



Mulloon Institute

Controls on flow and patterns in physico-chemical properties of groundwater on a landscape rehydration enterprise at Mulloon Creek, New South Wales, Australia.

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1. INTRODUCTION

Mulloon Institute is a research, education and advocacy not-for-profit organisation that showcases landscape rehydration and aligned farming and natural resource management (NRM) initiatives. On-site scientific research, under the oversight of a scientific advisory committee (SAC), ensures that the impacts of innovative land management practices are documented and that there is rigour in the collation of baseline and monitoring data. This enterprise began at the Mulloon Home Farm (MHF) near Bungendore on the Southern Tablelands, New South Wales (Figure 1), a community of practice that continues to foster scholarship while maintaining farm productivity. This report summarises the findings from analysis of meteorological, hydrological, and hydrogeological data collected consistently from 2014 to 2020, augmented by available data collected at less regular intervals from 2006 to 2014.



Figure 1. Mulloon Creek locality and site map (Johnson and Brierley, 2006)

On the Home Farm, Mulloon Creek runs south to north along the axis of an upland valley flanked by a range of low hills to the west, developed on Late Silurian sedimentary rocks (conglomerate, sandstone and siltstone) of the De Drack Formation, with enclosed pods (<0.25 ha) of the Sandhills Creek Limestone, and to the east a sub-parallel range developed on a Late Silurian silicified porphyritic rhyolite of the De Drack Formation (formerly Mount Fairy Beds) and Ordovician meta- sandstones and mudstones with associated weathered Quaternary duricrusts (Fitzherbert et al. 2017) (Figure 2). The lower slopes preserve locally sourced monomict colluvial deposits, and the valley floor hosts a succession of polymictic alluvial deposits associated with Mulloon Creek.

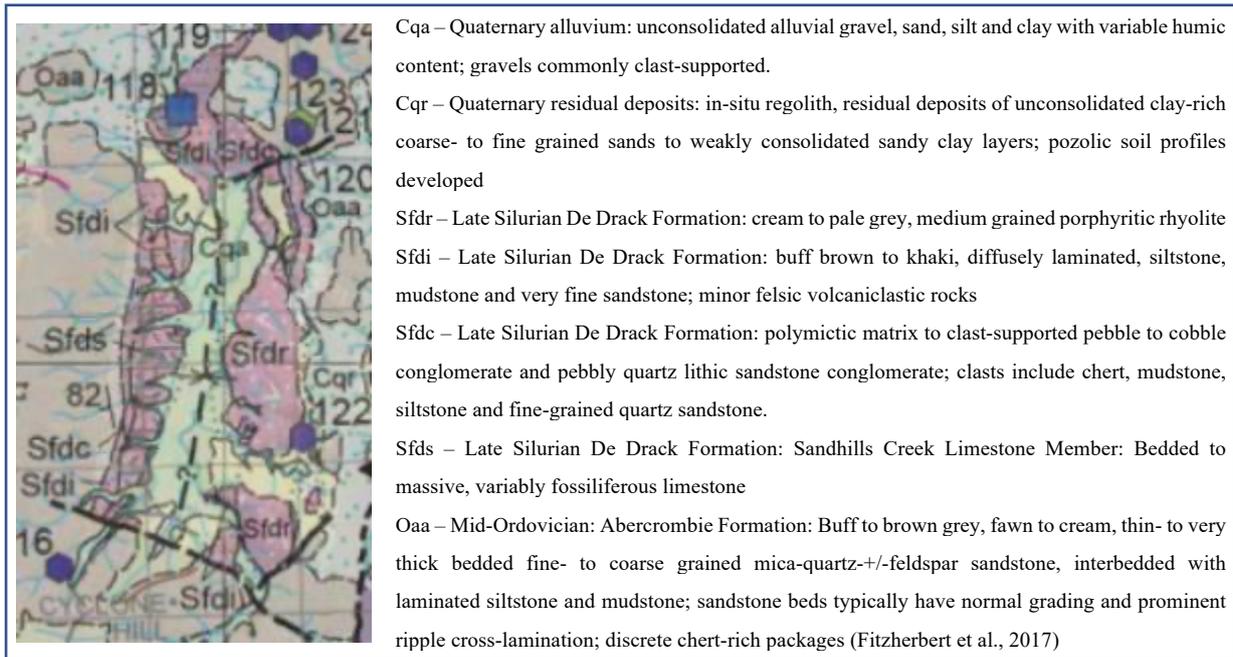
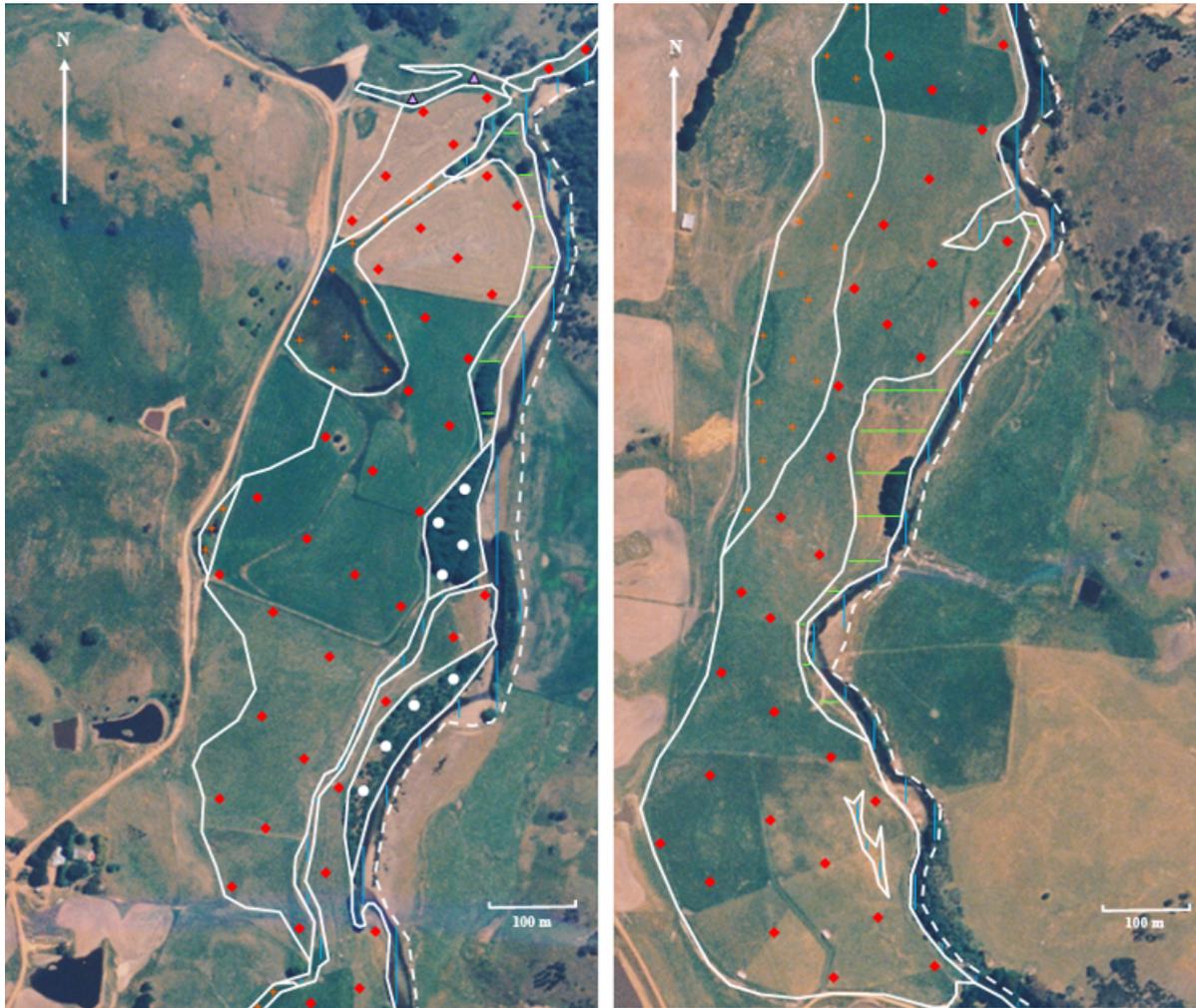


Figure 2. Geology of mid-Mulloon Creek (Fitzherbert et al. 2017).

The Bobbaduck Hills Hydrogeological Landscape (HGL) unit describes the landscapes that characteristically develop over the Silurian De Drack Formation (Jenkins et al. 2010). The HGL study recognises that land salinity is expressed along some lithological contacts in the De Drack Formation, in association with ferruginous duricrusts, and locally at the break in slope, and that there is limited but consistent salt load in streams. This generic descriptor is consistent with De Drack Formation landscapes to the north of the Home Farm, but salt expression of this type is not recognised in the study area.

Regolith landform mapping of the mid-Mulloon Creek floodplain has defined 6 regolith landform units (RLUs) on the eastern side of the channel (Figure 3). They are: an Alluvial Channel RLU (ACah) following the course of the contemporary stream, the lower parts of four tributary streams and a small remnant channel deposit (flood runner) south west of the channel on the alluvial plain (Figure 3b); an Alluvial Overbank floodplain RLU (AOaf) running the length of the mid-Mulloon Creek valley; an Alluvial Overbank floodout RLU (AOao) adjacent to the Creek on the mid- and northern floodplain; an Alluvial Channel alluvial terrace RLU (ACat) (rudimentary levee) proximal to the Creek on the mid-northern part of the valley floor; a back plain Alluvial Overbank alluvial swamp RLU (AOaw) on the western side of the valley

floor; and a Colluvial Sheet flow alluvial channel RLU (CHah) on the north-west of the valley floor.



	AOaw – Alluvial Overbank alluvial swamp
	AOaf – Alluvial Overbank floodplain
	ACah – Alluvial Channel alluvial channel
	AOao – Alluvial Overbank floodout
	ACat – Alluvial Channel alluvial terrace
	CHah – Colluvial Sheet flow alluvial channel
	RLU boundary
	Unspecified RLU boundary

Figure 3. Regolith Landform unit mapping for (a) northern half of the mid-Mulloon Creek flood plain (b) southern half of the mid-Mulloon Creek flood plain (Weber, 2003)

Three soil landscapes (SL) are present on the Home Farm: the Misery SL to the west, the Fairy SL to the east, and the Larbert SL along the channel of Mulloon Creek (Jenkins et al. 1995; Isbell et al. 2016) (Figure 4). The Misery SL catena is characterised by Lithosols (Lithic Tenosols) on the crests and Yellow Podzolic Soils (Chromosols) with localised Lithosols (Lithic Tenosols) on the upper to mid-slopes, and Yellow Podzolic Soils (Chromosols) on the lower slopes. The Fairy SL catena is characterised by Lithosols (Lithic Tenosols) on the crest, Yellow Earths (Yellow Chromosols) on the upper to mid-slopes and Yellow Podzolic Soils

(Chromosols) on the lower slopes. The Larbert SL has subdued topography with Red Earths (Red Chromosols) on the margins of footslope colluvial deposits, Solodic Soils (Sodosols) on older alluvial terraces, Non-Calcic Brown Soils (Brown Chromosols) and Prairie Soils (Vertisols) on the younger alluvial terraces, and Alluvial Soils (Rudosols) on the proximal floodplain and interfluvies (Figure 4). In the 0cm to 30cm interval the soil organic carbon (SOC) is reported as 3-4% on the valley floor and 1.5% to 2% on the colluvial lower slopes; the soil electrical conductivity (EC) is 0.2 to 0.3 dS/m; the soil pH is 5.5 to 6; the exchangeable sodium percentage (ESP) is 4% to 6%; total phosphorous (P) is 300 to 400 mg/kg; the sum of bases (SB) is 10 to 15 cmol/kg and the cation exchange capacity (CEC) is 15 to 20 cmol/kg, so the calculated base saturation SB/CEC is 66% to 75% (NSW DPIE, 2018). These values are consistent with modelled data presented on the eSPADE database (NSW DPIE, 2020)

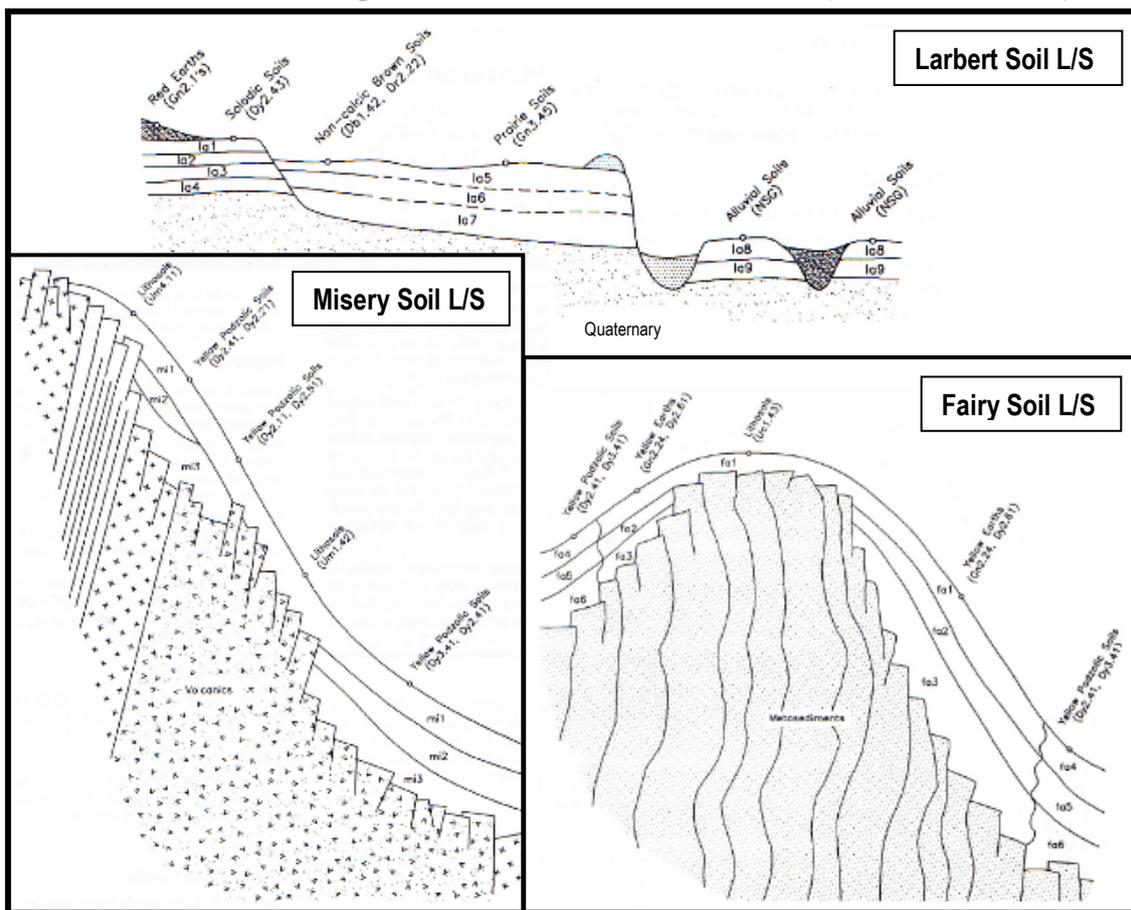


Figure 4. Soil Landscapes of mid-Mulloon Creek (Jenkins, 1995)

The principal land use on the Mulloon Home Farm is grazing on approximately 800 ha of modified pasture, mostly on plains (0-9m) flanked by low hills (30-90m) with treed upper slopes (Weber, 2010; DAWE, 2017). On the ridge crest, native dry sclerophyll forest is dominated by *Eucalyptus rossii*, *E. mannifera*, *E. dives*, *E. viminalis* and *E. bridgesiana* (Chivers, 1994) with integrated patches of relict old growth forest (Cavicchiolo, 1991). In this area, the dry sclerophyll forest has limited floristic and structural diversity, especially in the mid-story (Cavicchiolo, 1991; Chivers, 1994), attributed to poor soil fertility, including the presence of hydrophobic soils (Rath, 1993; Rao, 2005), and historic land-use impact (Chivers, 1994; Rao, 2005).

2. METHOD

2.1 Collection of Weather Data

The Home Farm weather station, located west of Mulloon Creek in the north of the valley (Figure 5), was commissioned in 2006, and data were initially collected by the Southern Rivers Catchment Management Authority (SR CMA) and later by interested researchers (e.g., Weber 2010-2012).



Figure 5. Location of stream gauging stations (n=2; P), weather stations (n=2; ○), boreholes (n=17; ●), rapid stream survey sites (n=17; W) and pond sampling sites (n=8) on the Mulloon Home Farm on the mid-section of Mulloon Creek.

Since 2014, hourly measurements of: rainfall (mm); air temperature (°C); relative humidity (%_{sat}); wind speed (km/hr); wind direction; total solar radiation (MJ/m²); and calculated evaporation (mm) have been monitored. Daily data gives average, maximum and minimum: air T (°C); windspeed (km/h); total solar radiation (MJ/m²); relative humidity (%); total rainfall (mm); and total evaporation (mm) using a 9 am to 9 am day. In addition, rainfall (mm) data is recorded every minute to enable calculation of rainfall intensity.

A new weather station, located west of Peter's Pond (Figure 5), was commissioned in August 2020 and is measuring: rainfall (mm); air temperature (°C); relative humidity (%); wind speed (km/hr); wind direction; barometric pressure (hPa); incoming solar radiation (W/m²); outgoing solar radiation (W/m²); calculated evaporation (mm); soil heat flux (8cm soil depth) (W/m²); soil temperature (8cm soil depth) (°C); and calculated dew point (°C), with scope to add a soil moisture sensor. Rainfall data is recorded at one-minute intervals, and all other measurements are recorded at daily, hourly and at ten-minute intervals. Collection of incoming and outgoing solar radiation, soil heat flux, soil temperature, and soil moisture enables calculation of the energy budget in this system. It provides information on the energy available for plant growth (including transpiration) and evaporation.

2.2 Collection of Stream Data

Rapid stream surveys have been conducted by university students annually since 2014. Sample sites are at: Black Jackie, south of Poplars Crossing, Poplars Crossing, Hazell Bank, Pokomy's Pond, Go Back Way Back, Platypus Pond, Triple Ponds Crossing, William's Wallow, Willows Crossing, Willows Runnel, north of Williams Crossing, Weather Station Crossing, Swamp Drain, north of Soil Con Inlet, Peter's Pond and Wombat Pond (Figure 5). Physicochemical data, including: water temperature (T; °C); Electrical Conductivity (EC; µS/cm); Dissolved Oxygen (DO; % and mg/L); pH; Oxygen Reduction Potential (ORP; mV); and Turbidity (NTU), were collected at each site.

Stream Pond water depth (manual stage) and physicochemical measurements, typically electrical conductivity (EC; µS/cm), water temperature (T; °C) and pH, have been manually sampled quarterly since 2014. Measurements were taken at: Black Jackie, Hazell Bank, Mitchell's Weir (near Pokomy's Pond), Triple Ponds, William's Wallow, Weather Station Crossing, Peter's Pond and Wombat's Pond (Figure 5).

2.3 Collection of Groundwater Data

Hydrogeological data have been acquired from an array of 17 boreholes aligned in 3 east-west transects across the valley, with 2 additional boreholes (BH 14 and BH1) west of the Creek, in the north (Figure 5). Data have been consistently collected from 13 of these boreholes (BH1-13) since December 2013, with sensors activated in 3 additional boreholes (BH3-2, BH5-2, BH8-2) in February 2017, and in 1 borehole (BH14) in December 2017. Manual readings have been collected episodically since September 2010, more reliably during periods when research projects were underway (e.g., Weber, 2010), and since December 2013 by NSW DPI. Manual readings are now taken every three months when sensors are manually downloaded. Stream gauging stations measuring Mulloon Creek water level are located at Black Jackie and at Peter's Pond, at the southern and northern ends of the Mid-Mulloon valley, respectively. From 2013, stream T (°C) and electrical conductivity (EC; µS/cm) were also measured at the gauging stations.

3. RESULTS

3.1 Weather

3.1.1 Rainfall

The historical cumulative rainfall deviation from the mean for the study area was calculated using data from Gidleigh BOM Station (1886 to 1998) and Palerang Station/Mulloon Home Farm (1999 to 2020). It shows a general drying trend from the late 1800s to 1948, then a general wetting trend to 1998 (Figure 6). From the late 1990s to the present, a period that includes the Millennium Drought (2003-2011), there has been a general drying trend. Since 1998, annual rainfall has exceeded the long-term mean in only two years: 2012 and 2016.

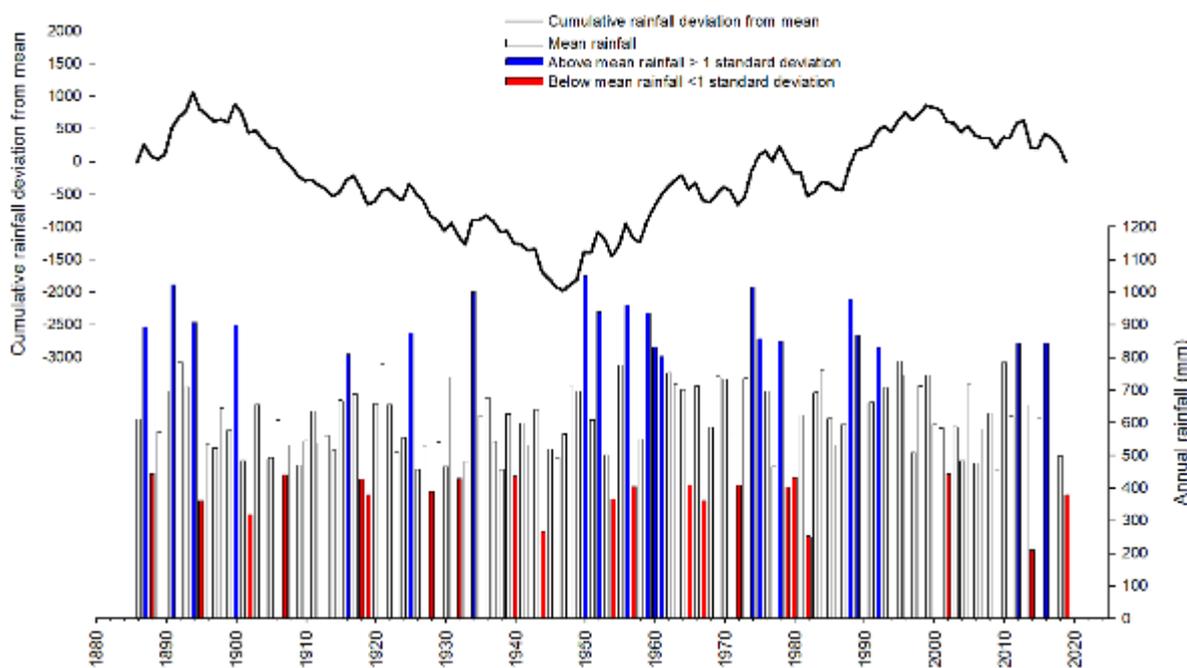


Figure 6. Historic rainfall information for the Mulloon Home Farm area, including: the cumulative rainfall deviation from mean, mean rainfall and indication of when rainfall was above the mean and below the mean for the period 1886 to 2020.

For the monitoring period (2006-2020), the measured median rainfall is 596mm, with the highest annual rainfall (845mm) in 2016 and the lowest (210mm) in 2014 (Table 1). Elevated rainfall in the 2010 (-2012) and (2015-) 2016 periods has been attributed to La Niña events nationally (Bureau of Meteorology, 2016; CSIRO, 2011; Hendon et al., 2014). Despite these changes in annual rainfall, the median monthly rainfall pattern remains similar for the monitoring period (Figure 7), with most rain falling in November, December and March.

