Investigating the impact of the Millennium Drought on catchment water balance

A study of four catchments in Victoria, Australia

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Abstract

Southeast Australia have between 1997-2009 experienced a severe drought, referred to as the *Millennium Drought*. During these years the region experienced a 11.4% decline in mean annual rainfall, an unprecedented decrease in runoff and a decline in soil moisture and groundwater storage. The drought officially ended in 2010 when one of the strongest La Nina-events on record occurred. However, it is still unknown how the behaviour of the catchments changed during the drought and if this change persists in the years following the drought.

Changes in catchment behaviour and fluxes are commonly determined using a catchment water balance, which is based on the law of conservation of mass. It states that rainfall should be equal to the sum of runoff, evapotranspiration and change in groundwater storage. Because of the assumption that the change in groundwater storage follow an interannual cycle, meaning that the groundwater level will change from year to year but will eventually return to its initial state, this term is commonly neglected when studying longer periods of time. However, studies have showed that this assumption might be inaccurate for catchments that experience a climatic disturbance such as a severe drought.

This study investigates if including the change in groundwater storage by using spatial groundwater head data can improve the catchment water balance. This was done by assuming that specific yields are unknown and to be determined in a calibration. An unknown scalar applied to the evapotranspiration was used to try to account for the uncertainties in the known fluxes and was also to be determined in the calibration. Two different calibration schemes were considered: one assuming no delay in groundwater head response to climate and one accounting for the delay. The fluxes were determined for the period before, during and after the drought. The results were analysed to determine if the catchments showed a change in behaviour during and after the drought.

The results showed that when not accounting for the delayed response of the groundwater head, at least one of the specific yields in the catchments became infinitely small. Including the delayed groundwater head response did improve one of the catchments significantly by producing plausible specific yields for all geological units. A conclusion of this is that including the change in groundwater storage could improve the water balance. However, for it to do so a thorough analysis of the groundwater and subsurface needs to be conducted. Further, the water balance error was the third biggest flux after rainfall and actual evapotranspiration suggesting that the evapotranspiration scalar reduced the actual evapotranspiration too much.

All fluxes did decrease during the drought, by how much differed between the catchments and the water balance components. Two of the catchments showed a change in behaviour during the drought that persisted in the years following the drought. The most likely fluxes to have caused this were the change in runoff and groundwater storage. The other two catchments showed a smaller change in behaviour during the drought and an indication that it was on its way back to the same state as before the drought. The likely fluxes to have caused the small change in behaviour was runoff and actual evapotranspiration.

**Keywords**

Catchment water balance, catchment behaviour, groundwater storage, specific yield, Millennium Drought.
Summary in Swedish


Flödena inom ett avrinningsområde bestäms vanligtvis genom en vattenbalans. Vattenbalansen är baserad på lagen om massans bevarande och innebär att nederbörd ska vara lika med avrinning, evapotranspiration och förändringar i grundvattenmagasinen. Då vattenbalansen över ett avrinningsområde studeras under en längre tid antas ofta att förändringarna i grundvattenmagasinen går att bortse från då grundvattennivån ofta återgår till samma stadie efter ett antal år. Nyare studier har dock visat att detta inte alltid är fallet vid exempelvis en svår torka och att det vid dessa fall inte är korrekt att anta att förändringen i grundvattenmagasinen är försumbar.


Resultaten visade att när ingen hänsyn togs till en eventuell försonad reaktion av grundvatten så går värdet för dränerbar porositet i minst en geologisk enhet mot noll medan det andra värdet är rimligt. När hänsyn togs till en försonad reaktion av grundvattnet, fick fler avrinningsområde rimliga värden för dränerbar porositet för hela området. Slutsatsen som kan dras kring detta är att vattenbalansen kan förbättras om förändringen i grundvattenmagasinen inkluderas. Detta kräver dock en djupgående analys av grundvattnet och geologin i avrinningsområdet. Vidare visar resultatet att skillnaden mellan in- och utflöden i avrinningsområdena (s.k. vattenbalans-felet) är det tredje största flödet efter nederbörd och avrinning. Detta indikerar att den faktiska evapotranspirationen för mycket då denna skillnad idealt ska vara noll.

Hur mycket flödena förändrades under och efter torkan varierar mellan avrinningsområdena och flödena, gemensamt var dock att alla flöden minskade under torkan. Två av avrinningsområdena påvisade en förändring i beteendet under torkan och de är som följde. Det är mest troligt att förändringarna i avrinning och grundvattenmagasinen har påverkat detta. De övriga två avrinningsområdena påvisade även de en förändring under torkan, om än mindre än för de föregående. Denna förändring ser även ut att vara på tillbakagående och att avrinningsområdet inom en snar framtid skulle kunna ha samma tillstånd som innan torkan. De mest troliga flödena som har påverkat dessa avrinningsområdena är förändringar i avrinning och den faktisk evapotranspirationen.
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1. Introduction

During the past century, there has been a climate change across the world which most likely is due to anthropogenic causes (IPCC, 2014). The concentration of greenhouse gases in the atmosphere has increased rapidly since the industrial revolution (IPCC, 2014) and the average surface temperature across the globe has increased with 0.85°C between 1880-2012 (BoM and CSIRO, 2017). It is also very likely that the number of cold days and nights has decreased and the number of warm days and nights has increased. Similarly, it is probable that the frequency of heat waves has increased in large parts of Australia, Asia and Europe (BoM and CSIRO, 2017).

The Australian climate differs widely across the country, from tropical in the north to temperate in the southeast and arid across central Australia. Australia has, just like the rest of the world, experienced a climate change during the past century. The temperature has increased in a trend similar to the global trend (IPCC, 2014; Timbal et al., 2010) and heat waves have increased in intensity, duration and frequency in numerous regions (BoM and CSIRO, 2017). For southeast Australia and the Murray-Darling Basin (Fig. 1), the annual average rainfall has decreased since the 1950s and so has the heavy daily rainfall (BoM and CSIRO, 2017). For the state of Victoria in southeast Australia, there has been a statistically significant decline in rainfall from 1997 to 2009 and it is likely that it is partly due to the climate change (Chiew and Prosser, 2011). This period is commonly referred to as the Millennium Drought (BoM, 2015).

The rainfall deficit has affected the water balance across the region and there has been an unprecedented decrease in runoff compared to historical records (Saft et al., 2015) as well as decrease in reservoir storage levels (Chen et al., 2016). This has led to a severe water shortage and it greatly affected the infrastructure of southeast Australia (van Dijk et al., 2013). It impacted annual agriculture and forestry (Semple et al., 2010; van Dijk et al., 2013), river ecosystems and tourism (van Dijk et al., 2013) and water availability (Semple et al., 2010). As a result of the drought, several areas had to impose water restrictions. The city of Melbourne had a water restriction from 2002-2008 when the state of Victoria implemented permanent water restrictions (Melbourne Water, 2003; Melbourne Water, 2014). The drought was ongoing until one of the strongest La Niñã-events on record occurred in 2010-2011 (BoM, 2012). 2010 was the wettest calendar year on record for the Murray Darling Basin and April 2010 to March 2012 was the wettest 2-year period on record in Australia (BoM, 2012).

Nevertheless, it is still unknown if the change in the fluxes of the water balance caused a change in behaviour in the catchments during and after the drought. A common way to determine the magnitude of the fluxes in a catchment is through performing a water balance, where it is generally assumed that the change in groundwater storage can be neglected when studying the water balance over greater time scale (Hiscock & Bense, 2014). However, if there has been a decline in groundwater storage because of a persistent or prolonged drought, like the Millennium Drought, the recovery of groundwater level might take some time (Hughes, Petrone and Silberstein, 2012) and recent studies have even showed that a large climatic disturbance can force a permanent change in groundwater table (Peterson et al., 2009). It might therefore not be accurate to neglect the change in groundwater storage for a drought of this magnitude.

The prediction for the future is that the temperature across Australia will continue to increase while the annual rainfall will decrease (BoM and CSIRO, 2017; Timbal et al., 2016). For southern Australia, the main decrease in rainfall is likely to happen during winter and spring. It is probable that the time spent in drought will increase across southern Australia as well as the frequency of severe droughts. It is also suggested that the evaporation rates will increase which could contribute to a reduction in soil moisture (BoM and CSIRO, 2017; Timbal et al., 2016).
Figure 1. Map of Australia and the states. Murray Darling Basin is the dark green area (Murray Darling Basin Authority, n.d.).

It is therefore essential to understand the water balance of catchments in the region so that a sustainable water resource management can be achieved in the future (Hiscock and Bense, 2014). This study will explore how the fluxes changed during and after the Millennium Drought and if the catchments' behaviour was affected. Newly developed groundwater head maps for Victoria (Peterson et al., 2017) provides a possibility to include the changes in groundwater storage in the water balance, and thereby determine the magnitude of the fluxes before, during and after the drought.

1.1 Aim and Research Questions

The aim of the study is to evaluate if including the change in groundwater storage by using groundwater head data improves the catchment water balance. Further, the aim is to determine if the catchments showed a change in behaviour during and after the drought. The research questions to be answered in this study are the following:

- Did the unknown parameters in the water balance reach plausible values when including the change in groundwater storage in the equation?
- How did the magnitude of the fluxes change during and after the Millennium Drought?
- Did the relationship between fluxes within the catchments change during and after the Millennium Drought?

Understanding what happens in a catchment during and after a drought and which components of the water balance are prone to shift due to a climatic disturbance, such as a severe drought, will enhance the possibility of maintaining a sustainable water management plan in the future.

2. Literature Review

To understand how the Millennium Drought affected the catchment water balance one must understand the components of the water balance. Therefore, in section 2.1 the water balance equation and its components are presented together with common assumptions. In section 2.2, the
groundwater storage and specific yield will be discussed in more depth and section 2.3 presents evapotranspiration and common ways to calculate it. Finally, an in-depth description of the Millennium Drought and what previous studies have shown are presented in section 2.4.

2.1 The Water Balance Equation

The water balance equation is commonly used when studying the behaviour of a catchment. This equation takes all inflows and outflows into consideration and is based on the law of conservation of mass (Hiscock & Bense, 2014; Sustainable Sanitation and Water Management, 2017). However, there are different physical, climatic and ecological factors that affects the catchment water balance (Potter, Chiew and Frost, 2010).

A simple catchment water balance can be defined as follows:

\[ P = ET + Q + \Delta S, \]  

(Eq. 1)

where \( P \) is the precipitation, \( ET \) is the evapotranspiration, \( Q \) is the runoff from the catchment including groundwater discharge and \( \Delta S \) is the change in total unconfined groundwater storage (Hiscock and Bense, 2014; Savenije, 1997; Sustainable Sanitation and Water Management, 2017). The runoff component can be divided up into two components: surface water runoff and groundwater discharge. The component for groundwater discharge is supplied by groundwater recharge (from e.g. precipitation that percolates to the groundwater) and includes river baseflow and artificial abstraction (e.g. pumping wells for domestic or agricultural use). The change in total groundwater storage is defined by a change in soil moisture and change in groundwater level due to change in recharge and discharge (Hiscock and Bense, 2014).

The soil moisture will vary throughout the soil profile, mainly due to capillary forces, adsorption and osmosis. The total change in soil moisture is therefore usually divided into smaller intervals \( d \), where the change is defined as \( d \ast \Delta \theta \) (Hiscock & Bense, 2014). The change in groundwater storage due to change in groundwater level is defined as \( \Delta h \ast S_y \), where \( \Delta h \) is the change in groundwater level and \( S_y \) is the specific yield (Hiscock and Bense, 2014; Leblanc et al., 2009). It is usually assumed that over timescales of multiple years the change in groundwater storage will be zero (Hiscock & Bense, 2014). However, this assumption might not be accurate when studying periods of drought (Hughes, Petrone and Silberstein, 2012; Peterson et al., 2009). This will be discussed more thoroughly in section 2.2.

2.2 Groundwater Storage and Specific Yield

The groundwater storage volume is something that is constantly changing due to recharge and discharge. Through downward percolation of rainfall and surface water, the volume will increase and the water table rise while the volume decreases through, for example, evapotranspiration and outflows into streams (Boonstra and de Ridder, 1990). The groundwater table might react with a delay to the recharge and discharge depending on the depth to the water table and the type of geological unit, because of the slow infiltration flow rate (Brouwer et al., 1985; Clifton et al., 2010). However, its commonly assumed that the change in groundwater storage follow an interannual cycle, meaning that the groundwater level will change from year to year but will eventually return to its initial state (van det Velde et al., 2013). This is one of the reasons why the change in groundwater storage commonly is neglected when studying the water balance over long-term timescales (Hiscock & Bense, 2014; van det Velde et al., 2013). Other reasons are the lack of consistent and catchment-wide data of the groundwater level fluctuations and the difficulty of estimating the specific yield of the aquifer because of the its complexity (Boonstra and de Ridder, 1990).
The specific yield is a physical property of the aquifer. It refers to the aquifers water-yielding capacity and will vary depending on aquifer characteristics. It is commonly defined as “the volume of water released from groundwater storage per unit surface area of aquifer per unit decline in water table in an unconfined aquifer” (Hiscock & Bense, 2014). In soil, specific yield varies with grain size and particle shape as well as the distribution of pores and the compaction of the soil (Punmia and Jain, 2005). In rocks, it varies with homogeneity, the connection of joints and faults as well as the degree of weathering the rock has experienced (Bell, 2007). For sedimentary rocks, it will also vary with size of the particles, degree of cementation and how sorted the material is (Morris and Johnson, 1967). Although the general concept of specific yield is well-known, it is still very hard to get a correct estimate of the actual value, especially on the catchment scale (Chen et al., 2003; Maréchal et al., 2003).

The general way to estimate aquifer properties such as specific yield is done by performing a pumping test in bores (Hiscock and Bense, 2014). The problem with estimating specific yield using pumping tests is that the test needs to go on for a sufficient period of time, which could be up to several weeks, (Boonstra and de Ridder, 1990; Hiscock and Bense, 2014) as well as the observation wells need to be placed in such a way that they properly reflect the drawdown from the pumping (Chen et al., 2003). Values for specific yield are given by using the results from the pumping test in the Theis equation (Theis, 1935). Some general values can be seen in Table 1. However, the Theis equation comes with a few assumptions. One of the assumptions is that the aquifer is homogeneous, isotropic, of uniform thickness and of infinite areal extent. In reality, this is rarely the case (Hiscock and Bense, 2014; Raghavan, 2004). Due to the difficulty in estimating specific yield, an average value for a region specific yield is sometimes used when determining change in groundwater storage. This might provide inaccurate results since the geological formation and layers usually varies over the region as well as with depth (Chen et al., 2016; Naik and Awasthi, 2003). There are also some more recent studies that try to find new reliable methods to determine specific yield by using numerical models or using new techniques (e.g. Dewandel et al., 2012; Durand et al., 2017; Gehman et al., 2009; Machiwal and Jha, 2014).

As mentioned earlier, it might not be accurate to neglect the change in groundwater storage for periods of severe drought. Hughes, Petrone and Silberstein (2012) argued that in catchments where there is a depletion of groundwater because of a persistent or prolonged drought, it might take a very long time for the groundwater level to recover because of the slow movement of water in the subsurface. A new concept regarding a possible existence of multiple stable states (also referred to as attractors) has also been introduced (Peterson et al., 2009; Ridolfi, D’Odorico, and Laio, 2006). Peterson et al. (2009) showed that it is possible for a hydrological system to have multiple water table attractors, meaning that a climatic disturbance such as a severe drought can force a permanent change in water table elevation. If a system has the potential to have multiple attractors will depend on its hydrogeology, boundary conditions and catchment shape as well as recharge (Peterson et al., 2009).

