. A maximum loss of 15 m^3 for a day was estimated in late December, with a plateau of around 5 m^3 per day from late January to early February. The total loss for this summer period was estimated to be 378.9 m^3, and the average daily loss was estimated to be 7.73 m^3.

Figure 38 shows the total losses for the spring of 2014. Again, it follows a similar pattern to the change in storage from the corresponding time. The largest loss estimated was approximately 8 m^3 in a day, in the last few days of July, followed by a sudden drop and rise again, before following a more slowly declining pattern for the rest of the period. The average daily loss was estimated at 4.06 m^3 with a total loss of 174.5 m^3.

The total loss estimate for 2016 (seen in Figure 39) was much more variable than the previous time periods. There is no clear pattern, although after the end of October the losses appear to show a steadier trend from day to day. The total estimated losses over this period was 1137.9 m^3, nearly double that of the inflows for the same year, with an average of 10.25 m^3 per day.

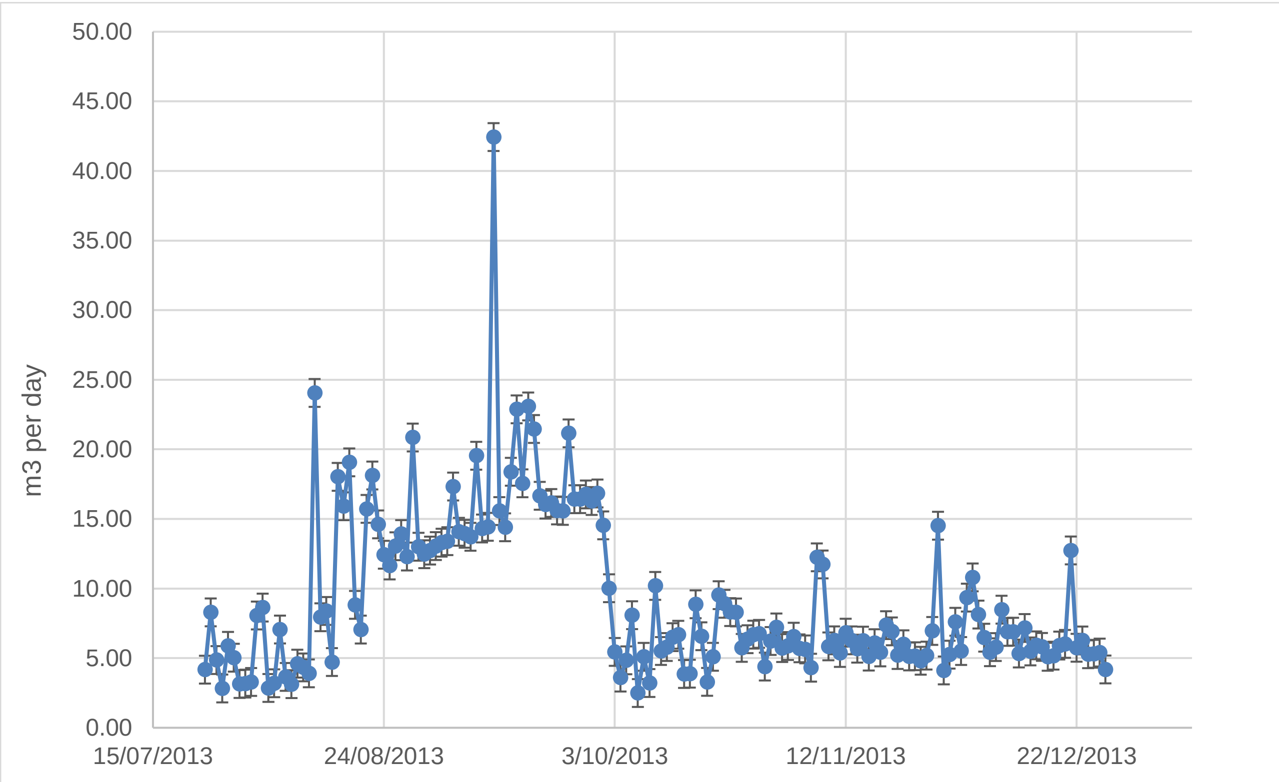

Figure 36: Total daily losses for 2013

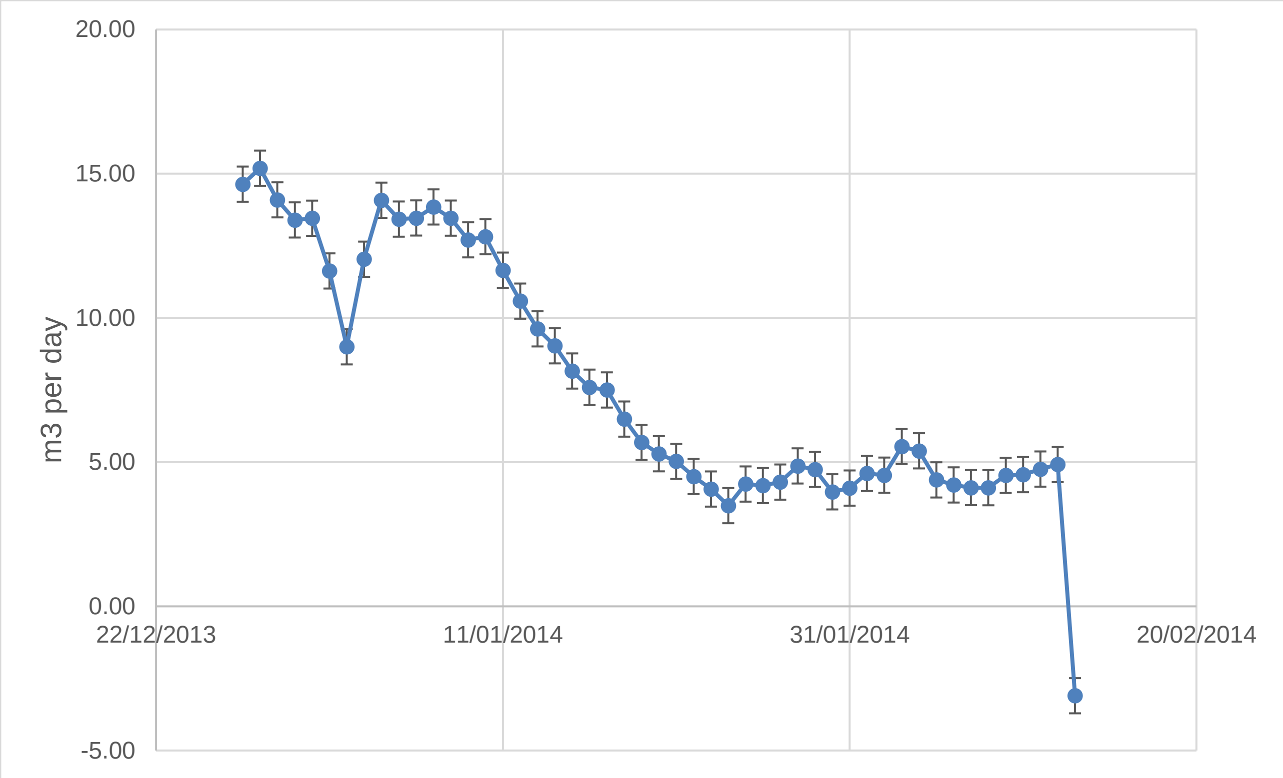

Figure 37: Total daily losses for the summer of 2013/2014

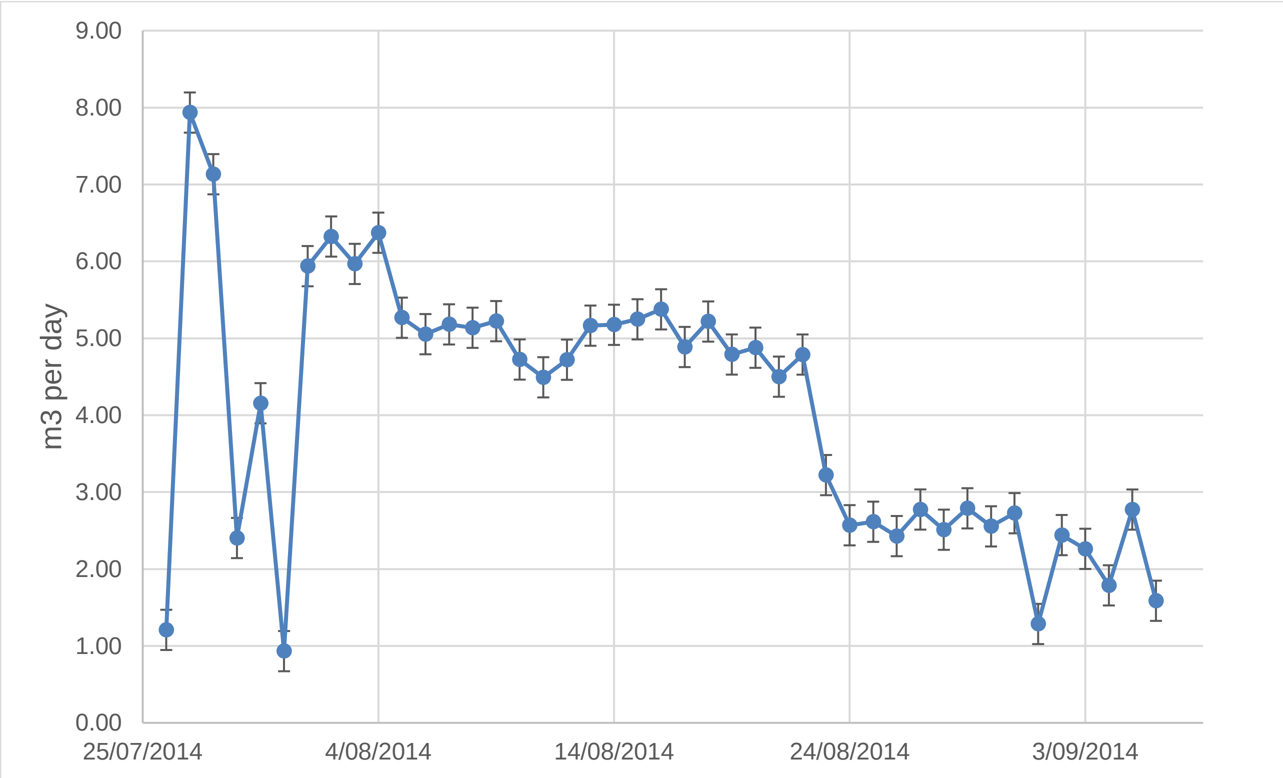

Figure 38: Total daily losses for the spring of 2014

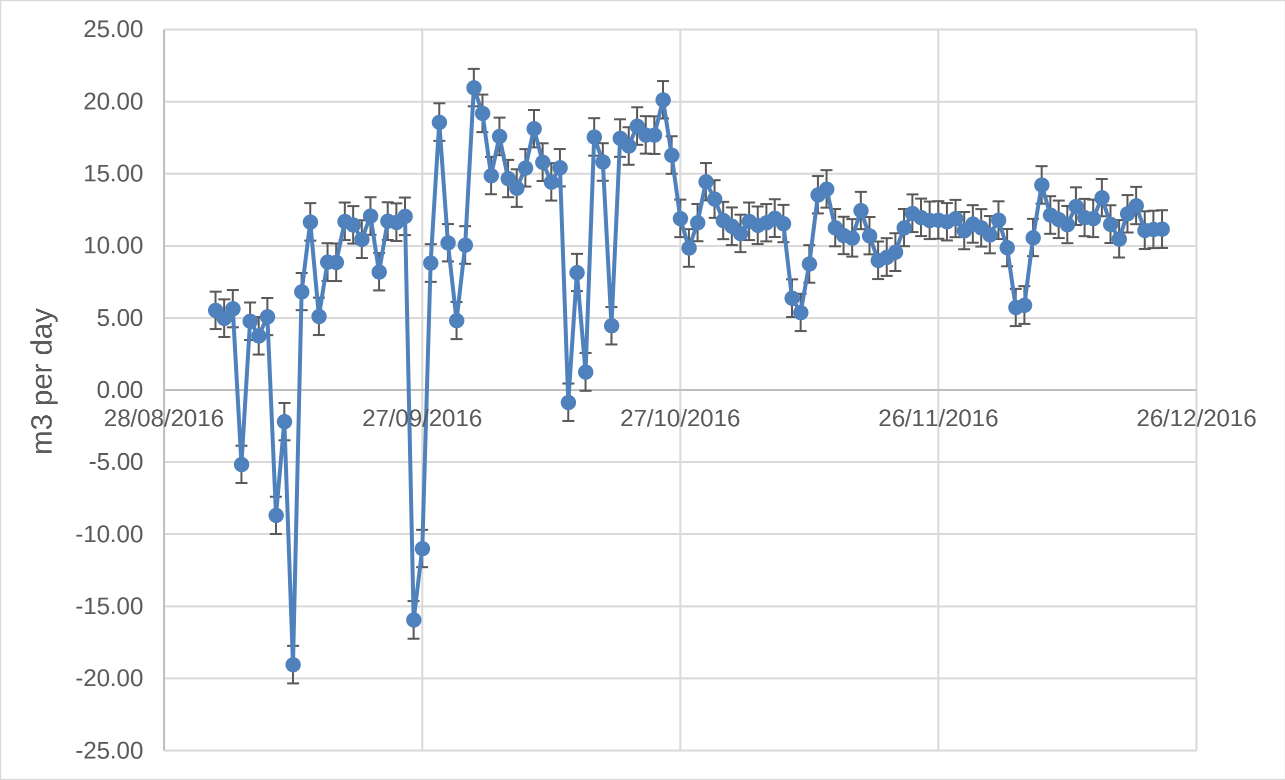

Figure 39: Total daily losses for 2016

4. Discussion

One of the main aims of this project was to gain understanding of the mechanisms and physical drivers behind the water balance of a farm dam. This is important as understanding the dynamics behind a single dam can be extrapolated into entire catchments, which can be utilised to understand how a network of farm dams influence the hydrologic dynamics of the larger catchment. The main drivers affecting the water balance of the dam identified in this study were rainfall, streamflow, evaporation, transpiration and infiltration.

Inflows for the dam from rainfall, streamflow and run-off were estimated through the water balance. 2013 saw inflows as large as 100 m^3 per day with an average inflow of 27.3 m^3 per day for the wet period (between the 6th of June and the 22nd of July). Inflows for 2016 were estimated to be up to 45 m^3 per day, with an average inflow of 9.7m^3 per day. In 2016, the dam only filled to around half the capacity of 2013, with both the average and maximum daily inflows being considerably lower than that of 2013, however 2016 saw a longer wet period, from the 22nd of June to the 2nd of September. The total inflows estimated in the wet period of 2013 was 1256 m^3, and the total for the wet period of 2016 was estimated to be 680 m^3. It is important to note that there were still inflows occurring outside of the wet period however, and there was no water level data available for estimation before winter in either year. Total losses from the dam were also estimated through the water balance. This included evaporation transpiration and infiltration, and potentially other losses such as overflow. The total loss for the dry period of 2013 was 1455.6 m^3, slightly more than the inflows for the wet period that year, with an average loss of 9.27 m^3 per day. The total losses for 2016 were 1137.9 m^3 with an average of 10.25 m^3 per day. This suggests that in 2016, the dam was losing water more rapidly, perhaps due to weather conditions or perhaps due to not filling as much as in 2013. The losses for 2016 were nearly double the inflows for the wet period of 2016. This may be in part due to there being more days in the dry period of 2016 than the wet period, and also any inflows before the start of the designated wet period not being accounted for. The summer of 2013 and 2014 produced an estimate of total losses of 378 m^3 with an average of 7.73 m^3 per day, while the spring of 2014 only estimated total losses at 174.5 m^3 with an average of 4.06 m^3 per day. This suggests that water is lost from the dam at a faster rate in summer, which is to be expected with climatic conditions of the season. There were also more days recorded in the summer than in the spring.

