Surface water and alluvial groundwater connectivity at Mulloon Creek and the implications for Natural Sequence Farming

Oliver Hickson

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Abstract
The effect of installing 22 instream weirs along a 2 km stretch of Mulloon Creek as part of a Natural Sequence Farming (NSF) pilot project was investigated. The outcomes of NSF are reportedly diverse: this study focussed specifically on floodplain aquifer rehydration. The alluvial groundwater response to NSF treatment was analysed by comparing floodplain piezometer measurements from two discrete monitoring periods. Using an ANOVA, the late period 0.37 m mean reduction in depth to floodplain water table was found to be significant (0.05). No monthly precipitation trends were detected by either the Mann-Kendall test or linear models over the monitoring periods, however the late period had higher rainfall intensity (1.8 vs 2.3 mm/day). Sedimentology conducted during installation and short-term monitoring of an additional piezometer network was used to determine alluvial groundwater flow dynamics at an untreated site located 2 km downstream of the pilot project site. A hydraulic gradient analysis technique was used to estimate and compare baseflow into the stream during each period and at each location. Groundwater flow across the Mulloon Creek floodplain is facilitated by semi-continuous coarse grained units transmitting water towards the gaining stream. Additional water is induced into the alluvial aquifer via the NSF process of step-diffusion. Often complex floodplain sedimentology results in groundwater flow patterns that are equally complex and difficult to predict purely from surface topography. Although the NSF treated site was improved, the degree of hydration in the untreated site appears to be higher. NSF is most effective in incised streams with disconnected and porous aquifers composed of hydraulically conductive floodplain material. This emphasizes the importance of site suitability and prior investigation before implementing river/floodplain restoration projects that emphasize the alteration of alluvial groundwater processes.

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Surface water and alluvial groundwater connectivity at Mulloon Creek and the implications for Natural Sequence Farming

A thesis submitted in partial fulfilment of the requirements for the award of the degree of
BACHELOR OF SCIENCE ADVANCED (HONOURS)
From
THE UNIVERSITY OF WOLLONGONG
by
OLIVER HICKSON

(School of Earth & Environmental Sciences, Faculty of Science, Medicine and Health)
(APRIL, 2017)
The information in this thesis is entirely the result of investigations conducted by the author, unless otherwise acknowledged, and has not been submitted in part, or otherwise, for any other degree or qualification.

Oliver Hickson
19\textsuperscript{th} April 2017
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CHAPTER 1 - INTRODUCTION

1.1 BACKGROUND

The prominence of river restoration science and practice has grown as global concerns about water and environmental sustainability have mounted. The term river restoration is used to describe the modification of river channels and the adjacent riparian zones and floodplains for the purpose of improving hydrologic, geomorphic, and/or ecological processes (Bennett et al., 2011, Wohl et al., 2015). Due to the degraded state of many Australian rivers and streams, river restoration is an important component of environmental management in Australia.

Natural Sequence Farming is a river restoration technique defined as an agricultural system based on understanding landscape and ecological processes and implementing vegetation, land and water management practices compatible with these processes to achieve sustainability (Williams, 2010).

This study will investigate a Natural Sequence Farming pilot project on Mulloon Creek in south eastern NSW, Australia. The groundwater-surface water interaction between the stream and alluvial floodplain aquifer will be assessed and characterized at two locations on Mulloon Creek, one restored, one unrestored.

1.2 AUSTRALIAN RIVERS TODAY

The Australia landscape has been significantly altered since European settlement. Agricultural practices developed in Europe were inappropriately applied to the Australian landscape, causing widespread alteration and degradation in the environment (Dobes et al., 2013). These adverse effects are prominent in the rivers and streams of south eastern Australia.

Australian rivers and streams are characterized by a climate that is highly variable and low in annual rainfall (Hatton and Nulsen, 1999). Floodplain alluvium, which is typically derived from ancient weathered parent material, is only replenished during infrequent flooding events (Hatton and Nulsen, 1999). The floodplains aquifers are often perched and disconnected from regional groundwater systems (Prosser, 1991, Rassam et al., 2006); therefore requiring surface water processes such as stream connectivity to function. This
connectivity sustains streams during periods of drought, with water from alluvial aquifers providing baseflow to the many ephemeral streams in Australia (Dobes et al., 2013).

Riparian vegetation provides the stability needed in the channel to prevent scouring and erosion (Prosser and Winchester, 1996). The upper catchment streams and rivers of Australia have incised and eroded primarily due to the European land management practices of woodland land clearing (Dobes et al., 2013) and the riparian and floodplain vegetation removal (Prosser and Winchester, 1996). By truncating alluvial aquifer flow paths (Promma et al.), channel incision has changed the hydro-geomorphic landscape functions that were dependent on stream-floodplain connectivity (Wallbrink et al., 1999). Figure 1 shows how the water table elevation in the floodplain will reflect the low level in the channel, adversely affecting water availability in the floodplain top soil.

Figure 1 – The water table in an incised and non-incised stream. Taken from Dobes et al. (2013).
An incised and un-vegetated channel is one that is more susceptible to further degradation. It is important for the health of Australian rivers to develop management practices that prevent initial degradation occurring, but also to develop solutions that can mitigate and reverse existing damage.

1.3 NATURAL SEQUENCE FARMING

Definition and origin of NSF

Natural Sequence Farming (NSF) is one of the many river restoration approaches that aim to prevent and reverse river and stream degradation. It shares some commonalities with ‘eco-engineering’ solutions by using natural ‘soft’ materials and design (Evette et al., 2009, Abbe and Brooks, 2011); however it differs to most other approaches in terms of both scale and breadth of principle. It aims to not only prevent and reverse river and stream degradation, but to benefit agricultural from improvements in landscape function.

Williams (2010) defines Natural Sequence Farming as, ‘an agricultural system based on understanding landscape and ecological processes and implementing vegetation, land and water management practices compatible with these processes to achieve sustainability”. Devised by Peter Andrews in the late 20th century on Hunter Valley properties Tarwyn Park and later Baramul, the holistic landscape repair technique rose in prominence following media coverage by ABC TV (2005) and books by Peter Andrews (Andrews, 2006, Andrews, 2008). Interest in NSF has previously resulted in a publication by CSIRO (2002) documenting restorations at Tarwyn Park. In 2006, a NSF pilot project commenced along Mulloon Creek, on the property Home Farm. But it was not until Williams (2010) outlined the fundamental principles of NSF did the phrase enter scientific literature.

Building on the work of Andrews (2006, 2008), Williams (2010) summarizes NSF in four principals:

“Restoring fertility held by nutrients and organic matter improves the biological function of soils;

Reinstating hydrological balance increases groundwater storage in the flood-plain aquifer, increasing freshwater recharge and hence reducing saline groundwater discharge;

Re-establishing natural vegetation succession through pioneer species promotes the healthy growth of native plant communities;
"Understanding the hydrological and biogeochemical processes that drive the natural landscape system allows their management to restore ecological function."

Implementation of NSF

Implementation involves a number of different structural and non-structural measures. The measures proposed by Williams (2010) are summarized in Table 1.

<table>
<thead>
<tr>
<th>Structural</th>
<th>Non-structural</th>
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<tr>
<td>Grade-control structures in the stream line</td>
<td>Avoidance of surface (spray) irrigation</td>
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<tr>
<td>Contour banks on the floodplain and at the hillslope-floodplain break of slope</td>
<td>Avoidance of herbicide use</td>
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<tr>
<td>Contour channels diverting water away from the stream line.</td>
<td>Minimal use of chemical fertilizers</td>
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<tr>
<td></td>
<td>Avoidance of ploughing on hillslopes</td>
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<td>Avoidance of storing water in dams on saline areas</td>
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<td></td>
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The first structural measure listed by Williams (2010), grade-control structures, are alternatively named ‘leaky-weirs’. The purpose and function of the leaky-weir in the context of incised Australian rivers and streams is shown in Figure 2, taken from (Dobes et al., 2013). The main principal at work is ‘step-diffusion’, whereby groundwater-surface interaction is encouraged at localised ‘steps’, a process which is argued to be an efficient use water and nutrients (Dobes et al., 2013). The weir is constructed by adding boulders to the incised channel to partially dam the surface flow, causing water to bank up in the stream at an elevated, pre-stream incision height. Groundwater-surface water interaction along the local channel margin will result in reconnection between the stream and the floodplain aquifers. Revegetated stream banks stabilize the channel margin and increase biological interaction in the hyporheic zone. An area of high hydrostatic pressure is formed in the stream, elevating the groundwater table across the entire floodplain, ‘rehydrating’ the landscape. Groundwater baseflow from this water bank is intended to sustain stream flow in dry periods and recharge again during wet periods (Dobes et al., 2013).
Many but not all of the structural and non-structural measures were implemented at Home Farm. The holistic nature of NSF makes scientific analysis difficult due to the influence and interaction of the range of measures. But it is predicated that the leaky-weirs will have the largest and most discernible effect on surface and subsurface flows; therefore it is the impact of these measures that will be the focus of this investigation.

1.4 MULLOON CREEK

A NSF pilot project began in 2006 on a property named *Home Farm* managed by The Mulloon Institute. Mulloon Creek runs through the property and the channel has been the focus of the restoration works. Project implementation was in accordance with the measures described by Williams (2010). The incised channel banks were flattened and replanted with colonizing plants. Grade-control structures - ‘leaky-weirs’, were installed in 22 locations within the channel in two stages in April and September 2006.

The largest body of research that has been conducted at Mulloon Creek is by Johnston and Brierley (2006). The study looked at ‘floodplain pocket’ development along Mulloon Creek during the Late Quaternary. The study revealed pre-European channel morphology, which is particularly important to river restoration studies. Floodplain and channel morphology is explained by their respective formation processes. Detailed geomorphological maps,
longitudinal and cross sectional surveying, sedimentary coring and $^{14}$C and $^{210}$Pb dating was produced.

A study by Dobes et al. (2013) is unique because it is the only published body of work exploring both Mulloon Creek and NSF. The study weighed up the economic and financial benefits of the NSF implementation at Mulloon Creek. In doing so, Dobes et al. (2013) produced a valuable resource in publishing the history of NSF and describing restoration measures at Mulloon Creek, as most other information regarding NSF is unpublished.

In addition to the work by Dobes et al. (2013) and Johnston and Brierley (2006), Mulloon Creek has been the focus of an unfinished postgraduate and several small undergraduate research projects from the University of Canberra (Kennett and Bernardi, 2016) and the Australian National University. One of these was a rapid stream appraisal was completed in 2016 which collected valuable stream water chemistry data. Unfortunately, the soil data collected by the PHD student and the drill logs for the original piezometers at Home Farm cannot be found.

1.5 AIMS AND OBJECTIVES

Assess the success of the pilot project at Home Farm by investigating floodplain water table patterns during the recording period.

Analyze the groundwater-surface water connectivity at Home Farm and compare this to what occurs at Lower Mulloon

Discuss the influence of soil and lithology on potential groundwater pathways.
CHAPTER 2 – LITERATURE REVIEW

2.1 ASSESSING RIVER RESTORATION

The term river restoration often inaccurately implies returning a river system to a prior ‘natural’ state (Wohl et al., 2015). In reality the conditions of the prior state may be unknown (William, 1996, Wohl and Merritts, 2007), and the conditions of the system may have been temporally variable (Van Diggelen et al., 2001, McDonald et al., 2004, Ward et al., 2001). The contemporary understanding is that river restoration aims to create or preserve river form and function that is desirable for a particular or range of purposes such as fish habitat, water quality or recreation, for example (Wohl et al., 2015).

The 20th century practice of river restoration generally used physical channel manipulation in an attempt to minimize loss of property and life (Wohl et al., 2015). This approach resulted in the homogenization of rivers into forms with low physical complexity and ecological diversity (Poff et al., 2007, Rahel, 2007). Recognition of the scale of channel alteration caused by river engineering approaches led to the development of ‘soft’ bioengineering solutions using living plants (Evette et al., 2009) and dead wooden debris (Abbe and Brooks, 2011). These solutions tended to use river form as the restoration goal; however restoration types that emphasize the importance of river process have increased in prominence in the last decade (Wohl et al., 2015). Restoration techniques have evolved to promote channel-floodplain and longitudinal connectivity (Shields et al., 2011, Gumiero et al., 2013).

Inadequate monitoring of river restoration project successfulness and the significant number of projects that do not achieve significant restoration outcomes are persistent themes identified as problems by the research community (Wohl et al., 2015). To build on the work by (Keene et al., 2006, Bush, 2010), it is necessary to objectively quantify the effectiveness of the pilot project at Home Farm, in order to increase scientific understanding of NSF.

Numerous methods are available to assess the success of river restoration projects. Belletti et al. (2015) groups methods into four categories: (1) physical habitat assessment; (2) riparian habitat assessment; (3) morphological assessment; (4) assessment of hydrological regime alteration. The restoration type and the temporal and data limitations of this project only warrant the conduct of a hydrological assessment only.
To rigorously assess a restoration project, there is a need for pre-existing data to define the unaltered reference hydrological regime (Belletti et al., 2015). Without control or reference data, it is difficult to estimate the magnitude of impact due to problems differentiating between natural and induced effects. For a valid analysis, the change measured must be due to the activity. A common and rigorous experimental approach that uses reference data to evaluate restoration impacts is a Before–After Control-impact (BACI) design (Smith, 2014). Due to historical project limitations, pre intervention reference data is not available at Mulloon Creek, however there are variations of BACI that are designed to accommodate for this scenario, such as the use of an ANOVA to compare periods of restoration maturity (Smith, 2014).

**2.2 NATURAL SEQUENCE FARMING**

The proclaimed benefits of NSF are promising; however its origins on Hunter Valley properties Tarwyn Park and Baramul lack the empiricism that is required for evidence based management. While there have been publications characterizing NSF (CSIRO, 2002, Williams, 2010), research investigating the effectiveness of NSF principles is less prominent.

Only two publications address NSF specifically. The first study assessed 30 year old NSF treated floodplain soils at Bylong Creek (Weber and Field, 2010), while the second reviewed the economics of NSF with a cost-benefit analysis of the Home Farm restorations (Dobes et al., 2013). More relevant and comprehensive bodies of work investigate the hydro-geomorphic effects of NSF on the restorations at Widden Brook in the Hunter Valley (Bush, 2010, Keene et al., 2006).

Keene et al. (2006) examined surface water-groundwater connectivity around a single bed control structure in Widden Brook. The study has no specific mention of NSF; however Widden Brook flows through the NSF demonstration site Baramul, therefore it is concluded that the restorations tested in the study are NSF restorations. This assumption is further supported by Bush (2010).

Four channel-floodplain piezometer transects were used by Keene et al. (2006) to monitor groundwater and stream water flow around an instream structure over a period of 14 months at Widden Brook. The connectivity between the stream water and alluvial groundwater was assessed by plotting water chemistry and water table measurements against distance from the
stream or distance downstream. Zones of groundwater-stream water exchange were predicted by attributing fluctuations at certain points to a characteristic of that site.

Keene et al. (2006) summarized several key findings from Widden Brook:

“Stream water and groundwater levels reflected strong hydrological linkages in coarse channel deposits.
The alluvial groundwater storage of the floodplain was important for maintaining base flow conditions.
The redox status, ionic concentration and salinity of the alluvial aquifer appeared unrelated to the water table depths in the floodplain.
The effect on the hyporheic zone from the in-stream structure was localised.
Alluvial groundwater discharge from the hyporheic zone to the channel occurred under base flow conditions.”

The findings of Keene et al. (2006) are important to this study as they demonstrates the means to investigate stream-groundwater interaction with equipment available at Mulloon Creek. It should be noted, however, that the scale of the Mulloon Creek study is much greater due to the more numerous bed control structures.

Bush (2010) addressed the NSF implications at the site studied initially by Keene et al. (2006), and found ‘NSF stream works have facilitated sand storage, vegetation recovery and localised channel-floodplain hydrological exchange, important for pool-riffle development, channel contraction and hyporheic function’. Both Bush, 2010 and Keene et al., (2006) acknowledge the localization of induced connectivity. Bush (2010) found no measurable change in stream flow, most likely due to study length constraints. Similarly, the report by CSIRO (2002) found little change in downstream flow at Tarwyn Park.