### Table 1. General values for specific yield for different soil and rock types.

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Yield [-]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>0.15-0.30</td>
<td>Morris and Johnson, 1967</td>
</tr>
<tr>
<td>Sand</td>
<td>0.10-0.30</td>
<td>Morris and Johnson, 1967</td>
</tr>
<tr>
<td>Silt</td>
<td>0.05-0.10</td>
<td>Morris and Johnson, 1967</td>
</tr>
<tr>
<td>Clay</td>
<td>0.01-0.05</td>
<td>Morris and Johnson, 1967</td>
</tr>
<tr>
<td>Sandstone</td>
<td>0.05-0.25</td>
<td>Morris and Johnson, 1967</td>
</tr>
<tr>
<td>Claystone</td>
<td>-</td>
<td>Morris and Johnson, 1967</td>
</tr>
<tr>
<td>Shale</td>
<td>-</td>
<td>Morris and Johnson, 1967</td>
</tr>
<tr>
<td>Granite</td>
<td>0.0009</td>
<td>Heath, 1983</td>
</tr>
<tr>
<td>Basalt</td>
<td>0.08</td>
<td>Heath, 1983</td>
</tr>
</tbody>
</table>
2.3 Evapotranspiration

Evapotranspiration (ET) is commonly used to describe a combination of two effects: evaporation and transpiration. Evaporation occurs from a free water surface while transpiration is the loss of water through the leaf stomata of plants. ET is commonly talked about in terms of potential evapotranspiration (PET) or actual evapotranspiration (AET). PET is the water that would be removed from a vegetated surface if there was sufficient water available to meet the demand of the atmosphere. If there is not sufficient water, the AET will be less than PET. When determining the water balance of a catchment it is important to estimate the AET (Hiscock & Bense, 2014). It is however difficult to estimate its magnitude compared to estimating the magnitude of precipitation and runoff (McMahon et al., 2013a).

Evapotranspiration is an important component of the water balance and is affected by various factors (Hiscock and Bense, 2014; Peel, McMahon and Finlayson, 2010) where vegetation is one of them (Allen et al., 1998). One example of this is that tropical and temperate forested catchments have a statistically significant higher median evapotranspiration than non-forested catchments for catchments with an area that is less than 1000 km². The opposite relationship applies to cold forested and non-forested catchments (Oudin et al., 2008; Peel, McMahon and Finlayson, 2010). Other factors that affect evapotranspiration are solar radiation and the difference in vapour pressure at the evaporating surface and the surrounding air (Allen et al., 1998).

There are several different models and equations that can be used for estimating ET. In simpler catchment water balance equations, it is assumed that ET is the sum of precipitation minus the runoff (when assuming the change in groundwater storage is zero) (Peel, McMahon and Finlayson, 2010). One of the most well-known models used to estimate open-water evapotranspiration is the Penman equation. This equation requires information about the aerodynamic resistance (McMahon, Finlayson and Peel, 2016; Penman, 1948). Monteith developed the equation to also involve surface resistance. This equation is known as the Penman-Monteith equation and is generally used to estimate evapotranspiration from the vegetation canopy (Monteith, 1965).

Another frequently used model is the Priestly-Taylor equation which is used to estimate the PET using solar radiation and temperature. This model is also a variation of the Penman equation and is ideally used in humid regions with low advective transport of heat (McMahon, Finlayson and Peel, 2016; Priestley and Taylor, 1972).

Most of the models for estimating both PET and AET require information about wind speed. This causes a problem when it comes to estimating evapotranspiration in Australia since wind data are generally unavailable. One model that does not require any wind data is Morton’s CRAE model. Morton makes an important assumption that vapor transfer coefficient is independent of wind speed and bases this assumption on how the vapor transfer coefficient relates to surface roughness, atmospheric instability and wind speed (McMahon et al., 2013b). It has therefore been used extensively when estimating AET in Australia (McMahon et al., 2013a).

Morton developed three different models: CRAE computes evapotranspiration for land environments, CRWE computes evaporation for shallow lakes and CRLE computes evaporation for deep lakes. The CRAE model uses the complementary relationship to estimate the AET by first estimating the point PET and wet-environment areal evapotranspiration (McMahon et al., 2013a). The complementary relationship was proposed by Bouchet in 1963 and is based on the assumption that for large homogeneous surfaces with minimal advective heat and moisture, the PET and AET are strongly dependent on each other through land-atmosphere feedbacks (McMahon et al., 2013a).
There are some limitations with using Morton’s CRAE model, one of them being that the model requires accurate measurements of humidity data as well as the climatological station used must be representative for the specific area of interest. Furthermore, the model should not be used for time-steps less than three days (McMahon et al., 2013b). It is however commonly used for monthly time-steps (McMahon et al., 2013a; Morton, 1983). Since the model does not require information about the soil-vegetation system, it should not be used to study the impact of natural or man-made change in the system (McMahon et al., 2013b).

2.4 The Millennium Drought

A drought can be defined by meteorological conditions (decrease in precipitation), agricultural conditions (decrease in soil moisture) or hydrological conditions (e.g. decrease in river flows or groundwater levels) (Hiscock and Bense, 2011). Most studies done on the Millennium Drought seem to define it by meteorological conditions which delimit the drought to 1997-2009 (Chiew and Prosser, 2011; Saft et al., 2015; Sawada and Koike, 2016; Timbal et al., 2010). The mean annual rainfall across southeast Australia between 1900-2009 was 580.8 mm (Timbal et al., 2010) but it differs widely across the region. In Victoria, most of the rainfall occurs during winter and early spring as well as being more frequent during the winter compared to summer (Agriculture Victoria, 2017). During the Millennium Drought, southeast Australia experienced the lowest 13-year rainfall period in recorded history (1900-2009) with a 11.4% decline in mean rainfall. This is significantly larger than the previously driest 13-year period that occurred during World War 2 (1933-1945) when the decline was 7.4% (Timbal et al., 2010). Gerig et al. (2011) determined that there was a 97.1% probability that the rainfall anomaly of the Millennium Drought was the worst on record since European settlement of Australia. Even though the main driver for this drought was due to El Niño-conditions (van Dijk et al., 2013), Delworth and Zeng (2014) showed that the low levels of precipitation during the drought could be due to anthropogenic changes in CO₂ and ozone. Timbal et al. (2010) agrees with this theory and describes the drought as being related to global warming.

Murphy and Timbal (2008) propose three possible factors that could explain why the Millennium drought was more severe than previous long-term droughts. Firstly, global warming has contributed to an increase in mean temperature across Australia, and the increase has been especially steep since 1970 (Murphy and Timbal, 2008). Figure 2 presents the temperature anomaly for Victoria between 1970-2017, and it shows an 0.1-0.2°C increase per decade in the state (BoM, 2018). Because of this, Murphy and Timbal (2008) propose that it is likely that the evaporation has increased. However, they also aware that this assumption could be inaccurate based on observations of pan evaporation across the world that show a decreasing trend both in the Northern and Southern hemisphere (e.g. Moonen et al., 2002; Peterson, Golubev and Groisman, 1995; Roderick and Farquhar, 2004; Thomas, 2000). Roderick and Farquhar (2004) observed a decline in pan evaporation of approximately 4 mm/α² across Australia between 1970-2002 and that the decreasing trend was strongest in north-western and south-eastern part of the country.

Secondly, the year-to-year variability in precipitation between 1997-2006 has been below average (Murphy and Timbal, 2008). Finally, the decline in annual rainfall is likely due to lower rainfall in during the autumn and early winter months (Hope, Timbal, and Fawcett, 2009; Murphy and Timbal, 2008). Figure 3 shows that the monthly decline is biggest for the months of March, April and May. This is of importance because it is during these months that the soil profile is wetted and runoff is generated before the summer season starts. As a consequence of these anomalies, there has been a reduction of water storage, increased stress on native trees and increased risks for bushfires (Murphy and Timbal, 2008).
The vegetation was also affected as a result of the Millennium Drought. The stress on native trees increased (Murphy and Timbal, 2008) and a widespread change in phenology could be seen between the driest (2002) and wettest year (2010) (Ma et al., 2015). However, there have been studies that show that the aboveground ecosystem could become resilient to severe droughts by altering its traits to adapt to the conditions of a drought (Bréda et al., 2006; North and Nobel, 1992; Sawada and Koike, 2016; Tron et al., 2015). Bréda et al. (2006) showed that the root system can adapt to periods of water shortage and Tron et al. (2015) argues that the root system adapts to environmental changes so it can access sufficient soil moisture. North and Nobel (1992) stated that specific plants could shrink their roots and decrease the root-soil conductivity during a drought while recovering after re-wetting. For longer time-periods, the root system will follow the groundwater fluctuations which may cause a change in root depth so it can meet the water demand of the canopy (Tron et al., 2015).

The deficit in rainfall during the Millennium Drought has resulted in an unprecedented decrease in runoff compared to historical records (Potter and Chiew, 2011; Potter, Chiew and Frost, 2010; Saft et al., 2015). The recurrence interval for the rainfall reduction between 1997-2006 is up to 100 years while the recurrence interval for the runoff reduction in the same area and during the same years is more than 300 years (Potter, Chiew and Frost, 2010). Furthermore, there has been a roughly 35% reduction of the long-term mean runoff compared to the 11% reduction of long-term mean rainfall in the southern part of southeast Australia (Chiew et al., 2011). Potter, Chiew and Frost (2010) argues that change in rainfall patterns could be an explanation and Potter and Chiew (2011) states that groundwater extraction and recent changes in land use also could be a factor. Chiew et al. (2011) suggests that the change in runoff reduction could be because of a large decrease in autumn rainfall while Saft et al. (2015) could not find a significant difference in runoff reduction due to this. However, Saft et al. (2016) did find that the decline in spring rainfall was of significance for the change in the rainfall-runoff relationship. It is likely that the autumn rainfall anomaly has an indirect effect on the runoff in such a way that it may delay the time before the catchment becomes sufficiently wet (Saft et al., 2016).

Despite these observations, Saft et al. (2015) and Saft et al. (2016) found that it is more likely that the shift in rainfall-runoff relationship is linked to endogenous factors such as the catchments biophysical structure rather than exogenous factors such as higher temperatures during drought. Characteristics

![Figure 2. Trend in annual mean temperature between 1970-2017 (BoM, 2018).](image-url)
that implies that the catchment is more susceptible to a change in rainfall-runoff relationship is high variability in groundwater storage, arid catchments and catchments that have less variable monthly rainfall as well as catchments that have deeper soils (Saft et al., 2016).

Furthermore, observations showed that the groundwater levels significantly declined during the Millennium Drought (Chiew et al., 2014). Chen et al. (2016) have observed both in-situ groundwater level measurements and measurements from Gravity Recovery and Climate Experience (GRACE) in Victoria. The in-situ measurements from 1395 bores in Victoria show a steady depletion of the groundwater storage since the early 1990s until the trend reversed in early 2010 due to the La Niña-event. The GRACE estimates for 2003-2012 strongly coincides with this trend. The depletion rate is particularly strong between 2005-2009 (Fig. 4). There is also a correlation between the annual changes in groundwater storage and the anomalies in precipitation during the same period. Chen et al. (2016) suggested that this correlation implies that the change in groundwater storage is primarily due to the drought and the groundwater abstraction for agricultural and domestic consumption.

One major uncertainty to the in-situ measurements is that only one value was used as specific yield, which was the regional mean value of 0.1. The reason for using one mean value was due to the lack of reliable geological data in the region and the uncertainty in the results due to this was estimated to be about 40% (Chen et al., 2016). It is known that groundwater level decline is generally related to an increase of losing conditions for streamflow and Saft et al. (2015) could see that there was a relationship between catchment flatness and losing conditions for the streamflow. This is supported by Parsons, Hoban and Evans (2008) who found that flatter catchments are more likely to transit from gaining to losing conditions and from connected to disconnected streams throughout a drought.

Although there is a lack of soil moisture data, the modelled values show an indication of a decline in soil moisture during the Millennium Drought (Leblanc et al., 2009; Leblanc et al., 2011). The trend in the Murray-Darling Basin is that the decline is rapid during the start of the drought and then stabilises at low levels for the rest of the drought (Leblanc et al., 2009; Leblanc et al., 2011). Raupach et al. (2009) showed that the soil moisture deficit relative to average conditions was severe between 2002 and 2007.
3. Method

In this section, a description of the study area and its geology is presented in section 3.1, followed by the software used and the data in section 3.2 and 3.3. Section 3.4 presents the assumptions made and the limitations with the study and section 3.5 presents how the rainfall, runoff and groundwater head data were analysed. The modelling method that was used is presented in section 3.6 and how the calibration was done is presented in section 3.7 followed by how the fluxes were determined in section 3.8. Finally, the sensitivity analysis approach is presented in section 3.9.

3.1 Study Area

The study area consists of three catchments in western Victoria and one catchment in eastern Victoria. The catchments were chosen based five criteria with the purpose of studying actual change in the catchment due to changes in the climate and not due to human activity. Another reason for these criteria were to minimise the unknown parameters used. The criteria were the following:

- Little or no groundwater usage
- Minimal land use change
- Catchments are unregulated and have high-quality streamflow data
- Reliable groundwater data
- Maximum of three different major geological units within the catchment

The four catchments are: catchment number 405245 (Ford Creek at Mansfield), 407230 (Joyes Creek at Strathlea), 415226 (Richardson River at Carrs Plains) and 415237 (Concongella Creek at Stawell). The locations of the catchment and the geology of the area can be seen in Figure 5. The characteristics of each catchment are described in Table 2. The climate for all catchments are temperate with warm summers (Cfb Köppen-Geiger type) (Peel, Finlayson and McMahon, 2007). Figure 6 shows the topography of the region.
3.1.1 Geology of the Study Area

The surface geology for the four catchments consist of five different lithostratigraphic units (hereon referred to as geological units): regolith, sedimentary siliciclastic, igneous felsic intrusive, igneous mafic and felsic volcanic as well as igneous felsic volcanic and sedimentary siliciclastic. Table 3 provides a more in-depth description of each lithostratigraphic unit and the geological units in all catchments are presented together with the depth to the water table for April 2000 in Figure 7.

In catchment 405245, the regolith is an alluvium. The sedimentary siliciclastic unit mainly consists of the Mansfield group (99.7%) and the remaining is the Delatite Group. There is also a small part of igneous felsic volcanic rock and sedimentary siliciclastic that is the Wellington Volcanic Group.

In catchment 407230, the regolith consists to 81.2% of Newer Volcanics and the remaining is alluvium. The sedimentary siliciclastic unit is a Castlemaine Supergroup. The catchment also has a fault going through parts of the regolith and the sedimentary siliciclastic unit from northeast to southwest.

Catchment 415226 also consists of two geological formations: regolith and sedimentary siliciclastic. The regolith consists mainly of alluvium (77.8%) and to 15.9% of Wunghnu Group. The remaining consists of Pooraka Formation. The sedimentary siliciclastic formation consists to 60.4% of Loxton Sands which is located to the northwest in the catchment, i.e. closest to the outlet, and to 27.0% of the Saint Arnaud Group, which is located furthest away from the outlet. The remaining is the Brighton Group, located in between the other formations.

Figure 5. Geological map over the study area and nearby region modified in ArcGIS with data from Liu et al. (2005) and Department of Land, Water and Environment (2017).
Figure 6. Topography at the study area and nearby region modified in ArcGIS with data from Department of Environment, Land, Water and Planning (2017) and Department of Land, Water and Environment (2018).