Another goal was to collate disjointed and missing data into coherent results. The following discussion reviews the individual components and results of the water balance found in this study before discussing them as a whole in an environmental management context.

4.1 Dam Storage

Figures 15, 17 and 18 showed the results of converting the water level into a daily volume. The time series for 2013 and 2016 occurred at the same time of year and so were compared. A large difference between the volumes of each year is that the volume in 2013 is significantly larger than in 2016. The maximum volume for 2013 (1850 m^3) is double that of the maximum value in 2016 (930 m^3). This could mean that 2016 was a drier year and the dam did not reach its full capacity, while in 2013 the dam was at full capacity and spilling, or there is an error in either the collection or processing of data for one of the years. The 2013 data was collecting using Solinst Levelogger while the 2016 data was collected with Diver water level loggers, and there could be potential discrepancy between the results of the two different water loggers. The water levels in 2013 declining faster than in 2016 is consistent with the theory that in 2013 the dam was at full capacity and was spilling, generating streamflow downstream of the dam for several days. Spillage or overflow from the dam was not considered as a parameter in the water balance, as there was no accurate way to estimate the volume being lost to this. It was also assumed that any overflow would not have a large impact on the volume of the dam.

The daily rainfall for 2013 and 2016 was analysed to attempt to understand the differences between the volumes in each year. The rainfall data showed that there was significantly less rainfall in 2013 than in 2016, which is contrary to what the results of the water levels shows. Judging from this period of rainfall alone, it appears that dam volume in 2016 should be at least as large, if not larger than the volume in 2013, suggesting an error in one of the sets of data. However, as the meteorological station was several kilometres away from the dam, there are margins of error that may not accurately affect conditions on Michael’s property. Other factors including increased or decreased vegetation surrounding the dam, and other climatic factors may be influencing the dam’s volume. Furthermore, there is no data available from 2016 before the 22nd of June, so rainfall prior to the dam filling up cannot be compared and this could also be influencing the volume of the dam. If there was more rainfall prior to June in 2013, the soil could have been already saturated, increasing run-off and streamflow into the dam, however it seems unlikely that this is the case, as the dam filled up earlier in 2016 than in 2013.

In the summer of 2013 and 2014 there were several days that overlapped with the 2013 data, from the 7th of December until the 27th of December. Comparing the dam volumes in Figure 15 and Figure 17, the data from the Druck sensors in the summer of 2013 and 2014 gives much lower volumes than the data from the Solinst loggers in 2013, even on the same days. The volume is declining with a slope of approximately -2.81 m^3 per day, which is the lowest decline of any of the time periods. The highest volume given in December from the Druck sensors is only 375 m^3 which is approximately half of the values given from the Solinst loggers which are between 800 and 700 m^3. The data given in December of 2016 ranges from approximately 450 to 350 m^3 which is more consistent with the summer of 2013 and 2014 data from the Druck sensors than the 2013 Solinst data. This, along with the discrepancy between the same time period of 2013 and 2016 and rainfall data, suggests that there is likely an error in the 2013 data, either from collection or processing the water level data from 2013.

The volume in the spring of 2014 (Figure 18) is lower than in the summer of 2013 and 2014, which is contrary to the expectation that water levels would be lower in summer than in spring. Both water levels were measured with the Druck sensors. Comparing the rainfall in this period with the rainfall that previous summer in Figure 16, the rainfall for 2014 was smaller than for 2013, which explains the lower results in Spring of 2014.