Table 1 Annual rainfall (mm) pattern for Mulloon Home Farm (2006-2020)

	<i>Total</i>	<i>Autumn</i>	<i>Winter</i>	<i>Spring</i>	<i>Summer</i>
Median	596	91	120	169	203
25 centile	482	82	72	112	143
95 centile	844	221	231	199	271
2006	477	78	185	43	173
2007	580	90	165	163	124
2008	629	81	116	191	206
2009	457	91	93	148	150
2010	785	166	140	195	263
2011	619	89	120	195	241
2012	844	274	119	188	291
2013	653	83	190	190	203
2014	210	105	55	32	42
2015	613	198	202	102	74
2016	845	73	284	207	250
2017	551	181	60	176	137
2018	498	36	66	142	219
2019	379	119	53	70	243
2020		174			175
Average	581	122	132	146	186

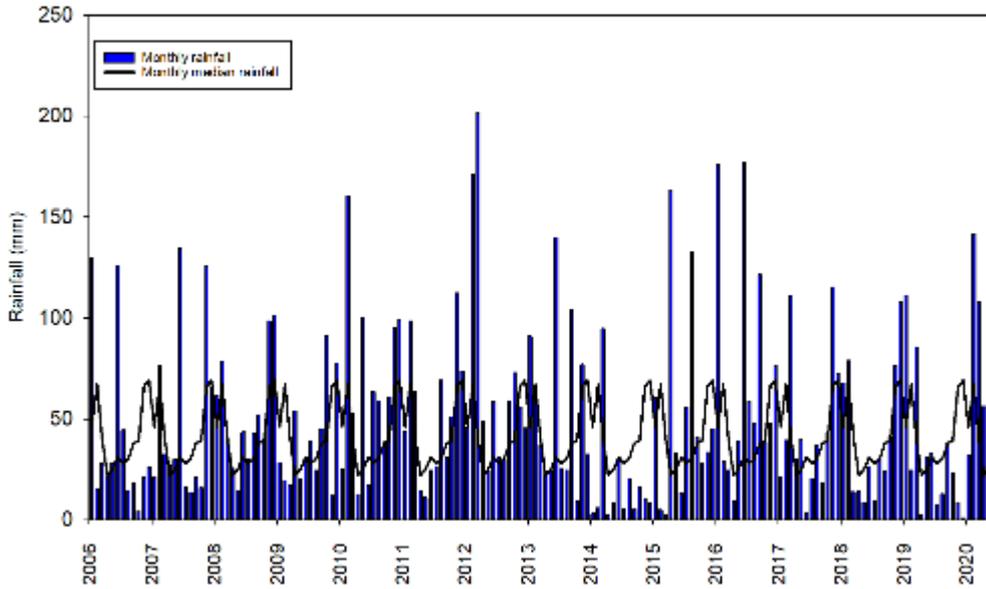


Figure 7. Measured monthly rainfall and running mean rainfall at the Mulloon Home Farm for the period 2006 to 2020

Rainfall at the Mulloon Home Farm is summer dominant, with approximately a third of the annual rainfall delivered in this season each year (Figure 8). Toward the end of the Millennium Drought (2006-2009), rain fell mostly in the summer and in late winter to early spring. In the subsequent La Niña period 2010-2011, rainfall increased across all seasons, but particularly in summer and spring. This pattern was similar in 2012, but with rain continuing from summer into the autumn months. In 2013, rainfall occurred in summer and from late winter into early spring. Leading into the El Niño period (2014-2015), rainfall was extremely low (210 mm) and mostly delivered in autumn. Similarly, in 2015, although the annual rainfall increased (613mm), it fell mostly in autumn and winter. In 2016, the annual rainfall was high for this area (845mm), falling in summer and late winter into spring. In part, this is because of a large rainfall event associated with an east coast low in early winter. In 2017, rain occurred in summer and autumn, was low in winter, then increased again in spring.

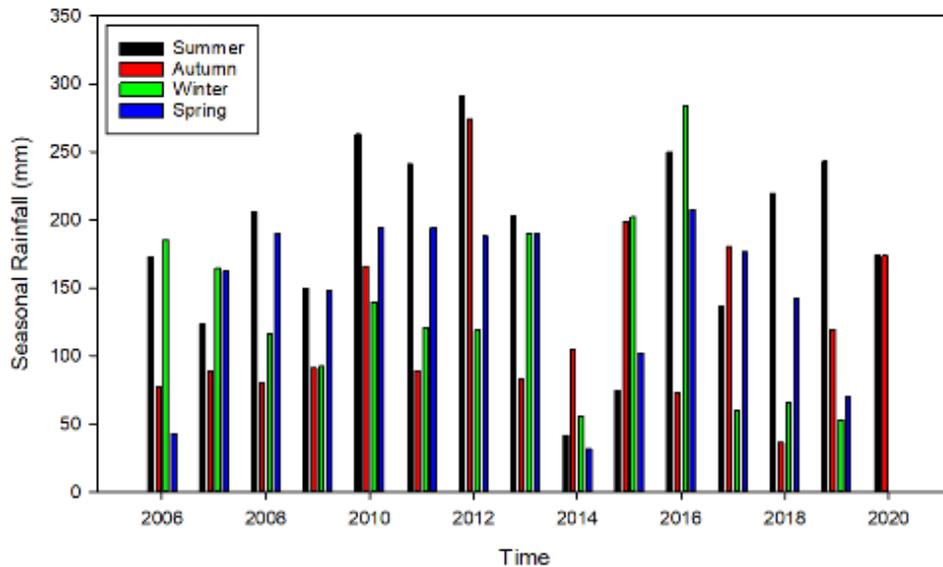


Figure 8. Measured seasonal rainfall at the Mulloon Home Farm for the period 2006 to 2020.

In 2019, rainfall was high in summer but very low for the rest of the year, leading to one of the worst bushfire seasons in history in late 2019-early 2020. Fortunately, the bushfires did not directly impact the Mulloon Home Farm area. This period is now referred to as the 2017-2019 Tinderbox Drought (BOM, 2023; Devanand et al., 2024). In 2020 rainfall increased in late summer and into autumn. Over the monitoring period, the lowest rainfall was typically in winter and autumn, and the highest in summer and spring.

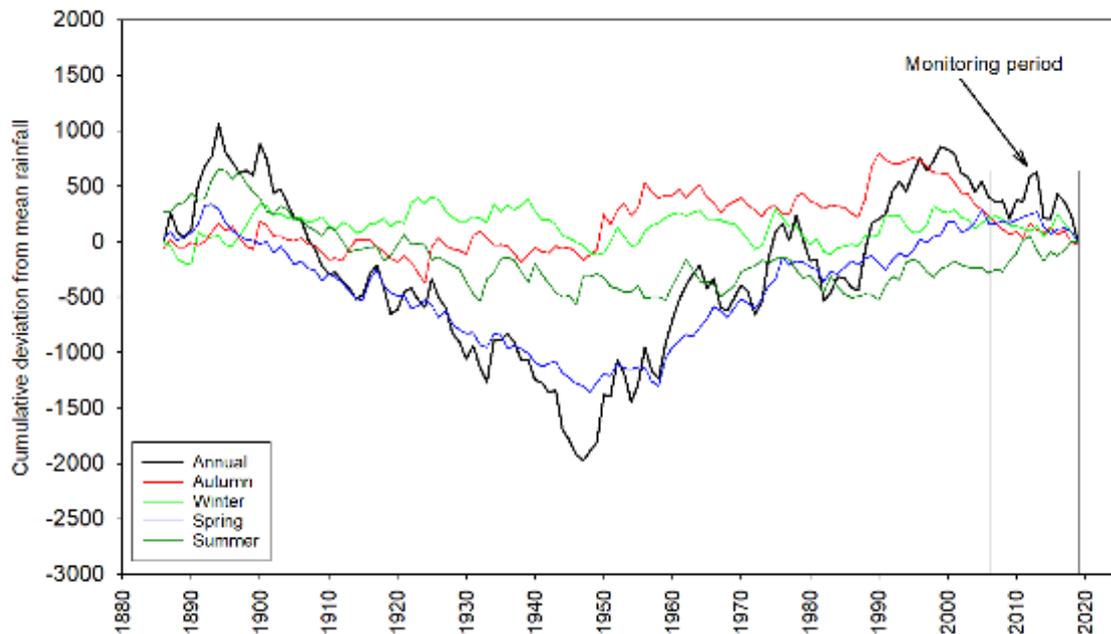


Figure 9. Historical cumulative rainfall deviation from the mean by season in the Mulloon area for the period 1886 to 2020.

When the historical cumulative rainfall deviation from the mean for the Mulloon area is considered by season (Figure 9) wetting and drying trends can be observed. When spring rainfall is below average (1886 to 1948), we see a decreasing (drying) trend, and when spring rainfall is above average (1948 to 1998), we see an increasing (wetting) trend. However, in recent decades (since 1998), rainfall in the autumn season most strongly reflects the drying trend. Changes in this pattern are potentially linked to a changing climate.

3.1.2 Air Temperature

The measured monthly air temperatures at the Mulloon Home Farm for the period 2006 to 2020 show a regular seasonal pattern with maximum temperatures (25°C to 30°C) in summer and minimum temperatures (-5°C to 13°C) in winter (Figure 10). The coldest winter temperatures are always below zero. The coldest minimum (-5°C) was in winter 2017, and the warmest maximum (30°C) was in summer 2019, during the Black Summer bushfire season.

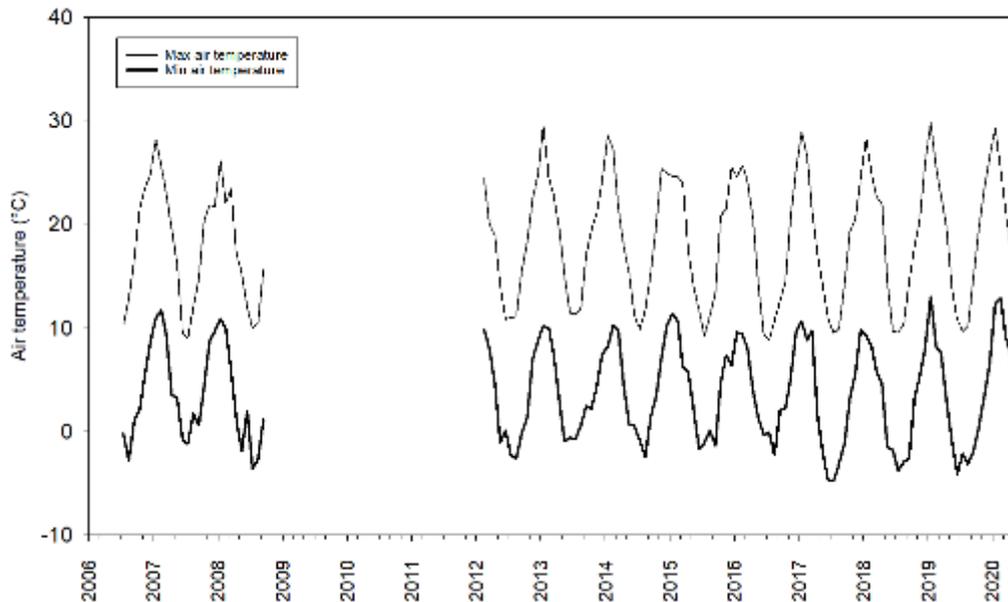


Figure 10. Measured maximum and minimum monthly air temperature at the Mulloon Home Farm for the period 2006 to 2020.

3.1.3 Wind Direction and Wind Speed

The measured wind direction at the Mulloon Home Farm for the period 2006 to 2020 shows that the prevailing winds are either from the west off the western highlands (Bearing 265°W to 285°W) or are coastal winds from the east (Bearing 085°W to 105°W) (Figure 11). In general, there is a broad pattern of winds from the north, north-west and west (Bearing 285°W to 350°N) and south, southeast and east (Bearing 105°E to 170°S). The south-east orientation also corresponds to the axis of a small valley east of the weather station, which might channel wind towards it (Figure 5). It is rare to experience winds from the north-east or south-west.

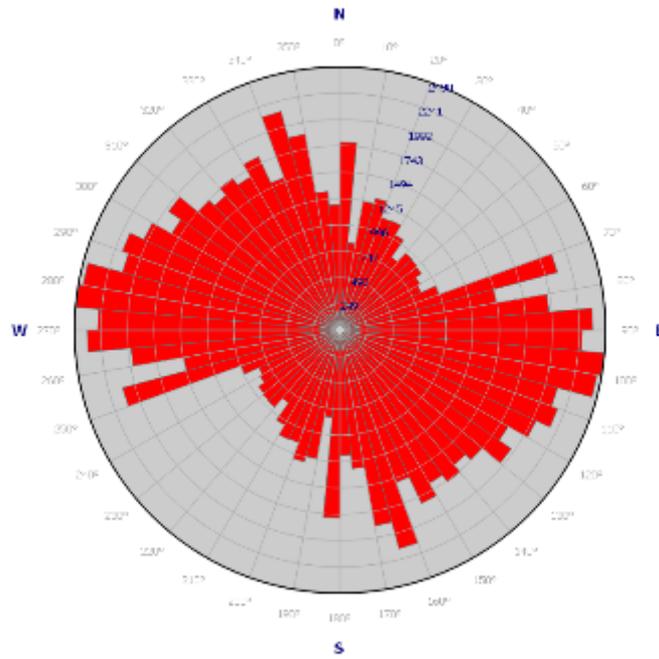


Figure 11. Measured wind direction at the Mulloon Home Farm for the period 2006 to 2020.

The measured wind speed at the Mulloon Home Farm for the period 2006 to 2020 indicates that winds generally have a low velocity (<15 m/s) (Figure 12). From 2006 to mid-2015, wind speeds typically ranged from 1 m/s to 15 m/s in the winter and 3 m/s to 8m/s in the summer. From mid-2015 to 2019, the pattern changed with lower velocities in the winter and higher wind speeds in the late spring and summer. Higher winds occurred in autumn and winter 2007 (28 m/s and 18 m/s), spring 2017 (18 m/s), autumn 2018 (25 m/s), and there was a general increase in average wind speed to the hot, dry summer of late 2019 (33 m/s) to early 2020 (26 m/s).

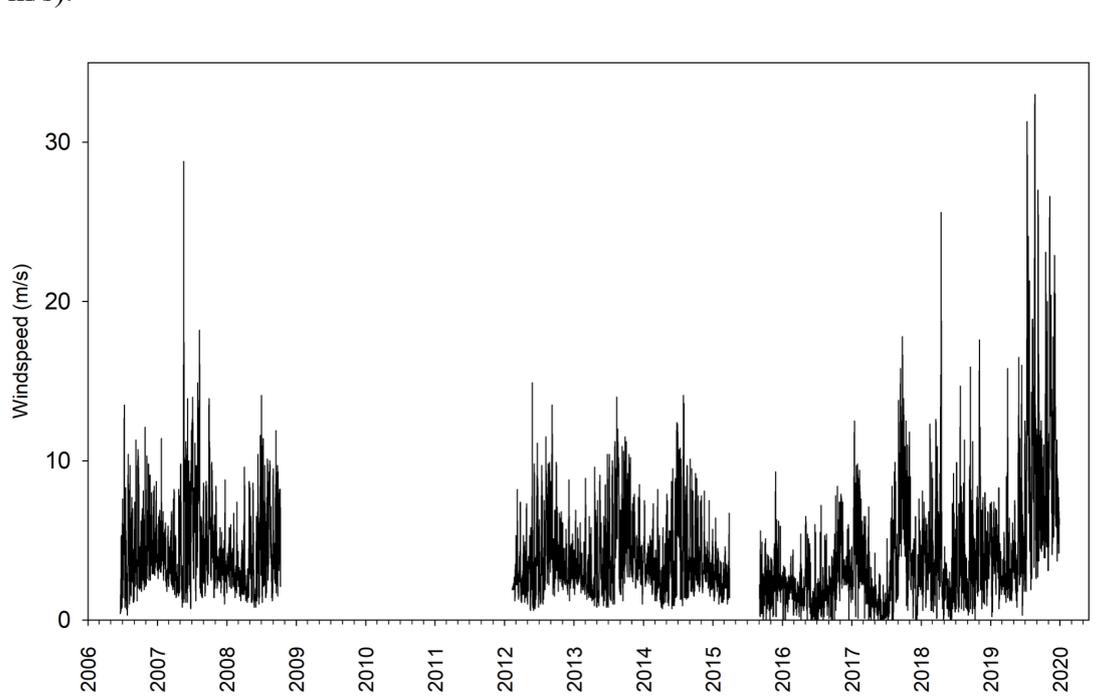


Figure 12. Measured average daily wind speed at the Mulloon Home Farm for the period 2006 to 2020.

3.1.4 Relative Humidity

Relative humidity is the amount of water vapour present in the air (%) relative to the amount of water the air could potentially hold if saturated, at the same temperature. At the Mulloon Home Farm the relative humidity varies seasonally, with values lower in summer (20-60%_{sat}) and higher in winter to early spring (60-90%_{sat}) (Figure 13). Relative humidity was low for an extended period in the hot, dry summer of 2007 (late Millennium Drought), and every summer in the 2017-2019 Tinderbox Drought. There is a small decrease in maximum relative humidity over the study period.

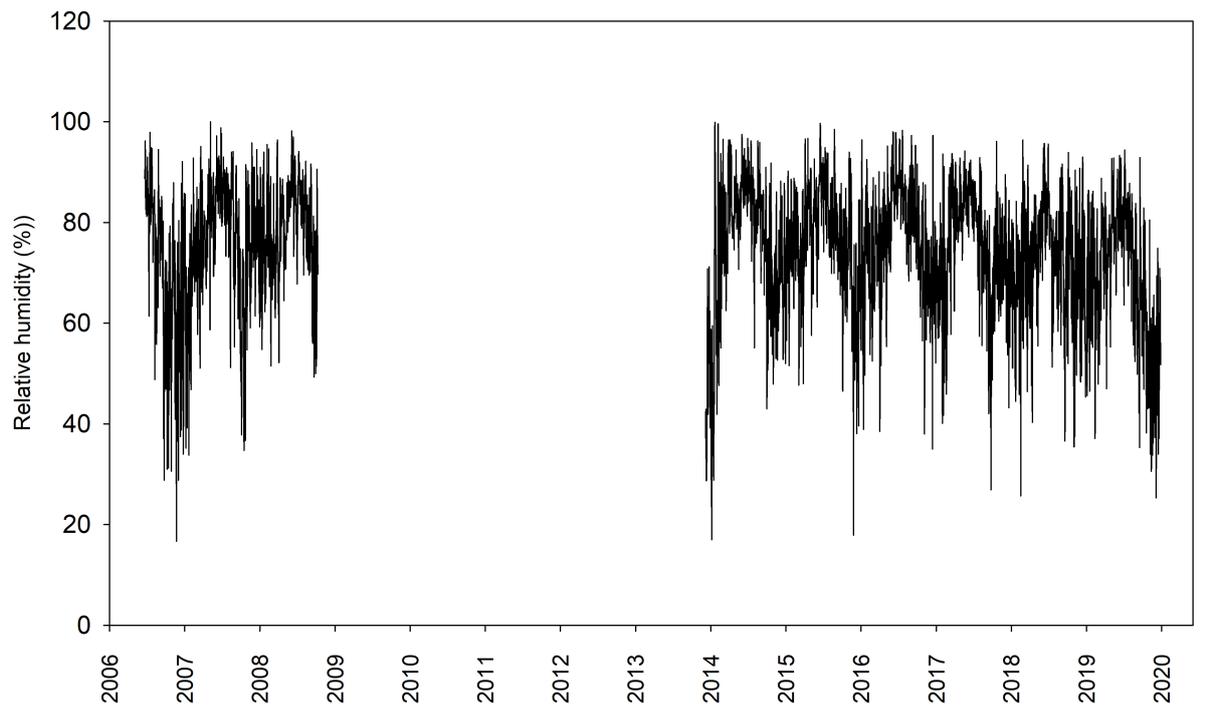


Figure 13. Measured relative humidity at the Mulloon Home Farm for the period 2006 to 2020.

3.1.5 Global Solar Radiation

Global solar radiation (MJ/m^2) is the total solar radiation measured on a horizontal surface of known area. Values change seasonally with higher radiation in summer ($120\text{-}380 \text{ MJ}/\text{m}^2$) and lower in winter ($10\text{-}120 \text{ MJ}/\text{m}^2$) (Figure 14). No notable changes in solar radiation patterns have been detected at Mulloon Home Farm over the study period.

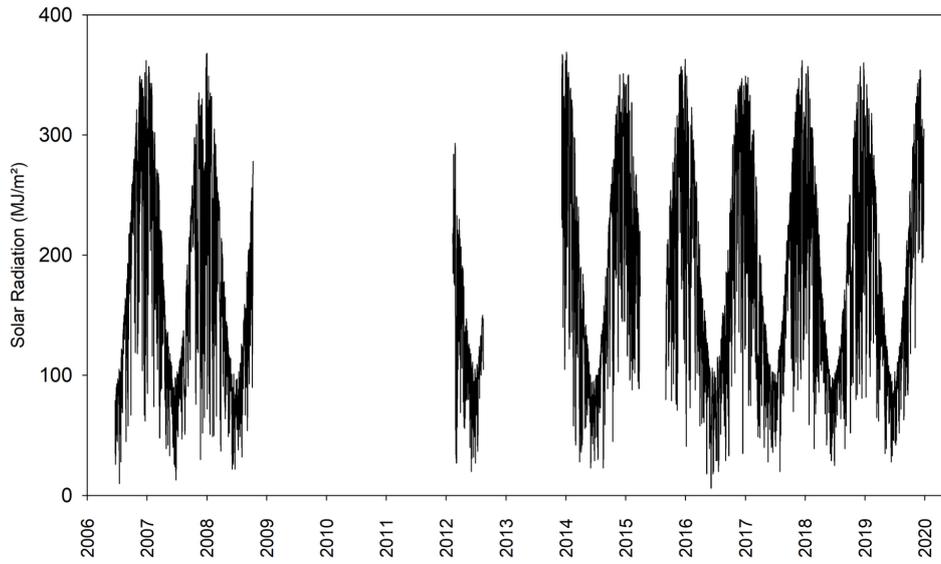


Figure 14. Measured daily global solar radiation at the Mulloon Home Farm for the period 2006 to 2020.

3.1.6 Potential Evapotranspiration

Potential evapotranspiration (PET) is the amount of evapotranspiration that would occur under optimum conditions where water is readily available. The potential evapotranspiration pattern is similar to the global solar radiation pattern, as these two parameters have a causal link; that is, the amount of evapotranspiration is related to the amount of solar radiation. At the Mulloon Home Farm, the PET has a higher maximum and a larger range in summer (1.5-13.0 mm/day) than in winter (0.5-2.0 mm/day) (Figure 15). The highest PET values (13 mm/day) were recorded in 2007 (late Millennium Drought) and in 2020 (late 2017-2019 Tinderbox Drought).

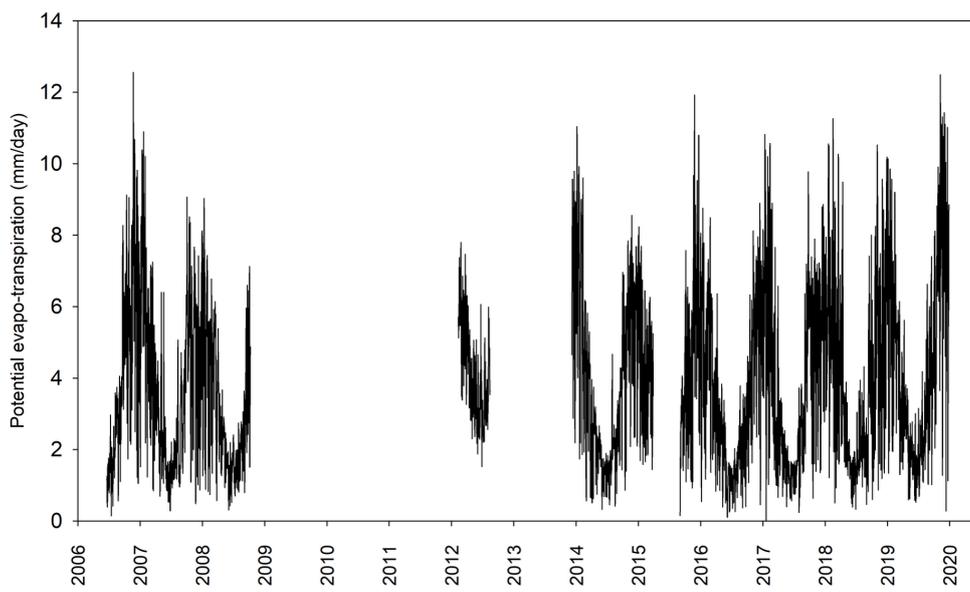


Figure 15. Potential evapotranspiration at the Mulloon Home Farm for the period 2006 to 2020.

3.2 Stream Flow

3.2.1 Stream Flow and Daily Stage (2006-2020)

Measures of water depth (daily stage) mirror the daily flow data, which were measured at the Black Jackie and Mid-Mulloon Stream Gauges (Figure 16a; Figure 16 b; Figure 17a; Figure 17b). Flow is typically very low (<200 ML/day; daily stage <0.5m) in the upper mid-Mulloon Creek, and there are many periods with no flow (Figure 16a) and no measurable water at the gauge (Figure 16 b). Higher flow and corresponding higher daily stage measurements (up to 2.5m) occur during and after sustained rain events (Figure 16b).