Figure 7. Map with the depth to the groundwater table and geological units for each catchment modified in ArcGIS with data from Department of Land, Water and Environment (2017), Department of Environment, Land, Water and Planning (2018), Liu et al. (2005) and Peterson et al. (2017). A negative value indicates that the groundwater head is located above the ground surface.
Table 2. Description of the catchment characteristics. Mean annual rainfall, PET and runoff is presented together with the standard deviation.

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>405245</td>
<td>Ford Creek at Mansfield</td>
<td>-37.06° / 146.14°</td>
<td>518 m</td>
<td>115.5 km²</td>
<td>≤ 20%</td>
<td>862 ± 203 mm</td>
<td>353 / 887 / 1331 mm</td>
<td>1069 ± 29 mm</td>
<td>1016 / 1067 / 1145 mm</td>
<td>85 ± 72 mm</td>
<td>2 / 76 / 245 mm</td>
<td>60% Sedimentary siliciclastic</td>
</tr>
<tr>
<td>407230</td>
<td>Joyes Creek at Strathlea</td>
<td>-37.27° / 144.01°</td>
<td>445 m</td>
<td>155.9 km²</td>
<td>≤ 10%</td>
<td>659 ± 147 mm</td>
<td>374 / 650 / 1026 mm</td>
<td>1033 ± 28 mm</td>
<td>972 / 1035 / 1098 mm</td>
<td>55 ± 53 mm</td>
<td>0 / 32 / 177 mm</td>
<td>40% Regolith</td>
</tr>
<tr>
<td>415226</td>
<td>Richardson River at Carrs Plains</td>
<td>-36.82° / 142.89°</td>
<td>277 m</td>
<td>125.4 km²</td>
<td>≤ 3%</td>
<td>477 ± 127 mm</td>
<td>208 / 474 / 768 mm</td>
<td>1086 ± 29 mm</td>
<td>1011 / 1087 / 1159 mm</td>
<td>21 ± 31 mm</td>
<td>0 / 3 / 110 mm</td>
<td>51% Sedimentary siliciclastic</td>
</tr>
<tr>
<td>415237</td>
<td>Concongella Creek at Stawell</td>
<td>-37.14° / 142.87°</td>
<td>288 m</td>
<td>244.3 km²</td>
<td>≤ 15%</td>
<td>545 ± 127 mm</td>
<td>259 / 548 / 837 mm</td>
<td>1049 ± 29 mm</td>
<td>985 / 1048 / 1119 mm</td>
<td>36 ± 43 mm</td>
<td>0 / 13 / 140 mm</td>
<td>71% Sedimentary siliciclastic</td>
</tr>
</tbody>
</table>

Catchment 415237 consists of four different lithostratigraphic units: regolith, sedimentary siliciclastic, igneous mafic and felsic volcanic as well as igneous felsic intrusive. The regolith consists of alluvium, just like the other catchments. The sedimentary siliciclastic unit consists of 85.1% of the Saint Arnaud Group and the remaining of the Brighton Group, which is spread out around parts of the regolith unit. The igneous felsic intrusive unit is Stawell Granite and the igneous mafic and felsic volcanic is Licola Volcanics, Jamieson Volcanics and Mount Stavely Volcanics. Additionally, the catchment has a fault going through the middle of the catchment from north to south.

3.2 Software

The software used for preparing the data, conducting the numerical modelling and calibration was RStudio 1.1.422, which is an open-source integrated development environment for R (Brigham Young University, 2017). R is a command driven and object-oriented programming language and data analysis system which offers an environment for statistical analysis and graphics (Horgan, 2009). In this study, R 3.4.4 was used. ArcMap 10.5.1. was also used for analysing the data. ArcMap is a geographic information system (GIS) used to collect, store, analyse and present geographic data and offers a platform for mapping and spatial analysis (ESRI, n.d).
### Table 3. Description of the lithostratigraphic units that are present within the catchments (Liu et al., 2005).

<table>
<thead>
<tr>
<th>Geological unit</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regolith</strong></td>
<td></td>
</tr>
<tr>
<td>Alluvium</td>
<td>A mix of channel and flood plain alluvium and gravel, sand, silt and clay.</td>
</tr>
<tr>
<td>Newer Volcanics</td>
<td>Cinder cones with scoria, minor ash and agglutinates as well as lava flows that consists of tholeiitic to minor alkaline and basanitic lavas.</td>
</tr>
<tr>
<td>Wungunu Group</td>
<td>Unconsolidated to poorly consolidated mottled variegated clay and silty clay with lenses of polymictic as well as coarse to fine sand and gravel.</td>
</tr>
<tr>
<td>Pooraka Formation</td>
<td>Unconsolidated red-brown poorly-sorted clayey sand, gravel and conglomerate, breccia.</td>
</tr>
<tr>
<td><strong>Sedimentary siliciclastic</strong></td>
<td></td>
</tr>
<tr>
<td>Mansfield Group</td>
<td>Fluvial red sandstone, conglomerate and mudstone.</td>
</tr>
<tr>
<td>Delatite Group</td>
<td>Fluvial conglomerate, sandstone, red mudstone and subaerial ignimbrite.</td>
</tr>
<tr>
<td>Castlemaine Supergroup</td>
<td>Marine turbiditic sandstone, mudstone, black shale and minor granule conglomerate.</td>
</tr>
<tr>
<td>Loxton Sands</td>
<td>Unconsolidated to weakly cemented yellow-brown fine to coarse well-sorted quartz sand and sandstone with interstitial white kaolinitic or gibbsite clay matrix towards top.</td>
</tr>
<tr>
<td>Saint Arnaud Group</td>
<td>Marine turbiditic sandstone, mudstone, shale.</td>
</tr>
<tr>
<td>Brighton Group</td>
<td>Fluvial quartz, conglomerate and sandstone.</td>
</tr>
<tr>
<td><strong>Igneous felsic intrusive</strong></td>
<td></td>
</tr>
<tr>
<td>Stawell Granite</td>
<td>Weakly foliated, pale, medium to coarse grained, hornblende-biotite granite which occasional include diorite, granodiorite and hornfels xenoliths.</td>
</tr>
<tr>
<td><strong>Igneous mafic and felsic volcanic</strong></td>
<td></td>
</tr>
<tr>
<td>Licola Volcanics, Jamieson Volcanics and Mount Stavely Volcanics</td>
<td>Calc-alkaline andesite which includes basalt, dacite and rhyolite.</td>
</tr>
<tr>
<td><strong>Igneous felsic volcanic rock and sedimentary siliciclastic</strong></td>
<td></td>
</tr>
<tr>
<td>Wellington Volcanic Group</td>
<td>Subaerial rhyolitic to ryhodacitic ignimbrite, minor lava and fluvic sediments.</td>
</tr>
</tbody>
</table>

### 3.3 Data

In this section, the data used for this study are presented. First, the catchment and hydrological data will be presented followed by the meteorological data. Lastly, the groundwater head data will be presented.

#### 3.3.1 Catchment and Hydrology Data

The catchment data used in this study are based on the Bureau of Meteorology’s Hydrologic Reference Stations (HRS) (Department of Land, Water and Environment, 2017). The data includes 222 catchments in Australia that Turner (2012) identified based on criteria developed by Knight Merz (2010). The criteria were that they had to be unregulated, have minimal land use and have high-quality streamflow data. The criteria are explained in more detail in Knight Merz (2010) and Turner (2012). For determining the slope of the catchments, a Digital Terrain Model (DTM) with a resolution of 20 meter was used (Department of Environment, Land, Water and Planning, 2018). A shape file describing the surface geology of Victoria with a resolution of 250 meters was used to identify the geology in the catchments (Liu et al., 2005).

The runoff data are from the Department of Land, Water and Planning (2016) and are given as monthly data between January 1980 and December 2016. The runoff data for catchment 405226 had missing data for October 1992, catchment 407230 had no missing data, catchment 415226 had missing data for December 2012, April 2011, July 2011 and August 2011 and catchment 415237 had missing data for August 2013. The missing data were replaced with the average value of the two nearby data points.
3.3.2 Meteorological Data

The meteorological data include data for maximum and minimum temperature, vapor pressure, Morton’s wet-environment potential areal evapotranspiration and rainfall between January 1980 and December 2016. Daily solar radiation is available from January 1990 to December 2016 and interpolated solar radiation from January 1980 and December 2016. The temperature, vapor pressure, solar radiation and rainfall data are from the Bureau of Meteorology (BoM) for the Australian Water Availability Project (AWAP) and was accessed using AWAPer (Peterson, 2018). The PET was derived using the Evapotranspiration-package in R (Guo, Westra and Peterson, 2017). All data were weighted for each catchment and monthly values were determined, the monthly values were then interpolated to daily (Peterson, 2018). There are no missing data for the meteorological data.

3.3.3 Groundwater Head Data

The groundwater head data and groundwater head variance data was available through Peterson (2018). The data set are based on 10 300 bores in Victoria that has more than 12 water level observations and are located in unconfined aquifers (Peterson, Western and Cheng, 2018; Peterson and Western, in press). The data was calibrated for April 2000 (this month had most available data) and the spatial mapping was done for every month between January 1985 to August 2014. The data set have a resolution of 250 meters (Peterson et al., 2017).

3.4 Assumptions and Limitations

In this study, a few assumptions had to be made. Firstly, due to the lack of consistent soil moisture data for the time-period in question it was assumed that the change in soil moisture was neglectable. Secondly, it was assumed that there is no lateral subsurface flow in or out of the catchment.

The study was limited to the years between 1990 and 2013. This period was chosen because the study required accurate and high-quality data and there are no available data for solar radiation before January 1990 and no groundwater head data after August 2014. However, the analysis of the rainfall and runoff data was conducted for the period of 1980-2016.

3.5 Data Analysis

To determine the quality of the data as well as any general trends, an analysis of the rainfall, runoff and groundwater head data were conducted.

3.5.1 Rainfall and Runoff

First, an analysis of the rainfall and runoff data were conducted to determine the consistency and quality of the data. This was done using double mass curve (DMC). The DMC was first developed by Merriam in 1937 and the theory behind DMC is that when the cumulation of one quantity is plotted against the cumulation of another quantity from the same time-period the slope of the graph should be straight if the variables have been affected to the same extent by the same trends. If there is a break in the slope, it indicates that the conditions have changed at the location of one of the variables but not the other, or that the proportionality is not constant. However, due to the complexity of streamflow data some curvilinearity of the slope might occur without it indicating that the data are not consistent (Searcy and Hardison, 1960). The year for which the break in the curve occur is referred to as a change-point year (Gao et al., 2017). In this study cumulative annual rainfall were plotted against cumulative average annual rainfall for nearby catchments. Same were done for runoff.
Furthermore, DMC was also used to check if any trends could be seen between the rainfall-runoff relationship for each catchment. This was done by plotting the cumulative annual rainfall against cumulative annual runoff for each catchment.

To determine that the extent of the drought over each catchment is consistent with previous research, an anomaly analysis was conducted for the rainfall and runoff data. Firstly, the annual average for the data set was determined followed by determining the anomaly from the average for each year. This was done by subtracting the annual average for the data set from the annual data for each year. When the anomaly is negative it means that for that year the rainfall/runoff was below the average value for that time-period, and vice versa when the anomaly is positive.

3.5.2 Groundwater Head

To determine if the assumption that there is no lateral subsurface flow in or out of the catchment is accurate, groundwater head contour maps was created for each catchment in ArcMap using the data from April 2000. A catchment is defined by topographic dividers that cause runoff from precipitation to flow to different catchments (Hiscock and Bense, 2014). Groundwater flow is also mainly influenced by the topography of the ground surface, but changes in lithologies could also influence the flow pattern (Hiscock and Bense, 2014). The contour maps were therefore examined to determine if the contours, i.e. the isolines of the groundwater head, were perpendicular to the catchment boundary. If they are, groundwater dividers are most likely aligned with the catchment boundaries.

To get an understanding of the general changes in groundwater head over the catchments for the time-period, the change in groundwater head between January 1990-December 2009 and December 2009-December 2013 were determined using ArcMap. The average groundwater head variance for the month of December between 1990-2013 was also determined.

The groundwater head data were also examined to determine if there was a difference in change in groundwater head between different geological units and if this could be related to change in effective rainfall (rainfall minus actual evapotranspiration) minus runoff (hereon referred to as inflow minus outflow). This was done by determining the inflow minus outflow for each month and the change in groundwater head between two months for all catchments using RStudio (Appendix 1).

Since it could be a delay in reaction between the change in groundwater head and inflow minus outflow the correlation between the two were analysed. The correlation was determined between the inflow minus outflow for every month and the change in groundwater head between two months where the groundwater head data were delayed from 0-12 months. The correlation was tested for each geological unit and for four different time periods: 1990-1996, 1997-2009, 1990-2009 and 2010-2013. This was conducted using RStudio (Appendix 1).

3.6 Water Balance Modelling

How the Millennium Drought influenced the water balance for the catchments was determined using a numerical model in RStudio. Firstly, the Evapotranspiration-package (Guo, Westra and Peterson, 2017) was used to determine actual areal ET (hereon referred to as AET). The model used was Morton’s CRAE model. The constants used for this is presented in Appendix 2. A limitation of using the R-package for calculating the actual areal evapotranspiration is that it could produce negative values. Since Morton (1983) designed the model to not allow the actual areal evapotranspiration to be negative (constraint C-38a), the negative values produced by the R-package were adjusted to zero.
After doing this, all fluxes except the change in groundwater storage were known. To determine this flux, the water balance equation was used where the specific yield, $S_y$, for each geological unit were an unknown parameter. Further, a ET scalar, $x$, were introduced as another unknown parameter to try to adjust for the uncertainty in the estimated AET and the uncertainty in the measurements of the other fluxes. The water balance equation (Eq. 1) was rearranged to determine the water balance error (Eq. 2).

$$ Water\ Balance\ Error = P - Q - xAET - \sum_{i=1}^{n} \left( \sum_{j=1}^{m} \Delta h_{j} \ast S_{y_{j}} \right)_{i} $$  

(Eq. 2)

\[ P = \text{rainfall [mm]} \]
\[ Q = \text{runoff [mm]} \]
\[ x = \text{ET scalar [-]} \]
\[ AET = \text{actual areal evapotranspiration [mm]} \]
\[ \Delta h = \text{change in groundwater head [mm]} \]
\[ S_y = \text{specific yield [-]} \]
\[ j = \text{grid cell j} \]
\[ m = \text{number of grid cells within catchment} \]
\[ i = \text{geological unit i} \]
\[ n = \text{number of geological units within catchment} \]

The groundwater head data are spatial data that are divided into grid cells. Therefore, a weighting factor $w_1$ was introduced representing how much of each grid cell were within the catchment and the specific geological formation. The second factor, $w_2$, was also a weighted factor but of the variance in groundwater head for each grid cell. This factor made sure that grid cells that have smaller variance affect the groundwater change more than grid cells that have a greater variance. This factor was introduced as an attempt to minimise the uncertainty relating to the groundwater head. These two factors were known for each time step.

The unknown parameters were determined by minimising the root mean square water balance error (RMSE) through an optimisation done for a monthly time step for the time-period in question (Eq. 3).

$$ RMSE = \sqrt{\sum_{k=1}^{u} \left[ P_k - Q_k - xAET_k - \sum_{i=1}^{n} \left( \sum_{j=1}^{m} \Delta h_{j} \ast S_{y_{j}} \ast w1_j \ast w2_j \right) \right]_{k}^{2}} $$  

(Eq. 3)

\[ u \] is the number of time steps for that optimisation. The code can be seen in its entirety in Appendix 1.

### 3.7 Calibration

The calibration was done through an optimisation of Equation 3, where the specific yield and the ET scalar were determined for the lowest value of RMSE. The calibration was done in RStudio with a monthly time step (Appendix 1).