2.3 SIMILAR RESTORATION TECHNIQUES

The use of grade control structures in river restoration science is not new (DeBano and Schmidt, 1987). Grade control measures have been extensively used to remediate rivers by controlling the downward cutting of a river bed in one reach, ultimately preventing upstream incision (Darby and Simon, 1999). The predominate names given to grade control structures is usually weir or checkdam, but they vary greatly in size and design. Boulders, concrete jacks, sheet piling, concrete rubble, gabions and logs may be used (Darby and Simon, 1999).
A model for raising an incised alluvial water table was introduced by DeBano and Schmidt (1987) and is illustrated Figure 3. The process uses intermediately sized in-channel structures to create a new flow dynamic that has proved to encourage the revegetation of riparian banks DeBano and Schmidt (1987). The process was demonstrated at Red Clover Creek, California, where the alluvial water table was raised by impounding stream water with checkdams. It was found that in treated areas, the gradient between stream and aquifer head was reduced, while in control areas a sharp sloping water table was draining the floodplain meadow. Forage production was found to increase in the floodplain depressions DeBano and Schmidt (1987).

\[\text{Figure 3} – \text{Function of instream structure on water table. Taken from DeBano and Schmidt (1987).}\]
2.4 ANALYSING HYDROLOGICAL RECORDS

Piezometers have been gathering hydrological data at Home Farm. A variety of statistical methods exist to detect changes in this type of record. As hydrological data is typically non-parametric, robust analysis requires the use of statistical tools that are optimized for distribution-free data. The Mann-Kendell test is one such tool.

The Mann-Kendell test identifies and estimates the direction and significance of a trend in a time series of non-parametric data (Mann, 1945, Kendall, 1975). The test is widely employed in hydrology (Kisi and Ay, 2014), with researches continuing to demonstrate its application to precipitation (Deng et al., 2017), streamflow (Garcia et al., 2017) and groundwater (Niu et al., 2017) records.

When detecting changes in a record caused by experimentation, the effect of external factors can be assessed using the Man-Kendell test to discern any significant trend over the period (Mu et al., 2007). This process allows an identified trend to be more accurately attributed to a single variable (Lane et al., 2005). Mu et al. (2007) applied the process when quantifying the significance of precipitation trends over a period in which the influence of soil conservation measures on stream flow was being assessed. The procedure of normalizing, removing or comparing annual precipitation variability as done by Mu et al. (2007) allows for the assessment of historical restoration projects that are not suitable for a paired catchment (Adelana et al., 2015) or BACI experimental design (Smith, 2014).

2.5 GROUNDWATER-SURFACE WATER CONNECTIVITY

The process of surface water and groundwater connectivity is complex. Tóth (1970) uses the term hydrogeoecological, to describe the framework of climate, landform, geology and biotic factors that control the interaction. This is because the two processes are open systems that feedback dynamically in a variety of climatic and physiographic landscapes. When dealing with water resource issues, it is therefore important to know how groundwater and surface water behaves, and to understand influential components of the landscape.

The subsurface region in which groundwater-surface water interaction occurs is called the hyporheic zone (Valett et al., 1993). The area is characterized by evidence of physical, geochemical and biological mixing (Triska et al., 1989) and the extent may range from centimeters to tens of meters from the stream depending on the a variety of factors.
Marco scale geomorphic units such as bars, ripples, dunes and boulders, combined with the physical parameters like hydraulic conductivity, results in hydraulic potential differences that lead to complex flow patterns (Woessner, 2000).

A network of near and instream piezometers can be used to uncover the nature of groundwater exchange and the extent of the hyporheic zone in a channel section (Lee and Cherry, 1978, Henry et al., 1994, Hendricks and White, 1991). Due to the potential for highly variable exchange over a fine scale, measurements taken from piezometers may be difficult to interpret. It is possible to have a micro flow gradient in the opposite direction to the larger flow gradient that it lies within (Woessner, 2000). Despite being limited in ability to assess fine scale flow systems, piezometers are the best tool available to analyse groundwater-surface water interactions on a channel scale (Rassam and Werner, 2008). Effort must therefore be taken to install piezometers in locations indicative of average regional processes (Rassam and Werner, 2008).

Groundwater flow in stream-aquifer connected systems will occur downslope along the gradient between river stage and aquifer head (Sophocleous, 2002). Flow between groundwater and surface bodies is termed baseflow (Woessner, 2000). An abundance of different approaches have been used to analytically and numerically model the connection at varying levels of complexity and dimension, many of which are unsuitable for narrow extent, computational and temporally limited projects (Werner et al., 2006). Although the approaches differ, most methods use estimations of groundwater discharge into streams as the basis of the analysis. Rassam and Werner (2008) reviewed the appropriateness of the following baseflow estimation techniques: flow differencing, hydraulic gradient analysis, longitudinal river chemistry and chemical and non-chemical hydrograph. Hydraulic gradient analysis is useful in locations that already have an existing piezometer network.

The hydraulic gradient method proposed by (Rassam and Werner, 2008) utilizes a piezometer network to calculate groundwater inflow into streams. This method uses Darcy’s Law to estimate the magnitude of flow between aquifer hydraulic head and stream water level. Flow is defined as the product of the hydraulic gradient and transmissivity:

\[
Q = T \frac{\Delta h}{x}
\]
Where \( Q \) is the flow rate per unit length of stream, \( T \) is the transmissivity, \( \Delta h \) is the difference in hydraulic head between the stream and aquifer, and \( x \) is the distance of the piezometer from the stream. Equation 1 assumes a linear relationship between head gradient and flow rate, which is less applicable to complex floodplain assemblages (Cook et al., 2012). Close proximity of the piezometers will result in the highest resolution of groundwater flow (Cook et al., 2012). As the distance between piezometer and stream increases, the calculated flow is progressively less representative of short-term groundwater and surface water relationships (Cook et al., 2012).

Accurate estimation of the transmissivity between the stream and aquifer is crucial (Cook et al., 2012). Transmissivity can be easily determined from a sedimentary log as it is directly proportional to the hydraulic conductivity and thickness of an aquifer (Fetter, 2001):

\[
T_i = K_i d_i
\]  

Where layer transmissivity \( T_i \) of \( i \)th soil unit is equal to the product of the saturated thickness \( d_i \) and hydraulic conductivity \( T_i \). Since the sedimentology of the floodplain is often complex (Johnston and Brierley, 2006), transmissivity needs to be calculated for each individual bed in the aquifer. For aquifers with multiple layers of varying composition, total aquifer transmissivity can be calculated using the following equation:

\[
T_t = \sum T_i
\]  

Where \( T_t \) is equal to the summation of all layers \( i = 1, 2, 3 \ldots, n \). Since Mulloon Creek is located in a temperate climate with relatively low precipitation (Bureau of Meteorology, 2017), the prevailing flow configuration will likely be a water table below the river stage or even below the base of the channel (Stephens, 1995). When the aquifer head is below the elevation of the channel base, channel seepage is the dominant source of recharge (Stephens, 1995). If the aquifer head is more than twice the width of the stream below the channel stage, seepage from aquifer to stream will be very limited (Bouwer and Maddock, 1997). Figure 4 illustrates the different potential stream configurations. Since Mulloon Creek has incised, the
river stage in sections may be relatively low set in comparison to the floodplain, therefore localized changes in configuration may occur.

Figure 4 – Stream-aquifer configurations. Taken from Winter et al. (1998)

2.6 ALLUVIAL AQUIFERS

Channel incision typically lowers the level of the alluvial water table, because the head elevation of the channel determines the depth to which groundwater drains (Schilling et al., 2006, Darby and Simon, 1999). The magnitude of water table lowering will be extend further from the channel in coarse grained deposits than in it will in fine grained deposits which have a lower permeability (Darby and Simon, 1999). If a substantial amount of recharge comes from the hillslope or tributaries, the lowering of the alluvial water table may be less pronounced.

The alluvial water table reflects the assemblage of floodplain deposits (Bridge, 2003). Floodplain deposits are composed of discretely formed sedimentological units that range from a millimetre to a decimetre thick, with varying quantities of fine to very fine sand, silt and clay (Anderson et al., 1996). The differing hydraulic conductivity of these units creates a water table surface that is quite irregular across the floodplain (Bridge, 2003). A reflection of
the ground topography in the water table is more pronounced in silt and clay rich, rather than coarse grained aquifers (Bridge, 2003). The type and distribution of floodplain deposits varies depending on energy and sediment supply. Generally, coarse gravel is found in the channel, sand and finer gravel form levees along the channel margins, and the finest material is situated further out on the floodplain (Fetter, 2001). Deposit shape may be lenticular, sheet-like or wedged shaped; and upward-fining or coarsening (Bridge, 2003). If a river is meandering, floodplain alluvium will be reworked and the distribution of deposition will change, resulting in a thicker and more complex floodplain (Anderson et al., 1996).

The flow dynamic across various floodplain units is illustrated in Figure 5, taken from (Anderson et al., 1996). The letter ‘A’ represents the sand and gravel units near to the channel. This area is well drained due a high hydraulic conductivity and gradient. ‘D’ signifies levees and intermediate floodplain flats. Groundwater flow may vary in this location due to stream meander or deposition of overbank deposits. ‘C’ shows flow away from the stream towards a backswamp environment confined to the floodplain margin. Finally, ‘D’ shows the leakage from a dam elevated above the water table.

Alluvial aquifers may be either separate or part of regional groundwater processes (Fetter, 2001). Recharge of alluvial aquifers in semiarid and arid regions may occur by way of flow from bedrock on the valley sides.
There has been little research demonstrating the raising of alluvial water tables by way of restoration induced stream-stage increases (Dobes et al., 2013, DeBano and Schmidt, 1987). However, the mechanism at work is well understood due to the similarity it shares with process of bank storage, a topic that have been extensively studied by hydrologists interested in the short-term flooding response of the stream-aquifer system.

Bank storage is the phenomenon whereby the hydraulic gradient in gaining streams is reversed during storm events due to a rise in stream water level in response to increased runoff (Rassam and Werner, 2008). New water flux is induced into the alluvial aquifer and released slowly back into the stream as the stream level returns back to low-flow conditions.

Rassam and Werner (2008) identify three conditions that are most important for bank storage to occur. Firstly, the stream must be subject to stage increase. Downstream reaches have larger catchments areas and are therefore more likely to produce flood peaks that induce bank storage (Kondolf et al., 1987). This factor is less important to the study of bank storage around artificially induced stream level rises.

The second condition for maximizing bank storage is the availability of highly hydraulically conductive bank material. Since coarse grain material has the highest hydraulic conductivity (Clapp and Hornberger, 1978), bank storage is most favourable in the alluvial fill of high-gradient straight-braided streams and those dominated by deposition during infrequent flooding events (Kondolf et al., 1987). The lithology of the watershed will also influence bank storage because different rocks weather to produce alluvium of varying grain size and hydraulic conductivity, i.e. bank storage is more likely in granite rather than shale terrane (Rassam and Werner, 2008). The hydraulic conductivity of bank material intern affects the bank storage drainage duration. In gravel banks the response between stream water level drop may occur over a period of days, while in sands it could take weeks and clays it may take decades (Rassam and Werner, 2008).

The third condition is for permeable bank and floodplain material to occur in a sufficient volume for storage, although Pinder and Sauer (1971) found that the hydraulic conductivity of the bank material is more important to bank storage than the volume of the alluvial aquifer.
This is because majority of the baseflow recharge is concentrated near the stream bank (Todd, 1955)

Bank storage is primarily a process of flood hydrology. Determining the role of bank storage in low flow hydrology is less straight-forward (Smakhtin, 2001). Although low flow conditions may be present along most of a stream, the processes of bank storage are synonymous to those occurring around a weir because a weir artificially reconfigures that stream reach with flood hydrology conditions. Bank storage normally attenuates flood peaks (Smakhtin, 2001), so a weir will attenuate low flow conditions.
CHAPTER 3 - REGIONAL SETTING

3.1 LOCATION

Mulloon Creek is headwater tributary in the Upper Shoalhaven River catchment, located in NSW approximately 40 km east of Canberra (Figure 6). Mulloon Creek flows northward from Tallaganda National Park along the eastern margin of the continental divide. It drains an area of 400 km$^2$ before joining the Shoalhaven River system and eventually flowing into the Pacific Ocean 90 km to the east. Mulloon Creek itself is composed of a series of discontinuous, bedrock confined floodplain pockets (Johnston and Brierley, 2006). The two floodplain pocket study sites, Home Farm and Lower Mulloon, occupy a 19 km reach of Mulloon Creek.

![Figure 6 – Mulloon Creek regional setting. Taken from Dobes et al. (2013).](image-url)
Home Farm is the name of the property at the upstream floodplain pocket (Figure 7). It contains a six kilometre reach of Mulloon Creek, but only 2.5 km this reach has developed a floodplain. The floodplain has a maximum width of 300 m and an area of approximately 1,020,000 m². It is the site of the NSF pilot project. The 22 installed leaky-weirs and 17 monitoring piezometers are shown in Figure 7.

Figure 7 - Home Farm with locations of leaky-weirs and piezometers
Lower Mulloon is the name of a downstream floodplain pocket that contains 11.5 km of Mulloon Creek (Figure 8). The floodplain pocket is significantly larger than Home Farm, with a maximum width of over 1 km. The pocket is almost severed into two sections by bedrock confining outcrop near the crossing of the Kings Highway. There are a total of 29 piezometers crossing Mulloon Creek in three transects.

Figure 8 - Lower Mulloon with piezometers location.
3.2 CLIMATE AND HYDROLOGY

The area experiences a temperate, subhumid to humid climate (Johnston and Brierley, 2006). The nearest weather station with a long term climatic record is at Braidwood, located 25 km to the southwest.

A rainfall record (1880-2017) from Bungendore Post Office (070011) located 14 km to the west show that the catchment area has a mean annual rainfall of 600 mm (Figure 9) (Meteorology., 2017). A climate record (1985-2017) at Braidwood Racecourse AWS (069132) located 20 km to the east, shows that seasonal rainfall is greatest in the summer months (Figure 10) (Bureau of Meteorology, 2017).

The temperature record at Braidwood Racecourse AWS (Appendix 1) shows that the area has a monthly mean maximum temperature range of 26.8 °C in January and 12.0 °C in July and a monthly minimum temperature range of 12.3 °C in January and 0.1 °C in July (Bureau of Meteorology, 2017). The two study sites of are sufficient proximity to each other (2 km) to assume that they have identical climates.
Figure 10 – Mean monthly rainfall at Braidwood Racecourse AWS. Taken from Bureau of Meteorology (2017).

3.3 GEOLOGY, LANDUSE AND SOILS

The Mulloon Creek subcatchment occupies the south-eastern section of the disturbed Ordovician to Devonian metasediments and granites of the Lachlan Fold Belt (Figure 11) (Fitzherbert et al., 2011). The complexity of folds, faults and lithology has resulted in accumulation of alluvium in a series of confined floodplain pockets that occur along the length of Mulloon Creek (Johnston and Brierley, 2006). The Home Farm and the Lower Mulloon are two such pockets. These sites were dramatically altered for agricultural purposes from the 1820s (Johnston and Brierley, 2006). While there has been regrowth on the hillslopes, both floodplain pockets have remained cleared for grazing ever since.
At Home Farm, a pocket of quaternary alluvium exists predominately on the western bank of Mulloon Creek in a valley confined on either side by Silurian aged metasediments of the Lachlan Fold Belt. Limestone lenses outcrop irregularly on both hillsides within the interbedded quart sandstone, siltstone and shale of the Adaminaby and Mount Fairy Group (Fitzherbert et al., 2011). The stream is constricted by the sedimentary bedrock of the Mount Fairy Group at the upstream and downstream ends of the Home Farm floodplain pocket.

The thickness of floodplain alluvium decreases from eight meters at the top of the pocket to two meters at the bottom (Johnston and Brierley, 2006). As the soil profile thins downstream, fine grained swamp deposits become more prominent than the fining upwards sequences of overbank deposits generally found in the upper half of the floodplain pocket (Johnston and

Figure 11 – Mulloon Creek geology and soil maps. Using Fitzherbert et al. (2011), Jenkins (1996).
Brierley, 2006). Paleo channel deposits in the mid-pocket indicate that the stream was once a sequence of discontinuous water courses that drained into the swamps downstream, before rejoining the confined main channel (Johnston and Brierley, 2006). Swamps are still present on the western edges of the floodplain. A half meter thick layer of post incisional alluvium overlies the floodplain material in the lower half of the floodplain pocket (Johnston and Brierley, 2006).