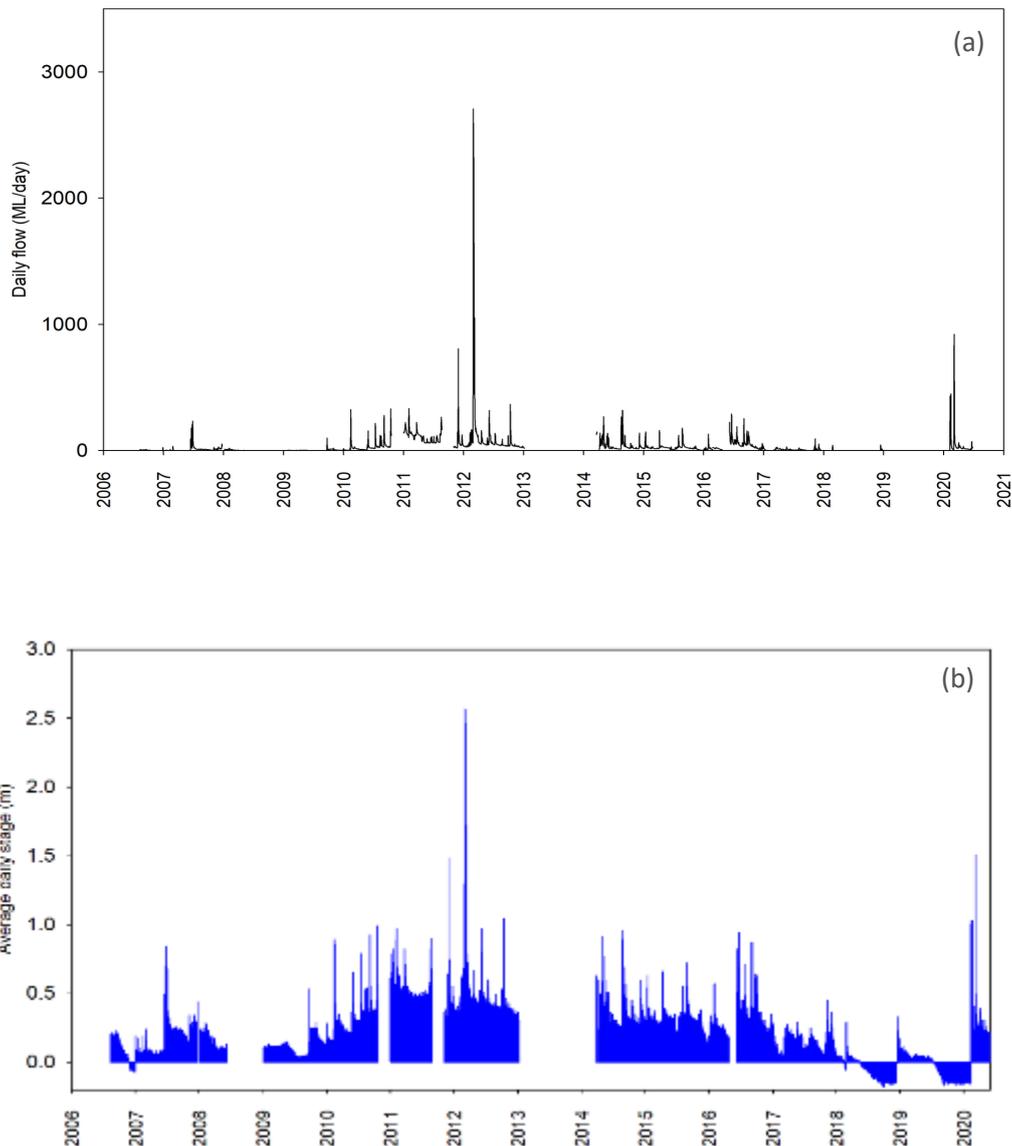


Figure 16. (a) Daily flow (ML/day), and (b) average daily stage (water depth in m) at the (southern) Black Jackie Stream Gauge, Mulloon Home Farm, for the period 2006 to 2020.

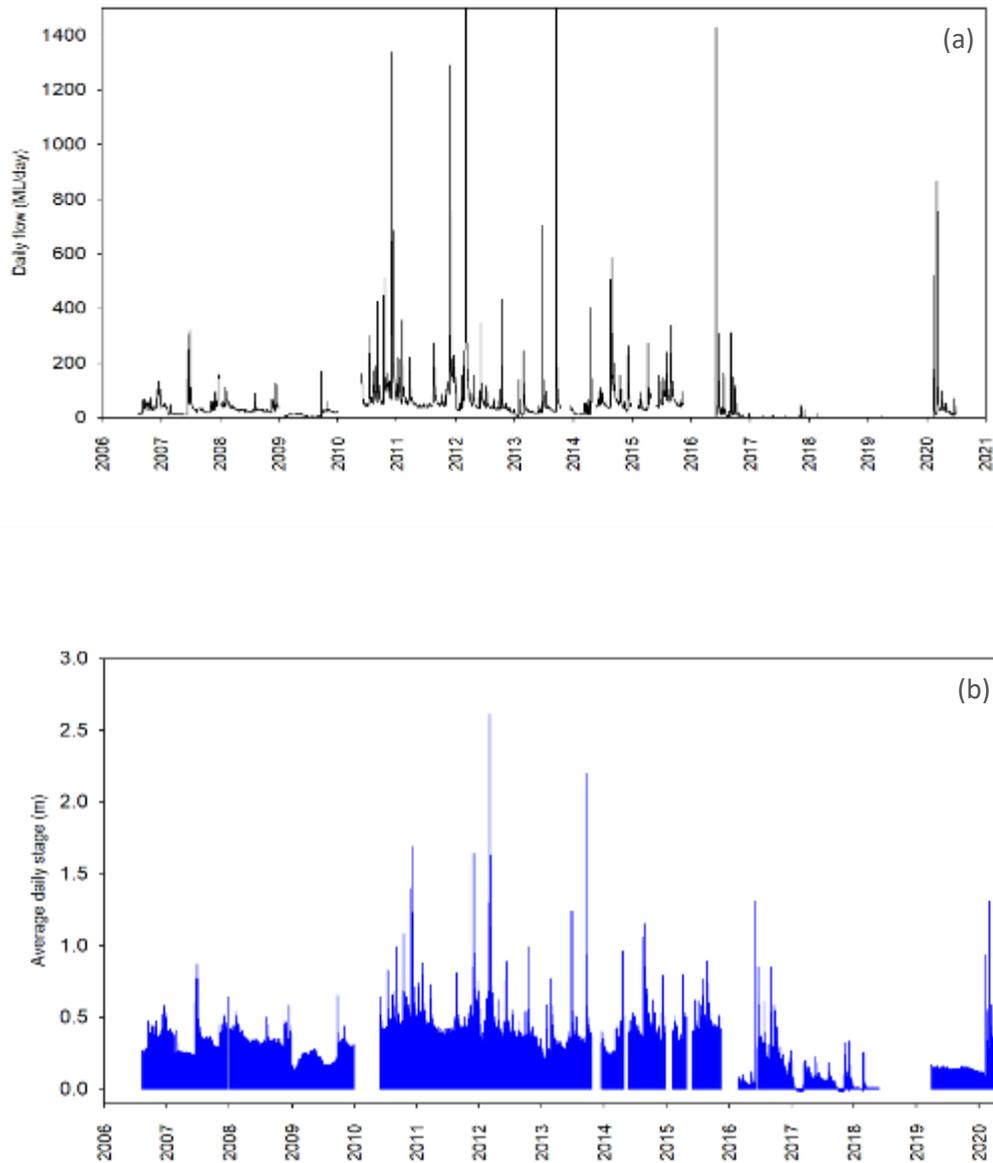


Figure 17. (a) Daily flow (ML/day), and (b) average daily stage (water depth in m) at the (northern) Mid-Mulloon Stream Gauge, Mulloon Home Farm, for the period 2006 to 2020.

Flow is generally a little higher (100-300 ML/day; daily stage 0.5-0.75m) in the lower mid-Mulloon Creek (as measured at the gauge), with fewer intervals of very low flow (Figure 17a; Figure 17b). Lower flow occurred during the Millennium Drought to 2010, and during the 2017-2019 Tinderbox Drought. Higher flow and corresponding higher daily stage measurements (up to 2.5m) occur during and after sustained rain events (Figure 17b).

There has been some concern from key stakeholders downstream that the in-stream modifications undertaken at the Mulloon Home Farm might intercept and hold water without releasing it down Mulloon Creek. These data show that there is a similar flow in and out of the Mulloon Home Farm part of the catchment, and typically a little more water leaves the study

area than enters via Mulloon Creek (Figure 18; Figure 19). This is likely attributable to runoff, interflow and possibly localised groundwater flow into the reach of Mulloon Creek that passes through Mulloon Home Farm. For example, in early 2017 and in early 2020 the amount of water passing the Mid-Mulloon Stream Gauge exceeded the water passing the Black Jackie Stream Gauge (Figure 20a; Figure 20b).

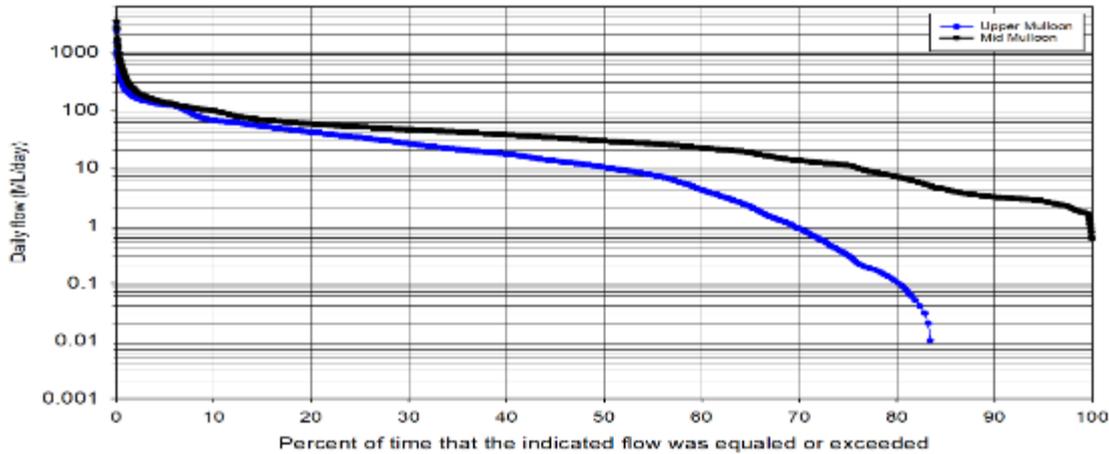


Figure 18. Daily flow (ML/day) for the Black Jackie and Mid-Mulloon Stream Gauges showing the percent of time the flow leaving the Mulloon Home Farm equals or exceeds the flow entering the Mulloon Home Farm, for the period 2006 to 2020.

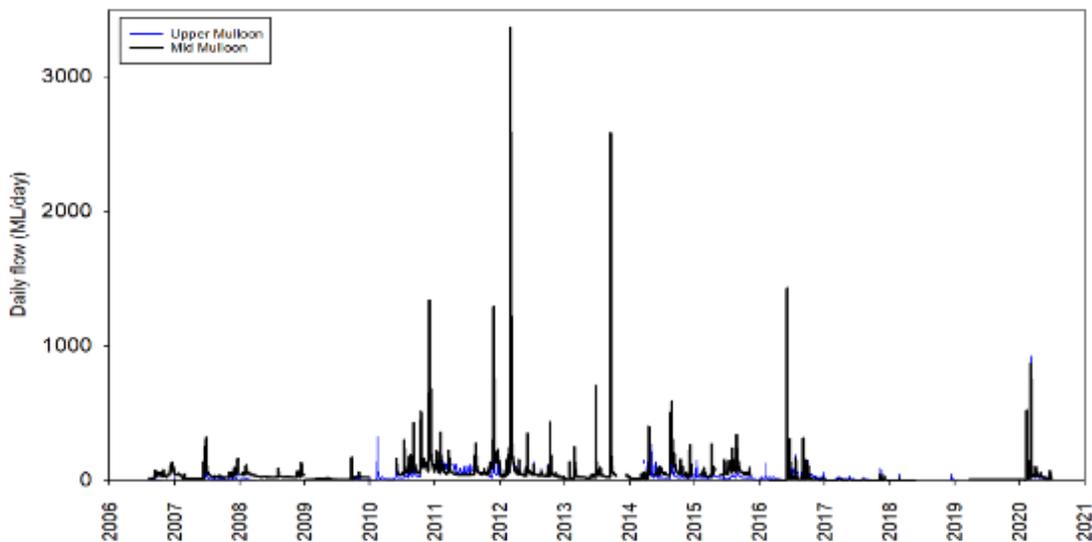


Figure 19. Daily flow (ML/day) for the Black Jackie and Mid-Mulloon Stream Gauges showing when the flow leaving the Mulloon Home Farm equals or exceeds the flow entering the Mulloon Home Farm, for the period 2006 to 2020.

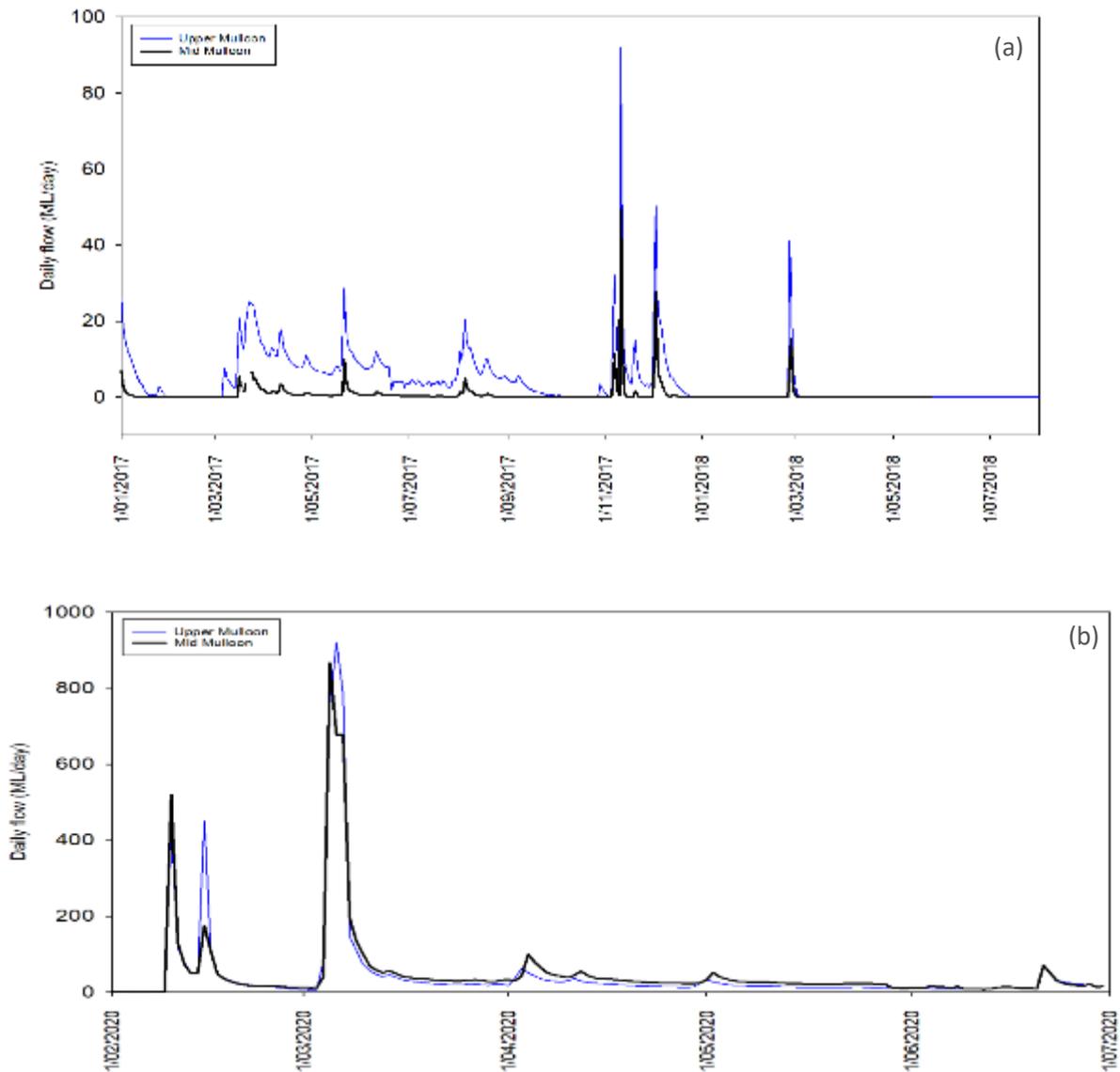


Figure 20. (a) Daily flow (ML/day) for the Black Jackie and Mid-Mulloon Stream Gauges in early 2017 and (b) in early 2020, showing a period when water exited the Mulloon Home Farm equals and at times exceeds the flow entering via Mulloon Creek.

3.2.2 Recent Stream Flow and Stream Physico-chemistry (2016-2020)

Mulloon Creek enters Mulloon Home Farm from the south, and the Black Jackie Stream Gauge monitors the water coming into this part of the valley (Figure 5). Stream flow is typically very low over the study period, approaching zero for extended periods, and increases significantly after rainfall events (Figure 21a; Figure 21c).

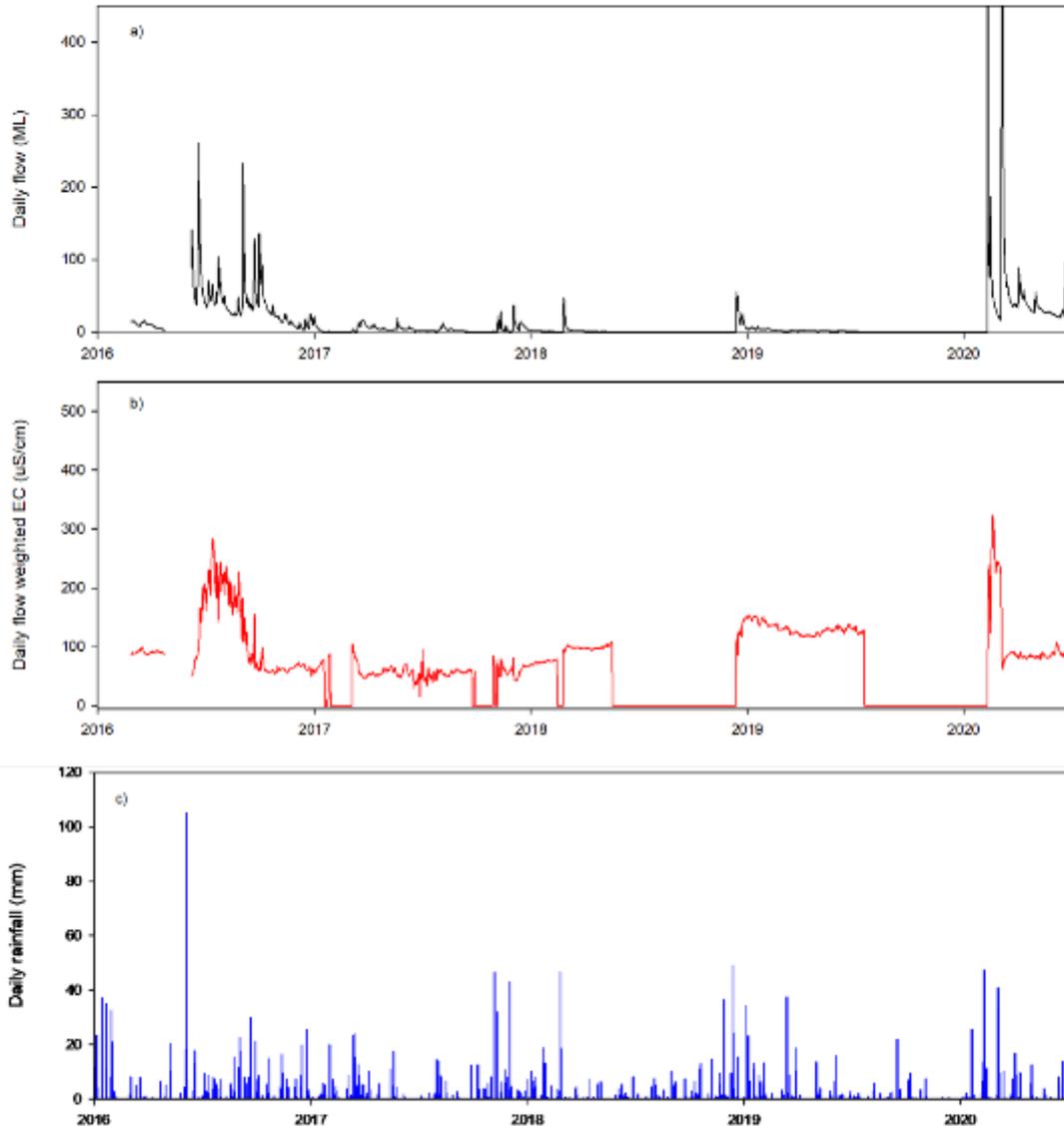


Figure 21. (a) Daily flow, (b) daily flow weighted electrical conductivity and (c) daily rainfall at the (southern) Black Jackie Stream Gauge, Mulloon Home Farm, for the period 2016 to 2020.

Waters are typically very fresh ($<100 \mu\text{S}/\text{cm}$) with elevated electrical conductivity (EC) associated with higher flow after rain events (Figure 21b). During a flood event in mid-2016, EC reached $290 \mu\text{S}/\text{cm}$, and after rains in early 2020, reached $320 \mu\text{S}/\text{cm}$ (Figure 21b; Figure 21c). These waters are still considered fresh (Table 4; Mayer et al., 2005).

Table 2 Salinity Status - Total Salt Concentration (EC) (after Mayer et al. 2005)

Salinity Status	Electrical Conductivity (EC)	Description and Use
Fresh	<500	Drinking, irrigation and stock water
Marginal	500-1,000	Most irrigation (manage duration), stock water
Brackish	1,000-2,000	Irrigation (certain crops), water for most stock
Saline	2,000-10,000	Water for some stock
Highly Saline	10,000-35,000	Very limited agricultural use
Brine	>35000	Specialised industrial use; seawater

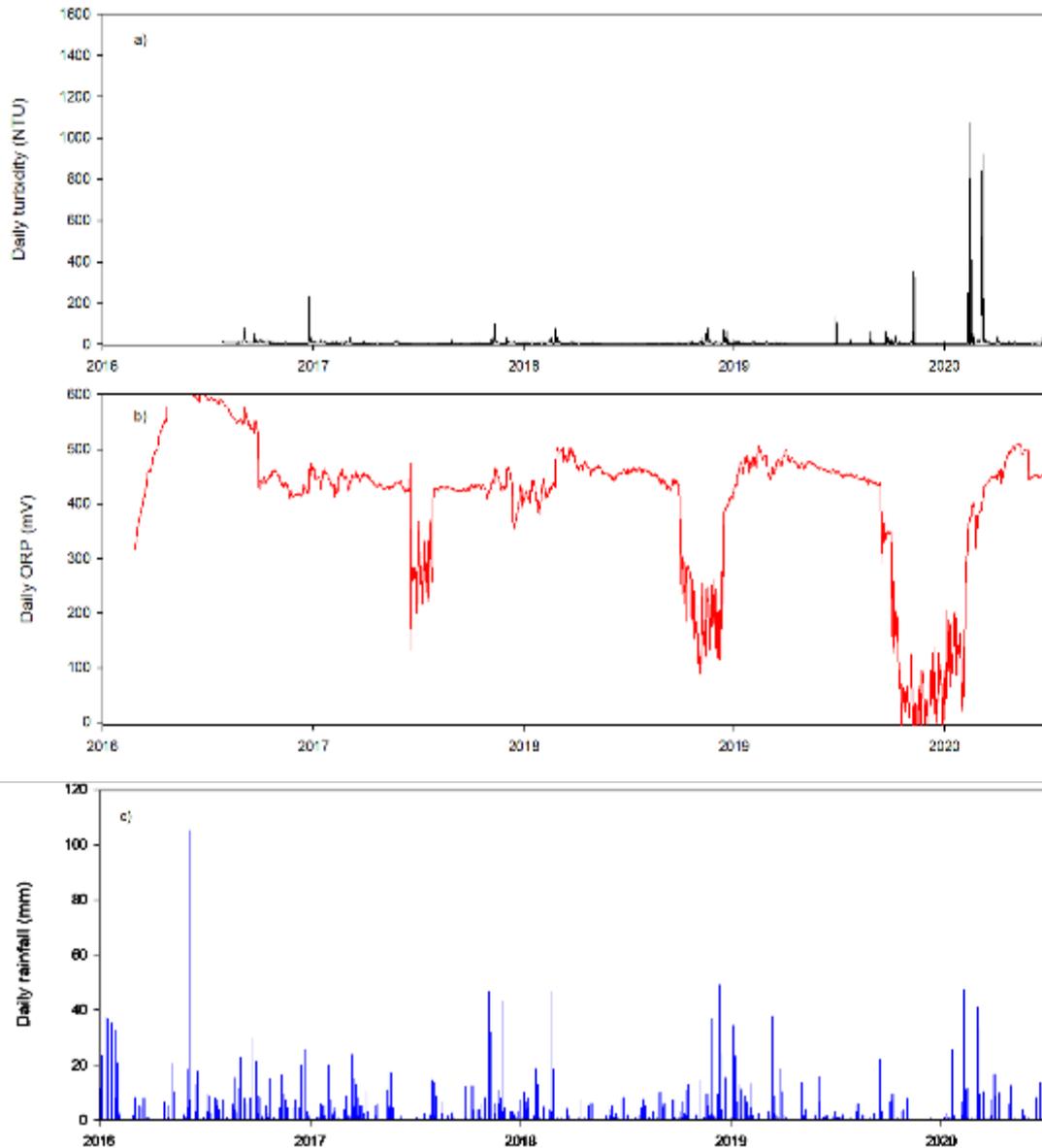


Figure 22. (a) Daily turbidity, (b) daily oxidation-reduction potential (ORP) and (c) daily rainfall at the (southern) Black Jackie Stream Gauge, Mulloon Home Farm, for the period 2016 to 2020.

Under normal flow conditions, the turbidity measurements are typically low ($\ll 100$ NTU) and the water relatively clear. Stream water is more turbid (400-1100 NTU) when there is higher velocity flow during and post major rain events (Figure 22 a; Figure 22 c).

Oxidation-reduction potential is a measure of the presence of oxidants (can gain electrons, e.g. oxygen) and reductants (can donate electrons, e.g. organic matter, dust, byproducts of micro-organism activity and other contaminants) in the water. If reductants are high, the ORP value is low, and vice versa. At Black Jackie, the ORP is typically relatively high (400-600 mV), but

there were lower ORP measurements in: mid-2017 and late 2018 (down to 100 mV) and in late 2019 (down to 0 mV) – periods when flow was low, and the impacts of the 2017-2019 Tinderbox Drought were severe (Figure 22b).