The calibration was done for three different time periods: January 1990 to December 2009, January 1990 to December 1996 and January 1997 to December 2009. It was also done for two different scenarios, referred to as calibration schemes. The first calibration scheme assumes that the time lag between inflow minus outflow and a change in groundwater head is less than one month, i.e. almost instant reaction. The second scenario assumes that there is a time lag in the groundwater heads response to inflow minus outflow, i.e. the reaction is delayed.
The results from the calibrations was employed to the years following the end of the drought, 2010-2013, in order to determine which calibration provided the lowest percentage difference in RMSE. This gives an indication whether or not there have been a change in behaviour in the catchment due to changes in the fluxes.

Once the calibration was conducted, response surfaces with the specific yield and the ET scalar on the vertical and horizontal axis and the RMSE on the z-axis was created for the calibration deemed to have the best fit for the years following the drought. This was conducted to analyse how the parameters change with each other and how this affects the RMSE.

The calibration deemed the best was mainly based on which calibration yielded the lowest difference in RSME between the calibration period and 2010-2013.

3.8 Determining the Fluxes

Once the calibration was conducted and the best calibration time-period was determined for each catchment and calibration scheme, the fluxes could be estimated. The calibrated values for the specific yields and the ET scalar were used to determine the fluxes for the optimal calibration period and 2010-2013. If the best calibration scheme was either 1990-1996 or 1997-2009, the calibrated values for specific yield was used for the other timer period but a new calibration was taken place for that specific period to determine the ET scalar (Appendix 1). This based on the assumption that the specific yields are stationary but the ET scalar can change over time. If the time lag correlation showed that there was no significant correlation between the change in groundwater storage and the inflow minus outflow, the specific yield was assumed to be zero for this time-period.

3.9 Sensitivity Analysis

A local sensitivity analysis of the RMSE was done for the optimal calibration periods for each catchment using the result from this calibration. A set of parameters was changed one at a time by one percent while the other parameters remained unchanged. The change in RMSE-value that the change in parameter caused was divided with the change in the parameter. The equation looks as follows:

\[
\text{Local sensitivity for parameter } A = \frac{\text{RMSE} - (\text{RMSE for } A * 1.01)}{A - (A * 1.01)} \quad (\text{Eq. 4})
\]

The parameters analysed were the specific yields and the ET scalar as well as parameters used to determine the AET. These parameters are: \( f_z \) which is a constant used to determine the vapor transfer coefficient \( f_v \), \( \varepsilon_s \) which is a constant describing the surface emissivity and \( \alpha \) which is a constant used to calculate the slope of the saturation vapour pressure (McMahon et al., 2013b).

4. Results

The results will be presented in this section. First, the results from the analysis of the rainfall and runoff data are presented in section 4.1 followed by the groundwater head data in section 4.2. The results from the numerical model and calibration will be presented in section 4.3 and 4.4 and finally, the results from the sensitivity analysis are presented in section 4.5.
### 4.1 Rainfall and Runoff

The results from the double mass curves for catchment cumulative annual runoff versus average annual cumulative runoff from nearby catchments shows that the data are consistent (Fig. 8). The double mass curves for the cumulative rainfall provided a correlation with an $R^2$-value of greater than 0.99 for all the catchments and no break in the slope, hence the rainfall data are consistent (Fig. 9).

**Figure 8.** Double mass curves for the runoff for each catchment. The cumulative annual runoff is plotted against cumulative average annual runoff from nearby catchments (in mm) for 1980-2016.

**Figure 9.** Double mass curves for the rainfall for each catchment. The cumulative annual rainfall is plotted against cumulative average annual rainfall from nearby catchments (in mm) for 1980-2016.
The double mass curves for the relationship between annual rainfall and annual runoff for all catchments indicate a change-point year around 1997 and 2011 (Fig. 10). The black lines are the average trend line for the catchments in that graph for the time periods of 1980-1997, 1997-2010 and 2012-2016. The cumulative annual rainfall and runoff is in percent.

Figure 10. Double mass curves where cumulative annual runoff is plotted against cumulative annual rainfall (in %) for catchment 405245 and 407230 (top) and 415226 and 415237 (bottom). The black lines show the average slope of the runoff-rainfall relationship within two catchments. The approximate change-point year is indicated with the black arrows.
The rainfall anomaly histograms show that the rainfall was below average between 1994 and 2009 more times than for the years leading up to 1994. This trend also continues after 2010-2011. The runoff anomaly histograms show that the runoff for all catchment was below average consistently between 1997 and 2009 (with the exception for 2000 in catchment 405245 and 407230). All the catchments also show that the runoff continues to be below average after the La Niña-event in 2010-2011 (Fig. 11).

Figure 11. The annual rainfall anomalies (left) and runoff anomalies (right) for the catchments (in mm) for 1980-2016.
4.2 Change in Groundwater Head

The contour lines for the groundwater head from April 2000 show that for catchments 405245, 415226 and 415237, the contour lines seem to be perpendicular to the catchment boundaries (Fig. 12). However, in catchment 407230 the contour lines seem to be perpendicular to the catchment boundaries on the eastern side of the catchment while the western side is more diffuse. This might indicate that there is some flow in and out of the catchment at these locations.

Figure 12. Groundwater head contour lines for the catchments showing the direction of the groundwater flow. Groundwater heads from April 2000 used.
The average groundwater head variance for the years between 1990 and 2013 show a variance that varies between 3.75 – 20.0 meters for catchments 407230, 415226 and 415237 and between 5 - 50 meters for catchment 405245 (Fig. 13). The average is based on the variance in December for each year. The groundwater bores in the region coincide well with the areas where the variance is lower.

**Average Variance in Groundwater Level, 1990-2013**

![Map showing average variance in groundwater level](image)

Figure 13. The average variance in groundwater head for the month of December 1990-2013.
The change in groundwater head for 1990-2009 show a general decrease for all catchments with the exception for catchment 415237 which showed a decrease in the regolith unit and increase in the sedimentary siliciclastic unit and igneous unit (Fig. 14). For the years following the Millennium Drought, catchment 415226 shows a general decrease in groundwater level while catchment 415237 shows a general increase (Fig. 15). Catchment 405245 and 407230 shows an increase in groundwater level for the sedimentary siliciclastic unit and a decrease in the regolith unit.

Figure 14. Change in groundwater head between January 1990 and December 2009.

Figure 15. Change in groundwater head between December 2009 and December 2013.
The annual change in groundwater head for each geological unit shows that the groundwater head changes from year to year, i.e. it fluctuates back to its initial state within a few years (Fig. 16). The fluctuations are smaller for the time periods where the rainfall is lower, and increases when the rainfall increases. It also appears that for catchment 407230 and 415226, the fluctuations show a small delay compared to the rainfall. For catchments 405245 and 415237, that delay seems to be bigger.

![Figure 16. Annual change in groundwater head for each geological unit (red, blue and yellow line) within each catchment (in mm) on the left axis and the difference between rainfall and runoff and unscaled actual evapotranspiration (dotted green line) (in mm) on the right axis.](image)

The lag correlation between inflow minus outflow (i.e. effective rainfall minus runoff) and the change in groundwater head for catchment 415226, show that for some periods there is a correlation while for other periods there are no significant correlation (Fig. 17). On the vertical axis, the correlation is shown and on the horizontal axis, the time lag in months are shown. A positive time lag means that the change in groundwater head is delayed compared to the inflow minus outflow of the catchment, i.e. there is a time lag, and a negative time lag would mean that the change in groundwater head is leading the inflow minus outflow. The blue dashed lines in the figures show the significance level with 95% significance. If the bins are between zero and the dashed line, it means that there is no significant correlation. The time lag with the strongest correlation for all the catchments are presented in Table 4 together with the approximate correlation shown within parenthesis. A zero lag means that there is no delay in the change in groundwater head and a hyphen means that there is no significant correlation. The time lag correlations for catchments 405245, 407230 and 415237 is seen in Appendix 3.
Figure 17. Correlation between change in groundwater head and the difference between effective rainfall and runoff for up to 12 months of time lag for catchment 415226. Significant correlation is marked by the blue dashed.
Table 4. The time lag with the highest correlation for each catchment. The approximate correlation is within parenthesis. A red box with a hyphen (−) indicates that there was no significant correlation and a blue box indicates that the correlation was almost not significant.

<table>
<thead>
<tr>
<th></th>
<th>405245</th>
<th></th>
<th>407230</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sedimentary formation</td>
<td>Regolith</td>
<td>Sedimentary siliciclastic</td>
<td>Regolith</td>
</tr>
<tr>
<td>1990-2009</td>
<td>1 (0.22)</td>
<td>1 (0.16)</td>
<td>1 (0.19)</td>
<td>1 (0.16)</td>
</tr>
<tr>
<td>1990-1996</td>
<td>0 (0.25)</td>
<td>0 (0.23)</td>
<td>-</td>
<td>3 (0.22)</td>
</tr>
<tr>
<td>1997-2009</td>
<td>1 (0.35)</td>
<td>1 (0.75)</td>
<td>1 (0.2)</td>
<td>-</td>
</tr>
<tr>
<td>2010-2013</td>
<td>1 (0.42)</td>
<td>1 (0.32)</td>
<td>1 (0.37)</td>
<td>1 (0.37)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>415226</th>
<th></th>
<th>415237</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sedimentary siliciclastic</td>
<td>Regolith</td>
<td>Sedimentary siliciclastic</td>
<td>Regolith</td>
</tr>
<tr>
<td>1990-2009</td>
<td>1 (0.24)</td>
<td>1 (0.32)</td>
<td>3 (0.28)</td>
<td>1 (0.28)</td>
</tr>
<tr>
<td>1990-1996</td>
<td>-</td>
<td>1 (0.20)</td>
<td>2 (0.23)</td>
<td>1 (0.30)</td>
</tr>
<tr>
<td>1997-2009</td>
<td>1 (0.4)</td>
<td>1 (0.42)</td>
<td>3 (0.40)</td>
<td>1 (0.20)</td>
</tr>
<tr>
<td>2010-2013</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1 (0.40)</td>
</tr>
</tbody>
</table>

4.3 Calibration of the Water Balance Error

Two different calibration schemes were conducted, one assuming the change in groundwater head is instant and one assuming that there is a delay between the inflow minus outflow (i.e. effective rainfall minus runoff) and the change in groundwater head. Both calibrations were done for 1990-1996, 1997-2009 and 1990-2009. The smallest difference in RSME between the calibrated period and 2010-2013 was found for the same time periods for both calibration schemes (Table 5 and 6). The calibration that was deemed to have the best fit to the years following the drought and having values for specific yield that are within a reasonable range are marked in green. In both tables, the RMSE for the calibration is shown as well as the RMSE when applying the calibrated values on the period of 2010-2013 together with the percentage difference.

Table 5. Results from the calibration where no time lag was assumed. The best calibration is marked with green boxes.

<table>
<thead>
<tr>
<th>Assuming no time lag</th>
<th>Sedimentary siliciclastic or Sedimentary formation</th>
<th>Regolith</th>
<th>Igneous formation</th>
<th>Evapotranspiration scalar x</th>
<th>RMSE</th>
<th>RMSE for 2010-2013</th>
<th>Difference between calibrated RMSE and RMSE for 2010-2013 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>405245</strong></td>
<td>1990-1996</td>
<td>0.162</td>
<td>&lt;10⁻¹²</td>
<td>-</td>
<td>0.916</td>
<td>50.07</td>
<td>44.99</td>
</tr>
<tr>
<td></td>
<td>1997-2009</td>
<td>0.0004</td>
<td>0.155</td>
<td>-</td>
<td>0.900</td>
<td>43.50</td>
<td>92.05</td>
</tr>
<tr>
<td></td>
<td>1990-2009</td>
<td>0.039</td>
<td>&lt;10⁻¹²</td>
<td>-</td>
<td>0.891</td>
<td>40.31</td>
<td>45.57</td>
</tr>
<tr>
<td><strong>407230</strong></td>
<td>1990-1996</td>
<td>0.023</td>
<td>&lt;10⁻¹²</td>
<td>-</td>
<td>0.836</td>
<td>43.71</td>
<td>38.13</td>
</tr>
<tr>
<td></td>
<td>1997-2009</td>
<td>0.026</td>
<td>&lt;10⁻¹²</td>
<td>-</td>
<td>0.774</td>
<td>36.29</td>
<td>38.81</td>
</tr>
<tr>
<td></td>
<td>1990-2009</td>
<td>0.025</td>
<td>&lt;10⁻¹²</td>
<td>-</td>
<td>0.796</td>
<td>39.01</td>
<td>38.53</td>
</tr>
<tr>
<td><strong>415226</strong></td>
<td>1990-1996</td>
<td>&lt;10⁻¹²</td>
<td>0.312</td>
<td>-</td>
<td>0.786</td>
<td>38.73</td>
<td>28.72</td>
</tr>
<tr>
<td></td>
<td>1997-2009</td>
<td>&lt;10⁻¹²</td>
<td>0.367</td>
<td>-</td>
<td>0.852</td>
<td>28.90</td>
<td>30.24</td>
</tr>
<tr>
<td></td>
<td>1990-2009</td>
<td>&lt;10⁻¹²</td>
<td>0.330</td>
<td>-</td>
<td>0.822</td>
<td>32.64</td>
<td>28.89</td>
</tr>
<tr>
<td><strong>415237</strong></td>
<td>1990-1996</td>
<td>&lt;10⁻¹²</td>
<td>0.133</td>
<td>&lt;10⁻¹²</td>
<td>0.795</td>
<td>39.88</td>
<td>32.10</td>
</tr>
<tr>
<td></td>
<td>1997-2009</td>
<td>&lt;10⁻¹²</td>
<td>0.078</td>
<td>&lt;10⁻¹²</td>
<td>0.839</td>
<td>32.44</td>
<td>31.46</td>
</tr>
<tr>
<td></td>
<td>1990-2009</td>
<td>&lt;10⁻¹²</td>
<td>0.102</td>
<td>&lt;10⁻¹²</td>
<td>0.824</td>
<td>35.17</td>
<td>31.66</td>
</tr>
</tbody>
</table>
Table 6. Results from the calibration where time lag was assumed to occur. The best calibration is marked with green boxes. The red boxes indicate where there was no significant correlation between groundwater head and the difference between effective rainfall and runoff. The blue box indicates that the correlation was almost not significant.

For catchment 405245, the strongest correlation for 1990-1996 occurred at no delay so the result for the specific yield and ET scalar from this calibration are the same as in Table 5.