4.2 Evaporation

Based on the results shown in Figures 19, 20 and 21, and also Table 2 it is more likely that the estimate from the method outlined by Chapra is closer to the estimate from the pan evaporation and is a more reasonable replacement method to use during periods with no available pan data. This was mostly due to the fact the results from Chapra varied with the results from the pan evaporation while the results from Chow showed smooth trends and did not vary from day to day. The results from Chow's method were not considered when moving forward with the water balance. Looking at Equation 4 and 8 in relation to the results presented, it appears that Chow's estimation method is not complex enough to pick up the nuances of climatic conditions day to day, and so does not accurately represent the patterns given by the pan evaporation data. Chow's method only relies upon three factors to calculate an evaporation rate: net radiation, air temperature and water density. The water density was assumed to be a constant value, instead of taking the temperature of the water and allocating the corresponding density. An estimate of extra-terrestrial radiation was also used in the absence of proper net radiation values. Both of these factors could have influenced results of evaporation estimates.

The method given by Chapra however, utilises several more factors and parameters for estimation, including wind speed, dew point temperature, water temperature and air temperature, and this may be why the results from this method more closely follow the estimates from the pan data, as more atmospheric conditions are considered. There were also several assumptions and estimates made in calculating the estimate from Chapra, such as a constant value was assumed for the water density, values for air and dew point temperature were averaged over the day, water temperature was taken from the water logger instead of the surface of the water, and wind speed was taken from the weather station several kilometres away instead of from 7 metres above the dam. All of these factors likely influenced the results, and differences between the pan estimation and Chapra's estimation could be attributed to these assumptions. Nonetheless, the estimations from Chapra are still the best reasonable approximations in the absence of pan evaporation data. The pan evaporation data also has associated assumptions that introduce margins of error in the results, for example there were several days where a measurement was not taken, and values were averaged out, and the placement of the pan did not follow proper specifications such as being placed in an open field. A constant pan coefficient k_p of 0.70 was also assumed based on literature (Chapra, 2008; Winter, 1981) and in reality, this likely varies depending on geographical and climatic factors. Despite this, pan evaporation data is widely accepted as the more accurate estimate of open water evaporation (Chapra, 2008; Winter, 1981).

4.3 Transpiration

Table 3 shows the transpiration estimates per month based on Marshall et al. (1997). This was applied as a daily value to each time period, as seen in the example in Figure 23 which shows the transpiration estimates from around the dam for the 2013 and 2016 periods. As shown in Figure 23 (and seen in more examples in Figures E1 and E2 in Appendix E), there are errors up to ± 0.25 m^3 based on the month the value was taken from. There are several factors creating potential errors in these estimates. Firstly, the estimates were derived from monthly values from Marshall et al. (1997) where the heat pulse method was used. Marshall notes there is potential for an error of ±10% simply from the heat pulse readings. Additionally, the extent of water uptake from trees is dependent on several factors such as soil type, root and leaf development of the tree and soil saturation. Differences between the trees used in Marshall et al. (1997) and the trees surrounding Michael's dam regarding these factors is likely. Finally, a large error undoubtedly comes from averaging total monthly values into daily estimates. Daily transpiration values would probably look more like the evaporation series shown in Figures 19-22, instead of the same values for every day of the month as in Figure 23. In order to be consistent with the time step of other parameters in the water balance, averaging into daily values was necessary, and in the absence of estimates of transpiration from other methods such as sap flow, these values provide a reasonable representation based on available literature. Despite these sources of potential error, the daily values were comparable to the reference evapotranspiration values for tall crops taken from the McLaren Vale weather station, discussed in Section 2.2.5, meaning they are reasonable estimates for the area. These estimates were also derived from values specific to river red gum trees, as opposed to other available transpiration estimates such as from the weather station, whose vegetation source was unknown. The values in Table 3 are the best available estimates for transpiration rates, although their potential errors should be noted.

4.4 Water Balance

4.4.1 Inflows

Figures 24 and 25 show the result of using the water balance to solve for inflows into the dam during periods where the dam is filling. Inflows is mainly referring to the flows coming into the dam from the stream, although it is likely that inflows from overland run-off are also occurring. In the absence of a rainfall-run-off model, only inflows from the stream were focused on, as they contribute significantly more to the dam's volume than run-off. Rainfall occurring directly on the dam was estimated in two different ways, using a dynamic surface area and multiplying the daily rainfall by the surface area of the dam on that day, and also using a constant maximum surface area, and multiplying the daily rainfall by that maximum, described in more detail in Section 2.2.7.

In Figure 25, in 2013, the inflows do not vary significantly depending on which method of rainfall estimation was used. The maximum error given was around 5 m^3, on a day that saw the dam lose volume instead of gaining it, and so the real inflow for that day may have been zero anyway. The largest differences occur during in the initial stages of the dam filling, when there were inflows but not a large change in storage. In Figure 26, showing results for 2016, the results also do not differ notable based on the method used to estimate rainfall inputs. This trend indicates that the difference in surface areas in the two methods is not large enough to alter results meaningfully, and either method could be used moving forward. This also indicates that rainfall falling directly on the dam is not a large influencing factor in the water balance. Only the rainfall calculated using the surface area of that day was used in the calculations for total inflows, as there was no significant difference between the methods. Furthermore, any rainfall falling in the direct vicinity but not directly on the water's surface could be encompassed under "run-off".

The 2016 data is opposite to the 2013 data, in that it starts with large inflows (although half as large as the highest inflows in 2013) and then fluctuates around zero from around the 11th of July until September. The 2016 data started two weeks later than the 2013 data when the dam was filling, and then plateaus as the volume of the dam stays roughly the same with a slight increasing trend. It should be noted that the accuracy of the 2013 dam volume results was questionable (discussed in

Section 3.1), and this is potentially why 2013 inflows are double that of 2016. The total inflows for both years follow the same patterns as the estimated inflow from streamflow shown in Figures 24 and 25. This supports the theory that rainfall falling directly on the dam's surface is not a large influence on the water balance. This also suggests that losses from the dam such as evaporation and transpiration do not have a large influence on the water balance during wet periods either.

There are several sources of potential errors in these results. Firstly, the water balance may be affected by the cumulative errors from each component such as evaporation, transpiration and the water levels. Secondly, there may be errors in the water balance equations. Infiltration was not considered during this time period, as it was assumed the soil was saturated. However, infiltration may be an influencing factor, particular in this first part of the 2013 data where the inflows were constant around zero. As there was rainfall recorded for this period, it is likely that there were more significant inflows during this period but that they moved into the groundwater and therefore did not influence the change in storage. Overflow and spillage from the dam was also not considered in the water balance. There was no downstream flow data or a way to properly estimate spills from the dam given the timing and scope of this project and potential spills were assumed to be insignificant. However, from Figure 15 there was possible evidence of overflow occurring, as the water levels for 2013 reached a large peak and then declined quickly. Overflows could be another factor influencing the water balance of the dam. Finally, it is difficult to know what portion of the inflows can be attributed to the input from the stream flow, and what is from run-off. Future research should involve streamflow gauges, both upstream and downstream of the dam, and a proper rainfall-run-off model.

4.4.2 Infiltration and Change in Storage

Figures 28 to 31 compare the results from 3 different ways of estimating the infiltration rate: solving for infiltration in the water balance and estimating infiltration from the water levels recorded in the piezometers, using k values of 10^{-8} and 10^{-5}. This was done in an attempt to determine which k value chosen was more accurate, and also determine how accurate the water balance estimations were. In all four graphs, neither infiltration estimated from the piezometers had a string correlation the infiltration estimated from the water balance. In all of the graphs, it appears that the infiltration with k = 10^{-8} cm/s is too small to detect trends, and k = 10^{-5} cm/s produces smooth trends as opposed to the larger variations from the water balance estimates. However, this does not mean that either k value is incorrect, it may be due to errors in the water balance or another factor that is driving losses from the dam.

In 2013, seen in Figure 28, the k value of 10^{-5} seems to be closer to the estimate from the water balance, although the values are consistently higher, it follows the same decreasing trend. It seems unlikely that this much infiltration would occur, particularly in the middle of winter where values as high as 25 m^3 a day were estimated, considering the soil would be mostly saturated in the middle of winter, and the water balance produced estimates much smaller for infiltration. However, it is still plausible if there were other factors unaccounted for in the water balance, such as inflow from the stream (which was assumed to be zero in dry periods) or spillage from the dam downstream (which has not been accounted for). The infiltration in Figure 29, in the summer of 2013 and 2014, from the water balance is also smaller than in Figure 28. Although infiltration rates may be higher in summer when the soil is less saturated, there is less water available to infiltrate and this may be the cause of this.

The estimated change in storage of the dam during dry periods is shown in 3.4.3, Figures 32 to 35. Three estimates of the daily change in storage of the dam were compared. The daily change in storage was initially calculated by subtracting the volume of a specific day from the volume of the previous day. Although there are likely errors from translating the water level data into volume of the dam, this was still considered to be the most accurate estimate of change in storage. As with the infiltration results, neither estimate from the water balance despite different k values appear to more closely resemble the estimate from the water level loggers. In 2013, shown in Figure 32, the estimates from the water balance do not match the estimate from the water levels at all. In the first half of the graph, the estimate from the water levels has a slight increasing trend while the estimates from the water balance have a slight decreasing trend. In the second half of the graph, the estimates from the water balance vary largely from day to day while the estimate from the water levels remains consistently around 5 m^3 per day. For the summer of 2013 and 2014 the estimates with $k = 10^{-5}$ cm/s are closer to the water level change in storage initially, but then the estimates from $k = 10^{-8}$ cm/s are closer from mid-January onwards. The spring of 2014 seems to show the closest relationship between the estimates from the water balance and the estimate in change in storage from the water levels. Both methods produce results that follow the same decreasing trend while rising and falling on the same days. The estimate from the water balance with $k = 10^{-5}$ cm/s produces closer values to the estimate from the water levels for the majority of the graph, but from late August onwards the estimates with $k = 10^{-8}$ cm/s give the closer values. In 2016, seen in Figure 35, both estimations from the water balance seem to initially follow the increasing trend from the water levels, although there are several days where the water balance estimates produce largely negative values while the estimates from the water levels remain positive and increasing. From late October until the end of December, the estimation with k = 10^{-8} cm/s appears to be more accurate, sitting at around the same values as the estimates from the water levels.