![Figure 12 – Home Farm floodplain pocket morphology. Taken from Johnston and Brierley (2006).](image)

The Lower Mulloon contains a much longer reach of Mulloon Creek than the Home Farm and as such the floodplain pocket occupies a much larger area between its confined end
points. Whereas the Home Farm floodplain pocket sits within a valley confined by metasediments, the Lower Mulloon reach straddles the Devonian granites of the Bega Batholith on the eastern side, while younger metasediments occur on the western side.

Figure 13 – Lower Mulloon floodplain pocket south morphology. Taken from Johnston and Brierley (2006).

The Lower Mulloon floodplain pocket south of the Kings Highway is roughly 3 km long. Floodplain material in bank exposures has an average depth of 3 m to bedrock, but the depth to bedrock is much deeper further from the stream on the western bank, where the floodplain predominately occurs. In the downstream section the soil proximal to the stream comprises of fining upwards sequences of floodplain material, while in the upstream proximal section near the Kings Highway the soil is dominated by sediment from a drained paleo swamp. The
floodplain material particularly on the western valley margins is overlain by terraces, sediment fans and aeolian sand dunes. Scour features are scattered across the west bank floodplain.

Figure 14 - Lower Mulloon floodplain pocket north morphology. Taken from Johnston and Brierley (2006)

Another large swamp deposit is found downstream of the Kings Highway. The thickness of the floodplain material in bank exposures is roughly 2 m and decreases downstream while the thickness of the overlying post incisional alluvium increases to a thickness of 1 m at a point.
4.5 km downstream. Sediment fans line the western valley margin and paleo channels are most numerous along the eastern valley margin.

### 3.4 HYDROGEOLOGY

Although this study is confined to looking alluvial flow dynamics, it is important to define the regional hydrogeological setting, as hard rock recharge may still be a significant component of the alluvial groundwater system (Anderson et al., 1996).

The hydrogeology of the region is broadly defined as a granite that forms a fractured or fissured, extensive aquifer of low-moderate productivity (Lau et al., 2015). Figure 11 can be used to more accurately define the hydrogeology of each site. The dominate lithology at the Home Farm is the sandstone of the Mount Fairy Formation (Fitzherbert et al., 2011). The Lower Mulloon is confined to the granodiorite boundary of the Bega Batholith (Fitzherbert et al., 2011). This formation is more indicative of the aquifer type described by Lau et al. (2015). A diamond core taken from eastern floodplain at Lower Mulloon Transect (Figure 15 and Figure 16) confirms the existence of this fractured granite aquifer.

No coring of the sandstone bedrock was completed at Home Farm. The aquifer is likely much more productive than the description of ‘low-moderate’ given by Lau et al. (2015) when it was classified as granite.
Figure 15 – Bega Batholith core photo 1.

Figure 16– Bega Batholith core photo 2.
CHAPTER 4 – METHODOLOGY

The methodology was selected to overcome the projects unique data limitations, but also to remain as similar in approach to the commonly used methods as possible, so that the results are applicable to the limited amount of work completed on NSF. The temporality and quality of each dataset is shown in Appendix 4.

4.1 HISTORICAL ANALYSIS

Piezometers have existed at Home farm since 2006, but the vast majority were not installed until late 2009. Since the piezometers have to be manually sampled, the recording intervals are sporadic. At best the recordings are monthly, but this is not always the case. Therefore, there is no logical way to analyze the data on a regular time-series. However, it is evident when the data is represented as a time-series (Figure 20) that there are two main groupings of data points.

The historical dataset was grouped into two periods for analysis. The ‘early period’ constitutes all measurements made from 01/12/09 to 15/08/12. The ‘late period’ constitutes all measurements made from 06/12/13 to 13/09/16. The corresponding rainfall during each period is also compared using data from Bungendore Post Office BOM station number 70011, located 14 km away from Mulloon Creek, at a similar altitude. It is not the closest BOM weather station to Mulloon Creek, but it does have the most complete and quality controlled climate record of all the weather stations within a 19 km radius.

Both the rainfall trends and totals and totals during the periods were analysed. Monthly rain totals was analysed using the Mann-Kendall test and linear regressions. Monthly rainfall was selected because this resolution is the nearest match to the resolution of piezometer dataset. Daily rainfall was used for the aggregation because the periods do not end coincide with the start of the months.

An analysis of variance (ANOVA) was ultimately used to test for a significant change in groundwater measurements between the early and late periods. All of the statistical analysis was done using the program R.
4.2 FIELDWORK

The fieldwork component of the project involved three main components: soil sampling, piezometer installation and groundwater sampling. It was conducted from November 2016 to January 2017, with the soil sampling and piezometer installation occurring concurrently in a three week block in late 2016.

Soil sampling

Soil was sampled whilst drilling holes for the 34 new piezometers. Samples were collected at every observed change in soil horizon or texture. Additional samples were collected at every half metre when no change occurred. Descriptions of the samples were recorded in NSW Soil Conservation Service ‘Soil Data System’ cards. The raw soil data was made available on the eSPADE soil data library (State of NSW and Office of Environment and Heritage, 2017)

In field descriptions recorded in the data cards included: site description, boundary depths, horizons texture, pH, organics, soil colour, mottles and mottle colour. A photograph of the procedure can be seen in Figure 17. The samples were bagged then sent away for weighing and drying, completion of the soil cards and put into storage for further analysis.
Figure 17 – Soil sampling station.

A Drilltech 550 rig was used to bore the holes. An augur was used to extract soil from depths of up to approximately 10 m. When the drilling was more stubborn or when installing piezometers at a depth greater than 10 m, mud rotary drilling with a rock roller bit was used. A spade was used to extract a block of top soil to classify the upper horizon and ground surface. The drill operator would then descend to 0.5 m which will in most cases identify the lower boundary of the upper soil horizon. To sample from the augur, the bit was raised to the surface and soil was removed from the augur. Often the outside of the sample was contaminated with soil from the hole walls during extraction, so care was taken in selecting the most representative sample for the recorded depth. It was important to be mindful that the auguring mechanism results in compaction of the soil sample, which does marginally alter the texture of soil, particularly for clays. The compaction will prohibit any bulk density analysis on the samples.

When mud rotary drilling, the recirculated crushed up mud was collected before entering the separation tank. First hand analysis of the material was difficult due to the disturbance, but it was bagged for further geochemical analysis. It was possible to differentiate between drilling through sand or clay when in alluvial units, or between sandstone and granite when drilling into hard rock. But accurately determining the original depth of the material was problematic because of the lag between abrasion at the drill bit and arrival at the surface. For these reasons, the sedimentary detail in the deep holes is poor.

**Piezometer installation**

The piezometers were installed in transects running perpendicular to Mulloon Creek to observe groundwater flow between the floodplain aquifer and stream water, as well as flows down the valley slope into the floodplain. This should show the groundwater flow dynamics across the entire width of the alluvial system.

Both shallow and nested sets of deep piezometers were installed. The shallow piezometers were designed to monitor the water table; the upper most saturated boundary that occurs where the pressure head and atmospheric pressure are equal. The surface of the water table was detected by the withdrawal of a saturated augur bit, as show in in Figure 18. Care was taken to identify potentially impermeable layers that are perching or confining additional deeper aquifers.
The most crucial part of the process is selecting the depth of the piezometer screen, as this will determine the aquifer depth that contributes water to the piezometer. The screening selection of a shallow piezometer is a balance between targeting only the upper unconfined aquifer and installing a piezometer that is deep enough to capture the water levels that occur during the majority of flow conditions. Four of the piezometers that were installed were to replace ones at Home Farm that were installed too shallow and typically dry, which will hinder water sampling and chemical analysis.

A 75 mm piezometer casing was installed into the hole. The screened depth was backfilled with sand and the top was plugged with bentonite to prevent seepage into the screen. A concrete monument was added to protect the equipment from cattle.

Figure 18- Saturated auger removal.

**Groundwater and stream water sampling**

Groundwater temperature, level and electronic conductivity were measured at each piezometer using a Solinst TLC. Temperature and EC was recorded at 1 m below the surface of the water in the well. The Lower Mulloon piezometers were sampled on 03/12/16, 14/12/16 and 10/01/17. Stream water EC and the Home Farm piezometers were also sampled on 10/01/17.

Ground surface elevation was determined using a Navmen GPS unit with 6 m accuracy. When not labelled, all elevation measurements are m AHD. Many of the piezometers lie on flat ground at a very similar elevation, often only tens of meters apart. These piezometers were assumed to have the same elevation. To overcome inaccuracy, the elevation recorded
with the GPS was averaged with values interpolated from a 30 m DEM to give the final value. The Mulloon Institute is completing more accurate surveying of the new Lower Mulloon piezometers later in 2017.

The final elevation results used in this project are sufficient to show the relative difference in elevation between the main landscape features in each transect. Using these values, the elevation gradient between hillslope, piedmont, floodplain and bank piezometers is recognisable.

There are no stream gauges with reliable datasets at any of the piezometer transects. Stream water level was estimated at Home Farm using the gradient of a longitudinal survey of Mulloon Creek completed by Johnston and Brierley (2006) (Appendix 7) and the known elevation of a stream gauge at the base of the Home Farm pocket. The water level is said to be the same in both historical periods, which acts as a control variable. The Lower Mulloon stream water level was estimated using an average channel incision of 2.5 m, which was surveyed by Johnston and Brierley (2006). The values were obtained by subtracting 2.5 m from the elevation of the near stream floodplain surface. The inherent error in these estimations is why this project contains a large qualitative component.

**4.3 GROUNDWATER-SURFACE WATER CONNECTIVITY**

Groundwater-surface water connectivity is assessed by estimating baseflow between the stream and the alluvial aquifer. The hydraulic gradient analysis method described by Rassam and Werner (2008) is used. Where flow is calculated using Equation 1, layer transmissivity is calculated using Equation 2 and total aquifer transmissivity is calculated using Equation 3.

Groundwater-surface water connectivity between the stream and alluvial aquifer is also illustrated graphically by plotting aquifer head and stream levels in cross section. A line of best fit that passes through these points is added to represent the theoretical water table. Since there is no sedimentology data for the historical Home Farm piezometers, flows in the historical period could not usually be determined. But using the water line of best fit, the historical level in the new piezometers that do have sedimentary logs can be extrapolated. Groundwater and stream EC measurements are also plotted to highlight areas of groundwater chemistry flux in the potential hyporheic zone.
4.4 ALLUVIAL AQUIFER CLASSIFICATION

A substantial amount of data was gathered about the soil profile at each bore hole. In order to assess the influence of aquifer properties on groundwater flow, the data had to be classified and reduced into a comparable format. Hydraulic conductivity is the physical property that is most utilized when studying groundwater flow (Rassam and Werner, 2008). A method was devised that attempts to classify the vast amount of soil data into qualitative groups that are representative of different hydraulic conductivity values.

Hydraulic conductivity is a function of a variety of material properties (Fetter, 2001). Soil hydraulic conductivity can be determined using pedotransfer functions, an empirically derived approach that uses soil properties, such as grain size and bulk density to estimate hydraulic conductivity (Zou et al., 2016). Since the drilling operation resulted in the soil sampling to occur at a fast pace, in a large volume and then result in offsite storage, laboratory grain size analysis was not conducted.

However, pedotransfer functions that estimate hydraulic conductivity purely from field texture descriptions are available (Børgesen et al., 2008) A classification issue arises when using pedotransfer functions, as the function can only be applied to a given soil texture classification system. A published pedotransfer function could not be found that relates to the classification system used in the NSW Soil Conservation Service soil data cards.

Ignoring the peat class which was not encountered, the system has 13 different textural grades; 20 if including grain size descriptions. A lumping approach was used to overcome the issue. Lumpng will result in a loss of fine detail, but will make it easier to identify the major alluvial units in a soil profile.

The 20 different textural grades that were employed to describe the soil samples are shown in Table 2. The textural classes were lumped into three categories: sand, loam or clay. The corresponding lumped texture is shown in the second column of Error! Reference source not found. To classify each lumped texture with a hydraulic conductivity, a pedotransfer function derived empirically for each lumped group by Clapp and Hornberger (1978) was used. The
value of saturated hydraulic conductivity assigned to each lumped group is show on column 3.

<table>
<thead>
<tr>
<th>Texture grade</th>
<th>Lumped texture</th>
<th>Saturated hydraulic conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>sandy clay</td>
<td>clay</td>
<td>$4.05 \times 10^1 \text{ m/year}$</td>
</tr>
<tr>
<td>silty clay</td>
<td>clay</td>
<td>$4.05 \times 10^1 \text{ m/year}$</td>
</tr>
<tr>
<td>clay</td>
<td>clay</td>
<td>$4.05 \times 10^1 \text{ m/year}$</td>
</tr>
<tr>
<td>sandy loam</td>
<td>loam</td>
<td>$2.19 \times 10^2 \text{ m/year}$</td>
</tr>
<tr>
<td>silty loam</td>
<td>loam</td>
<td>$2.19 \times 10^2 \text{ m/year}$</td>
</tr>
<tr>
<td>sandy clay loam</td>
<td>loam</td>
<td>$2.19 \times 10^2 \text{ m/year}$</td>
</tr>
<tr>
<td>clay loam</td>
<td>loam</td>
<td>$2.19 \times 10^2 \text{ m/year}$</td>
</tr>
<tr>
<td>clay loam sandy</td>
<td>loam</td>
<td>$2.19 \times 10^2 \text{ m/year}$</td>
</tr>
<tr>
<td>silty clay loam</td>
<td>loam</td>
<td>$2.19 \times 10^2 \text{ m/year}$</td>
</tr>
<tr>
<td>sand</td>
<td>sand</td>
<td>$5.55 \times 10^3 \text{ m/year}$</td>
</tr>
<tr>
<td>loamy sand</td>
<td>sand</td>
<td>$5.55 \times 10^3 \text{ m/year}$</td>
</tr>
<tr>
<td>clayey sand</td>
<td>sand</td>
<td>$5.55 \times 10^3 \text{ m/year}$</td>
</tr>
<tr>
<td>loamy sand</td>
<td>sand</td>
<td>$5.55 \times 10^3 \text{ m/year}$</td>
</tr>
</tbody>
</table>

Aquifer properties such as: thickness, saturated thickness, percentage saturated, confinement, dominate lithology and pressure; can be determined by looking at the relationship between the textural units, water table level and piezometer screen depth. An aquifer classification system was devised that employs the logic of a decision tree. The steps of the decision tree are shown in Figure 19.
Figure 19 – Aquifer classification decision tree.
CHAPTER 5 – RESULTS

5.1 HISTORICAL RECORD

Piezometer record

The historical hydrogeological response at Home Farm was analysed using a network of 14 piezometers. To overcome sampling irregularities, the record was split into two periods, ‘early’ and ‘late’ to allow for the assessment of change over the monitoring period. A time-series of all piezometers depth recordings available, categorized into the periods is shown in Figure 20.
Figure 20- Home Farm piezometers record and historical periods.
Rainfall Trends
To assess the significance of climatic variation over the course of the sampling periods, an analysis of precipitation was undertaken. A significance level of 0.05 is used. The non-parametric Mann-Kendall test and a linear regression were used to test the hydrological data. Auto-correlation plots for each dataset is contained Appendix 2. The results of both tests over each recording periods will be discussed.

Monthly precipitation at Bungendore Post Office over the entire piezometer recording period is shown in Figure 21. The results summarized in Table 3 show that the linear model has a p-value that indicates that there is no significant correlation between time and rainfall. Similarly, the Mann-Kendall’s 2-sided p-value greater than 0.05, indicates that the null-hypothesis of monthly precipitation belonging to a population of independent realizations that are identically distributed, cannot be rejected. There is no significant trend in the rainfall series, therefore it is inferred that the climatic influence over the entire piezometer recording period is negligible.
Figure 21 – Entire period rainfall analysis.

Table 3 – Entire period rainfall analysis.

<table>
<thead>
<tr>
<th>Mann-Kendall</th>
<th>Linear Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>-211</td>
</tr>
<tr>
<td>Var(Score)</td>
<td>60117</td>
</tr>
<tr>
<td>Denominator</td>
<td>3238.5</td>
</tr>
<tr>
<td>Tau</td>
<td>-0.0652</td>
</tr>
<tr>
<td>2-sided p-value</td>
<td>0.39173</td>
</tr>
</tbody>
</table>

The early period was extracted from the monthly precipitation dataset and the results are illustrated in Figure 22 and tabulated in Table 4. There is no significance to the downward trend identified by either the linear regression or the Mann-Kendall test. The null-hypothesis cannot be rejected in both tests.