<table>
<thead>
<tr>
<th>Assuming time lag</th>
<th>Sedimentary siliciclastic or Sedimentary formation</th>
<th>Regolith formation</th>
<th>Igneous formation</th>
<th>Evapotranspiration scalar x</th>
<th>RMSE 2010-2013</th>
<th>RMSE for 2010-2013</th>
<th>Difference between RMSE and RMSE for 2010-2013 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>405245</td>
<td>1990-1996</td>
<td>0.162</td>
<td>&lt;10^{-12}</td>
<td>-</td>
<td>0.916</td>
<td>50.07</td>
<td>44.99</td>
</tr>
<tr>
<td></td>
<td>1997-2009</td>
<td>&lt;10^{-12}</td>
<td>0.451</td>
<td>-</td>
<td>1.005</td>
<td>32.77</td>
<td>245.82</td>
</tr>
<tr>
<td></td>
<td>1990-2009</td>
<td>&lt;10^{-12}</td>
<td>0.023</td>
<td>-</td>
<td>0.897</td>
<td>47.10</td>
<td>43.91</td>
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<tr>
<td>407230</td>
<td>1990-1996</td>
<td>0.026</td>
<td>0.048</td>
<td>-</td>
<td>0.828</td>
<td>41.90</td>
<td>36.44</td>
</tr>
<tr>
<td></td>
<td>1997-2009</td>
<td>0.034</td>
<td>0.026</td>
<td>-</td>
<td>0.770</td>
<td>35.30</td>
<td>37.71</td>
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<tr>
<td></td>
<td>1990-2009</td>
<td>0.030</td>
<td>&lt;10^{-12}</td>
<td>-</td>
<td>0.803</td>
<td>38.74</td>
<td>38.12</td>
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<tr>
<td>415226</td>
<td>1990-1996</td>
<td>0.081</td>
<td>0.394</td>
<td>-</td>
<td>0.652</td>
<td>38.12</td>
<td>27.61</td>
</tr>
<tr>
<td></td>
<td>1997-2009</td>
<td>&lt;10^{-12}</td>
<td>0.869</td>
<td>-</td>
<td>0.876</td>
<td>26.28</td>
<td>26.51</td>
</tr>
<tr>
<td></td>
<td>1990-2009</td>
<td>&lt;10^{-12}</td>
<td>0.521</td>
<td>-</td>
<td>0.821</td>
<td>31.33</td>
<td>32.54</td>
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<tr>
<td>415237</td>
<td>1990-1996</td>
<td>0.074</td>
<td>0.258</td>
<td>0.104</td>
<td>0.826</td>
<td>36.01</td>
<td>29.93</td>
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<tr>
<td></td>
<td>1997-2009</td>
<td>0.193</td>
<td>0.135</td>
<td>0.100</td>
<td>0.934</td>
<td>30.22</td>
<td>28.62</td>
</tr>
<tr>
<td></td>
<td>1990-2009</td>
<td>0.085</td>
<td>0.203</td>
<td>0.037</td>
<td>0.864</td>
<td>33.32</td>
<td>29.61</td>
</tr>
</tbody>
</table>

The 2-dimensional response surfaces for the specific yield and the ET scalar, from the calibration assuming no delay in groundwater head response to inflow minus outflow, for catchment 405245 show that the specific yields do not change a lot when forcing a change of the ET scalar (Fig. 18). The RMSE however does increase when the ET scalar increase. When increasing the value for one specific yield, the other one decrease but the ET scalar and RMSE do not change by much. Catchments 407230 and 415226 show a similar behaviour (Appendix 4). The response surfaces for the calibration assuming a delay in response show the same behaviour (Fig. 19).

When assuming a delayed response in change in groundwater head, catchment 415237 show that when the specific yields are plotted against the ET scalar and one of the other specific yields is increased, the specific yield seem to not change significantly. This in contrast with how the other catchments behave. Further, the response surfaces show that the specific yields do change when forcing a change of the ET scalar. When the ET scalar is increased, both specific yields increases as well as the RMSE, although just slightly. For the calibration assuming no delay the surfaces react the same as for the other catchments (Appendix 4).
Figure 18. Response surfaces for catchment 405245 for 1990-2009 using calibration not assuming time lag. The top ones show when the ET scalar is fixed, the middle ones show when the specific yield for the regolith unit is fixed and the bottom ones show when the specific yield for the sedimentary siliciclastic unit is fixed. The RMSE are on the z-axis and is visible as the contour lines in the figures.
4.4 Fluxes in the Catchment Water Balance

In Table 7, the average annual precipitation, runoff, actual areal evapotranspiration and change in groundwater storage is presented for 1990-1996, 1997-2009 and 2010-2013 from the calibration assuming no delay in groundwater head response. The values used to determine the fluxes are from the calibration years that was deemed to be the best fit to the years following the drought. For
catchment 415226 and 415237, the best calibration was for the time-period 1997-2009. Therefore, a new calibration was conducted to determine the value of the scalar for the 1990-1996. For catchment 415226, the scalar was 0.697 and for catchment 415237 it was 0.804. In Table 8, the average annual precipitation, runoff, actual areal evapotranspiration and change in groundwater storage is presented for 1990-1996, 1997-2009 and 2010-2013 from the calibration assuming delay in groundwater response. The same years was deemed as the best calibrations as for the calibration scheme not assuming a delay. For catchment 415226, the scalar was 0.632 and for catchment 415237 it was 0.851.

Table 7. Average annual fluxes for the components of the water balance for each catchment when assuming no delay in groundwater head response. Values used for specific yield and ET scalar is from the calibration that was deemed to provide most accurate results.

<table>
<thead>
<tr>
<th></th>
<th>Average Annual Rainfall [mm]</th>
<th>Average Annual Scaled Actual Evapotranspiration [mm]</th>
<th>Average Annual Runoff [mm]</th>
<th>Average Annual Change in Groundwater Storage [mm]</th>
<th>Average Annual Water Balance Error [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>405245</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990-1996</td>
<td>989.5</td>
<td>618.5</td>
<td>163.7</td>
<td>10.8</td>
<td>204.5</td>
</tr>
<tr>
<td>1997-2009</td>
<td>723.2</td>
<td>521.4</td>
<td>30.6</td>
<td>-1.0</td>
<td>172.2</td>
</tr>
<tr>
<td>2010-2013</td>
<td>988.6</td>
<td>601.3</td>
<td>110.1</td>
<td>3.7</td>
<td>273.5</td>
</tr>
<tr>
<td><strong>407230</strong></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1990-1996</td>
<td>644.1</td>
<td>447.5</td>
<td>62.1</td>
<td>9.7</td>
<td>200.5</td>
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<tr>
<td>1997-2009</td>
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<td>407.0</td>
<td>6.5</td>
<td>3.2</td>
<td>151.7</td>
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<td>2010-2013</td>
<td>729.2</td>
<td>459.3</td>
<td>45.8</td>
<td>-0.9</td>
<td>232.5</td>
</tr>
<tr>
<td><strong>415226</strong></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1990-1996</td>
<td>528.8</td>
<td>292.8</td>
<td>36.0</td>
<td>28.3</td>
<td>155.3</td>
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<td>1997-2009</td>
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<td>304.6</td>
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<td>9.7</td>
<td>117.0</td>
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<td>2010-2013</td>
<td>517.3</td>
<td>343.1</td>
<td>39.6</td>
<td>74.6</td>
<td>78.7</td>
</tr>
<tr>
<td><strong>415237</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990-1996</td>
<td>582.8</td>
<td>363.3</td>
<td>48.6</td>
<td>7.4</td>
<td>170.8</td>
</tr>
<tr>
<td>1997-2009</td>
<td>494.1</td>
<td>345.7</td>
<td>6.8</td>
<td>-1.8</td>
<td>143.4</td>
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<td>2010-2013</td>
<td>576.9</td>
<td>376.6</td>
<td>33.9</td>
<td>-8.4</td>
<td>174.9</td>
</tr>
</tbody>
</table>

Table 8. Average annual fluxes for the components of the water balance for each catchment when assuming a delay in groundwater head response. Values used for specific yield and ET scalar is from the calibration that was deemed to provide most accurate results.

<table>
<thead>
<tr>
<th></th>
<th>Average Annual Rainfall [mm]</th>
<th>Average Annual Scaled Actual Evapotranspiration [mm]</th>
<th>Average Annual Runoff [mm]</th>
<th>Average Annual Change in Groundwater Storage [mm]</th>
<th>Average Annual Water Balance Error [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>405245</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990-1996</td>
<td>989.5</td>
<td>622.6</td>
<td>163.7</td>
<td>9.0</td>
<td>208.4</td>
</tr>
<tr>
<td>1997-2009</td>
<td>723.2</td>
<td>524.9</td>
<td>30.6</td>
<td>-1.9</td>
<td>170.9</td>
</tr>
<tr>
<td>2010-2013</td>
<td>988.6</td>
<td>605.3</td>
<td>110.1</td>
<td>-8.7</td>
<td>269.0</td>
</tr>
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<td><strong>407230</strong></td>
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</tr>
<tr>
<td>1990-1996</td>
<td>644.1</td>
<td>451.4</td>
<td>62.1</td>
<td>11.7</td>
<td>201.7</td>
</tr>
<tr>
<td>1997-2009</td>
<td>501.0</td>
<td>410.6</td>
<td>6.5</td>
<td>3.9</td>
<td>146.1</td>
</tr>
<tr>
<td>2010-2013</td>
<td>729.2</td>
<td>463.4</td>
<td>45.8</td>
<td>-1.1</td>
<td>230.0</td>
</tr>
<tr>
<td><strong>415226</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990-1996</td>
<td>528.8</td>
<td>265.5</td>
<td>36.0</td>
<td>63.7</td>
<td>154.2</td>
</tr>
<tr>
<td>1997-2009</td>
<td>425.4</td>
<td>313.2</td>
<td>0.9</td>
<td>17.2</td>
<td>97.2</td>
</tr>
<tr>
<td>2010-2013</td>
<td>517.3</td>
<td>352.8</td>
<td>39.6</td>
<td>0.0</td>
<td>141.7</td>
</tr>
<tr>
<td><strong>415237</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1990-1996</td>
<td>582.8</td>
<td>384.6</td>
<td>48.6</td>
<td>32.9</td>
<td>143.5</td>
</tr>
<tr>
<td>1997-2009</td>
<td>494.1</td>
<td>384.8</td>
<td>6.8</td>
<td>-25.8</td>
<td>118.4</td>
</tr>
<tr>
<td>2010-2013</td>
<td>576.9</td>
<td>419.2</td>
<td>33.9</td>
<td>-23.8</td>
<td>162.3</td>
</tr>
</tbody>
</table>
In Figures 20-23, all the annual fluxes and the water balance error are shown between 1990-2013 using values for specific yield and scalar for evapotranspiration from the best calibration.

Figure 20. Annual fluxes for the water balance components for catchment 405245 for assuming no delayed groundwater head response (top) and assuming a delayed response (bottom).
Figure 21. Annual fluxes for the water balance components for catchment 407230 for assuming no delayed groundwater head response (top) and assuming a delayed response (bottom).
Figure 22. Annual fluxes for the water balance components for catchment 415226 for assuming no delayed groundwater head response (top) and assuming a delayed response (bottom).
Figure 23. Annual fluxes for the water balance components for catchment 415237 for assuming no delayed groundwater head response (top) and assuming a delayed response (bottom).
4.5 Sensitivity Analysis

The results from the sensitivity analysis for the catchments show that the specific yield was by far the most sensitive variable (Table 9) followed by the ET scalar and the surface emissivity (Fig. 24). The sensitivity for the specific yield increased when the value for specific yield decreased.

Table 9. Results from the local sensitivity analysis of the specific yields for all catchments for both calibration schemes.

<table>
<thead>
<tr>
<th>ΔRMSE/ΔParameter, no assumed delay</th>
<th>Catchment 405245</th>
<th>Catchment 407230</th>
<th>Catchment 415226</th>
<th>Catchment 415237</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentary siliciclastic or Sedimentary formations</td>
<td>-197 296</td>
<td>-136 307</td>
<td>-1.1*10^16</td>
<td>-2.8*10^16</td>
</tr>
<tr>
<td>Regolith</td>
<td>-2.2*10^15</td>
<td>-6.6*10^15</td>
<td>-6 166</td>
<td>-33 276</td>
</tr>
<tr>
<td>Igneous formations</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ΔRMSE/ΔParameter, assumed delay</td>
<td>Catchment 405245</td>
<td>Catchment 407230</td>
<td>Catchment 415226</td>
<td>Catchment 415237</td>
</tr>
<tr>
<td>Sedimentary siliciclastic or Sedimentary formations</td>
<td>-8.5*10^15</td>
<td>-112 539</td>
<td>-1.1*10^15</td>
<td>-11 385</td>
</tr>
<tr>
<td>Regolith</td>
<td>-162 796</td>
<td>-1.9*10^17</td>
<td>-2 543</td>
<td>-16 371</td>
</tr>
<tr>
<td>Igneous formations</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-16 371</td>
</tr>
</tbody>
</table>

Figure 24. Sensitivity for parameters ET scalar, \( f_z \), surface emissivity \( \varepsilon \), and \( \alpha \) for all the catchments for both calibration schemes.

5. Discussion

In this section, the results presented section 4 will be analysed and discussed. First comes a discussion regarding the rainfall and runoff in section 5.1 followed by a discussion regarding the calibrated specific yields in section 5.2 and the ET scalar in section 5.3. Thereon follows a discussion of the groundwater head change in section 5.4 and the fluxes and the effect on the catchment in section 5.5. Finally, the assumptions and limitations of the study will be discussed in section 5.6.
5.1 Rainfall and Runoff

The double mass curves for rainfall and runoff (Fig. 8 and 9) show that the data is consistent, which means that the data used in this study is not affected by any malfunctions in the catchments or similar. The streamflow in catchments 407230, 415226 and 415237 went dry for several months during the drought which could affect the quality of the data. However, since the nearby catchments did not experience this as often and that the data still showed to be consistent, it should not affect the result of this study.

The annual rainfall anomaly indicates that the meteorological Millennium Drought started in 1997 and ended in 2010 for the four catchments (Fig. 11). This is in line with previous studies (Chiew and Prosser, 2011; Saft et al., 2015; Sawada and Koike, 2016; Timbal et al., 2010). However, the annual rainfall is also continuing to be below average for the years following 2011 for all catchments. This would mean that even though the Millennium Drought officially is over, the rainfall is still below average which could have effects on the water balance and the catchment. The annual runoff anomaly shows that the annual runoff was below average for most of the years between 1997 and 2009 (Fig. 11) which is consistent for the time of the drought. For the years following the drought, it appears that the annual runoff is still below average for most of the years. This would indicate that something in the catchment behaviour have changed. This is further discussed in section 5.5.

5.2 Specific Yields

The response surfaces and the sensitivity analysis provided similar results for the for both calibration schemes (apart from some of the response surfaces for 415237, this is discussed in section 5.3) (Fig. 18, 19 and 24). When the specific yield for one geological unit increases, it results in a decrease of the specific yield for the other geological unit while the RMSE do not change largely. This is probably due to the model trying to minimise the RMSE, and if one specific yield increases it means that the change in groundwater storage will increase for that geological unit. The model compensates for this by decreasing the change in storage in the other geological unit, hence decreasing the specific yield. This is furthermore supported by the local sensitivity analysis where specific yields were by far the most sensitive parameter for the RMSE.

The calibration that resulted in the lowest difference in RMSE between the calibrated time-period and 2010-2013 were the same for both calibration schemes. For catchment 405245 and 407230 it was 1990-2009 and for catchments 415226 and 415237 it was 1997-2009. This is further discussed in section 5.5.

When it comes to the calibration of the specific yields, it provides an unexpected result. The calibration scheme assuming no delay in groundwater head response resulted in that at least one of the specific yields became infinitely small (<10^{-12}) and one value was plausible in each catchment. The calibration assuming a delay significantly changed the specific yields, but for most of the calibrations one of the specific yields still became infinitely small while one value was plausible, with the exception of 415237. The RMSE did also decrease in catchments 407230, 415226 and 415237.

In catchment 405245, the regolith got an infinite small value for the calibration assuming no delayed groundwater head response and the sedimentary formation when assuming a delay. The regolith unit consists mainly of alluvium, which should provide a specific yield greater than <10^{-12} since they are treated as important aquifers in Australia. The sedimentary formation unit consists mainly of fluvial sandstone, mudstone and conglomerate which should give a specific yield that is greater than <10^{-12} as well. The values that respective unit got when not being infinitely small, is plausible values. Why
the calibrations gave different results are hard to determine when studying the response surfaces and the changes in groundwater head (Fig. 16) and further studies are needed.