From the results of both the infiltration comparisons and the change in storage comparisons, it is difficult to say which k value produces the more accurate results. Descriptive statistics give no further indication either. In Figures 29, 30 and 31, k = 10^{-5} cm/s appears to be a closer match to the infiltration from the water balance. However, in 2013 the k = 10^{-5} cm/s results are much larger than the water balance results. The mean and minimum values of the errors between change in storage from the water levels and change in storage from the water balance are lower for k = 10^{-8} cm/s, but the maximum error is much larger than for k = 10^{-5} cm/s. As both series using k values follow the same trend but at different magnitudes it is also hard to make a decision based on trends. The errors between the change in storage from the water levels and the change in storage from the water balance do not necessarily mean that both k values are incorrect. Instead it may mean that there were errors in the estimation of the infiltration series, or other factors in the water balance were not accounted for. The error between the change in storage and the total losses is likely largely due to other factors not considered.

There are several potential sources of error from the water balance. Firstly, it was assumed that there was no inflow from the stream during these dry periods, however there are several days with not-insignificant rainfall which may have produced inflow from run-off or stream flow. Secondly, overflow and spillage from the dam was not accounted for, as there was no way to properly quantify this for the purposes of the water balance, and it was also assumed to be negligible. Differences between the estimated values of infiltration from the water balance and from the piezometers may be due to these missing factors. There are also margins or error with all the separate components of the water balance, as discussed previously, which may also cumulatively influence the final result of the water balance. Due to these factors, it is very difficult to know which k value is correct even based on which gave results closer to the water balance infiltration or the water balance change in storage. For future research it would be extremely useful to conduct testing on the soil at the bottom of the dam in several conditions and use this to give a more accurate approximation of the k value.

4.5 Limitations and Future Research

As described in the previous sections 4.1 to 4.4, there were several limitations, assumptions and potential sources of errors from data collection and data processing that have likely impacted the accuracy of results. These limitations come from information gaps in individual components compiled and also the water balance as a whole.

There were several limitations associated with the weather data. The weather data was collected from a weather station in McLaren Vale, approximately 3 km away from Michael's property. Rainfall and other climatic parameters are very spatially variable, which may have influenced the results through small errors in the rainfall data and the evaporation data. Winter (1981) states that rainfall estimates can have a large error range, depending on the placement of the rainfall gauge itself, and the spatial distribution from the area of interest. The evaporation estimates were made through the temperature, dew point and wind speed of the day, which were all likely measured under different conditions to Michael's property, which is vegetation rich. The wind speed was supposed to be taken 7 metres above the surface of the water, and so the correct wind speed would have likely been less than the value from the weather station due to the obstruction from trees. Having an evaporation pan being monitored constantly on the property would eliminate any assumptions associated with the evaporation estimates. Any future research should ensure than pan is properly positioned according to BOM specifications, and that readings are taken every day so averaging between days does not need to occur. Having a rainfall gauge closer to the dam would also be a useful improvement to improve on the accuracy of the volume of rainfall contributing directly to the dam. There is a weather station on Michael's property, however most of the data obtained from it was unreliable. Additional sources of weather data could be procured, such as data from the Bureau of Meteorology, or data from several close-by gauges could be averaged to produce a more representative rainfall data set.

The limitations associated with the water levels and dam storage over time were mostly from data gaps. There were larger periods of time with no data between 2014 and 2016, and there was no data between summer in 2014 and spring, which would have showed when the dam is completely empty. For future research it would be beneficial to have two or more of consistent daily data to show all seasons over various years. Even nearby streamflow gauges or water loggers could be utilised for this. Using the same brand of water logger would also be valuable, as this study used three different brands. Converting the water levels to volume and surface area values was deemed to be reasonably accurate, based on the R^2 values from the fitted trend lines being extremely close to 1, however there was still potential uncertainty from the bathymetric survey, converting this to a smooth surface by averaging between points and calculating the associated volumes and surface areas in ArcMap.

The largest amount of uncertainty in this study came from the transpiration estimates. Several assumptions were made in the absence of more reliable data. Firstly, Marshall et al. (1997) note there is potential for an error of ±10% from the heat pulse readings on which the transpiration estimates in this study were based. Additionally, Marshall et al. (1997) studied river red gums in a different location, where the soil type, root and leaf development of the tree and soil saturation were likely different to the conditions on Michael's property. Finally, the total monthly values were averaged into daily estimates, which would have eliminated the day to day variation in transpiration. For future studies, a more accurate estimate of transpiration should be utilised, such as measuring sap flow from a surrounding tree or trees and converting this into a meaningful transpiration estimate.

Estimating the infiltration from the dam also involved several assumptions and limitations. In the absence of a known k value for converting water levels into a flux, two values were taken based on the observed properties of the soil at the site. Future research should conduct proper soil testing to more accurately determine the k value of the soil.

Finally, several limitations come from the water balance equation. There was no streamflow data and so this could not be included in the water balance. Instead the water balance was used to solve for inflows into the dam, but it is hard to determine what portion of inflows are from the stream and what is from overland run-off. This also meant streamflow was only estimated during wet periods, or times where the dam's volume was increasing. For future research, having streamflow gauges upstream of the dam would be useful to more accurately quantify the volume of water contributing to the dam from the stream, and for all time periods instead of just wet periods, which could be used to predict future hydrologic patterns of the dam and its surroundings. This agrees with the suggestions from Teoh (2006), who suggests that monitoring inflows from streamflow is necessary to present accurate results about the impacts of farm dams on surface water resources. Utilising a proper rainfall-run-off model would also be an improvement on this study, to more accurately model inflows, and to determine what percentage of inflows is coming from run-off compared to inflows from the stream, or rainfall falling directly on the dam's surface. This would also allow inflows to be considered during dry periods, unlike in this study.

Another factor not considered in the water balance equation was overflow when the dam is full. There was no way to properly quantify a volume lost to overflow or spillage, and it was also assumed to be negligible. However, there was evidence from the results of the dam volume over time in 2013 that overflow may have occurred. Future research should consider possible spillages and overflows from the dam. Monitoring this with a streamflow gauge could improve the overall accuracy of the water balance.

Other factors that were not considered in this study were the water quality of the dam and surrounding groundwater. While this was outside the scope of this research, water quality analyses of the dam water and groundwater could be useful in determining ecological impacts in the immediate sub-catchment of the dam, and potentially help predict possible impacts downstream. The retention time in the dam, as well as increased evaporation, transpiration and infiltration due to its existence could be impacting water quality in the immediate vicinity. However, may be difficult to determine if any impacts are directly caused by the presence of the dam or by other factors in the area such as land use changes or agricultural practices.

These proposed improvements are costly and time consuming. In many cases, only fragmented data such as has been presented in this research may be available, and assumptions must be made to gain further understanding. Considerable time, money and effort must be invested to limit information gaps and assumptions to produce more accurate estimates. However, with farm dam management becoming an important environment and water sharing issue, these may be necessary costs to properly understand the hydrologic dynamics of farm dams and therefore their impacts on the larger catchment.

4.6 Environmental Management Context

As discussed in the introduction and literature review in Section 1, water resources management is an important and current environmental management issue. Within that, farm dam management is also becoming an environmental management and policy concern. As surface water resources become more scarce, particularly in dry states such as South Australia, the effects of farm dams on the surrounding catchment, as well as water security concerns are being raised. Needs of the environment need to be balanced with agricultural needs.

Nathan and Lowe assert that conflicts over dams and associated allocation policies between competing users will probably increase as the knowledge and understanding of the hydrological and ecologic impacts of farm dams develops (Nathan and Lowe, 2012). Tingey-Holyoak (2014) explores farmer perceptions on dam management, governing bodies, regulations and other stakeholders (such as banks or insurers) to understand how water sharing can be made safe and fair. The survey of 404 farmers was carried out in South Australia, New South Wales, Victoria and Tasmania via telephone in 2011. Key findings from analysis of the survey data show that farmers in South Australia practice retaining water unfairly the most, such as water diversions and blockages of their spillways, which coincides with the fact that South Australia has the weakest policy environment related to farm dam management. South Australian farmers are also less likely to be fearful of regulators, again probably due to weak policy. Tasmania is the state with the strongest policies relating to farm dams, and unsurprisingly, farmers from the state are the least likely to engage in unfair dam practices based on the survey. However, Tasmanian farmers are also the most concerned about the uncertainty of future water provisions. They are also less likely to undertake budgeting for farm dam management or involve regulators in any decision making, than farmers in NSW. Farmers in NSW and Victoria were the most likely to attend community meetings, indicating that education in these environments could be beneficial. A concerning finding of the survey was that farmers in all states were not well educated about risks (both structural and environmental) of increased storage retention through activities such as blockages of spillways. Education of the risks posed by these practices and an effective way to communicate this to farmers is essential in the future of fair and safe operation of farm dams (Tingey-Holyoak, 2014). It is ultimately concluded that relying on owner responsibility to ensure proper use of dams is not adequate.