![Rainfall over early period](image)

Figure 22 – Early period rainfall analysis

Table 4 – Early period rainfall analysis

<table>
<thead>
<tr>
<th>Mann-Kendall</th>
<th>Linear Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>-33</td>
</tr>
<tr>
<td>Var(Score)</td>
<td>697</td>
</tr>
</tbody>
</table>
A similar result is found across the late period, with no significant trend identified. Figure 23 and Table 5 show the tests of the testing.

Figure 23 – Late period rainfall analysis

Table 5 – Late period rainfall analysis.

<table>
<thead>
<tr>
<th>Mann-Kendall</th>
<th>Linear Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Score</td>
<td>81</td>
</tr>
<tr>
<td>Var(Score)</td>
<td>14289.67</td>
</tr>
<tr>
<td>Denominator</td>
<td>1224</td>
</tr>
<tr>
<td>Tau</td>
<td>0.0662</td>
</tr>
<tr>
<td>2-sided p-value</td>
<td>0.50335</td>
</tr>
</tbody>
</table>
Rainfall Totals

Daily rainfall totals from Bungendore PO was aggregated for each period. The results are shown in Table 6. The late period is nearly three times as long as the early period, but has only roughly twice the amount of rainfall. Thus, rainfall intensity is actually higher in the early period than in the late period.

Table 6 – Historical period monthly rainfall totals.

<table>
<thead>
<tr>
<th>Early period</th>
<th>Late period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days</td>
<td>Days</td>
</tr>
<tr>
<td>547 days</td>
<td>1479 days</td>
</tr>
<tr>
<td>Rainfall total</td>
<td>Rainfall total</td>
</tr>
<tr>
<td>1271 mm</td>
<td>2667 mm</td>
</tr>
<tr>
<td>Rainfall intensity</td>
<td>Rainfall intensity</td>
</tr>
<tr>
<td>2.3 mm/day</td>
<td>1.8 mm/day</td>
</tr>
</tbody>
</table>
Summary
The comparison between the early and late periods is assessed using two metrics: groundwater elevation and groundwater depth below the surface. These two metrics are plotted in Figure 24 and Figure 25. The box and whisker plots show that groundwater is on average at a higher elevation and also closer to the surface in the late period compared to the earlier period. Highly raised water levels are abundant as outliers in the elevation plot, but both plots generally have the same shape apart from the late period having a higher minimum. The subtle difference between the two periods is more evident in Table 7.

Table 7 – Summary of historical piezometers measurements.

<table>
<thead>
<tr>
<th>Early Period</th>
<th>Late Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean elevation (m)</td>
<td>728.49</td>
</tr>
<tr>
<td>Elevation StDev.S (m)</td>
<td>2.60</td>
</tr>
<tr>
<td>Elevation Var.S (m)</td>
<td>6.78</td>
</tr>
<tr>
<td>Mean depth (m)</td>
<td>2.10</td>
</tr>
<tr>
<td>Depth std dev (m)</td>
<td>0.73</td>
</tr>
<tr>
<td>Depth variance (m)</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>Mean elevation (m)</td>
</tr>
<tr>
<td></td>
<td>Elevation StDev.S (m)</td>
</tr>
<tr>
<td></td>
<td>Elevation Var.S (m)</td>
</tr>
<tr>
<td></td>
<td>Mean depth (m)</td>
</tr>
<tr>
<td></td>
<td>Depth std dev (m)</td>
</tr>
<tr>
<td></td>
<td>Depth variance (m)</td>
</tr>
</tbody>
</table>

Groundwater in the late period has a mean elevation 0.22 m higher than in the early period. The late period is also characterized by lower variance and standard deviation within the samples. Although the groundwater is on average 0.37 m closer to the surface in the late period, the variance and standard deviation in the late period is higher than the early period. Using these values, the amount of water in the floodplain aquifers can be estimated. Table 7 shows that the saturated volume of the floodplain aquifer has increased by 10.57% from the early period to the late period, with the floodplain carrying an extra 376,639 Ml of water.

An analysis of variance (ANOVA) was ultimately used to determine whether or not the change between the early and late period is significant. Depth to water table measurements were used as this has the least amount of sampling bias. The results from the ANOVA are shown in Table 8. A p-value of 0.0001072 means that the null-hypothesis (both periods have the same mean value) is rejected. The change between the early and late period is of statistical significance. The Shapiro-Wilk and Levene’s test indicate that that datasets are normally distributed and possess no significant statistical difference in variance. The histogram, scale-location, Q-Q plot and residual plot for the tested data is contained in Appendix 3.
Table 8 – ANOVA for historical piezometer record.

**ANOVA for depth below surface: Early vs Late period**

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>P-value</strong></td>
<td>0.0001072</td>
</tr>
<tr>
<td><strong>F-value</strong></td>
<td>15.492</td>
</tr>
<tr>
<td><strong>Shapiro-Wilk Test P-value</strong></td>
<td>0.07444</td>
</tr>
<tr>
<td><strong>Levene's Test P-value</strong></td>
<td>0.8041</td>
</tr>
</tbody>
</table>

Figure 24 – Historical groundwater elevation: box and whisker.
Figure 25 - Historical depth to water table: box and whisker.
5.2 HOME FARM

Introduction
The following section will present the magnitude of alluvial groundwater flow calculated at each site, so that the relationship between the stream water and groundwater can be defined. The sedimentology of the site will be described. The influence of sedimentology on aquifer properties and groundwater flow patterns will also be theorized. The sites will be described in downstream succession.

The sedimentary logs from the 13 historical Home Farm piezometers cannot be found by The Mulloon Institute. The analysis of aquifer properties has therefore been limited in sedimentary resource to the four new piezometers installed at Home Farm in December 2016 which were designed to replace existing dry piezometers. A supplementary resource is the work by Johnston and Brierley (2006). A single new piezometer is located at each of the three Home Farm transects. All of the piezometers at Home Farm are characterised as shallow floodplain piezometers. The groundwater flow magnitudes are found in Appendix 5 and the aquifer properties are in Appendix 6.

Connectivity
A cross section and plan form of Home Farm Transect 1 is shown in Figure 26 and the plotted data is presented in Table 9. This transect is made up of seven piezometers and is the most upstream transect at Home Farm. Bore Hole 11 has been excluded from the analysis as the dataset contains an error where the water table elevation exceeds the surface elevation. Bore Hole 8a (BH8a) is the newly installed piezometer. A line of best fit representing the hypothetical water table during each period and groundwater EC measurements taken in January 2017 have been added to the plot. A plot of each two periods with corresponding error bars is in Appendix 9.

Table 9 – Home Farm Transect 1 piezometers measurements.

<table>
<thead>
<tr>
<th>Piezometer</th>
<th>Surface</th>
<th>Early</th>
<th>Late</th>
<th>Distance</th>
<th>Early</th>
<th>Late</th>
<th>EC</th>
<th>Hole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>elevation</td>
<td>water elevation</td>
<td>from stream</td>
<td>depth below</td>
<td>depth below</td>
<td>Jan 17</td>
<td>depth</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-----------</td>
<td>----------------</td>
<td>-------------</td>
<td>-------------</td>
<td>-------------</td>
<td>--------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>BH12</td>
<td>732.5 m</td>
<td>729.9 m</td>
<td>730.6 m</td>
<td>79.5 m</td>
<td>2.6</td>
<td>2.6 m</td>
<td>146 uS/cm</td>
<td>3.56 m</td>
</tr>
<tr>
<td>BH8</td>
<td>732.6 m</td>
<td>Dry</td>
<td>729.7 m</td>
<td>28.7 m</td>
<td>-</td>
<td>2.9 m</td>
<td>Dry</td>
<td>3.22 m</td>
</tr>
<tr>
<td>BH8a*</td>
<td>732.6 m</td>
<td>729.8 m</td>
<td>729.2 m</td>
<td>35.4 m</td>
<td>2.8 m</td>
<td>3.4 m</td>
<td>372 uS/cm</td>
<td>5.00 m</td>
</tr>
<tr>
<td>BH9</td>
<td>732.6 m</td>
<td>729.8 m</td>
<td>730.3 m</td>
<td>82.6 m</td>
<td>2.8 m</td>
<td>2.3 m</td>
<td>245 uS/cm</td>
<td>3.37 m</td>
</tr>
<tr>
<td>BH10</td>
<td>732.2 m</td>
<td>729.4 m</td>
<td>729.8 m</td>
<td>127.4 m</td>
<td>2.8 m</td>
<td>2.4 m</td>
<td>165 uS/cm</td>
<td>3.96 m</td>
</tr>
<tr>
<td>BH11</td>
<td>732.3 m</td>
<td>734.7 m</td>
<td>734.1 m</td>
<td>186.4 m</td>
<td>error</td>
<td>error</td>
<td>256 uS/cm</td>
<td>3.60 m</td>
</tr>
</tbody>
</table>

Stream water elevation = 729.0 m
Stream EC = 120 uS/cm

Figure 26 – Home Farm Transect 1 cross section and plan form.

The positive flow magnitudes in Appendix 5 reinforce what is evident in Figure 26 - this stream reach is gaining. It is also apparent that the water table is nearest to the surface in the late period, a configuration that has resulted in a larger hydraulic gradient between stream and groundwater. This effect of this gradient is evident in the magnitude of flow towards the stream from BH8a. A flow of 0.09 m²/year occurs in the early period, while 0.38 m²/year occurs in the late period.
Appendix 8 shows that there is no considerable linear correlation in either period between depth to the water table and proximity to the stream. However, the EC groundwater measurements taken in January 2017 do exhibit this trend.

**Floodplain sedimentology**

The sedimentary log of BH8a and proximal log completed by Johnston and Brierley (2006) is shown in Figure 27. The surface of the floodplain at BH8a is covered in 0.5 m of post incisional alluvium which is of a loamy texture, identified by Johnston and Brierley (2006) to be of a very small grain size. A clay unit occurs at depths of 1.5-3.5 m, which correlates to a sequence of fining upward floodplain sediments (Johnston and Brierley, 2006). The clay rich floodplain sediments overlie a coarse grained unit which is approximately 1 m thick, identified as a sand unit in the drill log and a gravel lag deposit by Johnston and Brierley (2006). The similarities in the two sedimentary logs discontinue below the course grained unit. Another clay unit extending down to 5.5 m is recognized in the BH8a, whereas bedrock is found at 4.5 m in MC1 (Johnston and Brierley, 2006). The thicknesses of the soil profile likely differ due to their relative proximities to the stream. MC1 is located within the macrochannel, whereas BH8a is 35.4 m from the stream. The bedrock at MC1 may well be boulder sized bedload material carried by the stream, rather than the marginally deeper bedrock-based channel substrate.

**Alluvial groundwater flow**

The properties of the BH8a aquifer are listed in Appendix 6. The dominate aquifer unit is determined to be ‘clay’ due to the substantial length of screen that passes through a thick clay unit. The unit most likely facilitating alluvial groundwater flow is the 1 m thick sandy unit 3.5 m below the surface, but the four-fold increase in flow during the late period has occurred by the water table rising 0.6 m up into the clay unit above. Lateral flow of water is also likely to occur along the contact between the course grained gravel lag and the underlying bedrock.
Figure 27 – BH8a and MC1 sedimentary log. MC1 taken from Dobes et al. (2013).
Transect 2

Connectivity

Figure 28 presents the mid-pocket Transect 2 in the same manner. The water table periods can only be interpolated from three piezometers. The new piezometer is Bore Hole 5a (BH5a). The plotted data is presented in Table 10.

![Figure 28– Home Farm Transect 2 cross section and plan form.](image)

<table>
<thead>
<tr>
<th>Piezometer</th>
<th>Surface elevation</th>
<th>Early water elevation</th>
<th>Late water elevation</th>
<th>Dist. from stream</th>
<th>Early depth below</th>
<th>Late depth below</th>
<th>EC Jan 17</th>
<th>Hole depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH6</td>
<td>729.9 m</td>
<td>727.6 m</td>
<td>727.7 m</td>
<td>36.5 m</td>
<td>2.3 m</td>
<td>2.2 m</td>
<td>262 uS/cm</td>
<td>3.22 m</td>
</tr>
<tr>
<td>BH5</td>
<td>729.8 m</td>
<td>727.8 m</td>
<td>728.4 m</td>
<td>49.0 m</td>
<td>2.0 m</td>
<td>1.4 m</td>
<td>Dry</td>
<td>2.49 m</td>
</tr>
<tr>
<td>BH5a</td>
<td>729.8 m</td>
<td>727.8 m</td>
<td>728.4 m</td>
<td>51.0 m</td>
<td>2.0 m</td>
<td>1.4 m</td>
<td>600 uS/cm</td>
<td>4.50 m</td>
</tr>
<tr>
<td>BH4</td>
<td>729.8 m</td>
<td>727.7 m</td>
<td>728.3 m</td>
<td>96.0 m</td>
<td>2.1 m</td>
<td>1.5 m</td>
<td>600 uS/cm</td>
<td>3.52 m</td>
</tr>
</tbody>
</table>

Stream water elevation = 727.4 m
Steam water EC = 125 uS/cm

Again it is evident that the late period possesses a water table closer to the surface than during the early period, with positive, towards stream flows (Appendix 5). The magnitude of flow increases from 0.05 m²/year in the early period to 0.31 m²/year in the late period.
Appendix 8 shows that no considerable linear trends in depth or EC are found laterally across Transect 2. When the EC sampling was undertaken in Jan 2017, BH5 was dry.

**Floodplain sedimentology**
The BH5a sedimentary log and the next nearest bank exposure completed by Johnston and Brierley (2006) is shown in Figure 29. Top soil in the 0.5 m at the surface is a post incisional loam unit. Further clay and loam layers are found to a depth 1.5 m, which are identified as fine grain organics (Johnston and Brierley, 2006). At the 1 m mark, a thick course grain sand unit is present in BH5a but not in MC2. Beyond the depth of 2.5 m, two MC2 sequences of fining upward floodplain sediment layers likely comprise the clay unit that extends to a depth of 4.4 m in BH5a. Bedrock was not encountered in the BH5a, but was found in MC2 at 4.5 m.

**Alluvial groundwater flow**
The 2017 water level in BH5a occurs at roughly the boundary between a sand and clay unit. The likely aquifer unit is the lower clay layer; however the interpolated water table elevation in the historical period utilizes an upper the sandy unit. A 44% late period increase in saturated thickness into this sandy unit, results in a 520% increase in flow towards the stream. A thin gravel lag present at the base of MC2, may not be of sufficient cross sectional area to transmit flows across the alluvial aquifer. It may be releasing excess water into the clay unit above, encouraging flow up through a unit which is typically of low hydraulic conductivity. The water table may raise another 1.5 m above the lower clay unit before it is confined by the dry fine grain organic rich layer near the surface.
Figure 29 – BH5a and MC2 sedimentary log. MC2 taken from Dobes et al. (2013).
Transect 3

Connectivity

Figure 30 shows the two historical piezometers that are located on either side of the stream at Transect 3. Bore Hole 3a (BH3a) has been added to the western floodplain. The plotted data is presented in Table 11. Once again a water table increase is found, this time observable in detail on both sides of the stream.