Catchment 407230 got in both calibrations that the regolith unit gave an infinitely small value while the sedimentary siliciclastic unit gave a plausible value considering that it mainly consists of mudstone and shale (apart from sandstone). The specific yield for sedimentary siliciclastic unit did not differ much between the two calibration schemes. The regolith unit consists mainly of volcanic residuals such as ash and minor alkaline and basanitic lavas which causes the subsurface environment to be very heterogenic. A small value of specific yield is therefore possible although not a value that is smaller than \(10^{-12}\).

For catchment 415226, the sedimentary siliciclastic unit got an infinitely small specific yield for both calibration schemes. The unit consists to most parts of Loxton Sands, which are unconsolidated to weakly cemented sandstone with a clay matrix towards the top. The clay matrix could be a reason for the groundwater surface identified in the head data to not have a connection with the climate of the catchment and therefore cause a specific yield of zero. However, the remaining part of the sedimentary siliciclastic unit should have a specific yield greater than zero since it is unconsolidated or weakly consolidated allowing more water to flow in the aquifer. The specific yield for the regolith unit almost doubles for the calibration assuming a delayed response in groundwater storage, from 0.39 to 0.87. The later value is too big to be plausible and raises the question why the model chooses to bring one value to zero and the other to almost 1. Figure 16 shows that both units follow almost the same fluctuations and the result should be about the same if both values were approximately half of the specific yield of the regolith unit.

It is possible that choosing to optimise for the smallest RMSE might not have been the best way to determine the specific yield. The water balance errors are sometime positive, meaning that it is a greater outflow than inflow to the catchment, and sometime negative. When determining the RMSE, the absolute value for the water balance error are used. Hence, it does not consider if it is too much or not enough water in the catchment. This might result in that the lowest RMSE do not provide the lowest total water balance error over the time-period. To determine if this is the case, it need to be investigated further.

Catchment 415237 got infinitely small values for specific yield for the sedimentary siliciclastic unit and the igneous formation when the calibration assumed no delayed response in groundwater head. When assuming a delayed response, the units got specific yields of 0.19 and 0.10 respectively. The sedimentary siliciclastic unit consists mainly of marine turbiditic sandstone, mudstone and shale which depending on its compaction and strata could have different specific yields. However, considering the sandstone, that is generally treated as important aquifers in Victoria, together with the typically low water-yielding rocks as shale and mudstone are, would cause 0.19 to be plausible although a bit too big. The igneous unit consists mainly of granite, which depending on its faulting and its joints could have a low value for specific yield. A specific yield close to zero is plausible if the granite has few joints or if the joints are not connected with each other. A value of 0.10 is plausible if the granite is very weathered and has many connecting joints. An investigation of the rock unit is needed to determine this, for example using geophysical methods. The catchment got plausible values for the regolith unit for both calibration schemes. The values do not differ too much from each other and since the unit consists of alluvium it is likely that it should be somewhere around these values.

One explanation to why some of the specific yields got so small values could be due to the depth to the groundwater table. At some parts of the catchments, the depth is up to 60 meters which could mean that the change in groundwater storage should not be accounted for in the water balance in these areas. It is more likely that the changes in groundwater table here are due to regional
groundwater flow and changes. If this was the case, it should not be any serial correlation between the change in groundwater level and the climate in the specific catchment. However, it was not determined that one geological unit lacked correlation for all periods of time (Table 4).

The results from the time lag correlation (Fig. 17) show that catchment 415226 do not have any correlation between changes in groundwater table and rainfall for the years before and the years following the drought. This could mean that the stream in this catchment is disconnected from the groundwater and this becomes clearer when the runoff is very low during the drought. This catchment is relatively flat and according to Parsons, Hoban and Evans (2008) it is more likely for flatter catchments to go from connected to disconnected streams during a drought. An interpretation of the results could be that the groundwater does react to rainfall at some parts of the catchment and should be included in the water balance for these areas.

The serial correlation is also important to study because of water slow movement in the subsurface. It is very likely that there will be a delayed response of change in groundwater head to effective rainfall minus runoff, and this need to be accounted for when the change in groundwater storage is included in the catchment water balance. However, this study proves that it is difficult to assess exactly how big this delay should be for different geological units. It is possible that in order to incorporate the groundwater storage into the water balance in a sensible way, the catchment needs to be divided into smaller subsections than was done in this study. The geology changes throughout the catchment, and often even within the same geological unit (Chen et al., 2016), as well as the depth to the groundwater table can change throughout the unit (Fig. 7). This could also mean that the magnitude of the delay changes throughout the geological unit and it is not possible to estimate the delay when the units are this big. Adding more subsections where the geology is more homogenous and the depth to the groundwater table is about the same could possibly improve the estimation of the time lag correlation.

Another possible factor that could affect the calibration for specific yield is the fact that the study uses the surface geology to determine the different geological units. At some parts of the catchments the depth to the groundwater table is up to 60 meters, which would mean that it is very unlikely that the geology at that depth is the same as the one at the surface. Although the lack of geological cross-sections in Victoria makes it hard to confirm this, it is a valid assumption to make. It is also very likely that there are a few meters of soil at the top of the geological unit, meaning that it is possible that at locations where the groundwater table is very shallow, the water table is in the soil instead of the geological unit.

It is however very hard to determine if the specific yields are plausible or not since the values can differ a lot between different locations and depths (Maréchal et al., 2003; Chen et al., 2003). It is therefore hard to say with certainty if one value is too big or too small.

5.3 Evapotranspiration Scalar

In catchments 405245, 407230 and 415226, a change in the ET scalar does not provide any major changes in the specific yields (Fig. 16). It does however show that the RMSE will increase when the ET scalar increases. This was also observed in the local sensitivity analysis (Fig. 24). This implies that the specific yields are not sensitive to changes in the ET scalar, but the RMSE however is. However, the catchment 415237 show a different result. When no delay is assumed, the parameters reacts the same way as the other catchments. But when assuming a delay it shows that when forcing an increase in the ET scalar, both specific yields increased as well as a slight increase of the RMSE. This could be interpreted as the model is trying to show that when the AET increases, the groundwater storage declines as it evaporates and that the plant uptake of water increases. A possible explanation for why
this is the only catchment that exhibits this behaviour could be that this is the only catchment that reach plausible values for specific yield for all geological units. It could be that this is the way all catchments would react if they had also got plausible values.

The ET scalar differs between 0.77-1.0 which would imply that the climate or behaviour of the catchments change over the region and over time. This seems reasonable since the catchments differ in elevation and topography which affects the rainfall, runoff and evapotranspiration. When studying each individual catchment, the ET scalar do not differ much between the two calibration schemes. This implies that the ET scalar is not affected by the delayed response in groundwater head.

It is very hard to determine the actual evapotranspiration (McMahon et al., 2013a) and there is a possibility that what has been determined in this study might be inaccurate. The use of the ET scalar was an attempt to try to improve the estimation and to account for the uncertainty that comes with it. However, studying the water balance error for the calibrated periods show that it is the third largest flux after rainfall and the scaled AET (Fig. 20-23 and Table 7). It might have been that introducing the ET scalar reduced the AET to much and that it might not actually have improved the estimation. Further investigations are needed to determine if this is the case.

5.4 Changes in Groundwater Head

For the period before and during the drought, the groundwater table is declining in catchments 405245, 407230 and 415226, while in catchment 415237 it is declining in the regolith unit but slightly increasing in the sedimentary siliciclastic and igneous unit (Fig. 14 and 15). Figure 16 show that the changes in groundwater head follow the same fluctuation pattern for all geological units within a catchment. The fluctuations are smaller during the drought than before or after the drought in catchment 405245 and 415226. This is likely due to the decrease in rainfall during those years. For 2010-2013, the groundwater level increased in some areas and decreased in other. A reason for this could be the depth to the groundwater table. Where the groundwater table is shallow an instant reaction happens and the groundwater table increases, while when the groundwater table is at a greater depth, it is still reacting to the conditions of the drought and therefor declining. This is however only the case in catchment 405245. There is no tendency that an increase in groundwater table during 2010-2013 is related to the depth to the water table for the other catchments.

A factor that is worth mentioning is that the variance of the groundwater head is between 3.75-50 meters in the catchments. This provides a large span of possible values for the groundwater head and would also affect the change in groundwater storage. Since the specific yields are the most sensitive parameters for the RSME, it is very likely an inaccuracy in the change in groundwater level would affect the RMSE and probably the specific yields as well.

Another factor that affects the change in groundwater head is that the groundwater head maps might not show the actual depth to the groundwater table due to the way they are computed. An indication of this could be that the groundwater head maps shows an increase in groundwater head in more mountainous areas for the period before and during the drought, which is unlikely. For more information regarding this see Peterson et al. (2017), Peterson, Western and Cheng (2018) and Peterson and Western (in press).

5.5 Fluxes and the Effect on the Catchment Behaviour

The results from both calibration schemes indicate that two of the four catchments (catchment 415226 and 415237) show a change in behaviour during and after the Millennium Drought since the calibration for the time-period of 1997-2009 gives the smallest change in RMSE for these two
catchments (Table 5 and 6). This implies that during the drought at least one of the water balance components shifted its behaviour more than the other components, and once the drought ended in 2010 it did not change back to the behaviour it had before the start of the drought. This is supported by the double mass curve for the catchments where cumulative annual rainfall is plotted against cumulative annual runoff (Fig. 10). In this graph, there is a clear break in slope around 1997 and 2011, years that coincides with when the drought began and ended. When looking at the slopes for the different time periods, they show that the slope for the years following the drought is much closer to the slope during the drought than before. This indicates that a change in behaviour between the rainfall and runoff occurred during the Millennium Drought and that this change persists even in the years following the drought.

Both calibration schemes show that catchment 405245 and 407230 do not exhibit a major change in behaviour after the drought compared to before (Table 5 and 6). For these two catchments, the calibration scheme that provided the smallest change in RMSE was for 1990-2009, i.e. both the period before and during the drought. This result would indicate that the catchments experienced a similar shift for all components of the water balance during the drought. However, the double mass curve for cumulative annual rainfall versus cumulative annual runoff for the catchments (Fig. 10) show that the slope for the years following the drought is not the same as before the drought neither the same as during the drought. The average slope of before and during the drought is almost equal to the slope for the years following the drought. This would mean that the catchment has experienced some kind of change in behaviour between rainfall and runoff during the drought and that the water balance for the catchment is not completely back to how it was before the drought. This explains why the calibration show that the years that give the smallest change in the RMSE is 1990-2009 and could indicate that the change decrease in runoff is a reason for the change in catchment behaviour. However, the change in slope during the drought is not as big as for catchments 415226 and 415237, indicating that the change was smaller for catchments 405245 and 407230.

The rainfall fluxes for all catchments show that the average annual rainfall during 1997-2009 is lower than for 1990-1996 (Table 7). However, even though the rainfall anomaly graph (Fig. 11) shows that the annual rainfall is below average for the years following the La Niña-event 2010-2011, average annual rainfall for this period is almost the same as for the years before the drought. This could however be because the rainfall during the La Niña-event in 2010-2011 makes up for the majority part of that rainfall and influence the average value.

The average annual runoff is the lowest for the years during the drought and the average annual runoff for the years after the drought is lower than the years before the drought, with the exception of catchment 415226 (Table 7). The reason for this catchment having a larger runoff after the drought could be because the stream in this catchment went completely dry during multiple years of the drought and therefore less water could infiltrate once the rainfall increased in 2010. The fact that the stream went dry also implies that the groundwater is disconnected from the stream, which could mean that the groundwater is not part of the water balance of the catchment as mentioned in section 5.2.

For the calibration assuming no delayed response of groundwater head (Table 7), it is only catchment 405245 and 415237 have a decrease in annual average groundwater storage during the Millennium Drought, the others have a slight increase. When assuming a delayed response, it was still these two catchments that showed a decrease in storage, although slightly bigger. An increase in the groundwater table is in contrast with the general trend for Victoria that Chen et al. (2016) presented.

For the years following the drought, the change in groundwater storage differs however between the two calibration schemes for all catchments except 407230. The calibration that accounts for the
delayed response show a decrease in groundwater storage for all these catchments. Catchment 415237, show a decrease when assuming no delay as well but the decrease is smaller. Catchment 405245 show a slight increase in groundwater storage when assuming no delay. Catchment 415226 show a large increase in groundwater storage when not assuming the delay. One possible reason for this is that the specific yields that were calibrated were larger when taking the delay into consideration and therefore are the decrease in groundwater storage bigger. Another can simply be that incorporating the delay in reaction in the groundwater storage changes the magnitude of the groundwater storage change. Catchment 407230 do also show almost the same small decrease in groundwater storage for both calibration schemes.

However, the magnitude of runoff and the change in groundwater storage is much smaller than the other fluxes in the catchments so an incorrect estimate of the groundwater change should not affect the water balance too much. The average annual water balance error did decrease for almost all catchments when assuming a delayed response in groundwater head. This would indicate that the result from this calibration is a slightly better representation of the reality.

The average annual AET did not change by a lot between the two calibration schemes (Table 7 and 8). Catchments 405245 and 407230 experienced a slightly larger percentage decrease in AET compared to the rainfall, and the runoff experienced a significantly larger percentage decrease compared to both the rainfall and AET. This could be one reason that the catchments experienced a change in the water balance during the drought.

Catchment 415226 did not experience a decrease in AET during the drought, this could however be due to the fact that a smaller ET scalar was used for years leading up to the drought than for the other years. The catchment did experience a decrease in runoff that was vastly bigger than for the other catchments, which could very likely be the reason for the change in water balance. Another factor that might have affected the water balance is the very large increase in groundwater storage for the calibration not considering the delayed response to groundwater head change.

It is harder to determine the cause of the change in the water balance for catchment 415237, since it does not experience any major differences in fluxes compared to the other catchments when not considering the delay in groundwater head change. However, the groundwater storage continues to decline in the years following the drought and this decline is even greater when considering the delay. It is therefore possible that the decrease in groundwater storage is the reason for the catchment experiencing a changed behaviour.

It is however important to note that according to McMahon et al. (2013b), Morton’s CRAE model should not be used to determine natural changes in a system because the model lacks knowledge of the soil-vegetation dynamics. Since vegetation affects the ET, and studies have showed that the phenology changed during the drought, it could be possible that the calculated AET is not representing the real magnitude. More studies concerning how the vegetation changed during the drought as well as how this would affect the AET would have to be conducted to make any conclusion regarding this. Vegetation also affects the runoff. Since the double mass curves indicates that there has been a shift in the relationship between rainfall and runoff for all catchments, it is likely that a change in vegetation could have been the reason for this. However, also this needs to be studied further before any conclusions can be made.

5.6 Limitations with the Model and the Assumptions Made

The groundwater head contour lines (Fig. 12) seem to be perpendicular to the catchment boundaries for catchment 405245, 415226 and 415237; indicating that the groundwater divider is aligned with
the catchment boundaries. Hence, there are no flow in or out of the catchment along the catchment boundaries. For catchment 407230 however, the contour lines are more diffuse for parts of the eastern side of the catchment. This could indicate that there is no clear groundwater divider at these locations, and some inflow of groundwater from outside the catchment could occur. This would be in conflict with the general assumption that there are no groundwater flows in or out of the catchment. This could affect the water balance and cause the numerical model to provide an inaccurate result. However, groundwater flow velocity rarely exceeds a few meters per day (Barackman and Brusseau, 2002) and a comparison of possible outflow from the aquifer through the subsurface with possible inflow from precipitation would show that the outflow would be substantially smaller. Therefore, even though there might be some inflow or outflow to the catchment, it should not greatly affect the water balance.