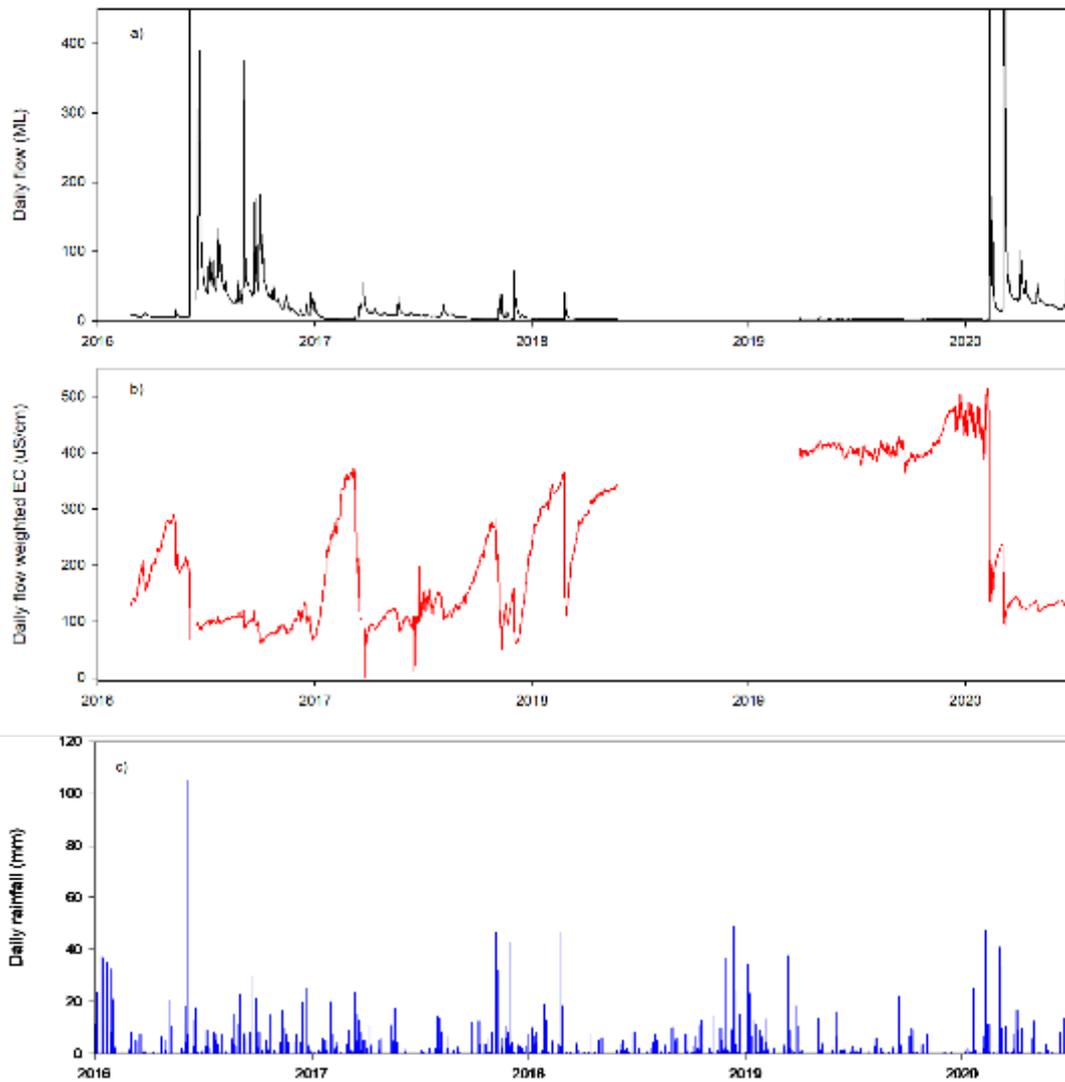


Figure 23. (a) Daily flow, (b) daily flow weighted electrical conductivity and (c) daily rainfall at the (northern) Mid-Mulloon Stream Gauge, Mulloon Home Farm, for the period 2016 to 2020.

Mulloon Creek leaves Mulloon Home Farm to the north, and the Mid-Mulloon Stream Gauge monitors the water exiting this part of the valley (Figure 4). Stream flow is typically low for the study period, reflecting the low flow entering the valley from the south. Again, significant increases in flow are observed after rainfall events, notably in the second half of 2016, and in early 2020 (Figure 23a).

Stream waters are considered fresh ($<500 \mu\text{S}/\text{cm}$; Table 4; Mayer et al., 2005) but have higher electrical conductivity (EC) values than those entering the Mulloon Home Farm (Figure 23b). Stream water EC shows increases between rain events, possibly due to evaporative

concentration and/or groundwater ingress, and the stream water is more dilute during periods of higher flow (late 2016 and early 2020) (Figure 23b; Figure 23c).

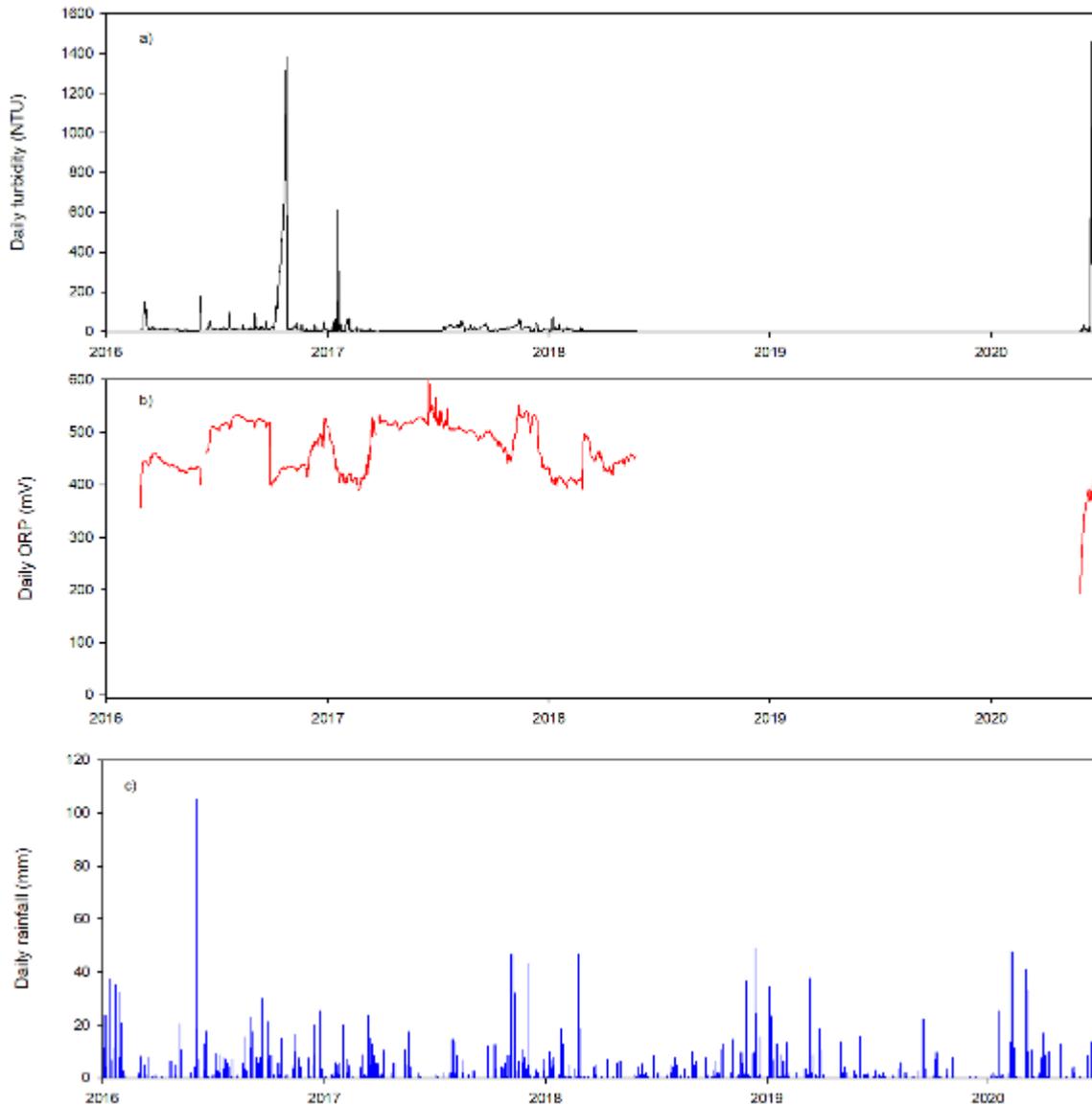


Figure 24. (a) Daily turbidity, (b) daily oxidation-reduction potential (ORP) and (c) daily rainfall at the (northern) Mid-Mulloon Stream Gauge, Mulloon Home Farm, for the period 2016 to 2020.

The turbidity measurements are typically low (<150 NTU), and the water carries some suspended sediment. Stream water is more turbid (600-1400 NTU) when there is higher velocity flow during and post major rain events, with peaks in late 2016 and in early 2020 (Figure 24a).

At Mid-Mulloon the ORP is relatively high (400-600 mV) (Figure 24b), indicating that the water can behave as an oxidising agent. The desirable range for potable water is 250-600 mV.

3.3 Rapid Stream Appraisal

A Rapid Stream Appraisal (RSA) was conducted at 17 sites on the mid-Mulloon Creek (Table 3; Figure 4) in August 2014, September 2014, November 2014, June 2016, November 2016, July 2017, May 2018 and March 2020; commonly as targeted studies by university placement students.

Site	Name	Latitude	Longitude
1	Black Jackie	-35 ° 17 ' 46.56 "	149 ° 35 ' 27.38 "
2	South of Poplars Crossing	-35 ° 17 ' 14.42 "	149 ° 35 ' 14.60 "
3	Poplars Crossing	-35 ° 17 ' 10.71 "	149 ° 35 ' 12.19 "
4	Hazell Bank	-35 ° 17 ' 04.34 "	149 ° 35 ' 15.62 "
5	Pokomy's Pond	-35 ° 17 ' 02.63 "	149 ° 35 ' 16.72 "
6	Go back way back	-35 ° 16 ' 55.06 "	149 ° 35 ' 23.01 "
7	Platypus pond	-35 ° 16 ' 52.12 "	149 ° 35 ' 21.01 "
8	Triple Pond crossing	-35 ° 16 ' 43.98 "	149 ° 35 ' 20.99 "
9	Williams Wallow	-35 ° 16 ' 34.03 "	149 ° 35 ' 26.14 "
10	Willows Crossing	-35 ° 16 ' 29.18 "	149 ° 35 ' 25.47 "
11	Willows Runnel	-35 ° 16 ' 25.13 "	149 ° 35 ' 26.80 "
12	Crossing - North of Willows	-35 ° 16 ' 21.97 "	149 ° 35 ' 28.52 "
13	Weather Station Crossing	-35 ° 16 ' 18.67 "	149 ° 35 ' 29.72 "
14	Swamp Drainage Channel	-35 ° 16 ' 13.84 "	149 ° 35 ' 28.13 "
15	North of Soil Con Inlet	-35 ° 16 ' 13.96 "	149 ° 35 ' 28.35 "
16	Peters Pond	-35 ° 16 ' 13.25 "	149 ° 35 ' 29.75 "
17	Wombat Pond	-35 ° 16 ' 12.11 "	149 ° 35 ' 31.49 "

3.3.1 RSA Stream Water Temperature

Stream water temperature showed a slight decreasing trend (13°C to 10°C) (Minimum to Maximum Air Temperature (M-MAT 6.3°C to 13.3°C) as it flowed northward on 23 August 2014, with a similar pattern observed, at higher temperatures on 25 September 2014 (18°C to 13°C) (M-MAT 9.8°C to 17.8°C) (Figure 25a). In both cases, stream water temperature increases were observed South of Poplars Crossing and at the Crossing North of the Willows. On 5 November 2014, the opposite trend was observed with temperatures increasing downstream (9°C to 11°C) (M-MAT 7.7°C to 26.0°C).

Winter stream water temperature ranges in June 2016 (4°C to 6°C) (M-MAT -0.7 to 14.2°C) and July 2017 (4°C to 7°C) (M-MAT -4.3 to 11.0°C) were the lowest observed, with no apparent increase or decrease in stream water temperature along mid-Mulloon Creek (Figure 25b). In the region, 2016 was a period of high rainfall and flooding. In contrast, the summer temperatures in November 2016 were much higher (24°C to 19°C) (M-MAT 9.4°C to 26.6°C), with the highest temperature (24°C) measured at 3 locations: South of Poplars Crossing, at Williams Wallow and North of the Soil Con Outlet. The lowest temperatures were measured at Willows Crossing (20°C) and Wombat Pond (19°C).

In May 2018, the winter stream water temperatures showed some fluctuation in temperature, typically decreasing slightly downstream (11.5°C to 7°C) (M-MAT 3.1°C to 23.9°C) (Figure 25c). In March 2020, the autumn stream water temperatures (15.5°C to 16.5°C) (M-MAT 12.3°C to 18.8°C) were similar along the length of the mid-Mulloon Creek. In general, stream water temperatures reflected broad patterns in air temperature, with cooling downstream indicating localised (constant temperature) groundwater gain.

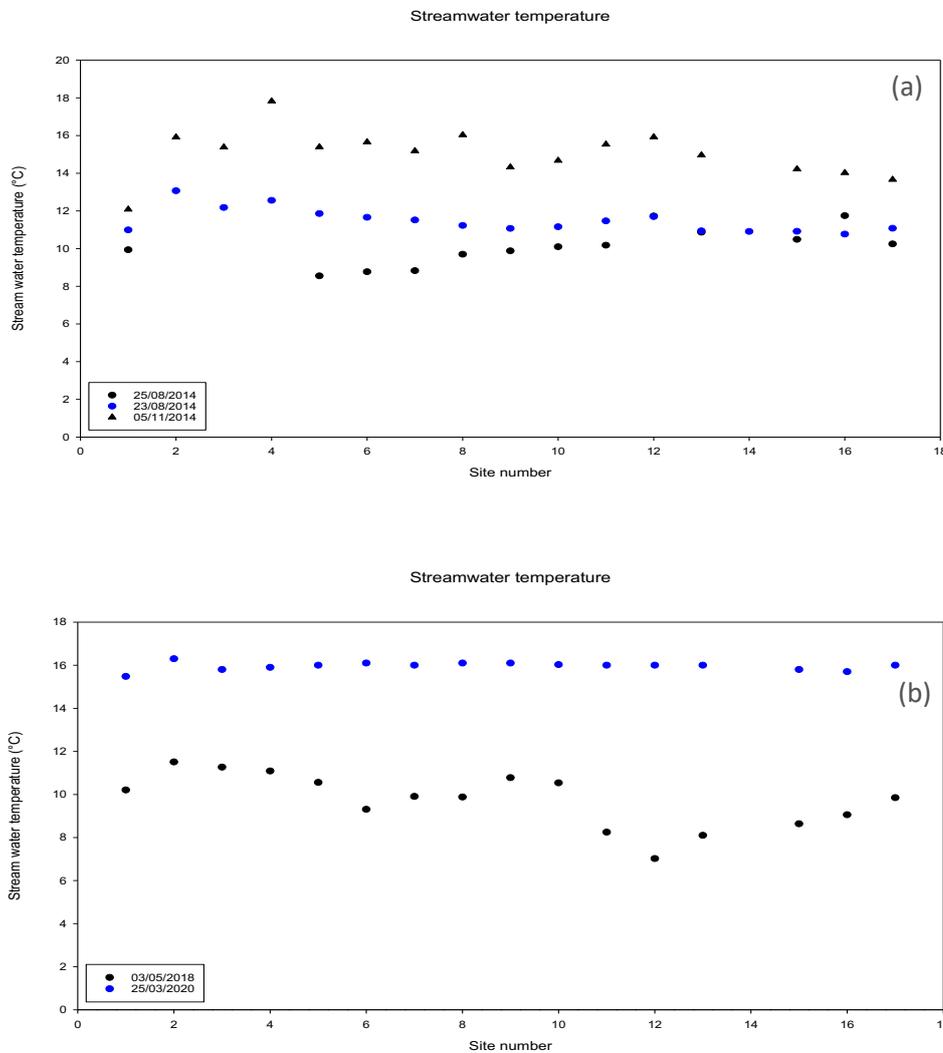


Figure 25. Stream Water Temperature at 17 sites on mid-Mulloon Creek (a) 2014; (b) 2016/2017; (c) 2018/2020

3.3.2 RSA Stream Water Electrical Conductivity

For all monitoring periods, the mid-Mulloon Creek water was very fresh, usually less than 200µS/cm and commonly less than 100µS/cm (Figure 26). In Australia, the maximum electrical conductivity (EC) threshold for potable water is 800µS/cm.

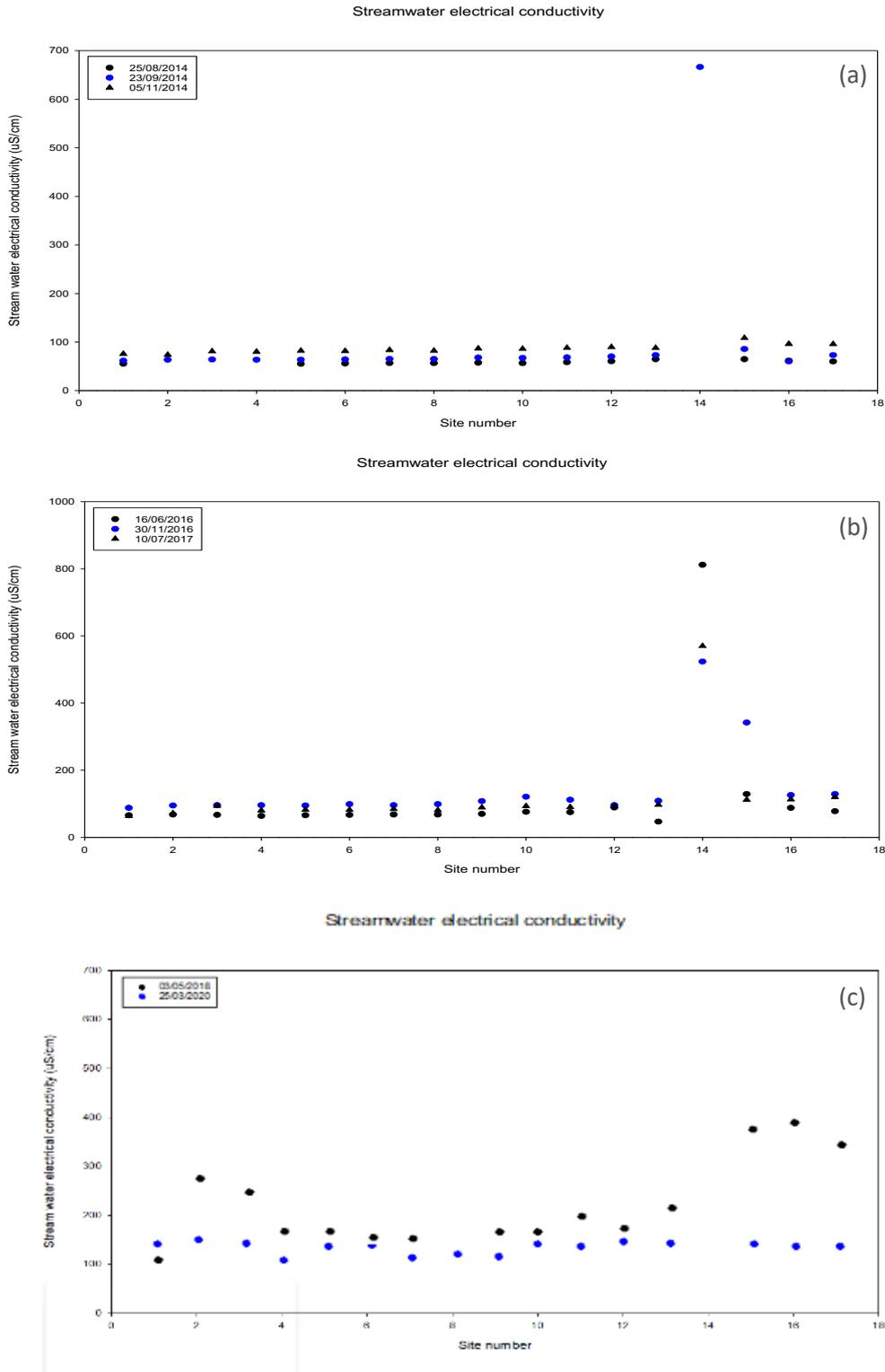


Figure 26. Stream Water EC at 17 sites on mid-Mulloon Creek (a) 2014; (b) 2016/2017; (c) 2018/2020

The exception to this pattern is water measured at the outlet to the Swamp Drainage Channel, where elevated EC values were measured in late winter 2014, 780µS/cm; winter 2016, 800µS/cm; late spring 2016, 500µS/cm; and winter 2017, 520µS/cm. The higher EC water from the Swamp Drainage Channel caused elevated values immediately downstream (North of

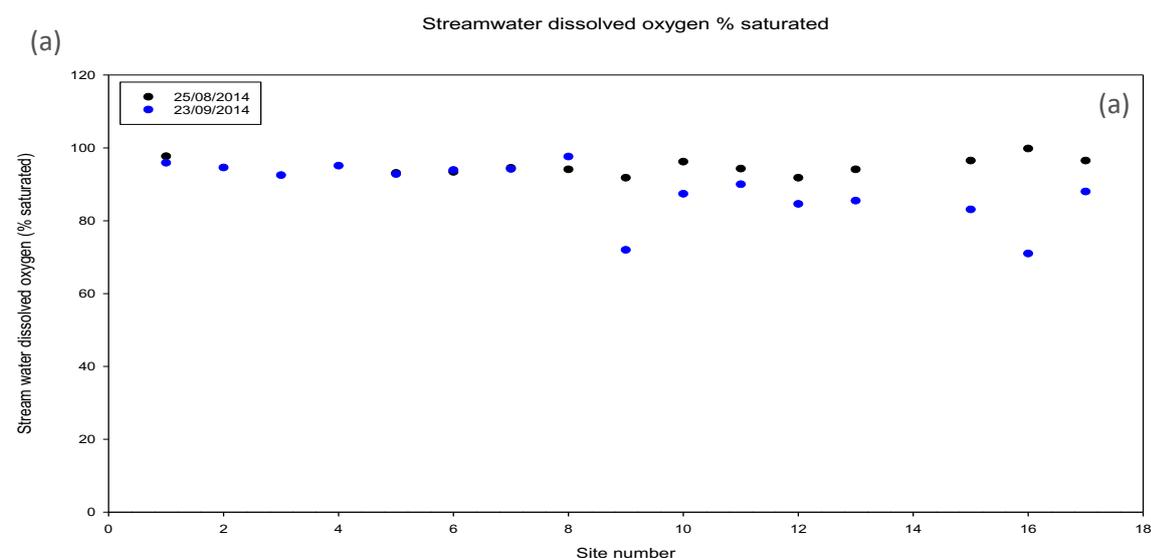
the Soil Con inlet), but these typically stabilised below $100\mu\text{S}/\text{cm}$ at Peter's Pond. A similar pattern was observed in the 2018 mid-drought, but EC levels downstream of the Swamp Drainage Channel stayed elevated at around $300\mu\text{S}/\text{cm}$. These data suggest that salts are concentrated due to evaporation from the Swamp, and waters draining this area introduce slightly saline water to mid-Mulloon Creek at the Swamp Drainage Channel outlet. In 2018, during the 2017-2019 Tinderbox Drought, EC values for water sampled South of and at Poplars Crossing had slightly elevated EC ($280\mu\text{S}/\text{cm}$ and $240\mu\text{S}/\text{cm}$), possibly associated with evaporation from ponded stream water.

3.3.3 RSA Stream Water Dissolved Oxygen

Natural waters with sustained dissolved oxygen levels in the range 80-100% saturation (~ 8 - 10mV at 15°C) are considered healthy and can support a wide range of aquatic organisms. Dissolved oxygen (DO) levels in the mid-Mulloon Creek measured in late winter and spring 2014 (Figure 27a; Figure 28a), winter 2016 (Figure 27b; Figure 28b) and autumn 2020 (Figure 27c; Figure 28c) were typically in this range. In winter 2016, the DO values exceeded 100% saturation, likely because waters were oxygenated during a series of flood events.

Waters measured in late spring 2016 and winter 2017 (Figure 27b; Figure 28b), as the 2017-2019 Tinderbox Drought commenced, had DO values mostly in the 60-80% saturation (6 - 8mV at 15°C) range. Dissolved oxygen at these levels can sustain aquatic ecosystems, but these conditions are sub-optimal.

In the winter of 2018 (Figure 27c; Figure 28c), mid-drought, the DO levels were in the range 0-40% saturation ($< 4\text{mV}$) saturation with considerable variation from site to site. Highest DO levels (40% saturation; $\sim 4\text{mV}$) were observed for Black Jackie, Platypus Pond and Wombat Pond. The lowest levels (0%) were observed at Williams Wallow and Willows Crossing, where flow was extremely low. In general, pond areas were able to sustain some aquatic ecosystems, but elsewhere these ecosystems were impacted.