It is hoped that accurately modelling the water balance of a single farm dam could be the basis for a larger model of a whole catchment, eliminating some of the errors that occur due to the generalisations and assumptions larger models make, as discussed in Section 1.2. There has been difficulties in isolating changes caused by farm dam development over a whole catchment versus other land use changes or climate changes, as well as issues in quantification of the number and sizes of farm dams. An accurate water balance model of a farm dam would serve to make the results of larger models such as TEDI (Nathan and Lowe, 2000, Neal et al. 2000) more accurate. More accurate results from catchment or state-wide simulations can more accurately inform decision making processes regarding farm dam development and water allocation as water security becomes a more important concern. The results can act as a good baseline, determining patterns and driving influences before the added stress of water usage is accounted for. The dam is also representative of the average size of dams in the surrounding area (Teoh, 2003) and so would be appropriate for generalising results. However, there can be large variability in the characteristics of farm dams despite similar size. Other variables include if the dam is lined or unlined, and if the dam is situated on or off stream, does the dam fill naturally or is water diverted. The dam studied in this investigation may not be the most appropriate representation of dams in the area, as it is unlined, increasing infiltration. Most dams in the area are also used for farming purposes, either irrigation or watering stock, while Michael does not use the water from his dam, instead it is used for observation purposes. Studies of other dams may also have different errors associated with data collection and processing, depending on availability and location of gauges and water loggers. Extrapolating from this study to a larger catchment would be a substantial undertaking, and careful planning would be required to account for all potential sources of error.

The results from this investigation highlight several drivers behind the water balance of a farm dam. Of these, the factors causing losses from the dam, evaporation, transpiration and infiltration are potential environmental concerns. Altering the natural processes of the site by the construction of a dam prevents the flow from contributing to the ecosystem and hydrological regime downstream. While the water is being held, these processes of evaporation, transpiration and infiltration occur, where in the natural state of the catchment without the dam, these would not be occurring at the magnitudes seen in these results. Retaining water in the dam with a large surface area allows open water evaporation to occur at volumes that would not occur if the water stayed flowing in the stream or running off overland. The presence of the dam also facilities transpiration from the trees around the dam. The trees would not have the same water available to them without the body of water being held in the dam. The same occurs for infiltration, seepage would not occur directly at the site of the dam without the water retention there. Increased infiltration due to the presence of a farm dam could be perceived as a positive if the aim was to increase the groundwater levels in the area, as infiltration would increase from a body of water with a large surface area, however this has a negative impact on the volume of surface water available for downstream.

These losses from the dam create an overall loss in the surface water availability downstream of the dam. Lack of surface water resources, as well as being a concern for downstream users, undoubtedly has a negative ecological impact, especially in Australia where water resources are already scarce. However, exact impacts and their magnitudes on ecological systems and habitats specifically due to farm dams is unknown. Nathan and Lowe stress the lack of literature on the environmental impacts of farm dams and the ecological responses to increased development. As of the date of publication, there has been no published studies that have specifically monitored and analysed the impacts of farm dams on the downstream ecology (Nathan and Lowe, 2012). Instead, there have been inferences made about likely ecological responses from indicators in the changes of flow regimes. Figure 3 (Nathan and Lowe, 2012) shows five key hydrological indicators and the impact farm dams have had on them in the Murray Darling Basin. A score of one signifies a natural or unaltered catchment while a score of zero shows a highly modified flow catchment. The indicators; low flow events (LF), high flow events (HF), variability of stream flows (CV), period of time there is zero flow (PZD) and seasonal characteristics of the flow regime (SP) were derived to represent the magnitude of changes in a flow regime. In turn, potential changes in ecological processes can be inferred from this, although Nathan and Lowe did not attempt to undertake this process. The plot shows the 5th, 25th, 50th, 75th and 95th percentiles of 162 catchments. It is immediately clear from the plot that low flow events are the most impacted by farm dams, with one quarter of the sites scoring less than 0.8. This aligns with the results from this study that evaporation, transpiration and infiltration are highest during low flow periods, especially in the time directly after winter. Infiltration is also high in the stages just before the dam begins to fill as the soil is completely unsaturated. Periods of zero flow were not affected as there is no flow for farm dams to capture. There was also minimal impact on the seasonal characteristics of the flow regime, 90% of the test sites scored greater than 0.9. High flows were moderately affected, as was the variability of stream flows. The authors suggest that this may be that as low flows decrease, the flow variability increases (Nathan and Lowe, 2012).

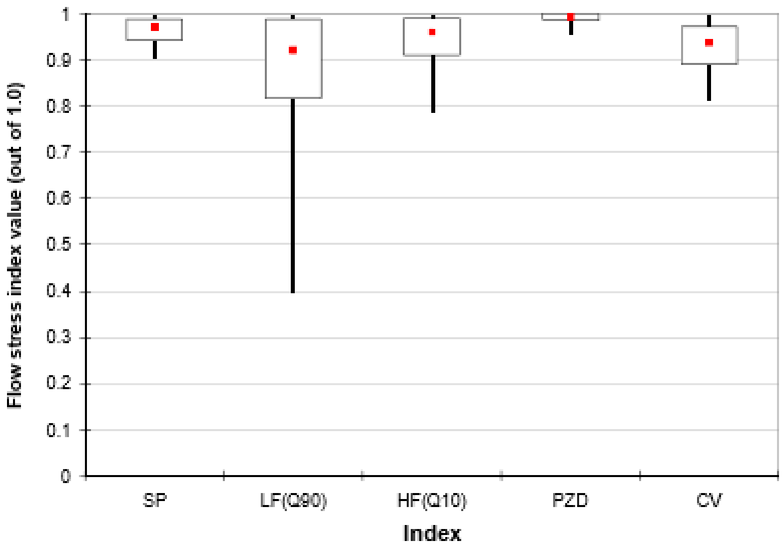

Figure 40: Distribution of hydrological indices showing the impact of farm dams for 162 catchments in the Murray Darling Basin (Nathan and Lowe, 2015)

Nathan and Lowe conclude that to mitigate the environmental impacts of farm dams, low flow bypasses could be installed, so low flows, which are the most impacted by farm dams can bypass the dam, and instead the dam can still capture water and be filled during periods of high flows. Nathan and Lowe suggest further research should be done in this field, to properly quantify ecological impacts and therefore decide the best way to mitigate these impacts. In France, the filling period for farm dams is regulated. Farmers can fill their dams from November to March, European winter (Habets et al. 2014). A system put into place such as this in Australia, for example where farmers can only fill their dams from May to September or October would likely be beneficial to the hydrological and ecological processes of the environment, as low flows, which are the most sensitive to impact from farm dams, would not be retained but instead contribute to the downstream catchment. Additionally, regulations should be monitored with consequences for breaching rules and regulations, to deter from unfair behaviours.

Before policy decisions or plans are made, it is important to model and quantify specific hydrologic and ecological impacts from farm dams. Better monitoring and planning is required for this to be an effective undertaking. Specific, thorough work on a single farm dam as undertaken in this study or small network of dams could be used as the basis of a larger model that can be used to outline current impacts of farm dams, impacts of future developments and the effectiveness of solutions such as low flow bypasses or restricted filling times.

5. Conclusion

This study modelled the components of the water balance of a farm dam in Willunga, South Australia, with the aim of identifying and gaining understanding of the processes that influence its storage over time. Through focusing specifically and thoroughly on a single site, it was hoped that the chances of confounding factors such as land use or climate changes that are present in literature models of farm dam impacts influencing results would be lessened or negated. Understanding the dynamics behind a single dam can be extrapolated into entire catchments, which can be utilised to understand how a network of farm dams influence the hydrologic dynamics of the larger catchment.

There were several challenges associated with the processes undertaken in this study. Another major aim of this research was to successfully collect and collate data from several sources or several methods into an overall water balance for the dam. There were gaps in some essential data such as water levels which presented difficulties in achieving this. Data gaps were overcome by splitting results into periods where the most important data was available and estimating missing parameters. Data was separated into two focused periods, "wet" periods where the dam was gaining volume to focus on the inflows into the dam, and "dry" periods where the dam was losing volume to focus on the drivers of loss from the dam.

The main drivers affecting the water balance of the dam identified in this study were rainfall, streamflow, evaporation, transpiration and infiltration. The losses from the dam, evaporation, transpiration and infiltration, would not occur in the same magnitudes in the absence of the dam, as having a large body of water retained in a single spot makes water more available and facilitates these processes. Flows in Australia provide critical contributions to ecosystem health (Dyson et al. 2003) and farm dams are reducing flows by retaining water at a single site, which is then subject to increased open water evaporation, transpiration and infiltration. However, farm dams provide an essential source of water for all components of the agricultural industry from livestock farming to irrigation schemes (Government of South Australia, 2011). It is important to balance the needs of the environment with the social and economic needs of individuals and the agriculture industry.

Further research in this field is recommended, to properly inform decisions made on the management of farm dams. Improved planning and modelling is needed to fill information and data gaps to further progress water balance models. It is hoped that a similar study to this could be improved and extrapolated and provide the basis for a model of a larger catchment, which can more reliably deliver estimates of the impacts of farm dams, which in turn can advise decision making on farm dam and water resources management to ensure responsible and equitable allocation of resources to meet individual, industry wide, and environmental needs. Currently, relying on owner responsibility for management of their dams is not an effective strategy. Proper management plans at regional and state levels need to be devised and enforced to ensure water resources are adequately shared between individuals, industry and the environment.

Several recommendations for improvements on data collection and processing were made for future research. Key recommendations included the installation of streamflow gauges upstream and downstream of the dam, to obtain assessable data on the volume of streamflow contributing to the dam, and the volume of any flow spilling over the dam when it is full. Developing and utilising a rainfall-run-off model for the sub catchment of the dam would facilitate determining the proportion of inflow coming from streamflow versus overland run-off, as opposed to valuing each individual component as one “inflow”. A properly placed and monitored evaporation pan should be installed for the availability of year-round estimates of evaporation from the surface of the dam. A more precise estimate of transpiration from the trees surrounding the dam could be accomplished through recording sap flow data. Proper soil testing to determine a k-value would yield more accurate estimates of infiltration from the dam. The addition of these processes would improve the overall reliability of the water balance, therefore improving any estimates of the impact of the dam on the surrounding catchment.