One limitation with the study is that by including the change in groundwater storage in the water balance as well as AET, some fluxes could have been counted for twice in the model. This due to the fact that there is some uptake of groundwater from the vegetation which would result in a change in groundwater storage. Some of this water would likely transpire into the atmosphere and thereby also be included in the AET. How much water this would include is hard to estimate and the change in vegetation in the catchments would have to be studied.

It was initially assumed that the change in soil moisture could be neglected for the catchments. This assumption could have affected the results of the study since it is an important part of the catchment water balance. However, it is possible that the change in soil moisture could have been included in the AET, just like it is possible that some of the change in groundwater storage could have been counted twice in the water balance.

6. Conclusion

It is hard to determine if including the groundwater change have improved the water balance. A few of the values for specific yield got infinitely small in some geological units which was deemed as not plausible. Accounting for a delay in the groundwater head response to inflow minus outflow changed the value of specific yield in three catchments although one value still remained infinitely small, with the exception of one catchment. This catchment got plausible values for all geological units. However, it is possible that a better result would have been achieved if the catchment had been divided up into smaller subsections where the geology is more homogenous and the depth to the groundwater table is more similar. The conclusion that can be made from this is that if the groundwater storage were to be included in the catchment water balance, a thorough analysis of the groundwater and subsurface need to be conducted.

Further, the water balance error was the third biggest flux after rainfall and actual evapotranspiration, when it preferably should be zero. A possible reason for this large flux could be that the ET scalar used to account for uncertainties in the actual areal evapotranspiration did actually reduce the actual areal evapotranspiration too much.

The fluxes for all components in the water balance decreased during the Millennium Drought and the magnitude of the decrease varies with components and the catchments. For the years following the drought, some fluxes continued to decrease while some was almost the same as before the drought.

Four catchments were studied and all four showed indications that the catchments behaviour have changed during the drought. The most likely reason for this is the decrease in runoff. It was however difficult to determine which other components of the water balance that could have caused this changed behaviour. For catchment 415226 and 415237, it is likely that the change in groundwater...
storage could have had an impact. In these catchments, the change in behaviour seem to persist into the years following the drought. The other two catchments (405245 and 407230) experienced a smaller change in behaviour during the drought and although the state of the catchment is still not like it was before the drought, it seems to be returning to its initial state. The most likely component to have changed its behaviour in these two catchments, except runoff, is the actual evapotranspiration.

Even though its limitation and uncertainties, this study is an important step towards understanding how the catchments in Victoria were affected during the drought and how the catchments behaviour has changed during and after the drought. Yet, it should not be interpreted as a representation for the whole state of Victoria.

7. Future Studies

A very important aspect of this study, that is worth investigating further, are the delay in groundwater storage response to inflow minus outflow. Possible suggestions on how to explore this further are by including a serial correlation term into the calibration or treating it as a function of the depth to the groundwater table. Further, it could also be explored how dividing the catchment up into smaller subsections with more homogenous geology would improve the water balance.

Another aspect to continue exploring is the use of the ET scalar. What is the reason for the model to want to reduce the actual evapotranspiration when the water balance error still remains a big flux? Furthermore, future studies could also include an improvement of this study by incorporating soil moisture data as well as allowing for the possibility of including subsurface flow. It would also be interesting to investigating how the time-periods used for the calibration could be improved and if choosing different time-periods could improve the model and provide a more accurate result.

Since the vegetation affects both evapotranspiration and runoff, and that the vegetation was affected during the Millennium Drought (Murphy and Timbal, 2008), it would be interesting to explore how the change in vegetation could play a part in the change in catchment behaviour.

On a final note, to get a better understanding of how the Millennium Drought affected the whole state of Victoria more catchments need to be studied.
References


Appendix I – R-code for the Numerical Model

library(sp)
library(raster)
library(maptools)
library(rgeos)
library(rgdal)
library(zoo)
library(Evapotranspiration)

# Set working folder
setwd("C:/Users/lmsundstroem/Documents/R")

# Import runoff for each month
runoff = read.csv("delwp_monthly2.csv")
keeps = c("gauge", "month", "q")
runoffMonthly = runoff[keeps]
runoffMonthly$month = as.character(as.Date(runoffMonthly$month, "%Y-%m-%d"))
runoffMonthly = runoffMonthly[runoffMonthly$month >= "1990-01-01" & runoffMonthly$month <= "2013-12-01",]
runoffMonthly = runoffMonthly$q

# Import precipitation data (for 415226 and 415237)
precip = read.csv("AWAP_monthly_subsetCatchments_precip_PET.csv")
keeps = c("year", "precip_mm")
precip = precip[keeps]
precip$year = as.character(precip$year)
precip = precip[precip$year >= "1990" & precip$year <= "2013", "precip_mm"]

# Process data for determining Morton’s areal AET
# Set constants for calculating ET
load("constants.RData")
# From Guo et al., 2017
constants["lat"] = -37.14 # degrees
constants["lat_rad"] = ((constants["lat"]) * pi) / (180) # Latitude in radians
constants["Elev"] = 288 # meter
constants["fz"] = 29.2 # W/m2*mbar
constants["b0"] = 1.0 # For Australia according to Chiew and Leahy, 2003, sect. 2.3
constants["b1"] = 13.4 # W/m2 For Australia according to Chiew and Leahy, 2003, sect. 2.3
constants["b2"] = 1.13 # For Australia according to Chiew and Leahy, 2003, sect. 2.3
PA = sum(precip)/24
constants["PA"] = PA # Change annual precipitation for the
# catchment (only needed if there are no monthly
# precipitation data)
constants["epsilonMo"] = 0.92
constants["alphaMo"] = 17.27
save(constants, file="constants415237.RData")

# Save new data frame with only catchment averages and new data frame for required catchment
load("AWAP_subsetCatchments_climateDataVic_AWAPer.RData")
climateAvg = subset(climateAvg, g_number == 415237 ) # Choose data for specific catchment

# for 405245 & 407230
load("AWAP_subsetCatchments_p2_climateDataVic_AWAPer.RData")
climateAvg = subset(climateAvg, g_number == 405245 ) # Choose data for specific catchment
# Build data from of daily climate data

dataRAW = data.frame("Year", "Month", "Day", "Tmin", "Tmax", "Rs", "va", "Precip")
cclimateAvg = subset(climateAvg, year >= "1990" & year <= "2013")
dataRAW = data.frame(Year = climateAvg$year, Month = climateAvg$month, Day = climateAvg$day,
                     Tmin = climateAvg$Tmin, Tmax = climateAvg$Tmax, Rs = climateAvg$solarrad_interp,
                     va = climateAvg$vprp/10.0, Precip = climateAvg$precip)

# Convert to required format for ET package with the headings of the data
# that is available form raw data
dataPP = ReadInputs(c("Tmin","Tmax","Rs","Precip","va"),dataRAW,stopmissing = c(20,20,20))

# Calculate actual areal ET
ETresults = ET.MortonCRAE(dataPP, constants, est="actual areal ET", ts="monthly", solar="data",
                           Tdew=FALSE, message='yes')
for (i in 1:288)
  if (ETresults["ET.Monthly"][[i]]<0)
    ETresults["ET.Monthly"][[i]] = 0.0
  else
    ETresults["ET.Monthly"][[i]] = ETresults["ET.Monthly"][[i]]

# Set working folder
setwd("C:/Users/lmsundstroem/Documents/R")

### CATCHMENTS
# Read in all catchments and change projectory to VicGrd
catchments = readShapeSpatial("GISdata/HRS_catchmentBoundaries/HRS_Boundaries_fromBOM_v0.1_20140326/HSR_Boundaries_fromBOM.shp", force_ring=TRUE)
proj4string(catchments) = "+proj=longlat +ellps=GRS80"
catchments = spTransform(catchments, CRS("+init=epsg:3111"))

# Filter for the catchment that we want
wantedCatch = catchments[,1]$CatchID == 415237
catchments = catchments[wantedCatch]

# FIRST, read in whichever head data, make it to a raster and crop it to the size of the
catchment to reduce its size. Then rasterize it and save that raster (w), it will be used
# when importing all head data later. Get the values that are inside the catchment and save
# the data in a logical vector (isInCatchment). Finally, save the coordinates from the raster
# layer that are inside the catchment (wEastingNorthing).
# Read in head grid
head_1990 = read.asciigrid("GISdata/Heads/head_model55_1990_01.asc", colname="Head_1990_1")

# Make catchment with head to a raster
head_1990 = raster(head_1990) head_1990 = crop(head_1990, extent(catchments))

# Get raster of cells weights within catchment
w = rasterize(catchments, head_1990, getCover=7)

# Extract the mask values (i.e. fraction of each grid cell within the polygon)
# 100 = the whole grid cell is within the catchment and 0 = the gridcell is not within the
# catchment
w2 = getValues(w); isInCatchment = w2>0  # Save the values that are inside the catchment
wEastingNorthing = coordinates(w)[isInCatchment,]  # Save the coordinates for the catchment
#save(wEastingNorthing,
   file = "C:/Users/lmsundstroem/Documents/R/wEastingNorthing407230.RData")
#save(isInCatchment, file = "C:/Users/lmsundstroem/Documents/R/isInCatchment407230.RData")
### GROUNDWATER HEADS
# Read in all head data in one list
setwd("C:/Users/lmsundstroem/Documents/R/GISdata/Heads")
f <- list.files(pattern="*.asc", full.names = TRUE)
ras <- lapply(f,raster, use.names=TRUE)
e = extent(catchments)
crop = lapply(ras,crop,e , use.names=TRUE)
heads = list()
for (i in 1:length(f)){
   heads[[i]] = extract(crop[[i]], wEastingNorthing, interpMethod='simple')
}
# Give each list a name specifying what year and month the data is from
setwd("C:/Users/lmsundstroem/Documents/R") name = read.csv("names_heads.csv")
name = as.vector(name[,1])
names(heads) = name
#save(heads, file="C:/Users/lmsundstroem/Documents/R/heads415237.RData")
# Read in all variance head data in one list
setwd("C:/Users/lmsundstroem/Documents/R/GISdata/HeadsVariance")
f <- list.files(pattern="*.asc", full.names = TRUE)
ras <- lapply(f,raster, use.names=TRUE)
e = extent(catchments)
crop = lapply(ras,crop,e , use.names=TRUE)
var = list()
for (i in 1:length(f)){
   var[[i]] = extract(crop[[i]], wEastingNorthing, interpMethod='simple')
}
# Give each list a name specifying what year and month the data is from
setwd("C:/Users/lmsundstroem/Documents/R") name = read.csv("names_heads.csv")
name = as.vector(name[,1])
names(var) = name
#save(var, file="C:/Users/lmsundstroem/Documents/R/var415237.RData")
### GEOLOGICAL UNITS
# Import geological shapefile
geoUUnit = readShapeSpatial("GISdata/Surface Geology Vic/geolpldd_vg94.shp", force_ring=TRUE,
   proj4string = CRS("+init=epsg:3111"))
# Filter for wanted units
filt = geoUUnit[,20]$LITH_GROUP == "sedimentary siliciclastic"
filt[is.na(filt)] = 'FALSE'
filt = as.logical(filt)
geoUUnit1 = geoUUnit[filt, 37]
filt = geoUUnit[,20]$LITH_GROUP == "regolith"
filt[is.na(filt)] = 'FALSE'
filt = as.logical(filt)
geoUUnit2 = geoUUnit[filt,37]
filt = geoUUnit[,20]$LITH_GROUP == "igneous felsic intrusive"
filt[is.na(filt)] = 'FALSE'
filt = as.logical(filt)
geoUUnit3 = geoUUnit[filt,37]
filt = geoUUnit[,20]$LITH_GROUP == "igneous mafic volcanic; igneous felsic volcanic"
filt[is.na(filt)] = 'FALSE'
filt = as.logical(filt)
geoUUnit4 = geoUUnit[filt,37]
filt = geoUUnit[,20]$LITH_GROUP == "igneous felsic volcanic; sedimentary siliciclastic"
filt[is.na(filt)] = 'FALSE'
filt = as.logical(filt)
geoUUnit6 = geoUUnit[filt,37]
# Union the catchment with the geological units
geolUnit1 = intersect(geolUnit1, catchments)
geolUnit2 = intersect(geolUnit2, catchments)
geolUnit3 = intersect(geolUnit3, catchments)
geolUnit4 = intersect(geolUnit4, catchments)
geolUnit6 = intersect(geolUnit6, catchments)

#save(geolUnit1, file="C:/Users/lmsundstroem/Documents/R/geolUnit1_415327.RData")
#save(geolUnit2, file="C:/Users/lmsundstroem/Documents/R/geolUnit2_415237.RData")
#save(geolUnit3, file="C:/Users/lmsundstroem/Documents/R/geolUnit3_415237.RData")
#save(geolUnit4, file="C:/Users/lmsundstroem/Documents/R/geolUnit4_415237.RData")
#save(geolUnit6, file="C:/Users/lmsundstroem/Documents/R/geolUnit6_405245.RData")

# The main function where calibration, response surfaces and sensitivity analysis are done

library(sp)
library(raster)
library(maptools)
library(rgeos)
library(rgdal)
library(zoo)
library(Evapotranspiration)
library(hydromad)

# Clear all variables
rm(list = ls())

# Set working folder
setwd("C:/Users/lmsundstroem/Documents/R")

# Load head data, catchment data and geological unit data as well as coordinates and raster
load("heads415237.RData")
load("catchments415237.RData")
load("geolUnit1_415237.RData")  # For all
load("geolUnit2_415237.RData")  # For all
load("geolUnit3_415237.RData")  # For 415237
load("geolUnit4_415237.RData")  # For 415237
load("geolUnit6_405245.RData")  # For 405245
load("w415237.RData")
load("wEastingNorthing415237.RData")
load("isInCatchment415237.RData")
load("var415237.RData")

# Load meteorological, climate and hydrological data
load("precip415237.RData")
load("runoffMonthly415237.RData")
load("AETresults415237.RData")

# Convert geolunit to raster and get fraction of how much of each geol unit is within the catchment
u = rasterize(geolUnit1[,1], w, getCover=T)
v = rasterize(geolUnit2[,1], w, getCover=T)
uu = rasterize(geolUnit3[,1], w, getCover=T)  # For 415237
vv = rasterize(geolUnit4[,1], w, getCover=T)  # For 415237
vvv = rasterize(geolUnit6[,1], w, getCover=T)  # For 405245

# Getting the fractions of how much each geol unit raster grid is within the catchment
# 100 = the whole grid cell is within the catchment and
# 0 = the gridcell is not within the catchment
u = getValues(u);
v = getValues(v);
uu = getValues(uu);  # For 415237
vv = getValues(vv);  # For 415237
vvv = getValues(vvv);  # For 405245
u = u[isInCatchment]  # Keep only the fractions that are within the catchment
v = v[isInCatchment]
uu = uu[isInCatchment]
vv = vv[isInCatchment]
vvv = vvv[isInCatchment]

# Get the fraction into values between 0 and 1
frac1 = u/100
frac2 = v/100
frac3 = uu/100
frac4 = vv/100
# frac6 = vvvv/100

# OPTIMIZE water balance error for CALIBRATION
# Jan 1990 - Dec 2009
source('../R/f.R')
o = SCEoptim(FUN = f, par=c(0.1, 0.1, 0.1, 0.8), lower= c(0.0, 0.0, 0.0, 0.0),
            upper=c(0.5, 0.5, 0.5, 2.0), control = list(ncomplex = 12, maxit = 10000,
            trace=1, rettol = 1e-8, tolsteps = 10))