![Figure 30– Home Farm Transect 3 cross section and plan form.](image)

<table>
<thead>
<tr>
<th>Piezometer</th>
<th>Surface elevation</th>
<th>Early water elevation</th>
<th>Late water elevation</th>
<th>Dist. from stream</th>
<th>Early depth below</th>
<th>Late depth below</th>
<th>EC Jan 17</th>
<th>Hole depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH13</td>
<td>727.9 m</td>
<td>Dry</td>
<td>726.9 m</td>
<td>132 m</td>
<td>1.0 m</td>
<td>315 uS/cm</td>
<td>2.79 m</td>
<td></td>
</tr>
<tr>
<td>BH7</td>
<td>727.7 m</td>
<td>726.3 m</td>
<td>726.6 m</td>
<td>84.6 m</td>
<td>1.4 m</td>
<td>483 uS/cm</td>
<td>2.70 m</td>
<td></td>
</tr>
<tr>
<td>BH3a*</td>
<td>728.9 m</td>
<td>727.0 m</td>
<td>727.5 m</td>
<td>105.1 m</td>
<td>1.4 m</td>
<td>310 uS/cm</td>
<td>4.50 m</td>
<td></td>
</tr>
<tr>
<td>BH3</td>
<td>728.9 m</td>
<td>726.9 m</td>
<td>727.4 m</td>
<td>47.3 m</td>
<td>2.0 m</td>
<td>507 uS/cm</td>
<td>2.58 m</td>
<td></td>
</tr>
<tr>
<td>BH2</td>
<td>729.1 m</td>
<td>727.5 m</td>
<td>727.4 m</td>
<td>188.7 m</td>
<td>1.6 m</td>
<td>-</td>
<td>2.73 m</td>
<td></td>
</tr>
</tbody>
</table>

Stream water elevation = 724.9 m
Steam water EC = 125 uS/cm

Bore Hole 13, located furthest to the east, was dry in the early period. The water table elevation was highest in the western floodplain, however in comparison to ground elevation; the water table in the eastern side is nearer to the surface. Appendix 8 shows that there are no considerable lateral linear trends in EC or water table depth. The highest magnitude flow at
Home Farm was found at BH3a, with a flow of 0.73 m²/year during the early period and a flow of 1.09 m²/year during the late period.

**Floodplain sedimentology**

In this low-pocket location, BH3a is composed of coarse grained material indicative of a paleochannel deposit. Figure 31 shows that this site is most analogous to the MC3 paleochannel exposure completed by Johnston and Brierley (2006) 100 meters upstream.

The topsoil at BH3a is composed of the same loamy post incisional material found at the other sites. This material has been of a fine grain composition elsewhere on the floodplain; however MC3 shows that the 0.5 m thick layer of post incisional alluvium found in this location is much coarser than what is found at MC2 and MC1. Unfortunately, the exposure only extends to a depth of 1.4 m. However, the drill log from BH3a shows that this coarse grained material extends further down to a depth of 4.4 m. This sand unit represents the substrate of the palaeochannel that once cut through the floodplain.

**Alluvial groundwater flow**

The aquifer of BH3a targets the water contained in the paleochannel deposit. In Jan 2017 only the lower half of the very thick sandy aquifer was saturated, but in the historical periods a much larger portion of the aquifer was saturated. This large saturated thickness of coarse material has facilitated the high magnitude flows that are found in this location. No impermeable or bedrock layer below the sand unit was found within an explored depth of 4.5 m. The clay unit found at the surface would usually confine the aquifer, but since Johnston and Brierley (2006) determined that the grain size of this layer was coarse, confinement is likely limited.

It is possible that paleochannel extends another 1 m below 4.5 m to roughly the base of the floodplain. Coarse grained alluvial deposits are typically well drained, so without a perching layer below, the large volume of water that would be expected to flow through the palaeochannel which may be occurring at a depth below the piezometer. In periods of high flow where water could reach the upper levels of the soil profile, fine grained organic material approximately 1 m below the surface would inhibit further rise.
Figure 31 – BH3a and MC3 sedimentary log. MC3 taken from Dobes et al. (2013).
Borehole 14

Floodplain sedimentology

The most downstream Home Farm drill log completed was in an entirely new location at BH14, therefore surveying of the sites surface elevation has occurred. Groundwater data is also unavailable. But the drill log can still be used to expand the understanding of floodplain sedimentology.

The nearest bank exposure completed by Johnston and Brierley (2006) is MC6, located at the confined end point of the floodplain pocket. Figure 32 shows that this location has the most varied assemblage of fine and coarse grained units found at Home Farm. No loamy top soil is found at BH14, but fine grained post incisional alluvium is found at MC6. But nevertheless, three course grained units can be identified in each column. The first course grained unit lies at the surface on BH14, but 0.9 m below the post incisional alluvium at MC6. The clay unit situated between the next gravel lag is composed of organics and floodplain sediments. The gravel lag from MC6 and the sand unit from BH14 are found at approximately 2 m in depth. Further fine grained organic material forms a loam unit above the lower course grained unit, which is situated on bedrock at MC6. Bedrock was again not encountered within the 4.5 m of floodplain explored in this study.

Figure 32 – BH14 and MC6 sedimentary log. MC6 taken from Dobes et al. (2013).
Summary – Home Farm

The magnitude of flows into Mulloon Creek at Home Farm is summarised in Table 12. On average the late period had more baseflow than during the early period.

Table 12 – Home Farm baseflow results.

<table>
<thead>
<tr>
<th>Transect</th>
<th>Piezometer and period</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>HF 1</td>
<td>BH8a early</td>
<td>0.09 m²/year</td>
</tr>
<tr>
<td>HF 1</td>
<td>BH8a late</td>
<td>0.38 m²/year</td>
</tr>
<tr>
<td>HF 2</td>
<td>BH5a early</td>
<td>0.05 m²/year</td>
</tr>
<tr>
<td>HF 2</td>
<td>BH5a late</td>
<td>0.31 m²/year</td>
</tr>
<tr>
<td>HF 3</td>
<td>BH3a early</td>
<td>0.73 m²/year</td>
</tr>
<tr>
<td>HF 3</td>
<td>BH3a late</td>
<td>1.09 m²/year</td>
</tr>
<tr>
<td>Early average</td>
<td></td>
<td>0.29 m²/year</td>
</tr>
<tr>
<td>Late average</td>
<td></td>
<td>0.59 m²/year</td>
</tr>
<tr>
<td>Both average</td>
<td></td>
<td>0.44 m²/year</td>
</tr>
</tbody>
</table>

Three of the four installed piezometers contained water. The aquifer properties at these locations is summarised in Table 13. The likely aquifer units were on average at least 3.6 m thick; 58.3% of this thickness was saturated.

Table 13 – Home Farm aquifer properties - 2017 measurements.

<table>
<thead>
<tr>
<th>Piezometer</th>
<th>Aquifer thickness</th>
<th>Percent saturated</th>
</tr>
</thead>
<tbody>
<tr>
<td>BH8a</td>
<td>&gt; 4.8 m</td>
<td>75%</td>
</tr>
<tr>
<td>BH5a</td>
<td>&gt; 2.5 m</td>
<td>50%</td>
</tr>
<tr>
<td>BH3a</td>
<td>&gt; 3.4 m</td>
<td>50%</td>
</tr>
<tr>
<td>Average</td>
<td>3.6 m</td>
<td>58%</td>
</tr>
</tbody>
</table>
5.3 LOWER MULLOON

Introduction
The following section will describe the results from the Lower Mulloon in downstream succession. Considerably more data was gathered for the Lower Mulloon, therefore this analysis is more detailed than the analysis at Home Farm. The groundwater flow magnitudes are found in Appendix 5 and the aquifer properties are in Appendix 6.

Transect 1

Connectivity
Transect 1 is the most upstream transect at Lower Mulloon, composed of six shallow piezometers. Figure 33 shows Transect 1 in both plan and cross sectional view. A granodiorite pluton on the eastern valley margin confines floodplain development to primarily the western side of the stream. A stratigraphic log (minus Floodplain 1 West) of each piezometer is shown in cross section in Figure 35. The Hillslope and Piedmont piezometers target groundwater flows down the valley slope, while two conventional floodplain piezometers target the alluvial aquifer beneath the floodplain. The Bank 1 and Bank 2 piezometers are located within the sandy channel macroform.
The plotted Jan 2017 measurements used for the analysis is shown in Table 14. Hillslope West was the only piezometer that did not contain water. Piedmont West contained water at 6.47 m below the ground surface, relatively deep compared to the levels in the other piezometers. Generally, the water table gets nearer to the surface with proximity to the stream. A similar trend occurs with EC, with groundwater values approaching the quality of
stream water linearly across the floodplain. These linear relationships are shown in Appendix 10, with r-squared values for depth below surface and EC at 0.839 and 0.9061 respectively.

Groundwater flow between the alluvial aquifer and stream was calculated at each piezometer. Table 14 shows that flow was highest through the coarse material within the macrochannel. Since Hillslope West was dry, no flow was recorded down the hillslope. The magnitude of flow from the Piedmont to the stream was negligible. The stream elevation of 704.5 m is 3 m below the average aquifer water table found in the adjacent floodplain piezometers. Assuming the groundwater flow direction is down gradient, the stream configuration at Transect 1 is gaining.

Figure 34 shows that the majority of head loss between the stream and aquifer occurs at Bank 1 and Bank 2. The plotted EC measurements show that most of the groundwater chemistry flux occurs between Bank 1 and Bank 2 West. Although Bank 2 West may be perched and confined, it appears to be well connected and in relative chemical equilibrium with stream water chemistry. The stream EC value doubles over the 15 m distance between the two near-stream piezometers to normalize at floodplain EC levels. Most hyporheic zone interaction appears to be limited to less than 34.9 m from the stream.

![Figure 34 - Lower Mulloon Transect 1 groundwater-surface water connectivity](image-url)
Floodplain sedimentology

Figure 23 shows that vestigial soil development predominates on the western margin of Transect 1 (Jenkins, 1996). The geological map labels the entirety of the transect as alluvium (GEO map), however it is evident from the current typography that present day floodplain processes are confined to the lower flats of the floodplain valley below the piedmont. Alluvial unit boundaries have likely been drawn to roughly follow the tree line bordering the paddocks; however land clearing has extended well beyond the modern floodplain margin. This convolutes the interpretation of the geological map. Floodplain sedimentology interpreted from the drill logs in Figure 35 will yield more accurate and detailed results. Additional interpretations can be made from the primary soil dataset (State of NSW and Office of Environment and Heritage, 2017)

Piedmont West and Hillslope West, respectively located 8.5 m and 21.5 m above the height of the stream banks, are beyond the reach of modern overbank deposition. A thin layer of loamy top soil covers 10 m of clay on the hillslope and piedmont. The soil profile on the hillslope is typical for an in situ developed vestigial soil. Course fragments appear in the Hillslope West clay units at a depth of 6 m, which marks the boundary of parent rock weathering in the C horizon. At Piedmont 1, the development of the clay rich BC horizon extents to a minimum of depth of 10.5 m, which is approximately at the same elevation as stream level. It is therefore possible that course fragments in the basal unit of Piedmont 1 are an alluvial deposit. These two drill logs indicate that alluvial and colluvial processes have been separate on the western floodplain margin for some time. The boundary between the alluvial and colluvial appears to be located at a depth greater than 10 m between the Hillslope and Piedmont piezometers.

Floodplain 1 West is located in an area much more indicative of modern floodplain processes. The drill log for the hole is not available, so the morphology of the site cannot fully be established. The site is in a slight depression on the edge of the floodplain, which may be a basin for surface water flow. A topographical high is situated in the middle of the floodplain at the piezometer Floodplain 2 West. Topsoil is highly developed in this location; with 1.5 m of loam overlying clay and possibly a coarse levee deposit.

The two piezometers in the macrochannel reveal a complex spatial distribution of course grained material around the channel. The western margin of the macro channel is composed
of a sand unit 4.5 m thick, while the sand unit in the hole nearer to the stream is disjointed by clays units.

**Alluvial groundwater flow**

The water table in the vestigial soils of the western hillslope is low. The weathered sandstone parent rock of the Adaminaby Group has resulted in a deep clay rich soil B horizon that is low in transmissivity and is constricting groundwater flow down the slope. A dry hillslope piezometer indicates that flow from the hillslope alluvial aquifer into the floodplain aquifer does not occur at a depth less than 10 m. Any alluvial flow down slope that does occur would be facilitated through the C horizon where the coarse material of the regolith increases transmissivity. Infiltration rates on the hillslope would be low because of the high slope of the terrain and the aquifer composition, which means that a major component of flow from the hillslope into the floodplain aquifer would be via surface water sheet wash.

Two flow groundwater flow directions may exist in the alluvial aquifer of the modern floodplain. A flow of 0.53 m²/year into Mulloon Creek can be traced from a topographical and water table high found at Floodplain 2 West. The aquifer found here may be confined, but it does not appear to be under pressure. Despite the topographical high at the surface, the water table at Floodplain 2 West is relatively deep. The highly transmissive sand aquifer may be relieving its pressure head by releasing flow into the near stream aquifer to the east and/or to the alluvial aquifer found in the topographical depressed western floodplain margin.

Despite a macrochannel ground surface composition of sand and gravel, the stream water level at Transect 1 is be surprisingly different to the aquifer head at Banks 1 and 2. The high hydraulic conductivity of coarse material around the immediate stream would usually result in a water table that closely reflects the stream water level; however the aquifer head in Bank 2 is considerably higher than the stream water level (Figure 34). The clay units found in the upper layers of the Bank 2 soil profile appears to be constricting the formation of a uniform gradient connecting the stream and aquifer levels, which is resulting in this surprising difference.
Figure 35 – Lower Mulloon Transect 1 sedimentary log transect.
Transect 2

Connectivity

Transect 2 contains 12 piezometers that target both shallow and deep aquifers on both sides of the stream. Figure 36 shows these shallow piezometers in plan and cross sectional form. Only a few hundred meters downstream from Transect 2, this location is still confined on the eastern margin by igneous bedrock, however the floodplain on the eastern side is slightly more expansive. Four near stream piezometers provide high resolution flow data around the stream. The additional piezometers located on the floodplain and valley margin are used to characterise groundwater flow down the hillslope into the alluvial aquifer. Transect 2 piezometer measurements are located in Table 15.

![Figure 36 - Lower Mulloon Transect 2 cross section and plan form.](image-url)
Table 15 – Lower Mulloon Transect 2 piezometers measurements.

<table>
<thead>
<tr>
<th>Piezometer</th>
<th>Surface elevation</th>
<th>Water elevation</th>
<th>Dist. from stream</th>
<th>Depth below</th>
<th>EC</th>
<th>Screen depth</th>
<th>Q (m³/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hillslope West</td>
<td>724.5 m</td>
<td>714.8 m</td>
<td>722.5 m</td>
<td>9.75 m</td>
<td>1395 uS/cm</td>
<td>9.75 - 1 m</td>
<td>0.00</td>
</tr>
<tr>
<td>Hillslope West D</td>
<td>724.5 m</td>
<td>707.9 m</td>
<td>722.5 m</td>
<td>16.58 m</td>
<td>696 uS/cm</td>
<td>40 - 35 m</td>
<td>0.27</td>
</tr>
<tr>
<td>Piedmont West</td>
<td>713.5 m</td>
<td>711.3 m</td>
<td>535.8 m</td>
<td>2.24 m</td>
<td>352 uS/cm</td>
<td>5.8 - 0.8 m</td>
<td>0.43</td>
</tr>
<tr>
<td>Floodplain 1 West</td>
<td>713.0 m</td>
<td>710.8 m</td>
<td>363.9 m</td>
<td>2.17 m</td>
<td>398 uS/cm</td>
<td>6.1 - 1 m</td>
<td>0.43</td>
</tr>
<tr>
<td>Floodplain 1 West D</td>
<td>713.0 m</td>
<td>711.9 m</td>
<td>363.9 m</td>
<td>1.14 m</td>
<td>537 uS/cm</td>
<td>8.8 - 5.4 m</td>
<td>0.69</td>
</tr>
<tr>
<td>Floodplain 2 West</td>
<td>710.0 m</td>
<td>708.9 m</td>
<td>216.0 m</td>
<td>1.06 m</td>
<td>515 uS/cm</td>
<td>4.4 - 1.3 m</td>
<td>0.81</td>
</tr>
<tr>
<td>Floodplain 3 West</td>
<td>709.0 m</td>
<td>707.1 m</td>
<td>43.4 m</td>
<td>1.91 m</td>
<td>608 uS/cm</td>
<td>5.2 - 1.2 m</td>
<td>1.43</td>
</tr>
<tr>
<td>Floodplain 4 West</td>
<td>707.5 m</td>
<td>705.2 m</td>
<td>21.9 m</td>
<td>2.28 m</td>
<td>742 uS/cm</td>
<td>4.4 - 1 m</td>
<td>2.80</td>
</tr>
<tr>
<td>Bank West</td>
<td>707.5 m</td>
<td>705.4 m</td>
<td>14.3 m</td>
<td>2.12 m</td>
<td>752 uS/cm</td>
<td>4.57 - 1 m</td>
<td>2.80</td>
</tr>
<tr>
<td>Floodplain East D</td>
<td>708.0 m</td>
<td>705.9 m</td>
<td>54.2 m</td>
<td>2.08 m</td>
<td>886 uS/cm</td>
<td>5.3 - 2.9 m</td>
<td>5.00</td>
</tr>
<tr>
<td>Floodplain East</td>
<td>708.0 m</td>
<td>706.0 m</td>
<td>54.2 m</td>
<td>2.05 m</td>
<td>512 uS/cm</td>
<td>2.95 - 1.8 m</td>
<td>0.13</td>
</tr>
<tr>
<td>Midslope East</td>
<td>729.5 m</td>
<td>728.0 m</td>
<td>408.7 m</td>
<td>1.50 m</td>
<td>317 uS/cm</td>
<td>1.65 - 0.65 m</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Stream water elevation = 704.0 m
Stream EC = 580 uS/cm

All the water table points at Transect 2 are above the stream water level of 704 m AHD, which means that this reach is gaining. Flows of considerable magnitude were found between the near stream piezometers and the stream on the western side, while flow was either very limited or negligible down the valley slopes.