Appendices

Appendix A: Study Site

Figure A1: Michael's Dam, April 2018

Figure A2: Michael's Dam, April 2018

Figure A3: Jetty on the western side of Michael's dam, April 2018

Figure A4: Screening well at the jetty, April, 2018

Figure A5: Michael's dam from the jetty, August 2017

Appendix B: Soil K-value

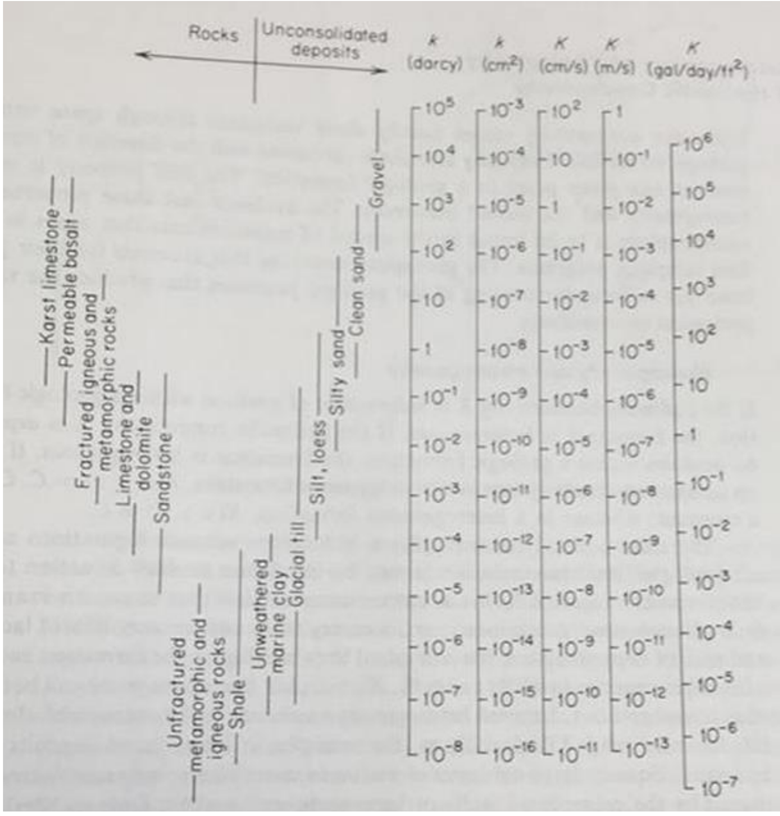

Figure B1: Range of values of hydraulic conductivity and permeability

Appendix C: Dam Volume

Table C1: 2013 daily volume descriptive statistics

Dam Volume 2013 (m^3)	
Mean	1162.9
Standard Error	28.3
Median	1063.4
Standard Deviation	405.9
Minimum	659.1
Maximum	1849.7
Sum	238395.3
Count	205
Largest (1)	1849.7
Smallest (1)	659.1
Confidence Level (95.0%)	55.9

Table C2: Summer 2013/2014 daily volume descriptive statistics

Dam Volume Summer 2013/2014 (m^3)	
Mean	134.1
Standard Error	13.3
Median	76.4
Standard Deviation	110.3
Minimum	40.9
Maximum	374.3
Sum	9249.9
Count	69
Largest (1)	374.3
Smallest (1)	40.9
Confidence Level (95.0%)	26.5

Table C3: Spring 2014 daily volume descriptive statistics

Dam Volume Spring 2014 (m^3)	
Mean	77.7
Standard Error	5.6
Median	69.5
Standard Deviation	36.9
Minimum	35.1
Maximum	151.2
Sum	3417.5
Count	44
Largest (1)	151.2
Smallest (1)	35.1
Confidence Level (95.0%)	11.2

Table C4: 2016 daily volume descriptive statistics

Dam Volume 2016 (m^3)	
Mean	583.6
Standard Error	16.8
Median	565.2
Standard Deviation	270.8
Minimum	145.6
Maximum	927.2
Sum	151741.9
Count	260
Largest (1)	927.2
Smallest (1)	145.6
Confidence Level (95.0%)	33.1

Appendix D: Rainfall

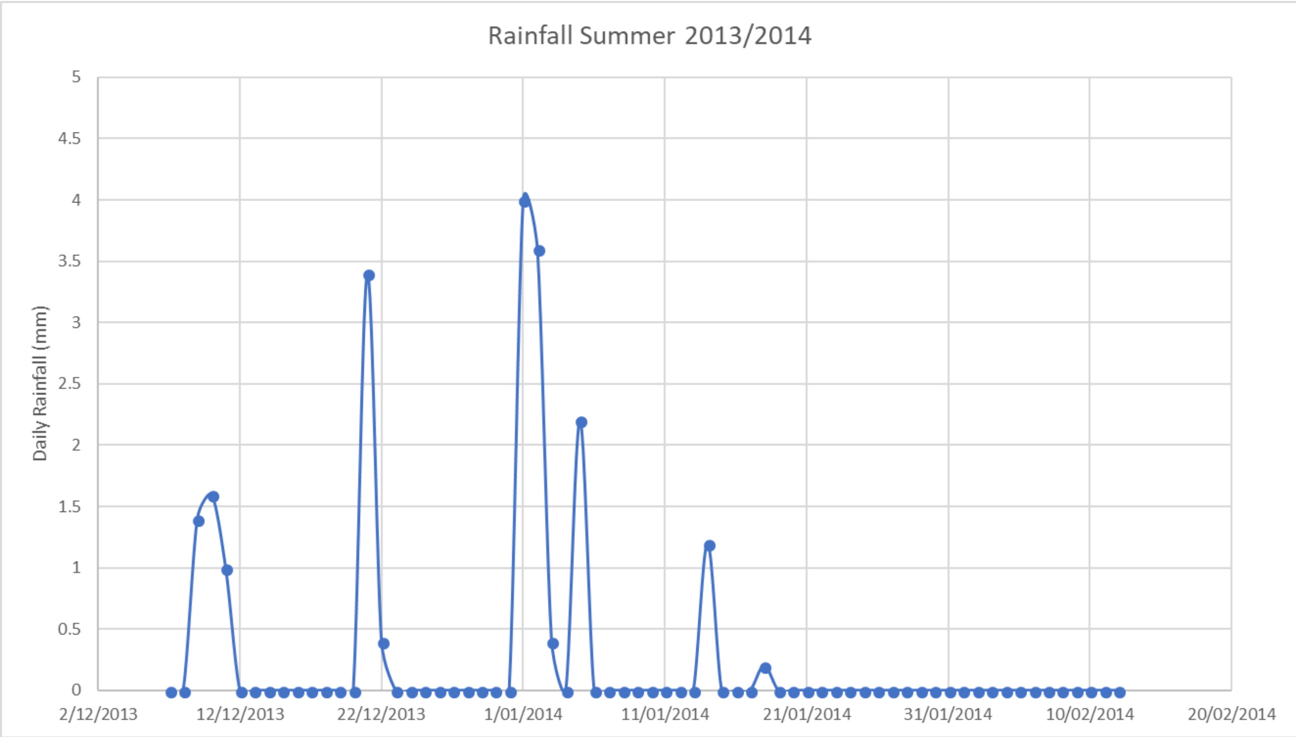

Figure D1: Daily rainfall for the summer 2013/2014 period

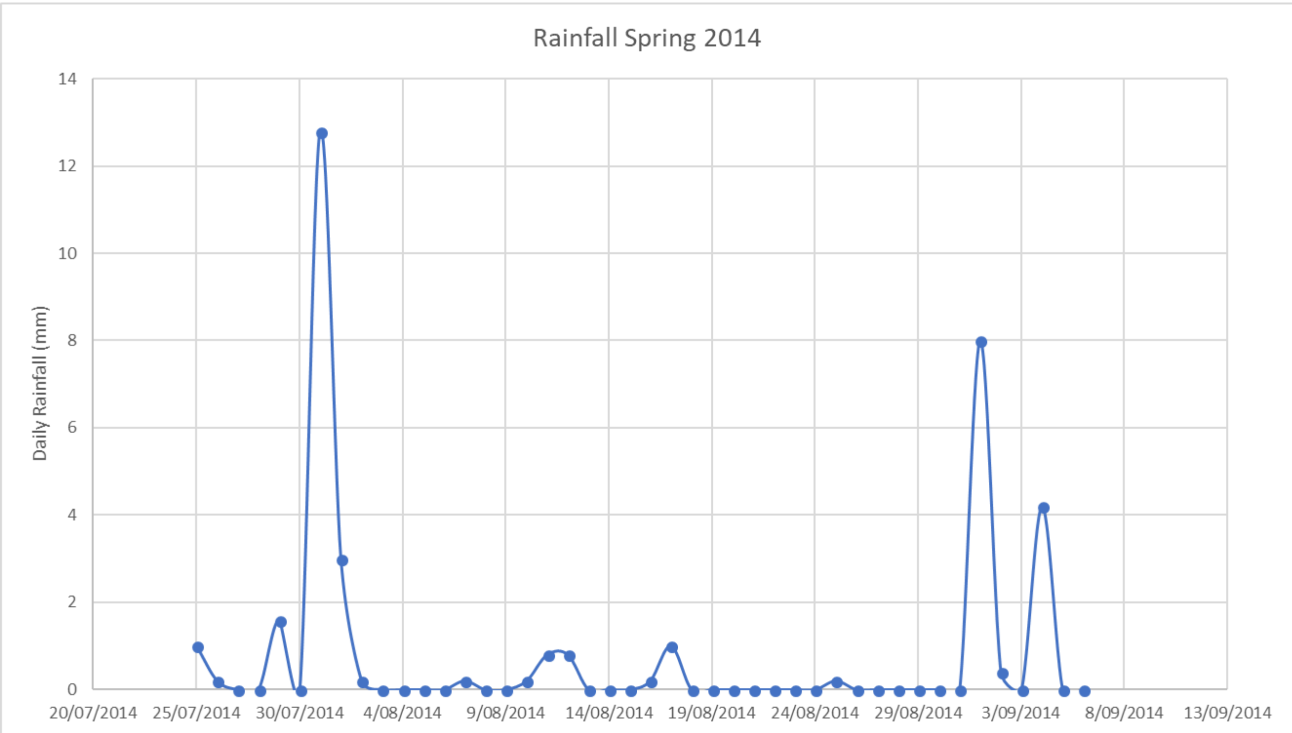

Figure D2: Rainfall for the spring 2014 period

Table D1: Descriptive statistics for the daily rainfall in the 2013 and 2016 time periods