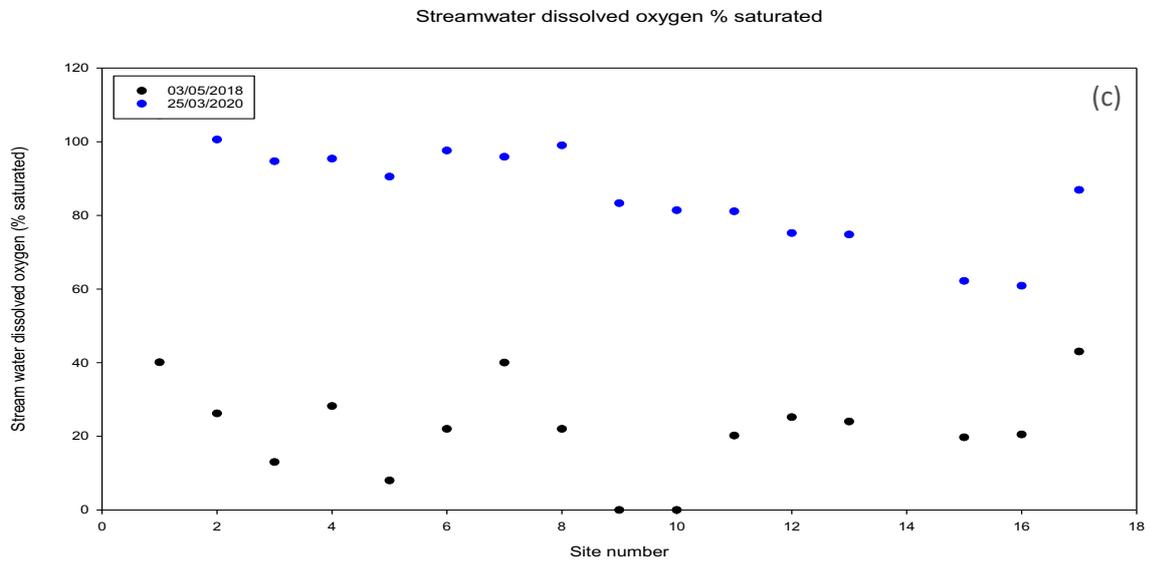
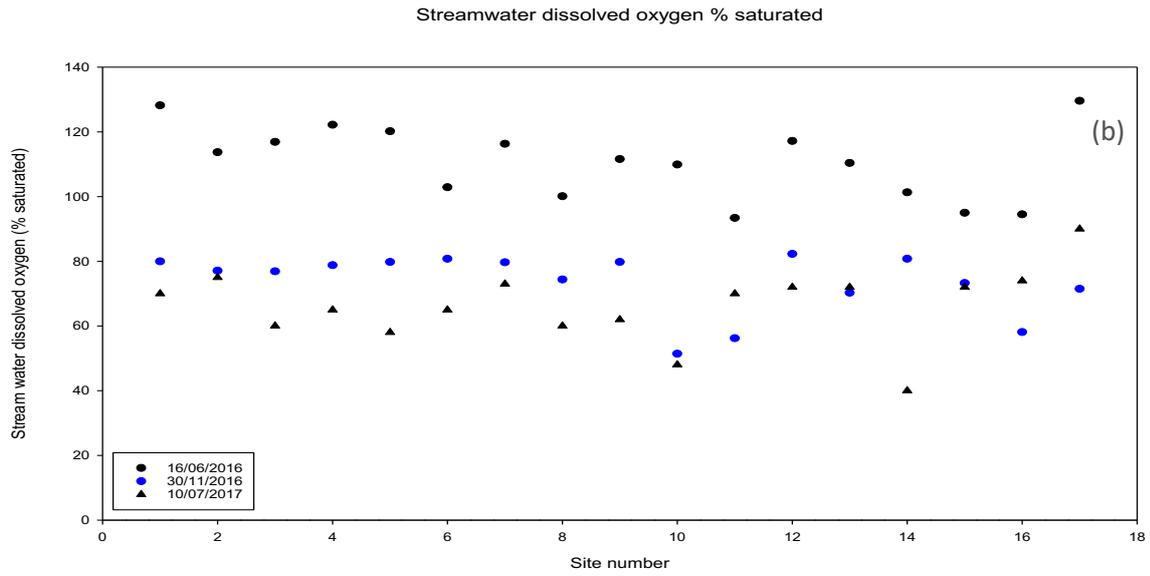
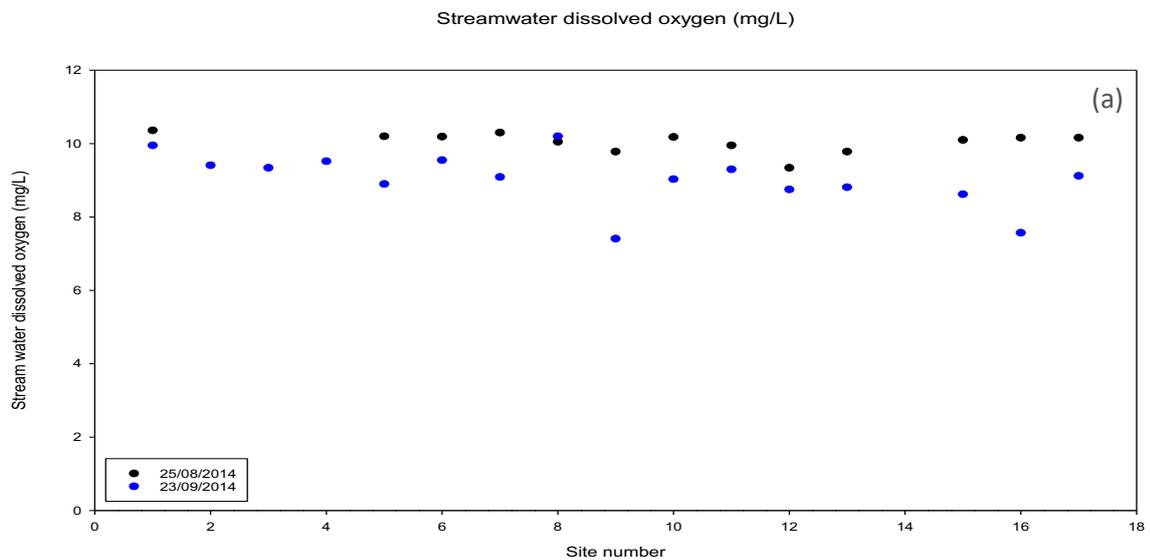


Figure 27. Stream Water DO (% sat.) at 17 sites on mid-Mulloon Creek (a) 2014; (b) 2016/2017; (c) 2018/2020



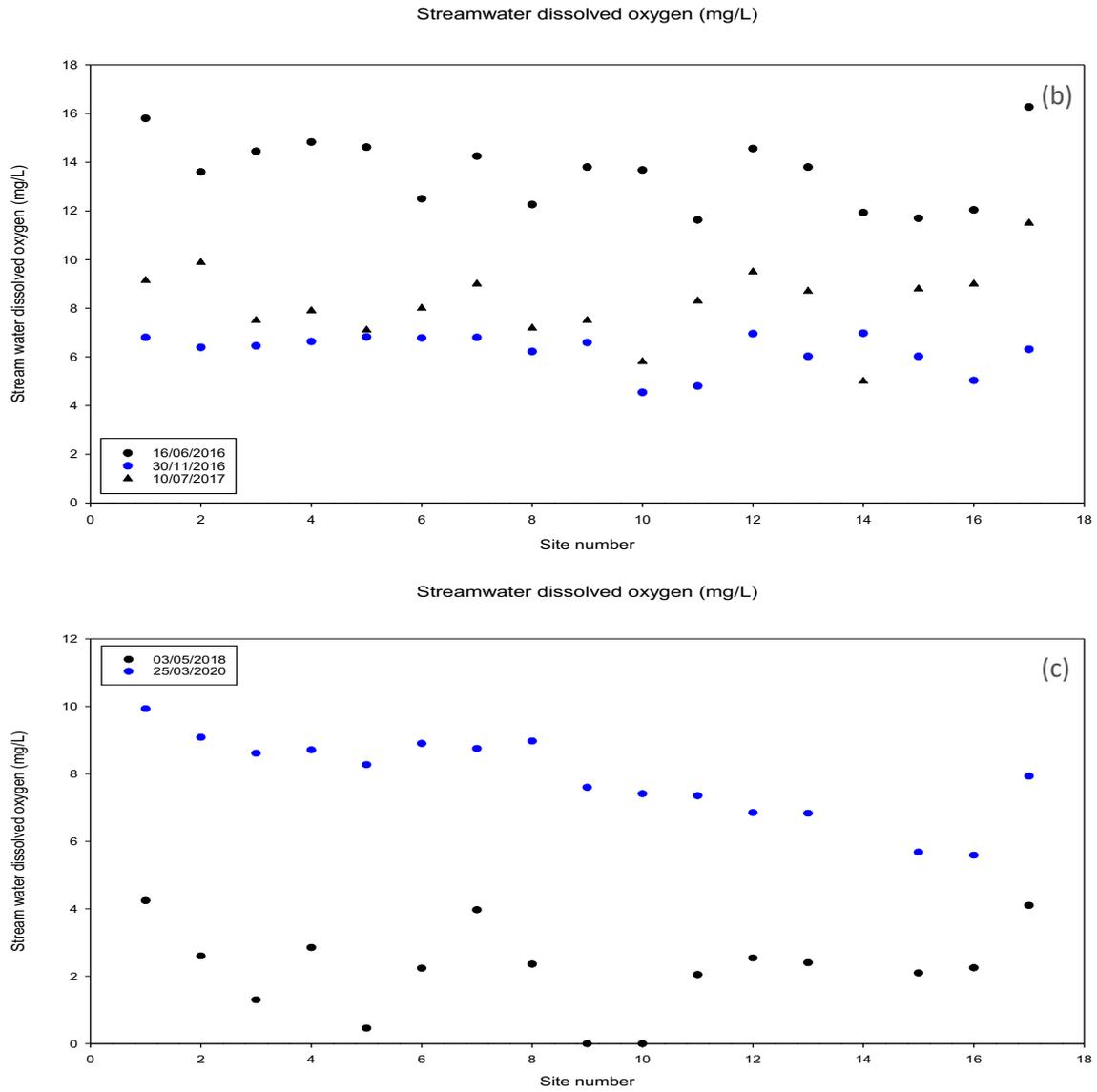


Figure 28. Stream Water DO (mg/L) at 17 sites on mid-Mulloon Creek (a) 2014; (b) 2016/2017; (c) 2018/2020

3.3.4 RSA Stream Water pH

All sites measured on mid-Mulloon Creek had stream pH values in the range 6.5 to 7.8 (Figure 29), within the normal range for natural waters (pH 5-9). Values around neutral (pH 7) are optimal for sustaining aquatic ecosystems.

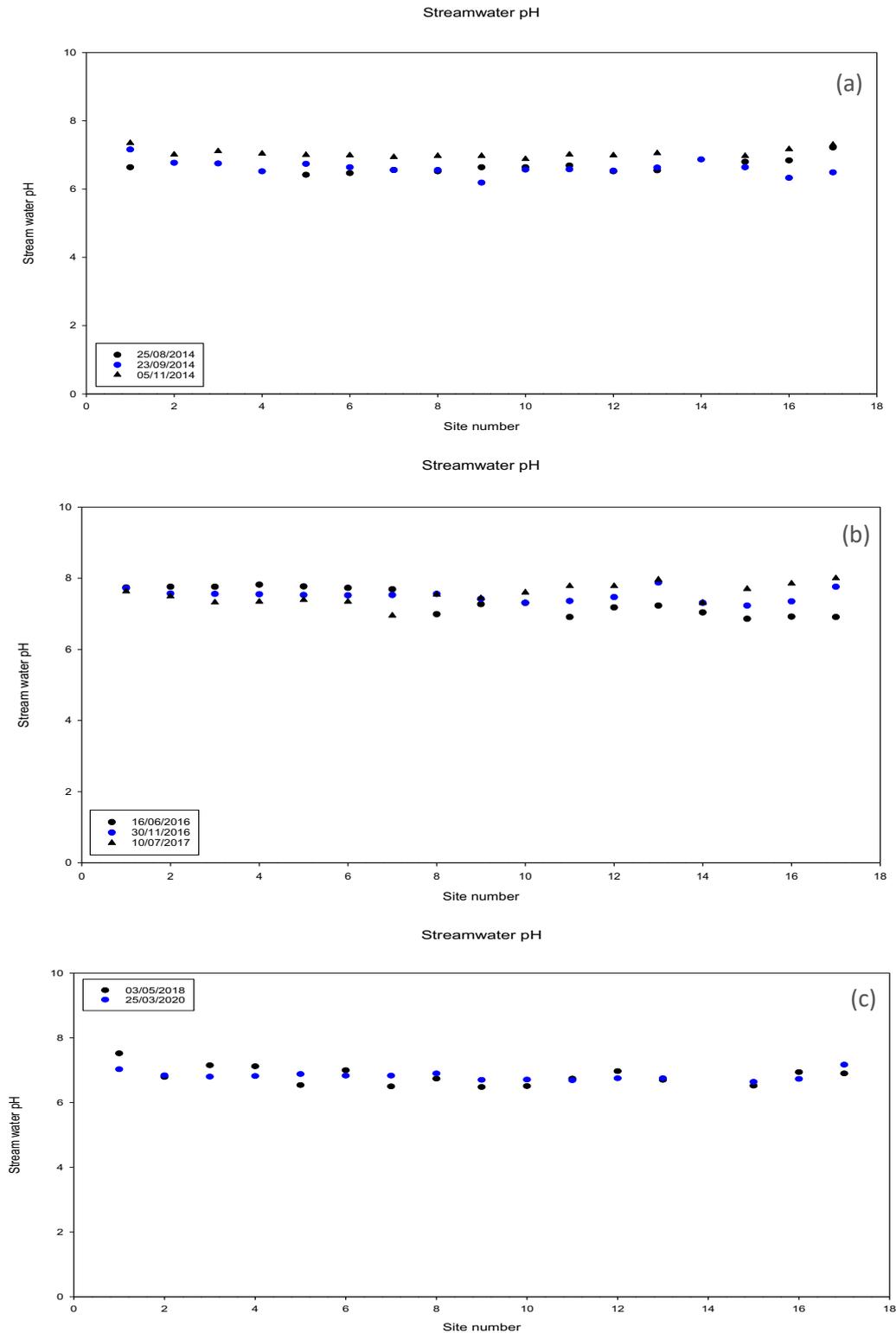


Figure 29. Stream Water pH at 17 sites on mid-Mulloon Creek (a) 2014; (b) 2016/2017; (c) 2018/2020

3.3.5 RSA Stream Water Turbidity

Stream water turbidity is an optical measure of water clarity. Values over 5 NTU show discolouration of water, and values over 15 NTU inhibit photosynthesis in the stream. Most Australian upland rivers have turbidity between 2 NTU and 25 NTU. Turbidity measurements for mid-Mulloon Creek were mostly less than 20 NTU for all sampling rounds when flow

exceeded 25 ML/day (Table 4). However, elevated turbidity was observed in spring 2016 (Figure 30a), winter 2017 (Figure 30a), and winter 2018 (Figure 30b) when flow was low (< 11 ML/day).

In spring 2016 elevated turbidity values were measured at Williams Wallow (80 NTU), Willows Crossing (75 NTU), Willows Runnell (70 NTU), the Crossing North of Willows (40 NTU), the Swamp Drainage Channel (35 NTU), North of the Soil Con inlet (80 NTU) and at Peter’s Pond (100 NTU) (Figure 30a). Stream flow at this time was very low (7.60 to 10.70 ML/day) (Table 4).

In winter 2017 elevated turbidity values were measured South of Poplars Crossing (80 NTU), Hazell Bank (180 NTU), Williams Wallow (130 NTU), Willows Crossing (180 NTU), Willows Runnell (40 NTU), the Swamp Drainage Channel (145 NTU), North of the Soil Con inlet (100 NTU) and at Peter’s Pond (60 NTU) (Figure 30a). Stream flow at this time was extremely low (1.10 to 6.80 ML/day) (Table 4).

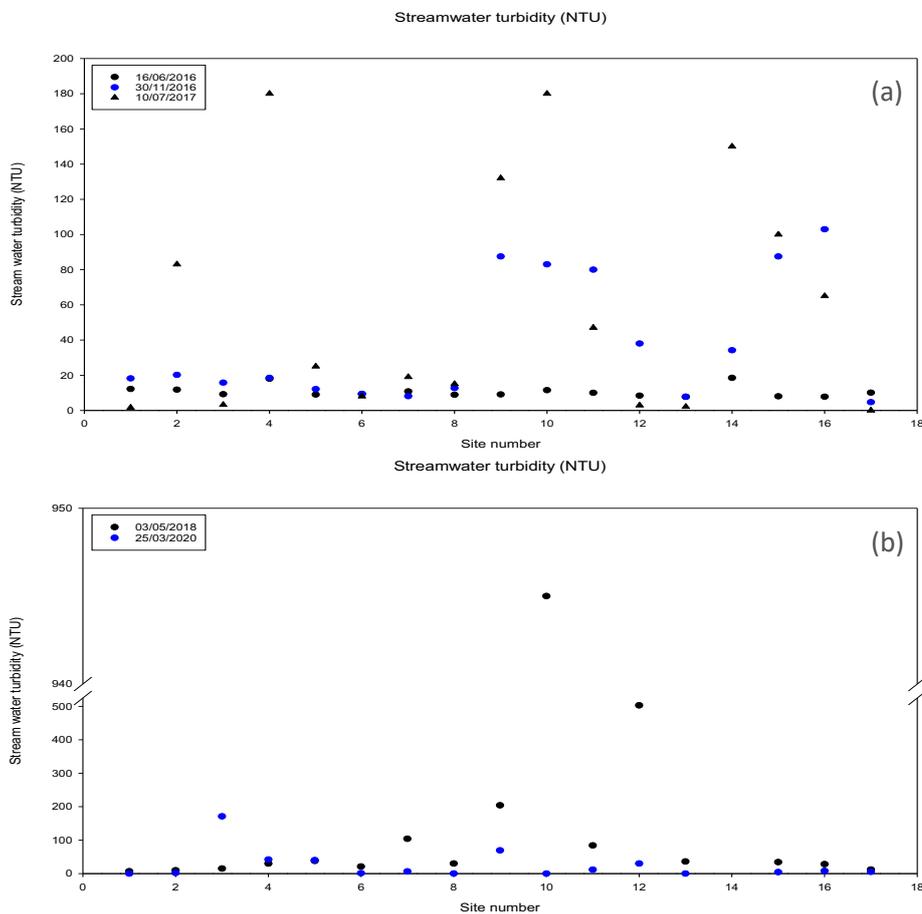


Figure 30. Stream Water Turbidity (NTU) at 17 sites on mid-Mulloon Creek (a) 2016/2017; (b) 2018/2020. In 2014, most turbidity readings were less than 20 NTU (Site 14 Swamp Drain >2500 NTU).

In winter 2018, elevated turbidity values were measured at Poplars Crossing (180 NTU), Platypus Pond (90 NTU), Williams Wallow (200 NTU), Willows Crossing (950 NTU), Willows Runnell (80 NTU), and the Crossing North of Willows (500 NTU) (Figure 30b). Stream flow at this time was extremely low (0.20 to 2.90 ML/day) (Table 4), with flow ceasing

at some sites. Turbidity was typically higher when stream flow was very low or extremely low at or immediately downstream of river crossings and in areas where stock accessed water.

Date	Black Jackie flow (ML/day)	Mid-Mulloon flow (ML/day)
25/08/2014	60.64	145.60
22/09/2014	26.37	66.73
03/11/2014	16.09	41.24
16/06/2016	37.60	43.09
30/11/2016	7.60	10.70
10/07/2017	1.10	6.80
03/05/2018	0.20	2.90
25/03/2020	35.00	31.00

3.4 Pond Water Levels and Electrical Conductivity (EC)

For mid-Mulloon Creek, pond water level and manual electrical conductivity were sampled at 8 in-stream ponds at relatively regular intervals from 2014 to 2020. Gaps in the pond water level data relate to periods when the water level was below the base of the manual stage, the manual stage was damaged, or the manual stage could not be read (e.g. during flood events). From upstream to downstream, the Ponds are: Upper Mulloon Pond (downstream of the Black Jackie stream gauge), Hazell Bank Pond, Mitchell's Pond (upstream of Go Way Back Crossing), Triple Pond, Williams Wallow Pond, Weather Station Crossing Pond, Peter's Pond and Wombat Pond (Figure 31).

When pond water levels are considered relative to periods of drought and the intervening wetter periods, most show relatively consistent water levels from 2014 to mid-2016 with variations (<25 cm) relating to isolated periods of rainfall in late 2014 and late 2015 during an otherwise dry interval (Figure 32a-h). From mid-2016 to the end of 2016, larger and more sustained rain events contributed to higher (maximum) water levels in ponds during this wet period. From the beginning of 2017 to late 2018, most ponds had lower water levels during the early stages of the 2017-2019 Tinderbox Drought. Pond levels rose slightly over the late 2018-early 2019 period in response to isolated periods of summer rainfall during an otherwise dry interval. From early 2019, the ponds began to dry, with a low stand in all ponds by late 2019, at the peak of the 2017-2019 Tinderbox Drought. Rains in early 2020 refilled the ponds to levels approaching those at the start of the monitoring period.



Figure 31. Location of stream gauging stations (n=2; P) and pond sampling sites (n=8) on the Mulloon Home Farm on the mid-section of Mulloon Creek.

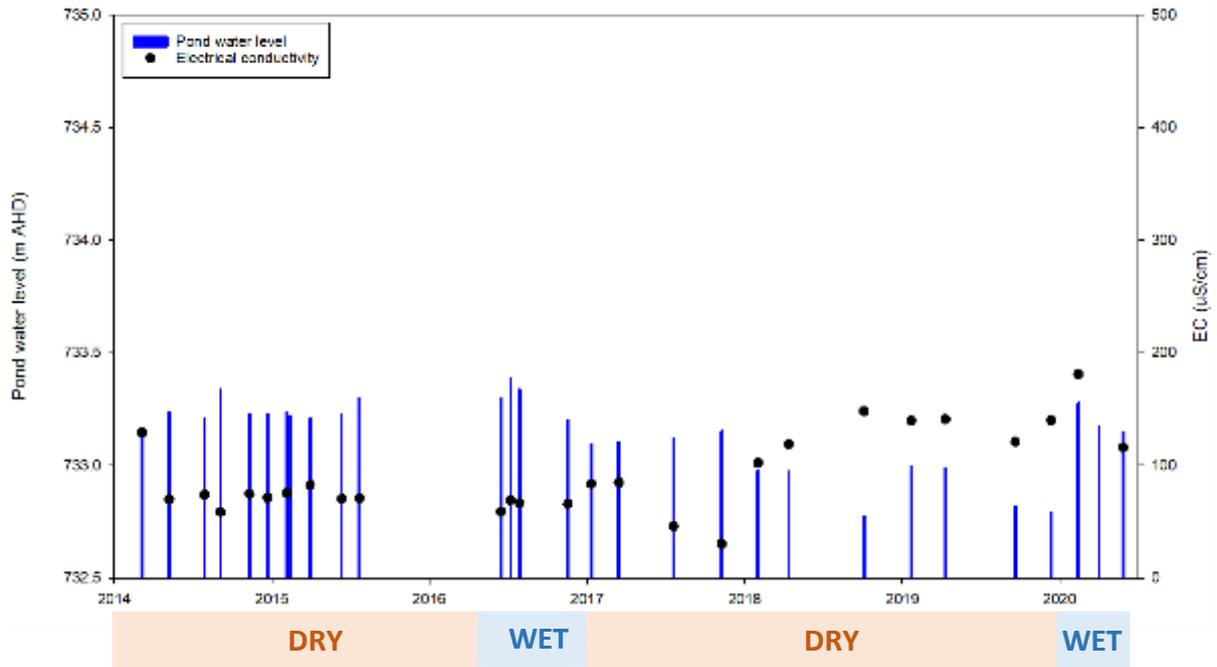


Figure 32a. Upper Mulloon Pond (downstream of Black Jackie) water level, manual electrical conductivity measurements and drought/wet periods from 2014 to 2020. No data recorded when the water level is below the base of the manual stage or when the manual stage cannot be measured (2016).