![Lower Mulloon: Transect 2 connectivity](image-url)

Surface water and alluvial groundwater connectivity at Transect 2 is conceptualised in Figure 37. The plotted stream EC measurements taken from January 2017 were much higher than previously measured at Mulloon Creek. Appendix 11 shows that the typical stream EC at this reach of Mulloon Creek is 120 uS/cm (Kennett and Bernardi, 2016). However, groundwater EC particularly in the near stream piezometers reflects this anomalous stream EC value. The
majority of groundwater chemistry flux appears to occur in a hypotheic zone within a 20 m lateral distance from the stream. This area also corresponds with the area of most considerable aquifer head loss. But unlike what was found at Transect 1, there is no linear relationship between stream proximity and water table depth or EC. Appendix 10 shows Transect 2’s much lower r-squared values of 0.4178 and 0.0739.

**Floodplain sedimentology**

The weathered sandstone profile of the western hillslope of Transect 2 is covered by an aeolian sand unit (Jenkins, 1996). The thickness of the unit tapers out down slope, with a thickness of 7 m at Hillslope West Shallow but just 1 m at the surface of Piedmont West. At Hillslope West this sand overlies clays derived from weathering in the B horizon, while at Piedmont West the sand overlies both fine and coarse alluvial deposits. This means the paleofloodplain margin is located in the subsurface someone between Piedmont West and Hillslope West.

A distinguishing feature of the Transect 2 floodplain is the thin surface layer of post incisional alluvium that overlays a paleoswamp deposit. Johnston and Brierley (2006) identify the historical name of the area as Longswamp. Longswamp was drained by a series of channels that incised and coalesced to form the present day stream (Johnston and Brierley, 2006). The drained area was beneficial for cattle grazing, which resulted in the development of up to 0.4 m of post incisional alluvium across the paddock. The alluvium is illustrated by a loam unit that is visible at the surface of all of the floodplain drill logs in Figure 38.

The soil profile at each floodplain piezometer is similar. Each contains a slither of post incisional loam overlying the clays of the paleoswamp. Approximately 2 m of coarse grained material indicating lateral channel migration and a heavy clay basement indicating paleoswamp deposition is present in all holes. Floodplain 1 West Deep reveals that this assemblage of alluvium occurs down to a depth of at least 10 m. Floodplain 3 West is an exception to this trend, with 4 m thick sand unit in place of the paleoswamp deposit. The proximity and elevation of the unit in relation to the stream means that the sand unit is likely a bank or levee sequence that was deposited by channel migrating towards and into the paleoswamp.
The eastern floodplain is much narrower than the western floodplain, but the character of the soil profile in Floodplain East Shallow is much the same, albeit with a thinner layer of post incisional and swamp alluvium. The eastern hillslope is composed of granodiorite of the Mount Fairy formation. Vestigial soil development is minor, with outcrop visible on the hillslope. The piezometer installed on the slope, Midslope East, reached the siliceous BC horizon at a depth of only 1 m. A deep hole installed in the eastern floodplain revealed that the granodiorite bedrock was present at a depth of 20 m below ground surface. The stream may be situated at the contact between the sandstone and granodiorite formations and although there is a small amount of floodplain formation, the stream is ultimately valley confined.

**Alluvial groundwater flow**

The aeolian units on the eastern hillslope make poor aquifers. The high transmissivity of the down slope tapering sand aquifer has resulted in a well-drained soil profile that quickly transmits flow downslope. Due to the high infiltration rate of the dune, water will quickly reach the base of the sand unit, where it will flow downslope along the clay unit. Water will rarely pool long enough to yield a high level in Hillslope West piezometer.

A notable feature of the groundwater flow on the eastern side of the stream is the shallowness of the water table on the hillslope. The unsaturated aeolian hills on the western side of the stream are a stark contrast to what occurs in the granodiorite to the east. Although the slope is steeper and the ground cover sparser, the water table at Midslope East is only 1.5 m below the surface, shallower than all but one of the floodplain piezometers to the west. A diamond core of this fractured granodiorite bedrock was shown in Figure 15 Figure 16.

Appendix 6 the primary aquifer unit in the floodplain is the sand unit that is fairly uniformly thick and prominent in most floodplain drill logs. This unit is often confined by both the thin layer of post incisional alluvium and the fine grained paleoswamp deposit. A secondary deeper aquifer was identified at Floodplain 1 West Deep, which is pressurised likely due to the aforementioned confinement.

In general, groundwater flow across the floodplain will occur in the roughly uniformly thick sand unit. The spatial distribution of the piezometers containing this unit indicates that this unit is also fairly continuous. Both the topographic surface and water table level facilitate a
surface and groundwater flow direction that is towards the stream. The flow direction in the second and deeper pressurised aquifer at Floodplain 1 West cannot be determined.

The level in the stream is closely reflected in the sandy aquifer found at Floodplain 4 and Bank West. These aquifers are thought to be confined (Appendix 6), but may still share linkages to the primary floodplain sand aquifer because both of these aquifers have similar compositions and both are the most elevated saturated units in the profile. It is reasonable to suggest that flow could occur along the predicted upper most saturated unit that theoretically occurs between Floodplain 3 West and Floodplain 4 West. The spike in groundwater EC at Floodplain 4 and Bank West is evidence for this confinement by the inference that this area is flushed by smaller quantities of fresher groundwater flow.

Alternatively, the two near-stream aquifers may share groundwater connections with the secondary deep aquifer identified at Floodplain 1 West Deep, as the elevation of these aquifers are more similar. Asserting this connection involves the extrapolation of a 2 m thick sand unit over 300 m laterally, which is unreasonable considering the complexity in floodplain composition which has been encountered. It can however be postulated that instead of one continuous unit connecting the deep secondary aquifer to the near stream aquifers, multiple discontinuous units may facilitate a connection along a flow path that is less uniform and isotropic. In both circumstances there is evidence of multiple aquifer flow paths. Thus, the actual zone of stream and groundwater mixing may be occurring on multiple fronts at potential different depths and distances from the stream.
Figure 38– Lower Mulloon Transect 2 sedimentary log transect.
Transect 3

Connectivity

Transect 3 is located 3 km downstream of Transects 1 and 2. The channel is situated roughly in the centre of the floodplain, which is no longer confined by volcanic outcrop on the eastern margin. Eleven piezometers span across both sides of the channel. The shallow piezometers are plotted in plan and cross sectional form in Figure 39 and the corresponding measurements for all holes are tabulated in Table 17.

Figure 39 - Lower Mulloon Transect 3 cross section and plan form.

The groundwater flow pattern that exists around the stream at Transect 2 is illustrated in Figure 40. Flow does not occur through Bank West as the level in the piezometer is identical to stream water level. The two bodies do however have very different EC values which means the chemical equilibrium being established in the hyporheic zone is acting over a
shorter distance than the majority of headless. The highest magnitude of flow towards the stream occurs at the edge of this head loss gradient at Floodplain 2 West.

Table 16 – Lower Mulloon Transect 3 piezometers measurements.

<table>
<thead>
<tr>
<th>Piezometer</th>
<th>Surface elevation</th>
<th>Water elevation</th>
<th>Dist. from stream</th>
<th>Depth below</th>
<th>EC</th>
<th>Screen depth</th>
<th>Q (m2/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hillslope West S</td>
<td>717.5 m</td>
<td>715.7 m</td>
<td>333.3 m</td>
<td>1.83 m</td>
<td>224 uS/cm</td>
<td>3.95 - 1.45 m</td>
<td>1.15</td>
</tr>
<tr>
<td>Hillslope West D</td>
<td>717.5 m</td>
<td>700.6 m</td>
<td>333.3 m</td>
<td>16.88 m</td>
<td>581 uS/cm</td>
<td>46.4 - 41 m</td>
<td>0.58</td>
</tr>
<tr>
<td>Piedmont West</td>
<td>708.0 m</td>
<td>702.6 m</td>
<td>252.7 m</td>
<td>5.36 m</td>
<td>655 uS/cm</td>
<td>8.35 - 1 m</td>
<td>0.42</td>
</tr>
<tr>
<td>Floodplain 1 West</td>
<td>698.5 m</td>
<td>697.2 m</td>
<td>122.9 m</td>
<td>1.32 m</td>
<td>353 uS/cm</td>
<td>4.3 - 1 m</td>
<td>0.15</td>
</tr>
<tr>
<td>Floodplain 2 West</td>
<td>698.5 m</td>
<td>696.9 m</td>
<td>30.7 m</td>
<td>1.64 m</td>
<td>295 uS/cm</td>
<td>4.3 - 1 m</td>
<td>0.44</td>
</tr>
<tr>
<td>Floodplain 3 West</td>
<td>698.0 m</td>
<td>696.1 m</td>
<td>23.7 m</td>
<td>1.86 m</td>
<td>367 uS/cm</td>
<td>4.5 - 1 m</td>
<td>0.00</td>
</tr>
<tr>
<td>Bank West</td>
<td>697.5 m</td>
<td>695.5 m</td>
<td>13.6 m</td>
<td>2.05 m</td>
<td>287 uS/cm</td>
<td>4.97 - 0.9 m</td>
<td>1.01</td>
</tr>
<tr>
<td>Floodplain 1 East</td>
<td>699.0 m</td>
<td>697.2 m</td>
<td>53.7 m</td>
<td>1.84 m</td>
<td>234 uS/cm</td>
<td>4.2 - 1 m</td>
<td>0.67</td>
</tr>
<tr>
<td>Floodplain 2 East D</td>
<td>699.0 m</td>
<td>697.9 m</td>
<td>124.9 m</td>
<td>1.13 m</td>
<td>619 uS/cm</td>
<td>10.9 - 7.5 m</td>
<td>0.00</td>
</tr>
<tr>
<td>Floodplain 2 East S</td>
<td>699.0 m</td>
<td>697.7 m</td>
<td>124.9 m</td>
<td>1.31 m</td>
<td>644 uS/cm</td>
<td>4.5 - 1 m</td>
<td>1.15</td>
</tr>
<tr>
<td>Midslope East</td>
<td>708.0 m</td>
<td>699.8 m</td>
<td>305.7 m</td>
<td>8.22 m</td>
<td>5784 uS/cm</td>
<td>10.95 - 1 m</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Stream water elevation = 695.5 m
Stream EC = 125 uS/cm

The exact distance at which the groundwater water interacts with stream water is hard to determine due to a wide grouping of EC measurements in the near-stream piezometers. The majority of the interaction seems to be facilitated over a very short distance in the course grained aquifer at Bank West. Although the Bank West aquifer very closely reflects the level in the stream, their EC values are of substantial difference to argue that the majority of chemical exchange occurs in a hyporheic zone that acts principally over a 13 m distance from the stream.

In this gaining reach, groundwater flow out of the western hillslope through the piedmont and into the floodplain is considerable. However, this process is not reflected on the eastern hillslope where flow is negligible.
Appendix 10 shows that there exists no considerable linear trend between stream proximity and groundwater EC; however there is a negative feedback between stream proximity and water table depth in the shallow piezometers, the opposite of which was found at the upstream. The r-squared of this relationship is 0.8476.

**Floodplain sedimentology**

The Transect 3 drill logs are shown in in Figure 41. Sandstone of the Adaminaby Group forms a steep western hillslope composed of rounded spurs with visible outcrop at the surface. The Midslope West piezometers sit on a small plateau half way up the hillslope where soils development is colluvial. The ground surface is covered in pebble sized material from the outcrop upslope. The B horizon occurs at just 0.5 m below the surface and extends to the bedrock found at only 4 m below. The drill logs from the nested pair of piezometers located only a few meters apart, Hillslope West Shallow and Hillslope West Deep, illustrate the spatial variation in soil grain size. Although the soil horizons are very similar in both holes, the texture of the horizons varies. The Deep hole has a much thicker loam unit in the topsoil, whereas the shallow hole has a slither of loam at the surface and a clay rich top soil. The piedmont piezometer sits at the base of this hillslope. Similar to the other piedmont sites, the soil profile here is dominated by clay.

The morphology of the floodplain is comparable to Transect 2, however this site has a thicker layer of post incisal alluvium covering the surface. The loam unit which reaches a maximum
thickness of 2 m thick at Floodplain 3 West, but is approximately 0.8 m thick at the other drill holes. A sandy unit was found at a depth of approximately 3 m in all of the floodplain holes. The sandy unit is exclusively found to be sandwiched between two fine grained units, but the relative thickness of the clay units does not indicate the presence of any extensive paleoswamp deposit, nor does the present topography indicate any current large scale backswamp processes.

The near stream drill holes are not that morphologically different to the rest of the floodplain. Bank West has the same order of alluvial units as the adjacent sites, but possesses a slightly thicker course grained unit which would be a relic of prior channel deposition. The Bank West piezometer is located on the outside bend of a particularly incised section of the stream. There is no course grained unit at the surface because the location is currently beyond the extent of vertical accretionary processes.

The eastern floodplain has a width of almost 200 m. The Floodplain 1 East drill log reveals the same pattern of floodplain deposition on the eastern side of the stream. Coarse grained units are apparent near the surface at the eastern floodplain margin. A topographic low along the edge of the floodplain appears to funnel surface flows down the hillslope during heavy downpours. The location of the confluence between this small tributary and Mulloon Creek was not determined, but a small backswamp is apparent. A coarse grained paleochannel type deposit with a high degree of spatial distribution is found in this location, as shown by the different assemblages found at the Deep and Shallow Floodplain 2 East holes, which are only a few metres apart.

The hillslope to the east of the paleochannel is formed by an unnamed formation of undifferentiated consolidated sediments. Vestigial soil development on the hillslope has resulted in an 11 m deep profile of almost exclusively clay. The slope of the eastern hillslope is much gentler than the western slope, which has aided the development of the highly weathered, deep soil profile.

**Alluvial groundwater flow**

There are potentially multiple aquifers in the western hillslope. The water table on hillslope is recognised by saturation in the shallow Hillslope West piezometer. An impermeable layer perching the water table was not encountered in the drill hole, however the presence of such a
layer can be inferred due to pressurised nature of Hillslope West Deep. The same layer that confines and forms the pressure head in the deep hole, would be perching the surface aquifer in the shallow hole.

Groundwater flow from the hillslope flat down into the piedmont via the perched surface aquifer will be limited by the thinning soil profile found on the steep terrain separating the two sites. Thinner soil development on the slope results in a smaller cross-sectional area for groundwater to transmit through. This process combined with the impermeable nature of clay, has resulted in the very low water table found in the very deep clay rich profile at Piedmont West. Recharge of the Piedmont aquifer by the deeper secondary flow identified at Hillslope West Deep will also be hampered.

Lateral transmission of alluvial groundwater occurs through the sandy aquifer found in all of the floodplain piezometers. Flow in the western floodplain can occur through a continuous sand unit along a hydraulic gradient linking Floodplain 1 West to the stream via Bank West. An upper and lower clay unit bound the aquifer, with flow said to be confined at Floodplain 2 West and at and Bank West.

The influence of the paleochannel and backswamp deposits on groundwater flow is evident in the nested pair of piezometers at on the eastern floodplain margin. At Floodplain 2 East Shallow, the water table is nearer to the surface than was found at the other floodplain margins due to the thickening of the sandy unit caused by paleochannel deposition. The pressure head at Floodplain 2 East Deep was substantial, with water rising up 8 m above the height of the screen, nearing the elevation of the surface. The piezometer has targeted a major alluvial aquifer which has formed in the pore space of the course grained paleochannel deposit. Flow direction in this aquifer may be static if the system is primarily connected to backswamp processes. But it is also possible that the flow in the aquifer reflects the paleoflow direction of the former channel.