2013 Rainfall (mm)		*2016 Rainfall (mm)*	
Mean	1.7	Mean	2.6
Standard Error	0.3	Standard Error	0.4
Median	0.2	Median	0.2
Standard Deviation	3.5	Standard Deviation	5.2
Minimum	0	Minimum	0
Maximum	21.4	Maximum	37.6
Sum	318.2	Sum	483.3
Count	184	Count	184
Largest (1)	21.4	Largest (1)	37.6
Smallest (1)	0	Smallest (1)	0
Confidence Level (95.0%)	0.5	Confidence Level (95.0%)	0.8

Appendix E: Transpiration

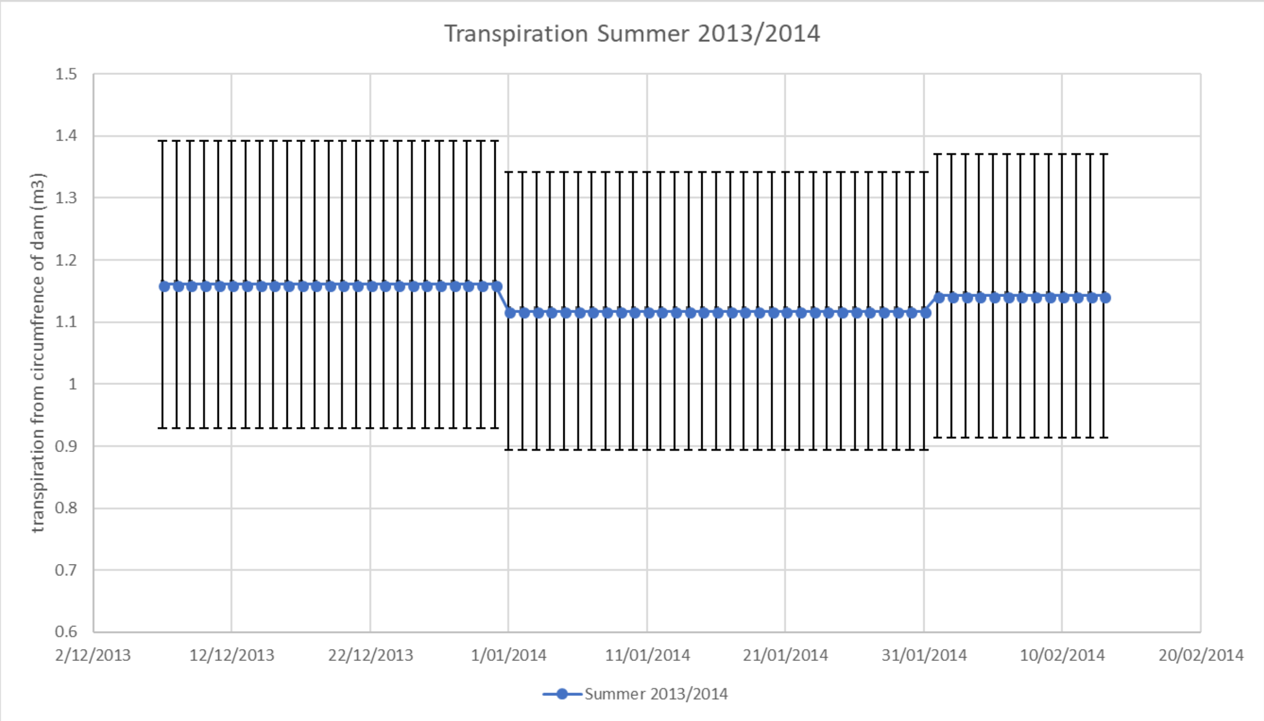

Figure E1: Transpiration estimates for the summer of 2013 and 2014

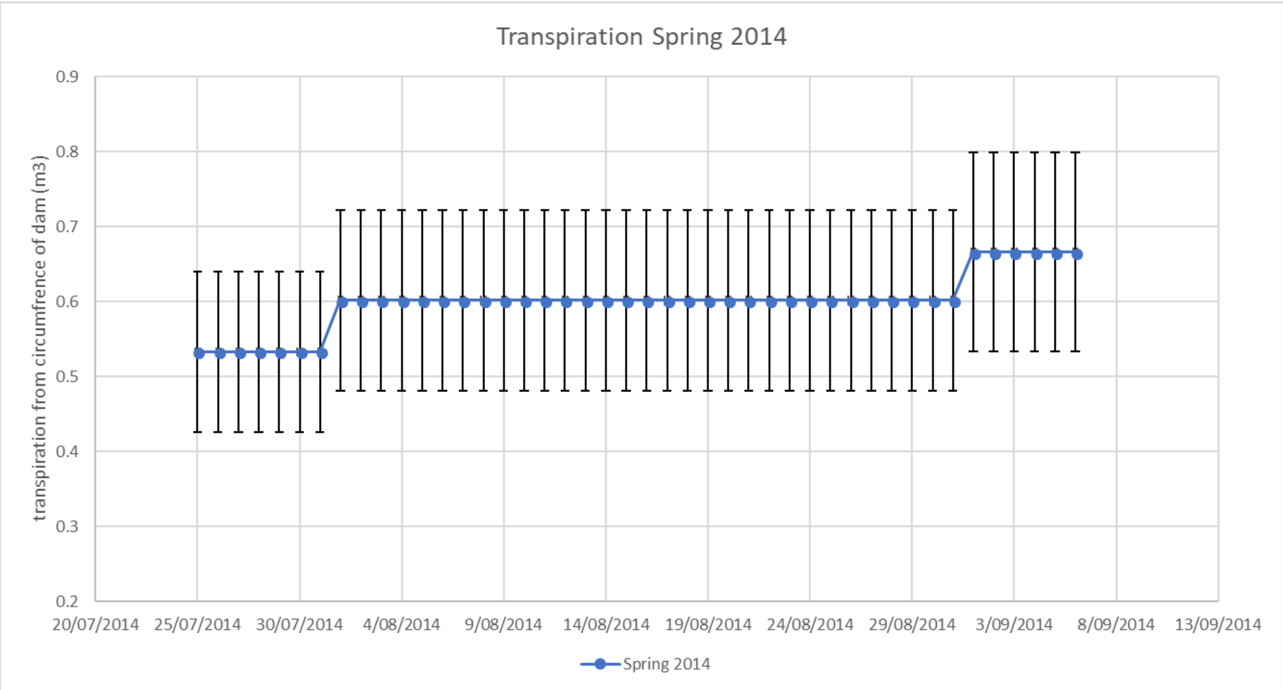

Figure E2: Transpiration estimates for spring 2014

Bibliography

Allen, R., Pereira, L., Raes, D. and Smith, M., 1998 "Crop evapotranspiration – Guidelines for computing crop water requirements" Food and Agriculture Organisation of the United Nations, Rome, Italy [online] accessed 1st May, 2018 <http://www.fao.org/docrep/x0490e/x0490e00.htm#Contents>

Beavis, S., Zhang, L., Evans, J., Jakeman, A., and Smith, D., 1997, *Impacts and implications of farm dams on catchment hydrology: Methods and application to Chaffey catchment,* Centre for resource and Environmental Studies, The Australian Nation University, Canberra, ACT, Australia

Bellette, S., and Lee, G. 2003, NT Waterwatch Education Kit. Part 2: Mapping Catchments, Department of Infrastructure, Planning and Environment, Darwin [online] accessed 15th January 2018 <https://denr.nt.gov.au/__data/assets/pdf_file/0011/269309/Part2-Mapping-catchments.pdf>

Brainwood, M. and Burgin, S. 2009, "Hotspots of biodiversity or homogeneous landscapes: Farm dams as biodiversity reserves in Australia" *Biodiversity and Conservation* vol. 18, no. 11, pp. 3043-3052 [online] accessed 15th February, 2018 < https://link.springer.com/article/10.1007/s10531-009-9623-5>

Burgess, S., Adams, M., Turner, N., Beverly, C., Ong, C., Khan, A., and Bleby, T., 2001, "An improved heat pulse method to measure low and reverse rates of sap flow in woody plants" *Tree Physiology,* vol. 21, no. 01, pp. 589-598, [online] accessed 18th August, 2017, <https://academic.oup.com/treephys>

Callow, J. and Smettem, K., 2009 "The effect of farm dams and constructed banks on hydrologic connectivity and runoff estimation in agricultural landscapes" *Environmental Modelling and Software,* vol. 24, no. 08, pp. 959-968, [online] accessed 31st July, 2017, <http://www.sciencedirect.com/science/article/pii/S1364815209000358>

Cetin, L., Mosley, L. and Jordan, P., 2009, *Assessing the Impacts of Farm Dams on the Streamflow of the Mount Lofty Ranges Watershed,* 32nd Hydrology and Water Resources Symposium: Adapting to Change, Engineers Australia, Newcastle, Australia, [online] accessed 31st July, <http://search.informit.com.au/documentSummary;dn=758549241069681;res=IELENG>

Chapra, S. C., 2008 "Surface Water-Quality Modelling" Waveland Press, Illinois, USA

Chow, V. T., Maidment, D. R., and Mays, L. W., 1988, "Applied Hydrology" McGraw-Hill Education, London, England