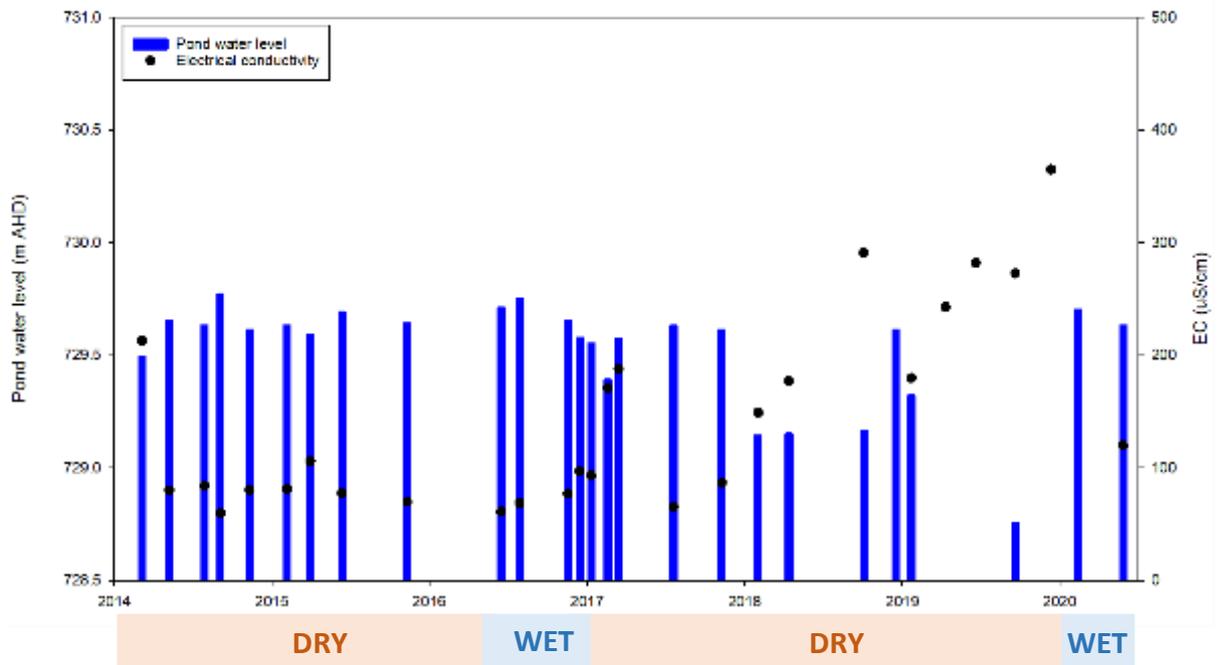


Figure 32b. Hazell Bank Pond water level, manual electrical conductivity measurements and drought/wet periods from 2014 to 2020. No data recorded when the water level is below the base of the manual stage or when the manual stage cannot be measured (2016).

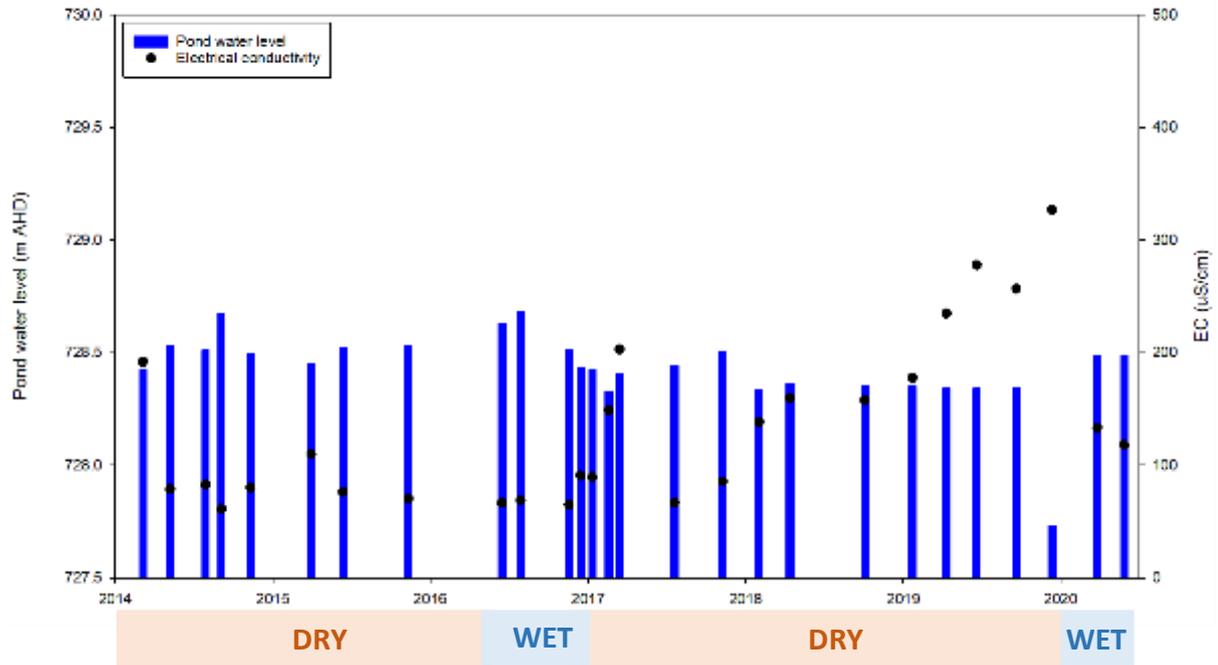


Figure 32c. Mitchell's Pond (upstream of Go Way Back Crossing) water level, manual electrical conductivity measurements and drought/wet periods from 2014 to 2020. No data recorded when the water level is below the base of the manual stage or when the manual stage cannot be measured (2016).

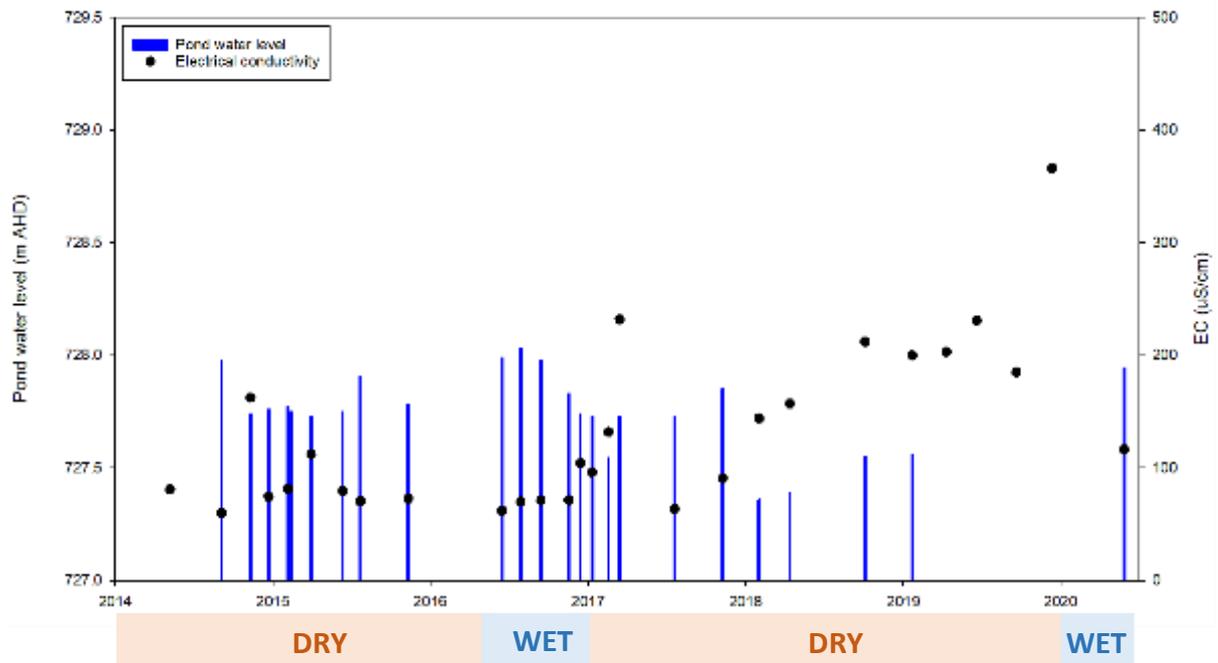


Figure 32d. Triple Pond water level, manual electrical conductivity measurements and drought/wet periods from 2014 to 2020. No data recorded when the water level is below the base of the manual stage or when the manual stage is unable to measure (2016).

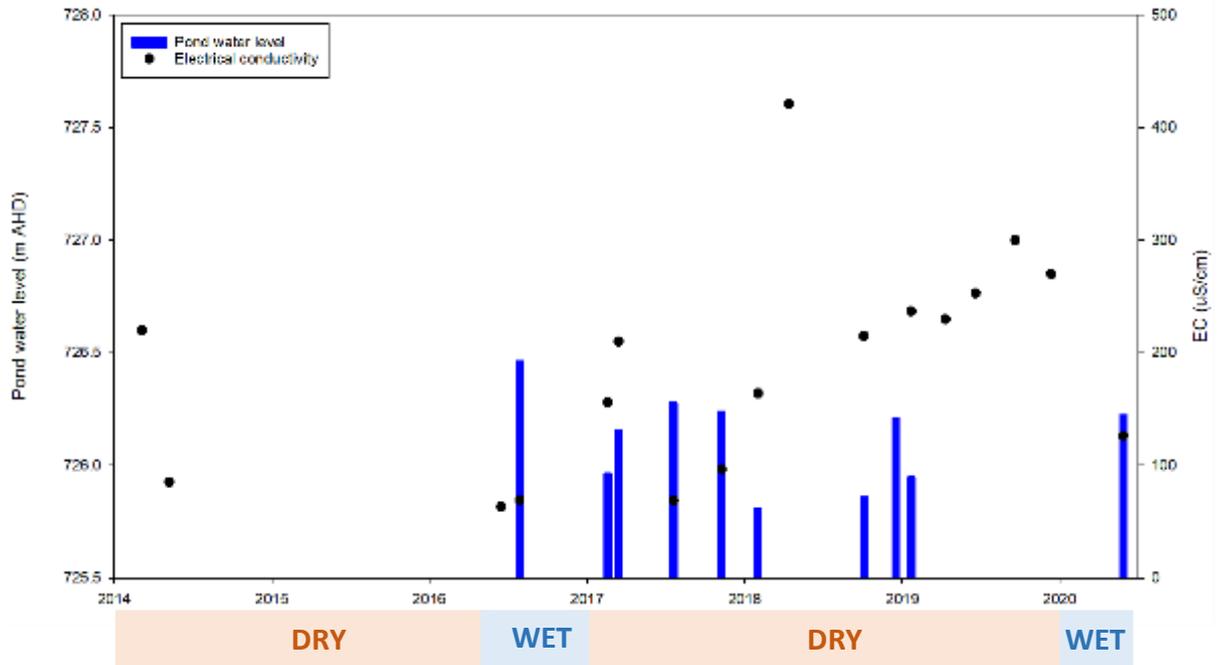


Figure 32e. Williams Wallow Pond water level, manual electrical conductivity measurements and drought/wet periods from 2014 to 2020. No data recorded when the water level is below the base of the manual stage or when the manual stage cannot be measured (2016).

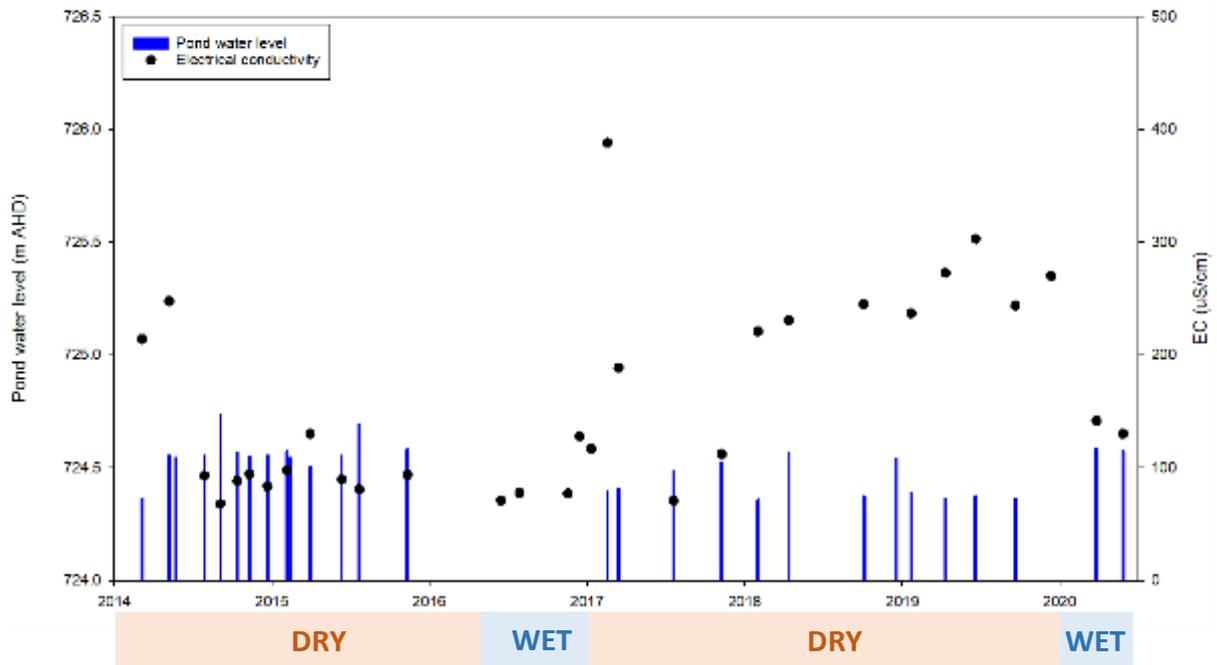


Figure 32f. Weather Station Crossing Pond water level and manual electrical conductivity measurements from 2014 to 2020. No data recorded when the water level is below the base of the manual stage or when the manual stage cannot be measured (2016).

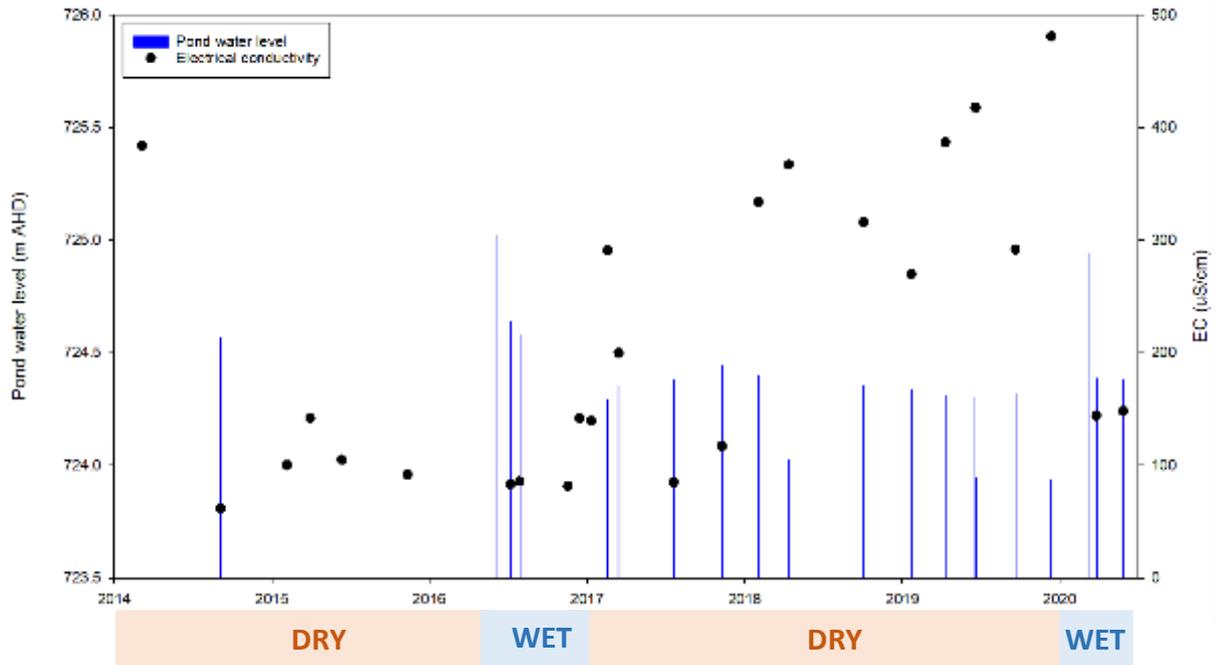


Figure 32g. Peter's Pond water level, manual electrical conductivity measurements and drought/wet periods from 2014 to 2020. No data recorded when the water level is below the base of the manual stage or when the manual stage cannot be measured (2016).

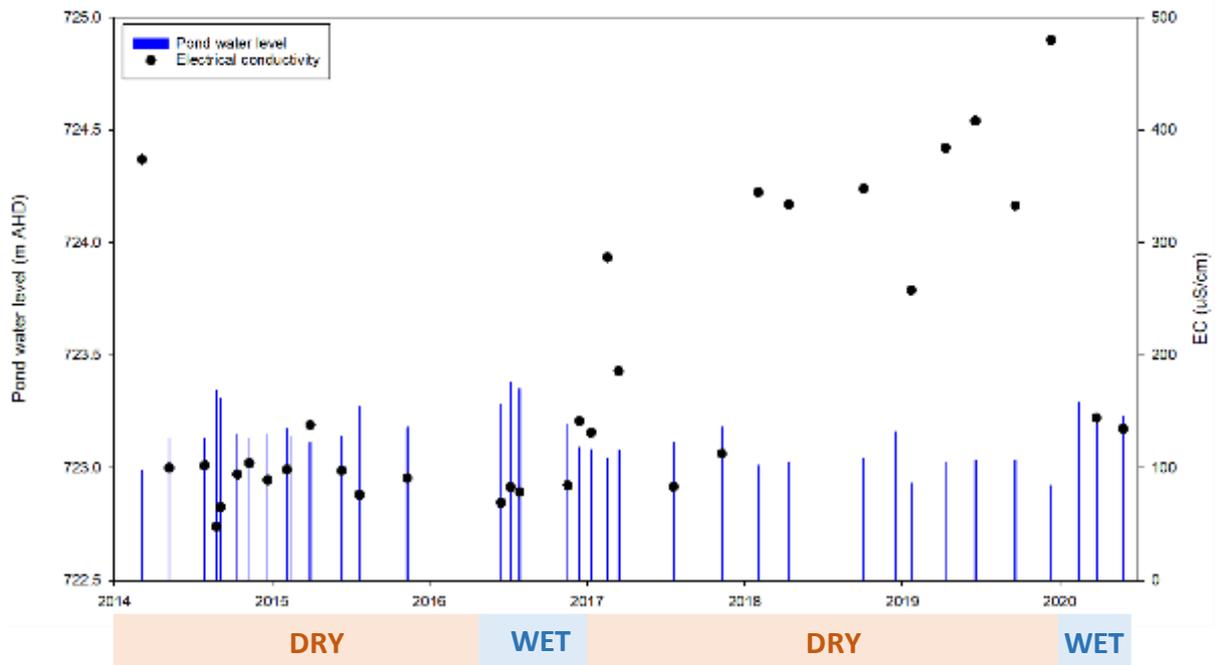


Figure 32h. Wombat Pond water level, manual electrical conductivity measurements and drought/wet periods from 2014 to 2020. No data recorded when the water level is below the base of the manual stage or when the manual stage cannot be measured (2016).

3.5 Groundwater

Groundwater has been consistently monitored at 13 sites (BH1 to BH13) since 2014, with earlier data manually recorded at some of these holes. The original boreholes were excavated by hand auger and are between 2.3m and 3.7m deep (Figure 33; Table 5).

Monitoring commenced in 2017 at four deeper (3.85m to 4.90m; Table 5), newly excavated boreholes sited proximal to the stream (BH3-2, BH5-2, BH8-2, BH14) (Figure 33; Table 5).



Figure 33. Location of borehole sites (n=17) forming three transects:
Transect A (BH11, BH10, BH9, BH8-1, BH8-2, BH12)
Transect B (BH4, BH5-1, BH5-2, BH6)
Transect C (BH2, BH3-1, BH3-2, BH7, BH13)
and two single boreholes (BH14, BH1)
on the Mulloon Home Farm on the mid-section of Mulloon Creek.

The borehole array is arranged in three transects: Transect A on the southern floodplain area (BH11, BH10, BH9, BH8-1, BH8-2, BH12); Transect B on the central floodplain area (BH4, BH5-1, BH5-2, BH6); Transect C on the northern floodplain area (BH2, BH3-1, BH3-2, BH7, BH13); and there are two single boreholes further north (BH14 and BH1) (Figure 33, Table 5).

Table 5: Mulloon Home Farm borehole specifications

	BOREHOLE DEPTH	BOH (AHD)	GROUND LEVEL (AHD)	RECORDED SCREEN INTERVAL
<i>Transect A (west to east)</i>				
BH11	3.37m	728.96	732.33	0.40m-3.25m
BH10	3.70m	728.53	732.23	0.40m-3.60m
BH9	3.02m	729.56	732.58	0.40m-2.90m
BH8-1	3.01m	729.55	732.56	0.40m-2.90m
BH8-2	4.90m	726.47	731.37	1.00m-4.80m
BH12	3.47m	729.04	732.51	0.40m-3.35m
<i>Transect B (west to east)</i>				
BH4	3.50m	726.29	729.79	0.40m-3.40m
BH5-1	2.25m	727.31	729.85	0.40m-2.15m
BH5-2	3.85m	726.09	729.94	1.00m-3.75m
BH6	3.32m	726.55	729.87	0.40m-3.20m
<i>Transect C (west to east)</i>				
BH2	2.72m	726.36	729.08	0.40m-2.60m
BH3-1	2.58m	726.33	728.91	0.40m-2.50m
BH3-2	4.40m	724.30	728.70	1.00m-4.30m
BH7	2.80m	724.91	727.71	0.40m-2.70m
BH13	2.29m	725.64	727.93	0.40m-2.20m
<i>Northern boreholes</i>				
BH14	4.00m	723.49	727.49	1.00m-3.90m
BH1	3.72m	723.57	727.29	0.40m-3.60m

Black - boreholes commissioned in 2014; **Blue** - boreholes commissioned in 2017

3.5.1 Groundwater Borehole Logs

The 4 boreholes commissioned in 2016 (BH3-2 – SALIS Profile ID 96262; BH5-2 – SALIS Profile ID 96264; BH8-2 – SALIS Profile ID 96961; BH14 – SALIS Profile ID 96963) have complete bore log descriptions that have been lodged on the SALIS soils database. For each of these holes, a detailed Profile Report, an abridged Essentials Report, and a Technical Report describing site context have been prepared (Table 6; Appendix 1).

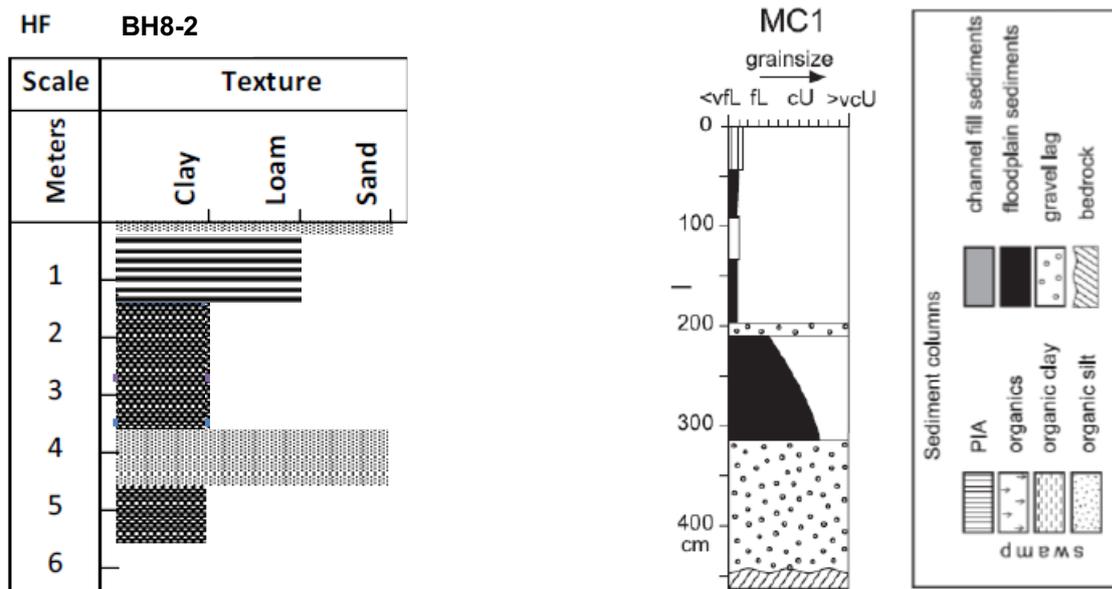


Figure 34. Stratigraphic log for Borehole 8-2 (Table 6; after Hickson, 2017) and stratigraphic log for borehole MC1 is more proximal to mid-Mulloon Creek (after Dobes et al. 2013).

BH8-2 piezometer installed to 4.9 m. Screened from 1 to 4.8 m.

Borehole 8-2 is hosted in a Tenosol, a soil with limited pedogenic structure, developed on recent alluvium (gravelly sands; 0.0-0.7m) overlying a paleo-swamp deposit (silty clay loam to heavy silty clay; 0.7-2.9m) (Table 6; Figure 34).

Borehole 5-2 is hosted in a Black Orthic Tenosol developed on: recent alluvium (sandy loam to silty clay loam; 0.0-0.5m) overlying a paleo-swamp deposit (heavy clay; 0.5-1.0m), an interval of silty clay loam (1.0-1.6m) and clayey sand (1.6-2.4m), an aquifer-bearing sandy clay (2.4-4.0m) and a sandy clay aquitard (4.0-4.5m) (Table 6; Figure 35).