The 13 m of homogenous clay found at Midslope East is inhibiting capillary forces bringing water to the surface. The water table depth is comparable to the ground surface elevation of the floodplain 300 m to the west. The gentle slope of the eastern margin is low enough to allow a substantial component of surface flow to infiltrate the soil. However, the clay rich soil would make this process extremely slow. The alluvial aquifer in the hillslope is therefore
situated at great depth, with a major recharge connection coming by way of regional flow from hard rock aquifers.
Figure 41 – Lower Mulloon Transect 3 sedimentary log transect.
Summary – Lower Mulloon

Groundwater-surface water connectivity and the alluvial aquifer properties at Lower Mulloon are summarized in Table 17. Flow through the floodplain piezometers appears to decrease downstream. The thick alluvial deposits at Transect 2 and 3 do not necessarily have higher flows. The deposits with larger percentages of the aquifer saturated tend to generate higher flows. A comparison to Home Farm will be made in the following section.

Table 17 – Lower Mulloon groundwater flow summary

<table>
<thead>
<tr>
<th>Transect 1</th>
<th>Piezometers</th>
<th>Aquifer thickness</th>
<th>Percent saturated</th>
<th>Average Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>LM 1</td>
<td>Shallow floodplain</td>
<td>2.8 m</td>
<td>88%</td>
<td>1.55 m³/year</td>
</tr>
<tr>
<td>LM 2</td>
<td>Shallow floodplain</td>
<td>4.12 m</td>
<td>66%</td>
<td>1.44 m³/year</td>
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<tr>
<td>LM 3</td>
<td>Shallow floodplain</td>
<td>3.9 m</td>
<td>82%</td>
<td>0.62 m³/year</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>3.6 m</strong></td>
<td><strong>70%</strong></td>
<td><strong>1.20 m³/year</strong></td>
</tr>
</tbody>
</table>
CHAPTER 6 – DISCUSSION

6.1 HISTORICAL ANALYSIS

Detangling the impact of natural climatic variation on restoration outcomes is challenging (Tague et al., 2008). A statistical analysis of precipitation data was undertaken to overcome the challenge. The precipitation dataset was compiled with recordings made from a location 14 km away from the site. No significant precipitation trend was found during the recording periods by either the Mann-Kendall test or a linear regression. Yielding the same result with two different statistical approaches has been proven a robust form of analysis (Kisi and Ay, 2014). The Mann-Kendall test can be susceptible to issues with auto-correlation (Kendall, 1975), but when the autocorrelation plots are assessed, the datasets appear to be random. The non-significant result from the Mann-Kendall test allows the changes in recording period to be assessed in a framework without interference from climate (Mu et al., 2007).

Although no significant trends were detected, the two periods were not similar. The tests look for a rainfall pattern over time; the magnitude of the pattern is not important (Kendall, 1975). The two periods are of a very different length; therefore a large discrepancy in total period rainfall is expected. When the daily rainfall intensity is compared, it is found that the late period was marginally drier than the early (1.8 - 2.3 mm/day). A characteristic of hydrological data is that as monitoring periods shorten, the influence of short term events have on data variance is increased (Li et al., 2010). The early period is half the length of the late period and is therefore more susceptible and likely reflecting short term, seasonal effects. Although it non-significant, it is possible that the downward trend in monthly rainfall over the entire period is related to the reduced rainfall totals. If anything, having less rainfall in the late period would give any NSF induced increase in groundwater storage increases more credence.

The significant rise in the Home Farm water table was found using an ANOVA model, a tool which is commonly used to assess river restoration projects (Smith, 2014). The ANOVA had three assumptions. The first was that data was independently and identically distributed first, i.e. was that there was no bias in sampling of observations. Secondly, that the data had a symmetric normal distribution and thirdly, an assumption of homoscedasticity, i.e. that there was no systematic change in variances across observations.

These assumptions were analysed using additional statistical tests. The Shapiro-Wilk test had a non-significant result which means the data was normally distributed and the Levene’s test found that there was no significant statistical difference in variances. The histogram, scale-location, Q-Q plot and
residual plots in Appendix 2 illustrate these findings. The assumption of independent and identically distributed data points is less certain. There was no bias during the sampling of the Home Farm piezometers; however the problem of integrating dry recordings into the will be addressed in the limitations section that follows.
6.2 ALLUVIAL GROUNDWATER FLOW DYNAMICS

The Home Farm alluvial groundwater table appears to have increased under the baseflow conditions of a gaining stream, which means it is unlikely that the elevated water table in the late period was caused by increases in surface water flowing from the stream into the alluvial aquifer. Flow from the stream into the alluvial aquifer can only occur along a gradient formed when channel elevation exceeds the height of the surrounding water table (Sophocleous, 2002). Since Mulloon Creek is a gaining stream and the configuration is reversed, increased alluvial aquifer water storage cannot occur via flow from the stream into the floodplain, as this would oppose the hydraulic gradient between the two water bodies. The water table rise appears to have occurred due to the effectiveness of the weirs at altering stream level elevation, a process which was theorized by Dobes et al. (2013) and demonstrated by DeBano and Schmidt (1987).

The step-diffusion process outlined by Dobes et al. (2013) appears to have successfully restored the alluvial aquifer water table height at Home Farm. Artificial ponds have formed immediately upstream of the leaky-weirs, causing the stream level to rise within the incised channel. If the stream level is thought of as an atmospheric pressure head, the stream water will be exerting hydrostatic ‘back pressure’ against connected alluvial groundwater systems. As stream flow is dammed and the hydrostatic pressure in the area is increased, the amount of baseflow out of the aquifer and into the stream reduces (Rassam and Werner, 2008). The flows calculated in 2017 indicate that baseflow has not stopped entirely. As long as there is still floodplain infiltration or regional groundwater flow into floodplain aquifer (i.e. positive water balance), less drainage into the stream will result in more water will be stored in the alluvial aquifer (Gleeson et al., 2012). If the alluvial aquifer is unconfined, the water table will rise uninhibited to a higher elevation that will relieve any pressure head caused by additional water storage (Darby and Simon, 1999).

An inference of the aforementioned step-diffusion hypothesis is that the magnitude of baseflow in the late period needs to be less than the early period. This is contrary to the results found. At Home Farm, the late period had an average baseflow 0.30 m²/year less than that of the early period. It is thought that the assigned stream level value used in the late period analysis is incorrect due to the stream water rising effect caused by the leaky weirs. This hypothesis could be readily tested by using more accurately obtained stream stage and groundwater elevation measurements, to determine whether baseflow has reduced as predicted.

An alternative hypothesis is that the water balance during the late period had increased amounts of regional groundwater input from hard rock aquifers, or more infiltration directly through the floodplain.
soil (Gleeson et al., 2012). For the water table to rise like it has, the input would have to be great enough to sustain larger and larger flows into the stream. The impact and character of the regional aquifer was not investigated by either this or any previous study. The regional aquifer is known to be a fractured granite, low-moderate productivity (Lau et al., 2015), but this description is also known to not match the sandstone geology of Home Farm (Fitzherbert et al., 2011). The hydraulic conductivity of sandstone can range considerably (Fetter, 2001), so the exact influence of this input cannot easily be determined.

Since the clay-rich floodplain topsoil has a low infiltration rate, the proportion of water entering the aquifer by infiltration may also be insufficient to keep the water balance positive (Gleeson et al., 2012). Although Weber and Field (2010) found that NSF can improve soil moisture, biomass growth, nutrient cycling and organic turnover, there was no evidence to indicating alteration of soil texture or structure over the 30-year study period was altered. Thus, any potential effect of infiltration will not be limited to just the late period, as both periods have similar soils. In addition, the historical analysis shows that precipitation during the late period was lower than the early period, further limiting the effect of infiltration. The increased infiltration hypothesis can be ruled out.

Figure 42 shows the strong feedback between aquifer material and water table depth. This was particularly noticeable in the large dataset from Lower Mulloon. Due to the large body of research into the influence of aquifer material on groundwater flow (Bridge, 2003, Clapp and Hornberger, 1978, JOUR et al., 1997), this result was expected.

However, when the variables in Equation 1 are analysed, the influence of hydraulic conductivity on baseflow is less pronounced. A linear analysis of each variable in using Equation 1 is in Appendix 12. The lumping approach used to assign aquifer material a hydraulic conductivity has limited the influence of hydraulic conductivity on baseflow calculations to three discrete groupings. There is a more considerable linear correlation between baseflow and aquifer transmissivity, which is to be expected because transmissivity is a more detailed form of measurement. There is also a correlation between baseflow and distance from the stream, however Cook et al. (2012) recognises that the linear nature of often fails to accurately flows at large distances.
Figure 42 – Soil texture and depth to the water table: box and whisker.

The relationship between flow and transmissivity suggests that alluvial groundwater flow is facilitated along units that are both hydraulically conductive and of a considerable thickness. A thick clay aquifer can potentially transmit a quantity of water similar to a thin sand aquifer. Weber and Field (2010) acknowledge that the observed change in floodplain soil properties at the NSF site in the Hunter Valley, was potentially allowed by groundwater flow though sandy alluvial sediments with high transmissivity. The much stronger correlation that exists between hydraulic conductivity and water table depth (Figure 42) suggest that hydraulic conductivity is more influential on vertical groundwater flow rather than lateral groundwater flow. This could be explained by the nature of alluvial deposits morphology, which has the potential be massive but with a high spatial distribution Bridge (2003). A levee deposit for instance may be relatively vertically uniform, but latterly discontinuous.

These correlations were determined using all shallow piezometers points in the landscape. When flow was calculated through the near stream piezometers that predict the likely baseflow through hyporheic zone, the results are consistent with other studies. The highest magnitude flows that occurred in the entire alluvial system were through piezometers LM1 Bank West, LM2 Floodplain 3 West and LM2 Bank West. Each of which contain a saturated sandy unit of at least 2 m thick. If the texture of one of these units was instead assigned clay a hydraulic conductive, the flow would stop entirely. This appears extreme; however material type can alter drainage durations in bank material from a period of days to years (Rassam and Werner, 2008). Keene et al. (2006) observed this behaviour at Widden Brook, where hydraulic linkages were stronger in coarse grained channel deposits.
Figure 24 (p.57) illustrates the significant rise in the Home Farm alluvial aquifer. But Figure 43 suggests that despite Home Farm being seemingly under the influence of the NSF treatment, the latest measurements from 2017 at shallow floodplain piezometers reveal that the untreated Lower Mulloon has a more elevated floodplain water table than the NSF treated Home Farm. The Home Farm floodplain aquifer is 58% saturated while the Lower Mulloon is 70% saturated. This is likely because two of the three floodplain drill logs at Home Farm found clay aquifers, whereas all 17 Lower Mulloon floodplain piezometers targeted sand aquifers. However, the relative lack in detailed Home Farm sedimentology means that the hypothesis remains inconclusive. It does however raise important implications for the Lower Mulloon.

Figure 43 – NSF vs non-NSF treatment in January 2017: box and whisker.
6.5 IMPLICATIONS FOR NATURAL SEQUENCE FARMING

The primary aim of Natural Sequence Farming is to rehydrate the alluvial aquifer to facilitate more water storage in the landscape (Williams, 2010). The significant rise in the Home Farm water table between the two recording periods indicates that this aim was achieved. But the fact the Lower Mulloon appears to have better NSF outcomes despite having no NSF treatment complicates the issues. It is important to determine why and how this response occurred at Home Farm, so the suitability of the approach to other locations such as the Lower Mulloon can be assessed.

The step-diffusion process of groundwater recharge encouraged by leaky weirs attempts to mimic the flow pattern that would have occurred along the discontinuous pre-incised channel (Weber and Field, 2010). Before incision occurred, low precipitation rates caused the Mulloon Creek channel to be limited to a series of discontinuous pools, palaeochannels and backswamps (Johnston and Brierley, 2006). A relationship exists between alluvial form and process (Bridge, 2003). Since alluvial groundwater flow responds to floodplain form (Sophocleous, 2002), the effectiveness of restoring paleo-flow processes is dependent upon having retained or restored the system to its corresponding paleo-form. NSF aims to achieve this by using the leaky weirs to artificially raise the level in the stream to its paleo-elevation (Dobes et al., 2013). There are, however, many more elements of channel form than just relative channel height.

In many locations at Mulloon Creek, the sedimentology of the channel and floodplain has undergone 200 years of significant post-European alteration (Johnston and Brierley, 2006). Two new sedimentary features now dominate the landscape. The first is the layer of post incisional alluvium that covers the majority of the floodplain and the second is a thick fine grained deposit left by a drained backswamp. Both of these deposits have altered the flow pattern of alluvial groundwater. These deposits are essentially permanent and now form a major component of landscape functionality, so any restoration technique that functionally relies on re-establishing paleo-processes, may not respond in a desired manner to the present channel-floodplain form. This raises the issue of restoration suitability to landscape, a major problem in river restoration science (Bennett et al., 2011).

The water table rise at Home Farm was enabled by the presence of a considerably thick and porous vadose zone which could store water if the aquifer head increased. Without sedimentary units that can facilitate storage, the amount rehydration that can occur will be minimal and the baseflow benefits described by Dobes et al. (2013) will be limited. Bush (2010) and Keene et al. (2006) both found that alluvial groundwater storage was an essential part of maintaining baseflow into Widden Brook, the sedimentology of which is composed of sandy floodplain material (Kovac and Lawrie, 1991).
In instances at Home Farm where clay units were close to the surface, water table rise was restricted. Impermeable units in the upper horizons are always going to limit the amount of rise and ultimately affect aquifer capacity. Backswamp deposits have the potential to distribute impermeable units over very large areas (Anderson et al., 1996), which means that these storage limitations can extend over equally large areas. Attempting to rehydrate this type of alluvial aquifer will not be an efficient use of restoration resources, because the drought resilience capability of the aquifer will be minimal.

The nature of the alluvium below or in the lower part of the floodplain aquifer is also of importance. At Home Farm the alluvial aquifer is perched atop bedrock that is close to the surface. In some floodplains, alluvium is so thick and well drained that the water table is found hundreds of meters below the surface (Anderson et al., 1996). A water table rise in such a setting would be insignificant compared to the potential size of the aquifer and due to the well-drained nature of course grained floodplain deposits (Rassam and Werner, 2008), an elevation increase in this type of aquifer would be difficult to induce with the localised effect of NSF type weirs (Keene et al., 2006).

The drought resilience capability of the Home Farm alluvial aquifer is enabled by two sedimentary features that utilize the storage to facilitate baseflow. The gravel lag that runs along the lower boundary of the Home Farm alluvial aquifer allows flow to traverse the width of the floodplain and recharge the draining areas nearer to the stream. Baseflow will stop when the bank storage component of the aquifer is emptied (Rassam and Werner, 2008). Even if the majority of the majority of the aquifer is hydrated, if the water is contained in separate alluvial unit reservoirs that are disconnected, the bank storage will never be replenished.

The ultimate connection between the near stream aquifer and the stream is the second and most essential feature enabling baseflow. Groundwater-surface water connectivity is depended on a connection between in-channel with the floodplain deposits. At Mulloon Creek this was linkage was enabled by coarse grained sand units, which is the same conclusion drawn by Bush (2010), Keene et al. (2006) at Widden Brook.

Even with a significant restoration induced water table rise, if there is no associated baseflow connection to the stream, the drought resilience capability of the hydrated aquifer will not be fully utilized. However, a paradox may prevent the formation of this configuration. If there is no existing flow path between the stream and aquifer, the hydrostatic pressure created by the increased stream level will not translate to the aquifer and cause less drainage.
Figure 7 shows that of the 22 leaky-weirs installed at Home Farm, only roughly half of them occur in locations that could have induced localised changes detectable by the piezometer network (Keene et al., 2006). Since the weirs and piezometers were not uniformly distributed in what turned out to be a complex sedimentary assemblage, it was not possible to discern the individual impact of each weir. If this information were available, it may be possible to predict the scaling effects of the NSF restoration by determining the most efficient use of the weir.