Dyson, M., Bergkamp, G. and Scanlon, J., (eds). 2003 Flow – The essentials of environmental flows, 2nd Edition. Gland, Switzerland: IUCN. Reprint, Gland, Switzerland: IUCN

Eijkelkamp Soil and Water, 2016, *Diver Water Level Loggers,* [online] accessed 28th March 2018 <https://diver-water-level-logger.com/en/diver-water-level-loggers/>

Fernandes, E., 2017, *"Methods to Estimate Sap Flow"* ISHS Working Group on Sap Flow, Commission on Irrigation and Plant Water Relations, Belgium, [online] accessed 18th August, 2017, <http://www.ishs.org/sites/default/files/documents/methods_0.pdf>

Freeze, R. A. and Cherry, J. A., 1979 "Groundwater" Prentice Hall, Inc. Upper Saddle River, New Jersey, USA

General Electric Company, 2013, *Druck Submersible Pressure Sensors Product Guide,* [online] accessed 28th March, 2018 <https://www.instrumart.com/assets/GE-Druck-Depth-Level-Brochure.pdf>

Government of South Australia, Eyre Peninsula Natural Resources Management Board, 2011, *Farm Dams – A guide to siting, design, construction and management on Eyre Peninsula,* EPNRMB, Port Lincoln

Google Maps, 2018, *McMurtrie Road McLaren Vale,* Google Maps [online] accessed 13th February 2018 <https://www.google.com.au/maps/place/McMurtrie+Rd,+McLaren+Vale+SA+5171/@-35.018545,137.8075749,243246m/data=!3m1!1e3!4m5!3m4!1s0x6ab12f710b1dc663:0xb1f22579d6b3554a!8m2!3d-35.2285011!4d138.5725916>

Habets, F., Phillippe, E., Martin, E., David, C., and Leseur, F., 2014, "Small farm dams: impacts of river flows and sustainability in a context of climate change" *Hydrology and Earth System Sciences*, vol. 18, no. 10, pp. 4207-4222, [online] accessed 30th September, 2017, <https://www.hydrol-earth-syst-sci.net/18/4207/2014/hess-18-4207-2014.html>

Hancock, G., 2005 "The use of digital elevation models in the identification and characterisation of catchments over different scale grids" *Hydrological Processes*, vol. 19, no. 09, pp. 1727-1749

Hughes, D. A., and Mantel, S. K., 2010, "Estimating the uncertainty in simulating the impacts of small farm dams of streamflow regimes in South Africa" *Hydrological Sciences,* vol. 55, no. 04, pp. 578-592, [online] accessed 22nd July, 2017, <http://www.tandfonline.com/doi/full/10.1080/02626667.2010.484903>

Hydrological Services America, 2018, *Class A Evaporation Pan*, [online] accessed 4th March, 2018 <https://www.hydrologicalusa.com/products/rainfall/class-a-evaporation-pan/>

Land and Water Australia, 2008. *Farm Dam Management* [online], updated March 9th, 2010 [online] accessed 2nd February 2018 <http://lwa.gov.au/node/2640>

Marshall, J., Morgan, A., Akilan, K., Farrell, B., and Bell, D., 1997, "Water uptake by two river red gum (*Eucalyptus camaldulensis)* clones in a discharge site plantation in the Western Australia wheatbelt" *Journal of Hydrology*, vol. 200, no. 01-04, pp. 136-148

McLaren Vale, 2017, *Weather stations* [online] accessed 7th February 2018 <https://www.weather-mclarenvale.info/station/3265/download>

McMurrary, D., 2004, *Farm Dam Volume Estimations from Simple Geometric Relationships: Mount Lofty Ranges and Clare Regions, South Australia,* (Report DWLBC 2004/48), Department of Water, Land and Biodiversity Conservation, South Australia, [online] accessed 31st July, 2017 <https://www.waterconnect.sa.gov.au/Content/Publications/DEWNR/ki_dwlbc_report_2004_48.pdf>

McMurrary, D., 2006, *Impact of farm dams on streamflow in the Tod River catchment, Eyre Peninsula, South Australia* (Report DWLBC 2006/22), Department of Water, Land and Biodiversity Conservation, South Australia, [online] accessed 19th September 2017 <https://www.waterconnect.sa.gov.au/Content/Publications/DEWNR/ki_dwlbc_report_2006_22_.pdf>

Meijer, E., Querner, E., and Boesveld, H., 2013, *Impact of farm dams on river flows; A case study in the Limpopo River basin, Southern Africa*, Dutch Ministry of Economic Affairs, Agriculture and Innovation, report 2394 ISSN 1566-7197, Alterra Wageningen UR, [online] accessed 17th September, 2017, <https://www.researchgate.net/publication/283069349_Impact_of_farm_dams_on_river_flows_A_case_study_in_the_Limpopo_River_basin_Southern_Africa>

Nathan, R., Jordan, P., and Morder, R., 2015, "Assessing the impact of farm dams of stream flows, Part 1: Development of simulation tools", *Australasian Journal of Water Resources,* vol. 09, no. 01, pp. 1-12, [online] accessed 7th July, 2017, <http://www.tandfonline.com/doi/abs/10.1080/13241583.2005.11465259?src=recsys>

Nathan, R., and Lowe, L., 2012, "The Hydrological Impacts of Farm Dams", *Australasian Journal of Water Resources,* vol. 16, no. 01, pp. 75-83, [online] accessed 7th July, 2017, <http://www.tandfonline.com/doi/abs/10.7158/13241583.2012.11465405?src=recsys>

Neal, B., Nathan, R. J., Schreider, S., and Jakeman, A. J., 2015, “Identifying the Separate Impact of Farm Dams and Land Use Changes on Catchment Yield”, *Australasian Journal of Water Resources,* vol. 05, no. 02, pp. 165-176, [online] accessed 7th July, 2017, <http://www.tandfonline.com/doi/abs/10.1080/13241583.2002.11465202>

Neal, B., Shephard, P., Austin, K. and Nathan, R., 2000 *The effect of catchment farm dams on stream flows - Victorian case studies*, In: Hydro 2000: Interactive Hydrology; Proceedings. Barton, A.C.T.: Institution of Engineers, Australia, 2000: 836-841. National conference publication (Institution of Engineers, Australia); no. 2000, [online] accessed 30th September, 2017, <http://search.informit.com.au/documentSummary;dn=582294280213894;res=IELENG>

O'Connor, T., 2002, “Effect of small catchment dams on downstream vegetation of a seasonal river in semi-arid African Savannah”, *Journal of Applied Ecology,* vol. 38, no. 06, pp. 1314-1325, [online] accessed 5th August, 2017, <http://web.b.ebscohost.com/ehost/detail/detail?vid=0&sid=a07a106d-32db-49c2bc2fed67b2c6fdf1%40sessionmgr104&bdata=JnNpdGU9ZWhvc3QtbGl2ZQ%3d%3d#AN=5721286&db=8gh>

Rosenberry, D., Winter, T., Buso, D., and Likens, G. “Comparison of 15 evaporation methods applied to a small mountain lake in the north-eastern USA” *Journal of Hydrology* vol. 340, no. 3-4, pp. 149-166, [online] accessed 4th April, 2018 <https://www.sciencedirect.com/science/article/pii/S0022169407002053>

Sinclair Knight Merz, 2006 “Wetland Extent and Drainage Line Mapping Project”, Report for the Wimmera Catchment Management Authority

Schreider, S., Jakeman, A., Letcher, R., Nathan, R., Neal, B., and Beavis, S., 2002, "Detecting changes in streamflow response to changes in non-climatic catchment conditions: farm dam development in the Murray-Darling basin, Australia" *Journal of Hydrology,* vol. 262, no. 01-04, pp. 84-98, [online] accessed 7th August, 2017, <https://www.sciencedirect.com/science/article/pii/S0022169402000239>

Solinst, 2018, *Levelogger Edge,* [online] accessed 28th March, 2018 <https://www.solinst.com/products/dataloggers-and-telemetry/3001-levelogger-series/levelogger-edge/datasheet/>

Teoh, K. S. 2003, *Estimating the Impact of Current Farm Dams Development on the Surface Water Resources of the Onkaparinga River Catchment* (Report DWLBC 2002/22), Department of Water, Land and Biodiversity Conservation, South Australia, [online] accessed 19th July, 2017 <https://edocs.geoleo.de/bitstream/handle/11858/00-1735-0000-0001-3370 3/DWLBC2002_22.pdf?sequence=1&isAllowed=y>

Teoh, K. S. 2006, *The Impact of Farm Dam Development on the Surface Water Resources of the South Para River Catchment,* (Report DWLBC 2003/19), Department of Water, Land and Biodiversity Conservation, South Australia, [online] accessed 31th July, 2017 <https://www.waterconnect.sa.gov.au/Content/Publications/DEWNR/ki_dwlbc_report_2003_19_1.pdf>

Tingey-Holyoak, J. 2014, Water sharing risk in agriculture: Perceptions of farm dam management accountability in Australia, *Agricultural Water Management*, vol. 145, no. 01, pp. 123-133 [online] accessed 14th February, 2018 <https://www.sciencedirect.com/science/article/pii/S037837741400050X>

Thoms, M., Suter, P., Roberts, J., Koehn, J., Jones, G., Hillman, T. & Close, A. 2000, Report of the River Murray Scientific Panel on Environmental Flows: River Murray - Dartmouth to Wellington and the Lower Darling River, Murray-Darling Basin Commission, Canberra

Walker, K. 2002, “Ecology and Hydrology”, in The Science of Environmental Water Requirements in South Australia, Adelaide, South Australia, 24 September 2002, The Hydrological Society of South Australia, pp. 1-7

Winter, T. 1981 “Uncertainties in estimating the water balance of lakes” *Journal of the American Water Resources Association,* vol. 17, no. 01, pp. 82-115