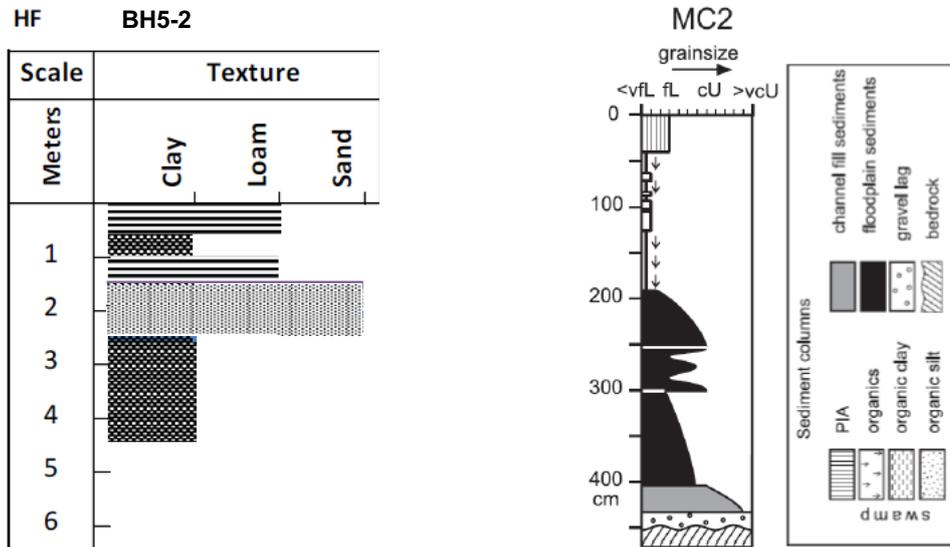


Figure 35. Stratigraphic log for Borehole 5-2 (Table 6; after Hickson, 2017) and stratigraphic log for borehole MC2 is more proximal to mid-Mulloon Creek (after Dobes et al. 2013).

BH5-2 piezometer installed to 3.85 m. Screened from 1 m to 3.75 m.

Borehole 3-2 is hosted in a Tenosol developed on: recent alluvium (silty loam: 0.0-0.1m; silty clay 0.1-0.4m; medium clay 0.4-1.0m) overlying aquifer-bearing coarse sand (1.0-2.0m) to coarse clayey sand (2.0-4.3m) and sandy clay (4.3-4.5m) (Table 6; Figure 36, Figure 38).

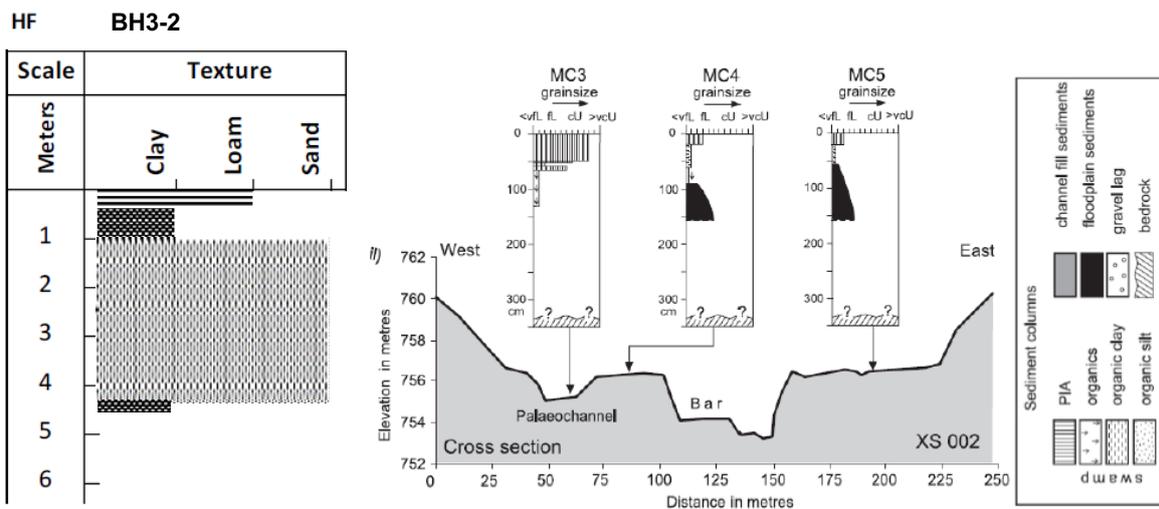


Figure 36. Stratigraphic log for Borehole 3-2 (Table 6; after Hickson, 2017) and stratigraphic log for A series of holes, MC2, more proximal to mid-Mulloon Creek (after Dobes et al. 2013).

BH3-2 piezometer installed to 4.5 m. Screened from 1 m to 4.3 m.

Borehole 14 is hosted in a Black Orthic Tenosol developed on: recent alluvium (loamy sand; 0.0-0.15m), overlying a paleo-swamp deposit (silty clay; 0.15-1.25m), an interval of medium clay (1.25-1.50m), coarse sand (1.50m-2.50m), clay loam sandy (2.5m-3.4m), an aquifer-bearing coarse sand (3.4-4.0m) and sandy clay aquitard (4.0-4.5m) (Table 6; Figure 37).

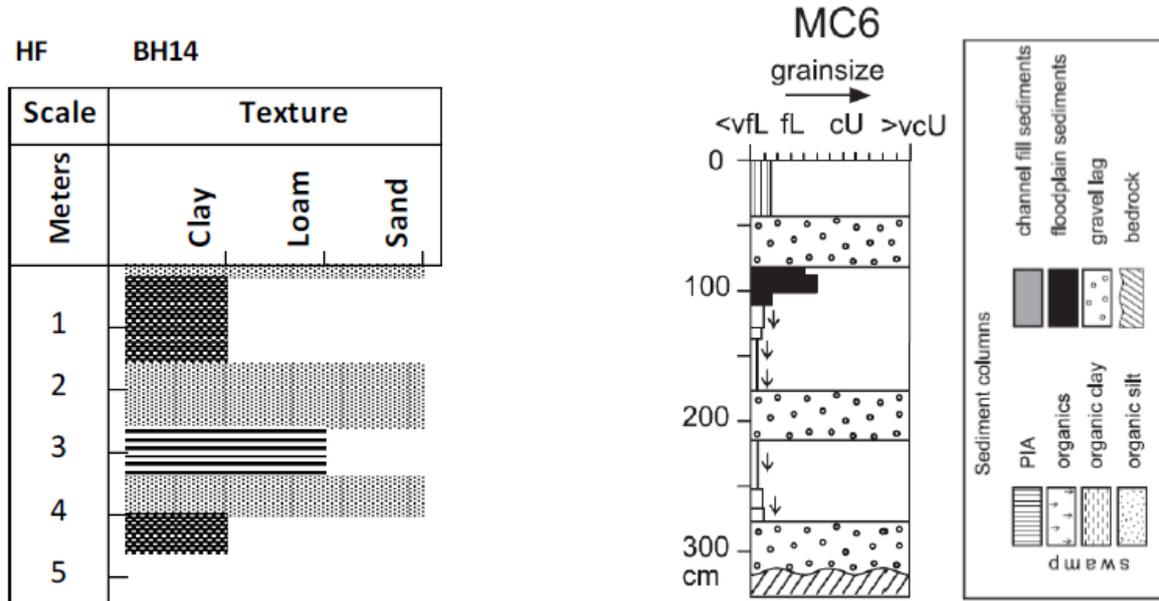


Figure 37. Stratigraphic log for Borehole 14 (Table 6; after Hickson, 2017) and stratigraphic log for borehole MC6 more proximal to mid-Mulloon Creek (after Dobes et al. 2013).
BH14 piezometer installed to 4 m. Screened from 1 m to 3.9 m.



Figure 38. Drilling the new boreholes (BH8-2- BH5-2, BH3-2, BH14) at the Mulloon Home Farm in December 2016 (Bernardi, 2016).

Table 6. Logs for Boreholes Commissioned in 2017 at mid-Mulloon Creek (BH8-2, BH5-2, BH3-2, BH14 – south to north)

<p>Borehole 8-2 (Profile ID 96961) Tenosol (ASC), Alluvial Soil (GSG) <i>Surface</i> Coarse fragments are very few (< 2%), other, fine gravel (2-6 mm) 0.00 - 0.08 m Horizon: very dark greyish olive (olive black) (10Y 3/2) [moist] coarse loamy sand, abundant (>100/10x10cm) roots (<1mm), many (25-100/10x10cm) roots (1-2mm), field pH is 6.0. Coarse fragments are common (10-20%), other, fine gravel (2-6 mm), gravel (6-20 mm). Recent alluvium with small gravel 0.08 - 0.70 m Horizon: dark brown (10YR 3/3) [moist] coarse light sandy loam, few (1-10/10x10cm) roots (<1mm), few (1-10/10x10cm) roots (1-2mm), field pH is 6.0. Coarse fragments are few (2-10%), other, fine gravel (2-6 mm), gravel (6-20 mm), coarse gravel (20-60 mm). Recent alluvium with coarse gravel 0.70 - 1.40 m Horizon: very dark grey (brownish black) (7.5YR 3/1) [moist] coarse light silty clay loam, none roots (<1mm), none roots (1-2mm), field pH is 6.5. Coarse fragments are common (10-20%), quartz, fine gravel (2-6 mm). Paleo-swamp transition layer sandy silt 1.40 - 2.90 m Horizon: dark brown (brownish black) (7.5YR 3/2) [moist] fine heavy silty clay, field pH is 6.5. Coarse fragments are few (2-10%), quartz, fine gravel (2-6 mm). Paleo-swamp silty clay 2.90 - 3.40 m Horizon: brown (dull yellowish brown) (10YR 5/3) [moist] coarse light sandy clay, field pH is 6.5. Coarse fragments are few (2-10%), quartz, fine gravel (2-6 mm) common (10-20%), other, fine gravel (2-6 mm), gravel (6-20 mm). Moist sandy clay 3.40 - 4.50 m Horizon: yellowish brown (10YR 5/8) [moist] coarse sand, field pH is 6.0. Coarse fragments are many (20-50%), quartz, fine gravel (2-6 mm) common (10- 20%), feldspar, fine gravel (2-6 mm). Gravelly sand aquifer. Presumed high energy paleo stream bed. 4.50 - 5.00 m Horizon: dark grey (brownish grey) (10YR 4/1) [moist] coarse light sandy clay with single grained, field pH is 6.0. Coarse fragments are few (2-10%), quartz, fine gravel (2-6 mm). Gravelly grey clay acting as aquitard to above aquifer. <i>Base of observation: soil continues</i></p>	<p>Borehole 5-2 (Profile ID 96964) Black-Orthic Tenosol (ASC), Alluvial Soil (GSG) 0.00 - 0.10 m Horizon: very dark brown (7.5YR 2.5/2) [moist] coarse light sandy loam with strong pedality (polyhedral, 5 - 10 mm, smooth-faced peds), many (25- 100/10x10cm) roots (<1mm), few (1 10/10x10cm) roots (1-2mm), none roots (2-5mm), none roots (>5mm), none (Root size unknown), field pH is 5.5. Coarse fragments are not evident 0.10 - 0.50 m Horizon: very dark grey (brownish black) (10YR 3/1) [moist] fine light silty clay loam, few (1-10/10x10cm) roots (<1mm), none roots (1-2mm), none roots (2-5mm), none roots (>5mm), none (Root size unknown), field pH is 6.5. Coarse fragments are not evident 0.50 - 1.00 m Horizon: very dark greyish brown (brownish black) (2.5Y 3/2) [moist] heavy clay, few (1-10/10x10cm) roots (<1mm), none roots (1-2mm), none roots (2-5mm), none roots (>5mm), none (Root size unknown), field pH is 7.0. Coarse fragments are not evident. Paleo-Swamp materials 1.00 - 1.60 m Horizon: light olive brown (yellowish brown) (2.5Y 5/6) [moist] coarse light silty clay loam, none roots (<1mm), none roots (1-2mm), none roots (2-5mm), none roots (>5mm), none (Root size unknown), field pH is 6.0. Coarse fragments are not evident 1.60 - 2.40 m Horizon: yellowish brown (10YR 5/6) [moist] coarse light clayey sand, none roots (<1mm), none roots (1-2mm), none roots (2-5mm), none roots (>5mm), none (Root size unknown), field pH is 7.5. Coarse fragments are abundant (50-90%), other, fine gravel (2-6 mm), gravel (6-20 mm), coarse gravel (20- 60 mm) 2.40 - 4.00 m Horizon: light olive brown (yellowish brown) (2.5Y 5/6) [moist] coarse light sandy clay, none roots (<1mm), none roots (1-2mm), none roots (2-5mm), none roots (>5mm), none (Root size unknown), field pH is 7.0. Coarse fragments are abundant (50-90%), other, fine gravel (2-6 mm), gravel (6-20 mm), coarse gravel (20-60 mm). Aquifer. 4.00 - 4.50 m Horizon: light olive brown (yellowish brown) (2.5Y 5/4) [moist] coarse light sandy clay, none roots (<1mm), none roots (1-2mm), none roots (2-5mm), none roots (>5mm), none (Root size unknown), field pH is 7.5. Coarse fragments are abundant (50-90%), not identified, fine gravel (2-6 mm). Moist Aquitard. Olive green in colour suggesting anoxic conditions. <i>Base of observation: soil continues</i></p>
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<p>Borehole 3-2 (Profile ID 96962) Tenosol (ASC), Alluvial Soil (GSG) <i>0.00 - 0.10 m</i> A1 Horizon: very dark grey (olive black) (5Y 3/1) [moist] coarse silty loam with moderate pedality (polyhedral, 20 - 50 mm, rough-faced peds), common (10-25/10x10cm) roots (<1mm), none roots (1-2mm), field pH is 5.0 <i>0.10 - 0.40 m</i> A2 Horizon: very dark greyish brown (brownish black) (2.5Y 3/2) [moist] fine light silty clay loam, field pH is 5.5 <i>0.40 - 1.00 m</i> B2 Horizon: light olive brown (yellowish brown) (2.5Y 5/6) [moist] light medium clay, field pH is 6.5 <i>1.00 - 2.00 m</i> 2D1b Horizon: dark yellowish brown (brown) (10YR 4/4) [moist] coarse sand, field pH is 7.5. Coarse fragments are common (10-20%), quartz, fine gravel (2-6 mm). Dry top of aquifer layer <i>2.00 - 2.50 m</i> 2D2b Horizon: light olive brown (yellowish brown) (2.5Y 5/6) [moist] coarse light clayey sand, field pH is 7.5. Coarse fragments are many (20-50%), other, fine gravel (2-6 mm), gravel (6-20 mm), coarse gravel (20-60 mm). Moist aquifer layer <i>2.50 - 4.30 m</i> 2D3b Horizon: light olive brown (yellowish brown) (2.5Y 5/4) [moist] coarse light clayey sand, field pH is 7.5. Coarse fragments are common (10-20%), quartz, fine gravel (2-6 mm) common (10-20%), feldspar, fine gravel (2-6 mm). Saturated aquifer <i>4.30 - 4.50 m</i> 3Db Horizon: olive yellow (bright yellowish brown) (2.5Y 6/6) [moist] coarse light sandy clay, field pH is 8.0. Moist aquitard <i>Base of observation: soil continues</i></p>	<p>Borehole 14 (Profile ID 96963) Black-Orthic Tenosol (ASC), Alluvial Soil (GSG) <i>0.00 - 0.15 m</i> Horizon: very dark greyish brown (brownish black) (2.5Y 3/2) [moist] coarse light loamy sand with weak pedality (sub-angular blocky, 20 - 50 mm, rough faced peds), many (25-100/10x10cm) roots (<1mm), few (1-10/10x10cm) roots (1-2mm), field pH is 6.0. Coarse fragments are not evident <i>0.15 - 1.25 m</i> Horizon: very dark grey (olive black) (5Y 3/1) [moist] fine light silty clay, field pH is 7.0. Coarse fragments are not evident. Paleo-swamp material <i>1.25 - 1.50 m</i> Horizon: (yellowish brown) (2.5Y 5/5) [moist] light medium clay, field pH is 7.5. Coarse fragments are not evident <i>1.50 - 2.50 m</i> Horizon: strong brown (brown) (7.5YR 4/6) [moist] coarse sand, field pH is 7.5. Coarse fragments are not evident <i>2.50 - 3.40 m</i> Horizon: dark yellowish brown (brown) (10YR 4/6) [moist] coarse light clay loam sandy, field pH is 7.5. Coarse fragments are abundant (50-90%), quartz, fine gravel (2-6 mm) <i>3.40 - 4.00 m</i> Horizon: olive grey (greyish olive) (5Y 4/2) [moist] coarse sand, field pH is 7.5. Coarse fragments are many (20-50%), quartz, fine gravel (2-6 mm). Saturated grey sandy gravels. Aquifer. <i>4.00 - 4.50 m</i> Horizon: yellowish brown (10YR 5/8) [moist] coarse light sandy clay, field pH is 7.0. Coarse fragments are many (20-50%), not identified, fine gravel (2-6 mm), gravel (6-20 mm). Appeared to be a thin 5mm layer of dark grey clay at top of this layer of dry sandy clayey gravels. The thin clay layer at top of this layer/base of above layer appeared to be acting as an aquitard. No sample was obtained due to disturbance from auger. This layer is unusual for alluvial soils in this valley and may be sampling the top of a geological high. Further analysis of sample may reveal nature of layer. <i>Base of observation: soil continues</i></p>
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3.5.2 Groundwater Level, Groundwater EC, Rainfall and Stream Height

3.5.2.1 Transect A – Mulloon Home Farm southern west-east transect

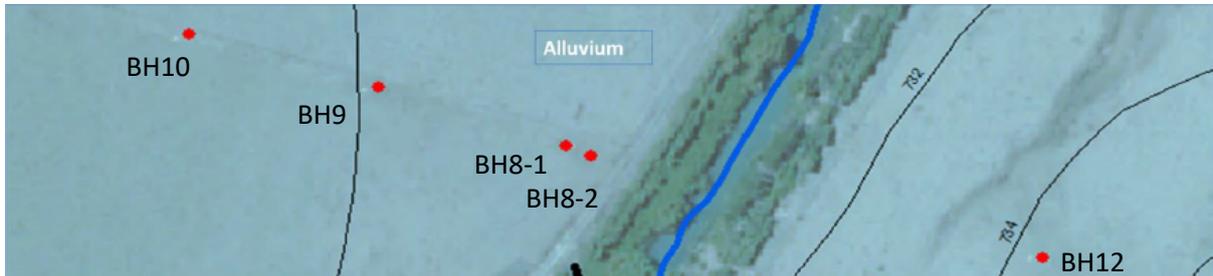


Figure 39. Borehole Transect A is a west-east line of boreholes perpendicular to Mulloon Creek, in the southern part of Mulloon Home Farm (after Hickson, 2017; see Figure 33).

Borehole 11 (3.25m to base of screen) is the westernmost borehole in Transect A (Figure 39). Pre-2014 manual readings show elevated groundwater levels in late spring 2010 (1.25m BGL), in spring 2012 (0.75m BGL), in late spring 2013 (1.45m BGL) and in spring 2014 (1.45m BGL) (Figure 40a). Patterns in this data also reflect the timing of manual sampling. Continuous recording shows a clear peak in spring 2015 (2.00m BGL), groundwater approached ground level (0.20m BGL) in spring 2016 in response to sustained winter rainfall, and there is a small rise in spring 2017 (2.50m BGL) (Figure 40b). Manual groundwater level readings coincide well with continuous readings measured since 2014. The pattern of elevated groundwater levels in spring at BH11 likely relates to groundwater movement off the adjacent hills as interflow after late winter to early spring rainfall (Figure 40b). Water level dropped considerably from spring 2016 (0.20m BGL) to spring 2017 (2.50 BGL) and then progressively to late 2018 (3.25m BGL), with the borehole remaining dry until 2020. The dry borehole indicates that there was minimal recharge over this period. This borehole is on an alluvial terrace and distal from Mulloon Creek, so the lack of correlation between groundwater levels and stream water levels is expected (Figure 40c). Both curves reflect the influence of the sustained winter rains in mid-2016, with an immediate (early-mid June) stream response and a delayed (late June/July) groundwater response.

Borehole 10 (3.60 to base of screen) is located on a fluvial terrace west of Mulloon Creek (Figure 39). Pre-2014 manual readings show elevated groundwater levels in autumn 2011 (2.10m BGL), in spring 2012 (1.30m BGL) and late summer 2014 (1.95m BGL) (Figure 41a). Patterns in this data also reflect the timing of manual sampling. Continuous recording shows a clear peak in spring 2014 (2.40m BGL), with groundwater in the root zone (0.50m BGL) in early spring 2016 in response to sustained winter rainfall, and a small rise in spring 2017 (2.75m BGL) (Figure 41b). Manual groundwater level readings coincide well with continuous readings measured since 2014. The pattern of elevated groundwater levels likely relates to groundwater movement off the adjacent hills as interflow after sustained rainfall (Figure 41b). Water level dropped considerably from spring 2016 (0.50m BGL) to spring 2017 (2.75m BGL), and then progressively until the borehole was dry in winter 2020 (3.60m BGL). The borehole is on an alluvial terrace and distal from Mulloon Creek, so the lack of correlation between groundwater levels and stream water levels is expected (Figure 41c). There is a gap in continuous groundwater recording. Still, both curves reflect the influence of the sustained winter rains in mid-2016, with an immediate (early-mid June) stream response and an apparent delayed groundwater response.

Transect A - Borehole 11

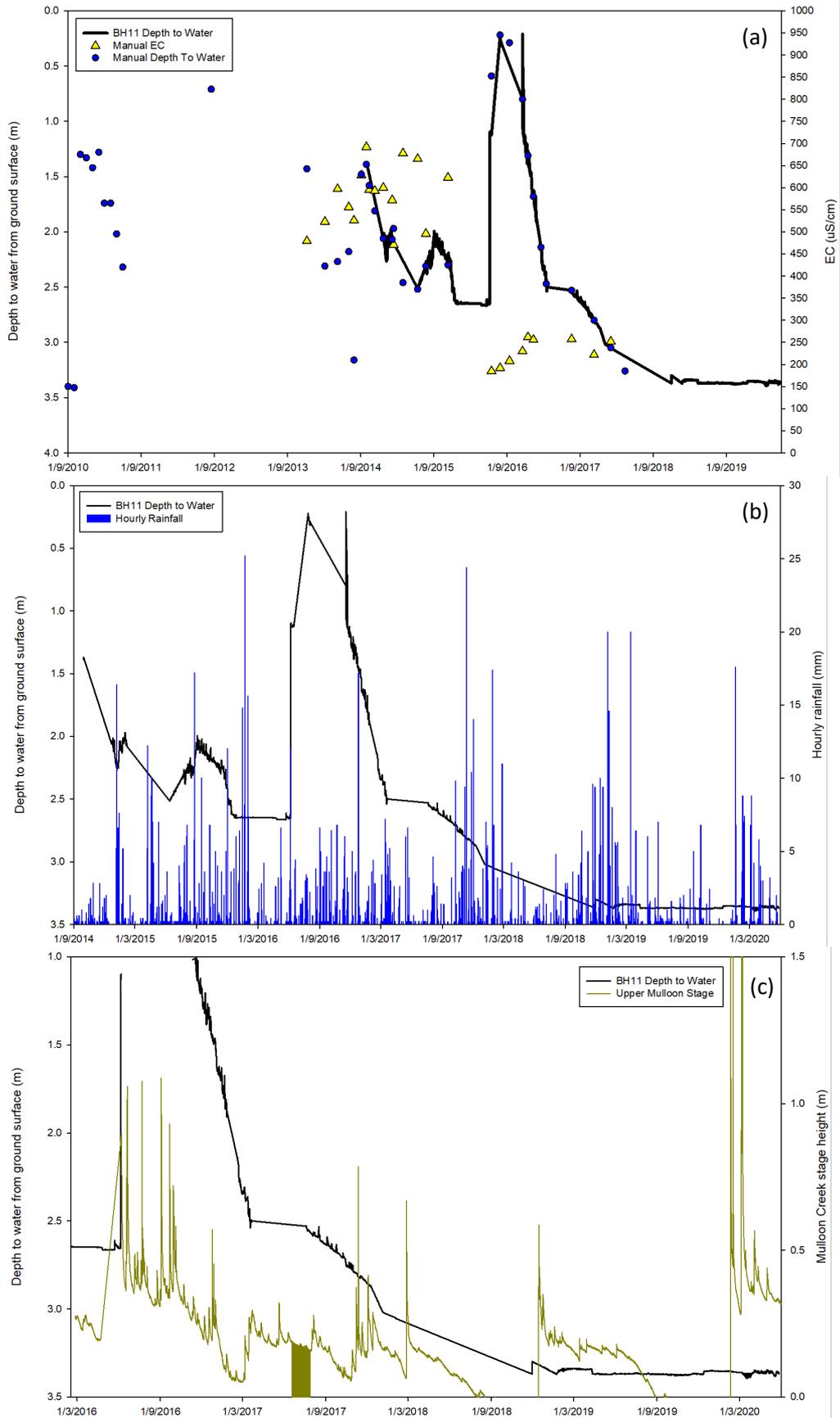


Figure 40. (a) BH11 water level and EC (2010-2020); (b) BH11 water level and rainfall (2014-2020); (c) BH11 water level and stream water level (2016-2020)