# SAVE ETMonthly when it is scaled according to the optimization
ScaledET = c()
for (i in 1:288){
    ScaledET[i] = ETresults[['ET.Monthly']][[i]]*o$par[4]
}
write.csv(ScaledET,
    file = "C:/Users/lmsundstroem/Documents/R/ETresultsMonthlySCALED415237.csv")

# Jan 1990 - Dec 1996
source('../R/f2.R')
o2 = SCEoptim(FUN = f2, par=c(0.1, 0.1, 0.1, 0.8),
              lower= c(0.0, 0.0, 0.0, 0.0),
              upper=c(0.5, 0.5, 0.5, 2.0),
              control = list(ncomplex = 12, maxit = 10000,
              trace=1, rettol = 1e-8, tolsteps = 10))

# Jan 1997 - Dec 2009
source('../R/f3.R')
o3 = SCEoptim(FUN = f3, par=c(0.1, 0.1, 0.1, 0.8),
              lower= c(0.0, 0.0, 0.0, 0.0),
              upper=c(0.5, 0.5, 0.5, 2.0),
              control = list(ncomplex = 12, maxit = 10000,
              trace=1, rettol = 1e-8, tolsteps = 10))

# DETERMINE how the calibrated values for specific yields a
and the scalar fit 2010-2013.
specificYield1 = o3$par[1];
specificYield2 = o3$par[2];
specificYield3 = o3$par[3];
xET = o3$par[4]
l = 1:49
waterBalanceError = rep(Inf, length(l)-1)
avgGWchange = rep(Inf, length(l)-1)
for (k in 2:length(l)){
    varWeights = 1 - (var[[k]]/sum(var[[k]]));
    # 415226 & 407230
    avgGWchange = sum(((heads[[239+k]]-heads[[239+k-1]])*specificYield1*frac1*varWeights +
                       (heads[[239+k]] - heads[[239+k-1]])*specificYield2*frac2*varWeights) /sum(frac1+frac2))*1000
    # 415237
    avgGWchange = sum((heads[[239+k]]-heads[[239+k-1]])*specificYield1*frac1*varWeights +
                       (heads[[239+k]] - heads[[239+k-1]])*specificYield2*frac2*varWeights +
                       (heads[[239+k]] - heads[[239+k-1]])*specificYield3*(frac3+frac4)*varWeights) /sum(frac1+frac2+frac3+frac4))*1000
    # 405214
    avgGWchange = sum((h[[239+k]] -
                       h[[239+k-1]])*specificYield1*(frac1+frac6)*varWeights +
                       (h[[239+k]] - h[[239+k-1]])*specificYield2*frac2*varWeights)/sum(frac1+frac2+frac6))*1000
    waterBalanceError[k-1] = (precip[239+k] - avgGWchange -
                            xET*ETresults[['ET.Monthly']][[239+k]] - runoffMonthly[239+k])
}
RMSE = sqrt(mean(waterBalanceError^2)) print(RMSE)

#SAVE the water balance error and average groundwater change
write.csv(avgGWchange,
    file = "C:/Users/lmsundstroem/Documents/R/407230_10-13_avgGWchange_noLag.csv")
write.csv(waterBalanceError,
    file = "C:/Users/lmsundstroem/Documents/R/407230_10-13_waterBalanceError_noLag.csv")

# DETERMINE avg groundwater change and the water balance error per month
# for optimised specific yields and scalar x.
specificYield1 = o$par[1]
specificYield2 = o$par[2]
xET = o$par[3]

l = 1:240
avgGWchange = c()
waterBalanceError = rep(Inf, length(l)-1)
for (k in 2:length(l)) {
  varWeights = 1 - (var[[k]]/sum(var[[k]]));
  # 415226 & 407230
  avgGWchange = sum( ((h[[k]] - h[[k-1]])*specificYield1*frac1*varWeights +
    (h[[k]] - h[[k-1]])*specificYield2*frac2*varWeights)/(sum(frac1+frac2))*1000

  # 405245
  waterBalanceError[k-1] = (precip[k] - avgGWchange -
    xET*ETresults["ET.Monthly"])[[k]] - runoffMonthly[k])
}
RMSE = sqrt(mean(waterBalanceError^2))
print(RMSE)

#SAVE the water balance error and average groundwater change
#write.csv(avgGWchange,
#file = "C:/Users/lmsundstroem/Documents/R/407230_90-09_avgGWchange_Lag.csv")
#write.csv(waterBalanceError,
#file = "C:/Users/lmsundstroem/Documents/R/407230_90-09_waterBalanceError_Lag.csv")

# Jan 1990 - Dec 1996
specificYield1= o2$par[1]
specificYield2= o2$par[2]
specificYield3= o2$par[3]
xET = o2$par[4]
l = 1:84
avgGWchange = c()
waterBalanceError = rep(Inf, length(l)-1)
for (k in 2:length(l)) {
  varWeights = 1 - (var[[k]]/sum(var[[k]]));
  # 415226 & 407230
  avgGWchange = sum( ((heads[[k]] - heads[[k-1]])*specificYield1*frac1*varWeights +
    (heads[[k]] - heads[[k-1]])*specificYield2*frac2*varWeights)/(sum(frac1+frac2))*1000

  # 415237
  waterBalanceError[k-1] = (precip[k] - avgGWchange -
    xET*ETresults["ET.Monthly"])[[k]] - runoffMonthly[k])
}
RMSE = sqrt(mean(waterBalanceError^2))
print(RMSE)

#SAVE the water balance error and average groundwater change
#write.csv(avgGWchange,
#file = "C:/Users/lmsundstroem/Documents/R/415237_90-96_avgGWchange_noLag_2.csv")
#write.csv(waterBalanceError,
#file = "C:/Users/lmsundstroem/Documents/R/415237_90-96_waterBalanceError_noLag_2.csv")

# Jan 1997 - Dec 2009
specificYield1 = o3$par[1]
specificYield2 = o3$par[2]
specificYield3 = o3$par[3]
xET = o3$par[4]
l = 1:157
avgGWchange = c()
waterBalanceError = rep(Inf, length(l)-1)
for (k in 2:length(l)) {
    varWeights = 1 - (var[k]/sum(var[k]));
    # avgGWchange = sum( ((h[83+k] - h[(83+k-1)])*specificYield1*frac1*varWeights +
        (h[83+k] - h[(83+k-1)])*specificYield2*frac2*varWeights)/sum(frac1+frac2))*1000
    # 415237
    avgGWchange = sum( ((h5[83+k] - h5[(83+k-1)])*specificYield3*(frac3+frac4)*varWeights) / 
        (sum(frac1+frac2+frac3+frac4))*1000
    waterBalanceError[k-1] = (precip[83+k] - avgGWchange - xET*ETresults["ET.Monthly"])[83+k] - runoffMonthly[83+k]) }
RMSE = sqrt(mean(waterBalanceError^2))
print(RMSE)

#SAVE the water balance error and average groundwater change
#write.csv(avgGWchange, 
# file = "C:/Users/lmsundstroem/Documents/R/415226_97-09_avgGWchange_Lag.csv")
#write.csv(waterBalanceError, 
# file = "C:/Users/lmsundstroem/Documents/R/415226_97-09_waterBalanceError_Lag.csv")

# Build a 2D response surface
source("~/R/f3.R")
# Set source
specificyield2 = 0.1
# Make two of the variables flexible and the rest as constants
specificyield1 = seq(0.0,0.15,by=0.01)
specificyield3 = o3$par[3]
xET = seq(0.6, 1.1,by=0.05)
obj=matrix(NA, nrow=length(S1), ncol=length(xET))
for (i in 1:length(S1)) {
    for (j in 1:length(xET)) {
        obj[i,j]=f3(c(S1[i],xET[j]))
    }
}
print(paste('... finished i=',i))

# Plot the 2D response surface and save as .png
png(file="ResponseSurface/415237_90-09_SY2_0-1_SY1xET.png", width=800, height=700, res=200)
contour(x = S1, y = xET, z = obj, xlab = "Specific yield, Sedimentary siliciclastic", 
    ylab = "Evapotranspiration scalar x", main = "Specific yield 1 vs. Scalar x, Sy2=0.1,Sy3=10^{(-12)}", 
    nxlevels = 15, cex.lab=0.8, cex.axis=0.8, cex.main=0.8, cex.sub=0.8)
dev.off()

# LOCAL SENSITIVITY ANALYSIS for RMSE
# The constants in CatchmentData.R are changed with 1%, 5% and 10% one at a time as well as 
# the specific yields and scalar x.
specificYield1 = o$par[1]
specificYield2 = o$par[2]
specificYield3 = o3$par[3]
xET = o$par[3]
l = 1:240; 
# From Jan 1997 to Dec 2009
waterBalanceError = rep(Inf, length(l)-1)
for (k in 2:length(l)) {
    varWeights = 1 - (var[k]/sum(var[k]));
    # avgGWchange = sum( ((heads[k] - heads[(k-1)])*specificYield1*frac1*varWeights +
        (heads[k] - heads[(k-1)])*specificYield2*frac2*varWeights)/sum(frac1+frac2))*1000
    # 415237
    avgGWchange = sum( ((heads[[84+k]] - heads[[84+k-1]])*specificYield1*frac1*varWeights +
        (heads[[84+k]] - heads[[84+k-1]])*specificYield2*frac2*varWeights)/sum(frac1+frac2))*1000
    waterBalanceError[k-1] = (precip[84+k] - avgGWchange - xET*ETresults["ET.Monthly"])[84+k] - runoffMonthly[84+k])
}
(heads[[(84+k)] - heads[[[(84+k)-1]]])*specificYield1*frac1*varWeights +
(heads[[(84+k)] - heads[[[(84+k)-1]]])*specificYield2*frac2*varWeights)
#*(sum(frac1+frac2+frac6))*1000
waterBalanceError[k-1] = (precip[k] - avgGWchange -
ETresults["ET.Monthly"])[k] - runoffMonthly[k])
} RMSE2 = sqrt(mean(waterBalanceError)^2))
print(RMSE2)
# CREATE a data frame with the results do they can easily be imported into Excel.
#delta= list("1%", "5%", "10%")
#sensitivity = data.frame() #sensitivity[1,1] = delta[1]
dRMSE = (RMSE - RMSE2)
dS = (o$par[1]-o$par[3])*1.01
sensitivity[1,2]=dRMSE/dS
# Define column names and save file
colnames(sensitivity) <- c("%change", "Sy1", "Sy2", "Sy3", "x", "fz", "epsilonMo", "alphaMo")
write.csv(sensitivity, file="sensitivityRMSE405245.csv")

THE OBJECTIVE FUNCTIONS USED

#### For Jan 1990-Dec 2009
f = function(x){
specificYield1=x[1];
specificYield2=x[2];
specificYield3=x[3];
xET=x[4]

for (k in 2:length(l)) {
  varWeights = 1 - (var[k]/sum(var[k]));
  # 415226 & 407230
  #avgGWchange = sum((heads[k] - heads[[k-1]])*specificYield1*frac1*varWeights +
  # (heads[k] - heads[[k-1]])*specificYield2*frac2*varWeights)/sum(frac1+frac2))*1000

  # 415237
  avgGWchange = sum((heads[k] - heads[[k-1]])*specificYield1*frac1*varWeights +
  (heads[k] - heads[[k-1]])*specificYield2*frac2*varWeights +
  (heads[k] - heads[[k-1]])*specificYield3*frac5*varWeights)
  #*(sum(frac1+frac2+frac5))*1000
  waterBalanceError[k-1] = (precip[k] - avgGWchange -
  xET*ETresults["ET.Monthly"])[k] - runoffMonthly[k])
}
RMSE = sqrt(mean(waterBalanceError)^2))
return(RMSE)
}

#### For Jan 1990 to Dec 1996
f2 = function(x){
specificYield1=x[1];
specificYield2=x[2];
specificYield3=x[3];
xET=x[4]
```r
l = 1:84;
waterBalanceError = rep(Inf, length(l)-1)

for (k in 2:length(l)){
  varWeights = 1 - (var[[k]]/sum(var[[k]]));
  avgGWchange = sum((heads[[k]] - heads[[k-1]])*specificYield1*frac1*varWeights +
                    (heads[[k]] - heads[[k-1]])*specificYield2*frac2*varWeights)/sum(frac1+frac2)*1000
  waterBalanceError[k-1] = (precip[k] - avgGWchange - xET*ETresults["ET.Monthly"][[k]] - runoffMonthly[k])
}
RMSE = sqrt(mean(waterBalanceError^2))
return(RMSE)
}

# For Jan 1997 to Dec 2009
f3 = function(x){
  specificYield1=x[1];
  specificYield2=x[2];
  specificYield3=x[3];
  xET=x[4]
  l = 1:156;
  waterBalanceError = rep(Inf, length(l)-1)

  for (k in 2:length(l)){
    varWeights = 1 - (var[[k]]/sum(var[[k]]));
    avgGWchange = sum((heads[[84+k]] - heads[[84+k-1]])*specificYield1*frac1*varWeights +
                       (heads[[84+k]] - heads[[84+k-1]])*specificYield2*frac2*varWeights)/sum(frac1+frac2)*1000
    waterBalanceError[k-1] = (precip[k] - avgGWchange -
                              xET*ETresults["ET.Monthly"][[84+k]] - runoffMonthly[k])
  }
  RMSE = sqrt(mean(waterBalanceError^2))
  return(RMSE)
}
```
### Appendix II – Input for Calculating Morton’s Actual Areal Evapotranspiration

Specific constants for each catchment:

<table>
<thead>
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<th>Description of constants</th>
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<th>407230</th>
<th>415226</th>
<th>415237</th>
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<td>Latitude at centroid [°]</td>
<td>lat</td>
<td>-37.06</td>
<td>-37.27</td>
<td>-36.82</td>
<td>-37.14</td>
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<td>Latitude at centroid [rad]</td>
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<td>-0.650</td>
<td>-0.643</td>
<td>-0.648</td>
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<tr>
<td>Elevation at centroid [m]</td>
<td>Elev</td>
<td>518 m</td>
<td>445 m</td>
<td>277 m</td>
<td>288 m</td>
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</table>

Constants used for all catchments:

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<tr>
<td>Symbol</td>
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<td>17.27</td>
<td>0.66</td>
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<td>b1</td>
<td>b2</td>
<td>β</td>
<td>0_m</td>
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<td>13.4</td>
<td>1.13</td>
<td>237.3</td>
<td>5.67e-08</td>
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Appendix III – Time Lag Correlations

Catchment 405245

Sedimentary formation, 1990-1996

Regolith, 1990-1996

Sedimentary formation, 1997-2009

Regolith, 1997-2009

Sedimentary formation, 1990-2009

Regolith, 1990-2009
Catchment 407230
Catchment 415237

Sedimentary siliciclastic, 1990-2009

Regolith, 1990-2009

Sedimentary siliciclastic, 2010-2013

Regolith, 2010-2013

Sedimentary siliciclastic, 1990-1996

Regolith, 1990-1996
Appendix IV – Response Surfaces

Catchment 407230, assuming no delayed groundwater head response.

Specific yield 1 vs. Specific yield 2, xET = 0.8

Specific yield 1 vs. Specific yield 2, xET = 1.2

Specific yield 1 vs. Scalar x, Sy2=0.001

Specific yield 1 vs. Scalar x, Sy2 = 0.1

Specific yield 2 vs. Scalar x, Sy1=0.001

Specific yield 2 vs. Scalar x, Sy1 = 0.1
Catchment 415226, assuming no delayed groundwater head response.
Catchment 415237, assuming no delayed groundwater head response.
Catchment 407230, assuming delayed groundwater head response.
Catchment 415226, assuming delayed groundwater head response.
Catchment 415237, assuming delayed groundwater head response.