Weirs essentially raise stream water levels by artificially mimicking the stage of a flood (Todd, 1955). When an actual flood does occur, water will spill out above the floodplain deposit material laterally on the agricultural pasture (Bridge, 2003). This has historically caused management issues with landholders who have not wanted their paddocks inundated (Darby and Simon, 1999). Weirs have also been prone to failure during large flooding events (Prince Czarnecki et al., 2014). There is an abundance of research to suggest that regulating stream flow byway of dams and weirs creates management issues due to changes in downstream water availability (Smakhtin, 2001). Bush (2010) found that NSF type leaky-weirs at Widden Brook did not succumb to these downstream problems, but the monitoring period was short. The leaky-weir design may release a sufficient amount of environment flow. These issues show that not only must the physical environment be suitable for NSF, but landholders must also be suitably aware and informed of land management issues.
6.5 IMPLICATIONS FOR LOWER MULLOON

If weirs were constructed further downstream in the Lower Mulloon, a response similar to what was found at Home Farm would be expected in only some locations. The hydrostatic pressure created by increasing the stream level is not likely to translate across the width of the Lower Mulloon floodplain and thereby affect the water table of the midslope (Rassam and Werner, 2008). The relatively small potential for stream water level rise is insufficient to induce a back pressure capable of influencing the water table depth in the relatively elevated midslope aquifers. Thick clay units found at piedmonts sever groundwater connections between alluvial and vestigial deposits. Since a strong hydraulic linkage between the midslope and floodplain aquifers could not be established, the induced NSF response is thought to be limited to primarily the floodplain aquifers.

The floodplain sedimentology of Transect 1 is understood in the least detail due to the few piezometers that were installed. This floodplain could facilitate considerable groundwater storage if the coarse grained aquifer that is found at a distance of 140 m from the stream is indicative of the rest of the unstudied floodplain system. An average percentage of saturated aquifer thickness of 88% suggests that the alluvial aquifer of Transect 1 are already nearing there storage capacity, however this value is affected by the small sample population. It is well understood that that the sandy material found in the macro-channel is the ideal medium through which baseflow can utilise aquifer storage.

It is difficult to predict the response at Transect 2 due to a complex alluvial assemblage and potential interference from paleoswamp groundwater flows. There is a thick and relatively continuous sandy aquifer spanning the width of the floodplain that is only 66% saturated, which would normally present the ideal scenario for additional aquifer storage. There is a possibility, however, that sections of this aquifer may be disconnected from the stream-aquifer system due to the abundance of fine grained material and instead linked to deeper pressurised flows related to paleoswamp connection. Area ‘C’ in Figure 5 conceptualises this process. Changes to the stream will not induce changes to separate groundwater systems, meaning the NSF response at Transect 2 may be localised to just the aquifers in close proximity to the stream.

In contrast, Transect 3 possesses an assemblage that is almost a best case scenario for additional restoration induced alluvial water storage. However, the aquifer is already 82% saturated. The continuous sandy aquifer is connected to the stream without interference from separate groundwater systems. A small amount of interference may arise from groundwater flow through the paloechannel that runs along the eastern floodplain margin, but the lateral extent of the unit facilitating this flow path is much smaller than the backswamp deposits of Transect 2, therefore its effect is most likely localised.
The pressurised secondary paloechannel aquifer may interfere with the restoration induced changes to floodplain hydraulic regime if it shares an unknown connection with the surface aquifers nearer to the stream.

Without a better understanding of weir efficiency at Home Farm, a recommendation on the number weirs required to induce the desired response cannot be made. If each leaky-weir raises the stream water level by 0.5 m (Dobes et al., 2013), then a number of weirs would be required to artificially elevate the Lower Mulloon water level to pre-incision height. To induce a change, there first needs to be the sufficient stream water availability to fill the new larger channel cross section (Rassam and Werner, 2008). This was not observed at Home Farm between periods with no significant difference in rainfall trends and a lower rainfall total overall, and hence it is also possible at Lower Mulloon, as this reach has an even larger downstream catchment and therefore more water availability (Kondolf et al., 1987).

The time it will take for the alluvial aquifer to adjust to the new stream water level is also unknown. It is known that the reaction to the pressure changes is not instantaneous in alluvial aquifers; instead it is related to the groundwater flow rate between the two bodies (Williams and Paillet, 2002). Calculating the propagation of a hydraulic pulse is often modelled using a forward finite difference equation modified from Darcy’s Law (Fetter, 2001), which was beyond the scope of this project. It is known that the change detected at Home Farm occurred in similar material during a 1.5 year period. In a simplified example, if the new pressure head is said to propagate back from the stream across the aquifer at the rate of current baseflow, the 0.62 m²/year flow into Mulloon Creek at Lower Mulloon Transect 3 will reach the 200 m margin of the western floodplain in 322 days.
6.3 LIMITATIONS OF METHODOLOGY

Project limitations have primarily arisen from data constraints (Appendix 4). The chosen methodology was adapted to best utilize what data was available. An ideal hydrogeological study will contain a consistent monitoring period of considerable length. The Home Farm historical piezometer record was fractionated and did not have the crucial pre-intervention data that Smith (2014) states is critical for any restoration study. Without such information, the differences between the early and late period can only be assessed with the knowledge that they reflect maturation along the restoration timeline, not deviation from original conditions. The potential impact of changes in riparian vegetation quantity and land and water usage was unknown and not taken into consideration. Comparisons to the much larger dataset gathered at Lower Mulloon did assist the analysis, but that is dependent on further assumptions of site similarity.

There was an element of sampling bias in the groundwater analysis because the presence of dry piezometers was not integrated into the quantitative results because a limit could not be integrating in the dataset composed of depth integers. There were 54 dry measurements in the early period and 57 dry measurements in the late period, a difference which is minor. Dry measurements in both periods generally occurred at the same piezometers. The effect of this sampling bias was mitigated by most of the analysis being conducted looking at water table depth below the surface, not water table elevation, which is highly dependent on the unique surface elevation of the piezometer.

The elevation of the Home Farm piezometers was formerly surveyed to a high degree of accuracy. The GPS and DEM averaging approach used for all of the new piezometers was a fast and easy way to obtain the elevation of the piezometers while waiting for Lower Mulloon to be surveyed in by The Mulloon Institute. This temporary solution was ultimately used for the analysis due to exceeding temporal limitations. Stream water elevation was also estimated with a considerable amount of error, but it was of satisfactory accuracy to determine the important parameters of stream configuration and flow directions. These limitations give further merit to the analysis conducted using accurately collected depth below surface measurements and sedimentology.

The lumping of the extensive soil dataset into three broad categories was needed to simply the analysis. Coarse fragment size and abundance can have a significant impact on hydraulic conductivity (Fetter, 2001), however this was not integrated into the soil texture classification. Empiricism interpreted from Figure 42 shows that the lumping process performs well at characterising the different groundwater response expected for each aquifer type. The much larger variance found in clay classified aquifers can
be attributed to the commonly found sandy clay texture and the abundance of coarse fragments often found in clay rich C horizons.
CHAPTER 7 – CONCLUSION

Natural Sequence Farming is a holistic landscape repair technique that employs a number of structural and non-structural measures to increase landscape water storage, the benefits being improved landscape resilience, biodiversity and agricultural productivity (Williams, 2010). In 2006, a NSF pilot project began along a length of Mulloon Creek at a property called Home farm, located in the upper Shoalhaven River catchment, NSW. The process involved the construction of 22 instream structures called leaky-weirs, the battering of incised banks, planting of riparian vegetation and changes to agricultural land management. In this study, the effect of these instream structures on the alluvial aquifer water table was studied using a network of piezometers and hydraulic gradient analysis.

A significant rise in the Home Farm alluvial water table was found between the early and late monitoring periods, an increase coinciding with restoration maturity and the temporal influence of the instream structures. Analysis of climate data from Bungendore PO, a BOM weather station located 14 km away from the study site, found no significant monthly rainfall trend during the study period, using both the Mann-Kendall test and a linear model. When rainfall totals were analysed, it was found that the increase in Home Farm alluvial groundwater storage occurred despite less rainfall intensity in the late period (1.8 mm/day) compared to the early period (2.3 mm/day). However, additional impacts on aquifer water balance were ignored.

Water is induced into the alluvial aquifer by use of weirs to artificially raise the stream water level within the incised channel. This causes the aquifer-stream hydraulic gradient to decrease and baseflow to subside; a process analogous to bank-storage during a flood peak (Kondolf et al., 1987) and the step-diffusion process predicted by Dobes et al. (2013), DeBano and Schmidt (1987). When stream flow reduces in dry periods, increased storage in the alluvial aquifer will sustain baseflow for a longer duration, a function vital to the health of Australian ephemeral streams (Dobes et al., 2013).

An additional 29 piezometers were installed at a downstream site called Lower Mulloon. Soil sampling was used to characterise the alluvial aquifers of both sites by soil texture. Groundwater flow paths across the alluvial valley were then determined by studying the relationship between aquifer lithology, water table elevation, pressure and confinement.

The observed alluvial groundwater flow dynamic was consistent with the work by (Krause et al., 2007, Woessner, 2000, Rassam and Werner, 2008). It was found that alluvial groundwater flows are influenced by potentially complex assemblages of floodplain units. Alluvial groundwater storage primarily occurs in coarse grain units. Confinement and perching of aquifers by clay units can result in
the formation of secondary or multiple aquifer configurations. To effectively store water in well-drained coarse alluvial units, it can be equally important to have impermeable material at both the upper and lower boundaries of the surface aquifer, which means that these fine grained units may actually serve an important role in water storage.

During the study period, Mulloon Creek was in a gaining configuration, which is to be expected for the region’s climate (Stephens, 1995), but may also be a reflection of corresponding seasonal variation. A hydraulic gradient analysis technique devised by Rassam and Werner (2008) was used to calculate the magnitude of baseflow into Mulloon Creek. Positive, gaining flows were exclusively found. The step-diffusion hypothesis formulated to explain the rise in the floodplain water table could be tested by more accurately monitoring the response stream water level and aquifer head and calculating the alluvial aquifer water budget. Graphical water table plotting methods assisted the analysis of groundwater-surface water connectivity. Connectivity can be thought of as the magnitude but also the potential for baseflow to occur. Aquifer transmissivity has the largest influence on flow magnitude. At both Mulloon Creek and Widden Brook, flow between alluvial groundwater and stream water is greatest through coarse-grained near-stream material (Keene et al., 2006, Bush, 2010).

Two key factors have resulted in the success of the Natural Sequence Farming restorations at Home Farm. The first is the presence of a floodplain composed of sedimentary units that are both porous and not at storage capacity. The second is the presence of groundwater pathways that connect the stream to the floodplain to utilize the increased storage. These factors are likely the two main site suitability requirements for any NSF restoration project.

If these suitability requirements are applied to the conditions of the Lower Mulloon, the outcome of a similar restoration project can be predicted. The Lower Mulloon is a large site that exhibits diverse sedimentary characteristics at each of the three transects. Due to a lack of data at Transect 1, the prediction is limited to the area around the near-stream floodplain aquifer. This area has suitable conditions and should therefore respond effectively to NSF restorations. At Transect 2, the floodplain form and subsequent groundwater processes are too complex to accurately predict a response to NSF treatment. Transect 3 displays the ideal sedimentology for NSF, but at the sampled time period it already had a considerably hydrated aquifer.

The intensity of NSF treatment to garner a response at Lower Mulloon or any other site is unknown. This efficient use of restoration resources is a key component of successful restoration strategies and presents a good opportunity for further research to expand on the practical nature of NSF. The
monitoring equipment installed during this study is a powerful resource that provides the foundation for more detailed studies utilizing conventional hydrogeological investigations including pumping tests and chemical and tracer analysis, and longer monitoring periods. The effect on NSF measures on downstream water availability is only understood on the short term (Bush, 2010) and instream structures are known to cause other downstream issues Ghanbarpour et al. (2013). This highlights the need for a long term surface water hydrology investigation at Mulloon Creek or other NSF sites.

This study reinforces the importance of suitability in river restoration science (Van Diggelen et al., 2001). Natural Sequence Farming is an effective means of inducing alluvial water storage and increasing landscape resilience in incised channels with good hydraulic linkages to porous floodplain material. Further monitoring of Mulloon Creek will lead the expansion of the science and strengthen evidence for the practise of Natural Sequence Farming.
CHAPTER 8 – REFERENCES


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CHAPTER 9 – APPENDICES

APPENDIX 1 – TEMPERATURE TRENDS

Location: 069132 BRAIDWOOD RACECOURSE AWS

Mean minimum temperature (°C)

Location: 069132 BRAIDWOOD RACECOURSE AWS

Mean maximum temperature (°C)
APPENDIX 2 – RAINFALL AUTOCORRELATION
APPENDIX 3 – ANOVA PLOTS

Histogram of depth below surface measurements: Early and Late periods

Scale-Location

Residuals vs Fitted
APPENDIX 4 – PROJECT TIMELINE AND DATA AVAILABILITY

Project Timeline

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<td>Bungendore PO BOM station</td>
</tr>
<tr>
<td>Climate</td>
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<td>Fieldwork</td>
</tr>
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<td>Johnson (2006)</td>
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<td>Early period</td>
<td>Late period</td>
</tr>
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<td>Fieldwork</td>
<td>Fieldwork</td>
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<tr>
<td>Stream level</td>
<td>Mid-Mulloon gauge</td>
<td>Mid-Mulloon gauge</td>
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<td>Stream EC</td>
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<td>Bungendore PO BOM station</td>
<td>Bungendore PO BOM station</td>
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<tr>
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<td>Johnson (2006)</td>
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<td>Late period</td>
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Data Availability

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<td>G</td>
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<tr>
<td>Stream EC</td>
<td>G</td>
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VG - very good, G - good, P - poor
## APPENDIX 5 – GROUNDWATER CALCULATIONS

<table>
<thead>
<tr>
<th>Location and name</th>
<th>Aquifer properties (m)</th>
<th>Saturated thickness (m)</th>
<th>Hydra. Conduct. (m/year)</th>
<th>Transmissivity layer (m²/year)</th>
<th>Transmissivity (m²/year)</th>
<th>Flow (m³/year)</th>
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<tr>
<td></td>
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<td>Surface elevation</td>
<td>Water elevation</td>
<td>Dist. from River elevation</td>
<td>Depth below</td>
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<td>728 Dry</td>
<td>816.9</td>
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<td>715.5</td>
<td>709</td>
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<td>54.2</td>
<td>2.05</td>
<td>0.01 15.21 0.01 0.00 13.68</td>
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<td>708</td>
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<td>2.05</td>
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<td>408.7</td>
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<td>717.5</td>
<td>715.7</td>
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<td>698.5</td>
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<td>697.7</td>
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<td>729.8</td>
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<td>728.9</td>
<td>727</td>
<td>105.1</td>
<td>1.9</td>
<td>0.01 20.53 0.02</td>
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<td>727.5</td>
<td>105.1</td>
<td>1.4</td>
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## APPENDIX 6 – AQUIFER PROPERTIES

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<th>Thickness</th>
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<tr>
<td>HF 2 BH5a</td>
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<td>&gt; 2.5 m</td>
<td>50%</td>
<td>Clay</td>
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<td>50%</td>
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<td>0%</td>
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<td>40%</td>
<td>Clay</td>
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<td>Sand</td>
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<td>NO</td>
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<td>5%</td>
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<td>60%</td>
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<td>NO</td>
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<td>NO</td>
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<td>LM 2 Floodplain 4 West</td>
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<td>50%</td>
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<td>YES</td>
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<td>LM 3 Floodplain 1 West</td>
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<td>&gt; 4 m</td>
<td>80%</td>
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<td>NO</td>
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<td>75%</td>
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<td>NO</td>
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<td>60%</td>
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<tr>
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<td>20%</td>
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APPENDIX 7 – HOME FARM LONGITUDINAL SURVEY
APPENDIX 8 – HOME FARM LATERAL FLOODPLAIN TRENDS

T1

T2
APPENDIX 9 – HOME FARM TRANSECT WITH ERROR BARS
APPENDIX 10 – LOWER MULLOON LATERAL FLOODPLAIN TRENDS

APPENDIX 11 – RAPID STREAM APPRAISIAL
Home Farm Transect 1 is located at approximately site 5.

Home Farm Transect 2 is located at approximately site 8.

Home Farm Transect 3 is located at approximately site 10.

Lower Mulloon is Transect 1 is located at approximately site 19.

Lower Mulloon is Transect 2 is located at approximately site 20.

Lower Mulloon is Transect 3 is located at approximately site 25.
APPENDIX 12 – ANALYSIS OF EQUATION 1

Q vs transmissivity

Q vs distance from stream

Q vs thickness

R² = 0.3174
R² = 0.2199
R² = 0.0571
Q vs hydraulic conductivity

Q vs head loss