Transect A- Borehole 10

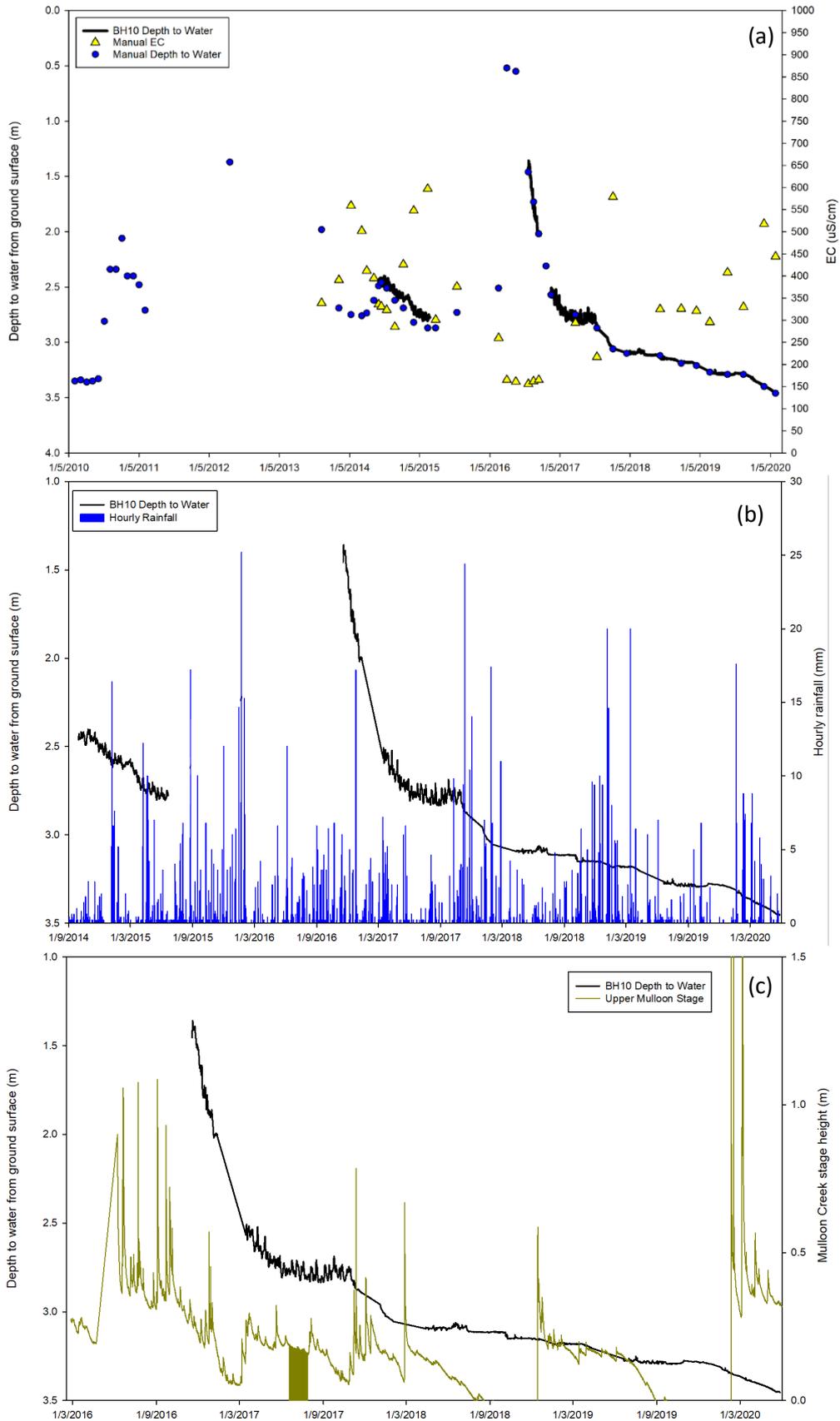


Figure 41. (a) BH10 water level and EC (2010-2020); (b) BH10 water level and rainfall (2014-2020); (c) BH10 water level and stream water level (2016-2020)

Borehole 9 (2.90m to base of screen) is located on the flood plain west of Mulloon Creek (Figure 39). Pre-2014 manual readings show elevated groundwater levels in autumn 2011 (2.50m BGL), in spring 2012 (2.00m BGL) and late spring 2013 (2.50m BGL) (Figure 42a). Patterns in this data also reflect the timing of manual sampling. Continuous recording shows a clear peak in winter to early spring 2016 (1.20m BGL) (Figure 42b). Manual groundwater level readings coincide well with continuous readings measured since 2014. The pattern of elevated groundwater levels likely relates to groundwater movement off the adjacent hills and terrace landscapes, as interflow after sustained rainfall (Figure 42b). Water level dropped considerably from late spring 2016 (1.20m BGL) to autumn 2017 (2.90m BGL), with BH9 remaining dry until 2020. The borehole is on an alluvial plain and is more proximal to Mulloon Creek, but there is no correlation between groundwater levels and stream water levels (Figure 42c). Both curves reflect the influence of the sustained winter rains in mid-2016, with an immediate (early-mid June) stream response and a delayed (late June/July) groundwater response.

Borehole 8-1 (2.90m to base of screen) is located on the flood plain immediately west of Mulloon Creek (Figure 39). This borehole has remained dry, apart from a clear peak in spring 2016 (2.10m BGL) (Figure 43a), following a period of sustained rainfall (Figure 43b). Manual groundwater level readings coincide well with continuous readings measured since 2014. Water level dropped considerably from early spring 2016 (1.20m BGL) to late spring 2016 (2.90m BGL), and then remained dry until 2020. The borehole is proximal to Mulloon Creek, but there is no correlation between groundwater levels and stream water levels (Figure 43c). Both curves reflect the influence of the winter rains in mid-2016, with an immediate (early to mid June) stream response and a delayed (September) groundwater response.

Borehole 8-2 (4.80m to base of screen) is located on the flood plain immediately west of Mulloon Creek (Figure 39). This borehole has only been monitored since January 2017 (3.40m BGL) and the water level has progressively dropped to March 2020 (4.30m BGL) (Figure 44a). This indicates that there was minimal recharge over this period. This borehole was very responsive after a period of sustained rainfall in March 2020 (Figure 44b), with a groundwater rise to May 2020 (3.70m BGL). This borehole is deeper than the adjacent BH8-1 borehole, and it shows an immediate response to the March 2020 rainfall. The start of this rise in groundwater level also coincides with the rise in the water level in Mulloon Creek (Figure 44c). This is the only Transect A borehole to show a synchronous response. Groundwater EC (300 μ S/cm) was higher than stream EC (125 μ S/cm), so this is a pressure head response.

Borehole 12 (3.35m to base of screen) is located on the flood plain, mid-way between the eastern foothills and Mulloon Creek (Figure 39). Pre-2014 manual readings show elevated groundwater levels in spring 2010 (1.95m BGL) and in early spring 2014 (1.15m BGL), but there were limited measurements in the intervening period (Figure 45a). Continuous recording shows a clear peak in spring 2015 (1.25m BGL), with water approaching ground level (0.20m BGL) in spring 2016 in response to sustained winter rainfall (Figure 45b). The pattern of elevated groundwater levels likely relates to groundwater movement off the adjacent hills, and terrace landscapes, as interflow after sustained rainfall (Figure 45b). Water level dropped from late spring 2016 (0.20m BGL) to mid-2017 (3.35m BGL), and apart from small fluctuations the borehole remained dry until 2020. This borehole is on the Mulloon Creek alluvial plain, but there is no correlation between groundwater levels and stream water levels (Figure 45c). Both

curves reflect the influence of the sustained winter rains in mid-2016, with an immediate (early-mid June) stream response and a delayed groundwater response (late June/July).

Transect A – Borehole 9

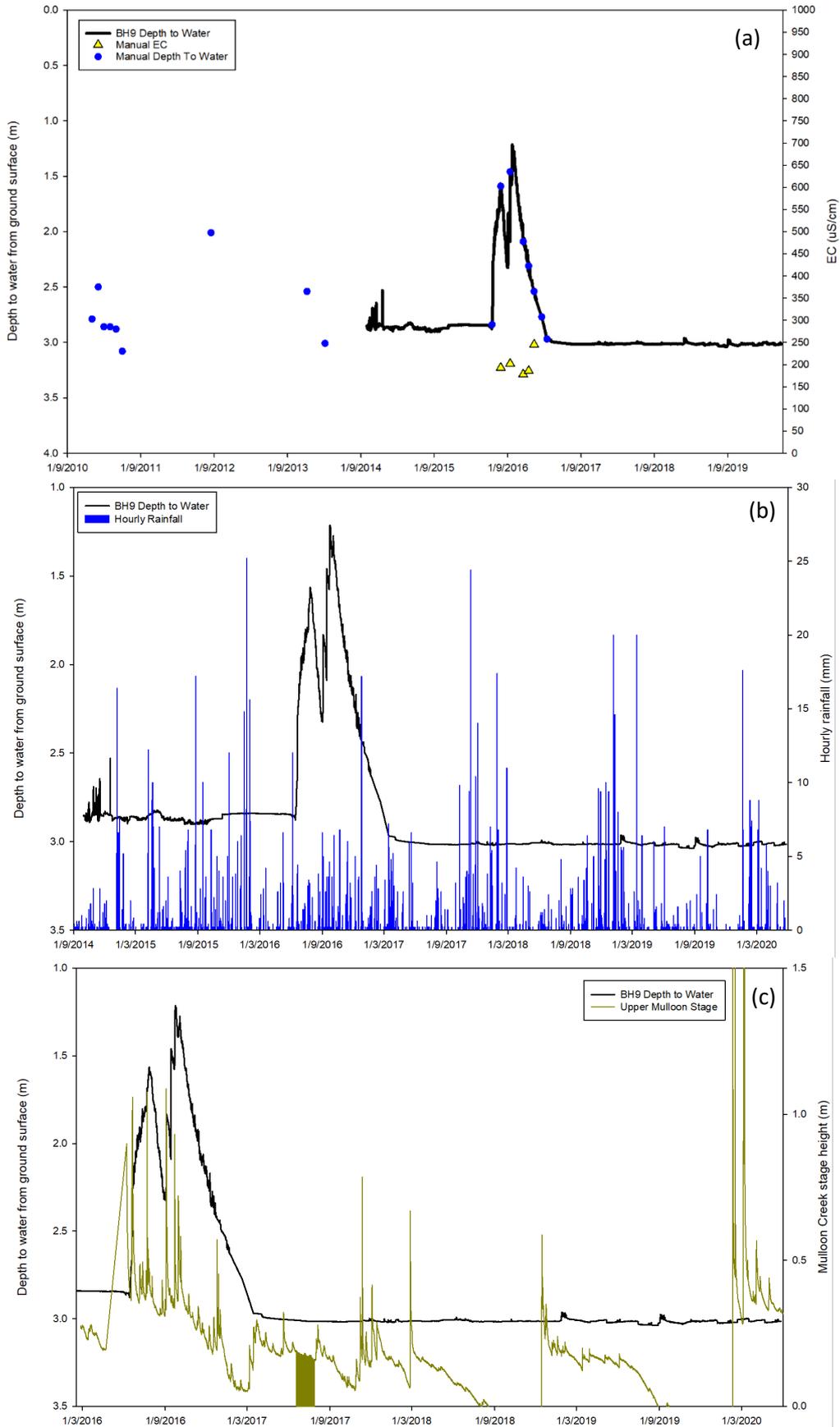


Figure 42. (a) BH9 water level and EC (2010-2020); (b) BH9 water level and rainfall (2014-2020); (c) BH9 water level and stream water level (2016-2020)

Transect A - Borehole 8-1

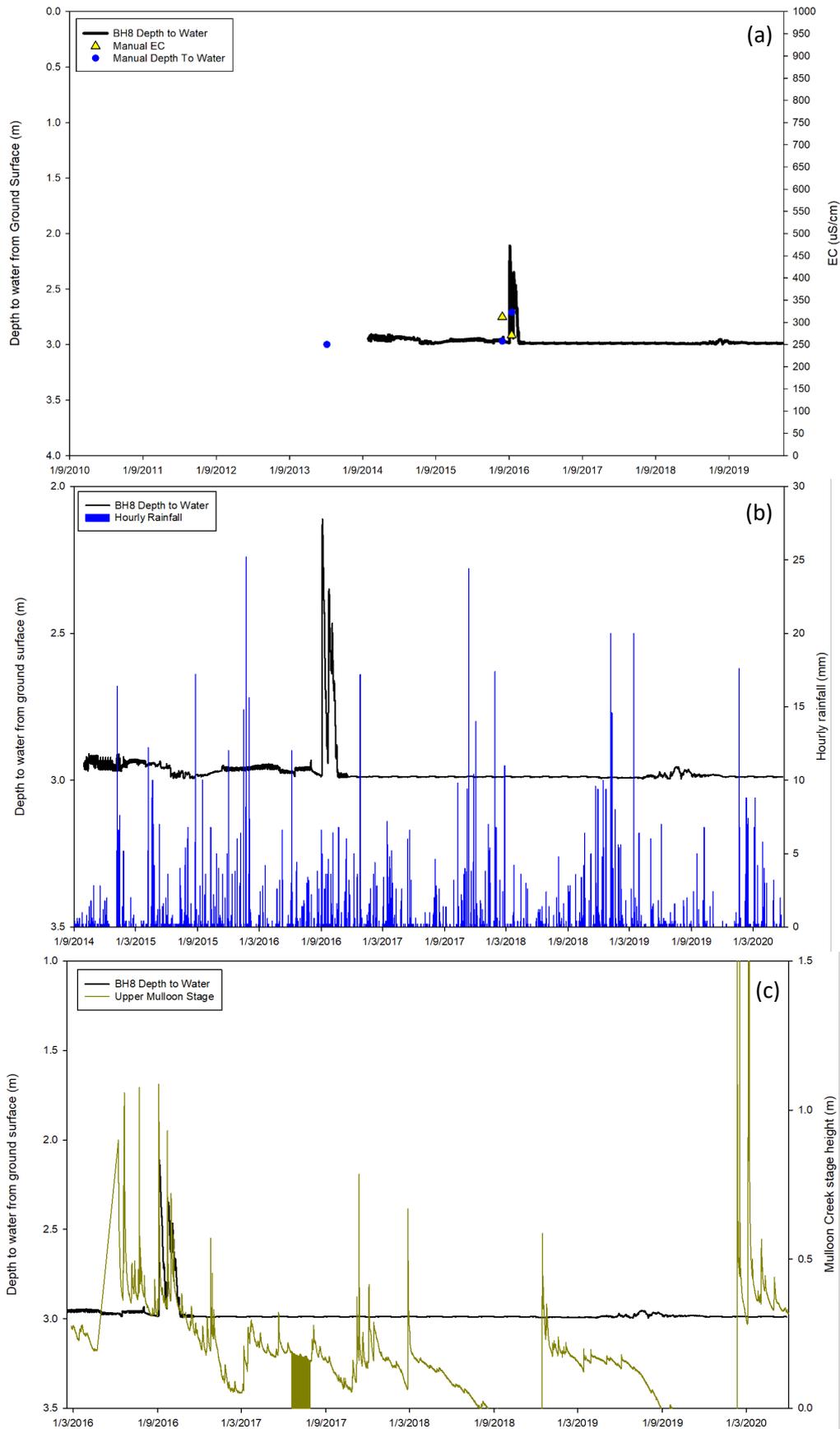


Figure 43. (a) BH8-1 water level and EC (2010-2020); (b) BH8-1 water level and rainfall (2014-2020); (c) BH.1 water level and stream water level (2016-2020)

Transect A - Borehole 8-2

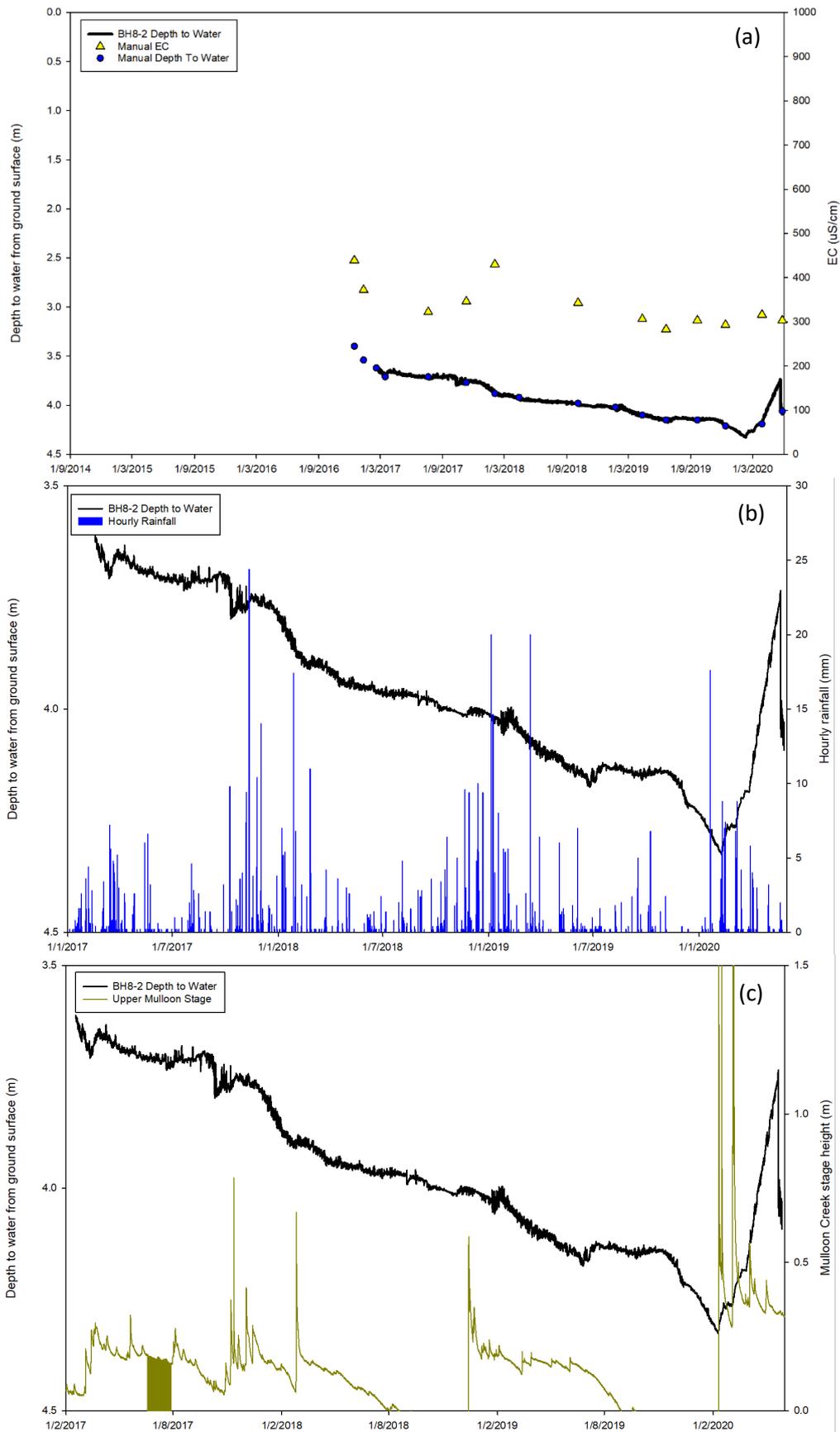


Figure 44. (a) BH8-2 water level and EC (2014-2020); (b) BH8-2 water level and rainfall (2017-2020); (c) BH8-2 water level and stream water level (2017-2020)

Transect A - Borehole 12

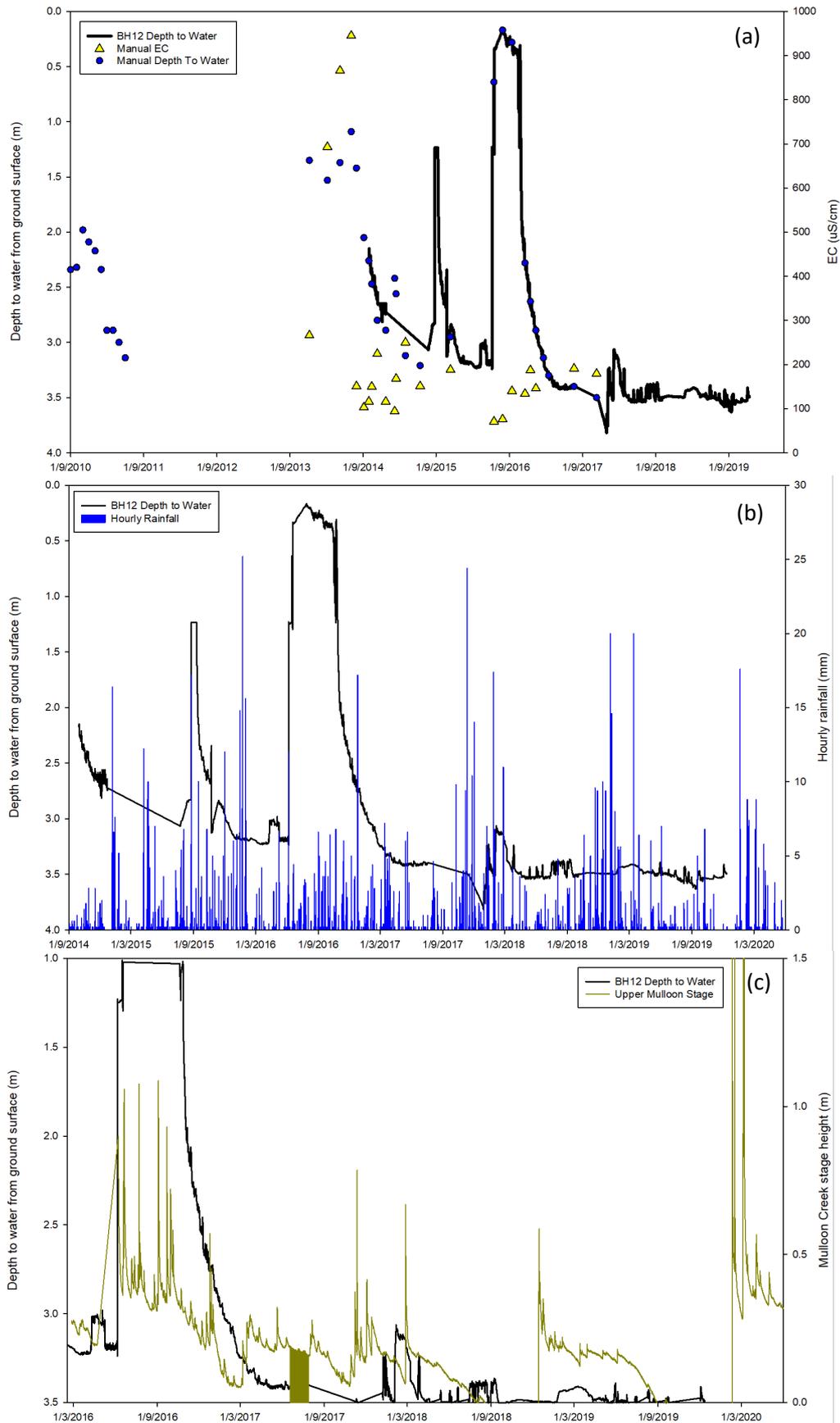


Figure 45. (a) BH12 water level and EC (2010-2020); (b) BH12 water level and rainfall (2014-2020); (c) BH12 water level and stream water level (2016-2020)

3.5.2.2 Transect B – Mulloon Home Farm central west-east transect



Figure 46. Borehole Transect B is a west-east line of boreholes perpendicular to Mulloon Creek, in the central part of Mulloon Home Farm (after Hickson, 2017, refer to Figure 33).

Borehole 4 (3.40m to base of screen) is the westernmost borehole in Transect B, located in a back-plain flood-runner on the western margin of the alluvial plain (Figure 46). Pre-2014 manual readings show elevated groundwater levels in late spring 2010 (0.95m BGL) and spring 2014 (1.45m BGL), but there were limited measurements in the intervening period (Figure 47a). Continuous recording shows a clear peak in spring 2015 (1.25m BGL), with water approaching ground level (0.20m BGL) in spring 2016 in response to sustained winter rainfall (Figure 47b). Manual groundwater level readings coincide well with continuous readings measured since 2014. The general pattern of elevated groundwater levels in spring at BH4 parallels that at BH11 in Transect A, and likely relates to groundwater movement off the adjacent hills as interflow after late winter to early spring rainfall (Figure 47b). Water level dropped considerably from spring 2016 (0.20m BGL) to early 2017 (2.00 BGL) and then, apart from small fluctuations, progressively dropped to March 2020 (2.50m BGL). This borehole was very responsive after a period of sustained rainfall in March 2020, with an immediate groundwater rise (1.80m BGL) sustained to May 2020 (2.00m BGL). Compared with other boreholes, BH4 has immediate groundwater responses to sustained rainfall events that parallel the runoff-related responses in Mulloon Creek. Although it is tempting to relate this groundwater pattern to changes in Mulloon Creek water level, it is more likely related to recharge via the back-plain flood-runner that BH4 is located in. This recharge episodically augments groundwater input from the adjacent hills.

Borehole 5-1 (2.15m to base of screen) is located on the flood plain immediately west of Mulloon Creek (Figure 46). This borehole has remained dry apart from a clear peak in spring 2016 (0.60m BGL) (Figure 48a) after a period of sustained rainfall (Figure 48b). Manual groundwater level readings coincide well with continuous readings measured since 2014. Water level dropped considerably from early spring 2016 (0.60m BGL) to late 2016 (2.15m BGL), with the BH5-1 remaining dry until the sensor was removed in March 2017. The borehole is proximal to Mulloon Creek, but there is insufficient data to identify if there is a correlation between groundwater levels and stream water levels (Figure 48c). Both curves reflect the influence of the winter rains in mid-2016, with an immediate (early-mid June) stream response and a delayed (late June/July) groundwater response. The general groundwater pattern parallels that observed at borehole 8-1, located upstream in a similar setting.

Transect B - Borehole 4

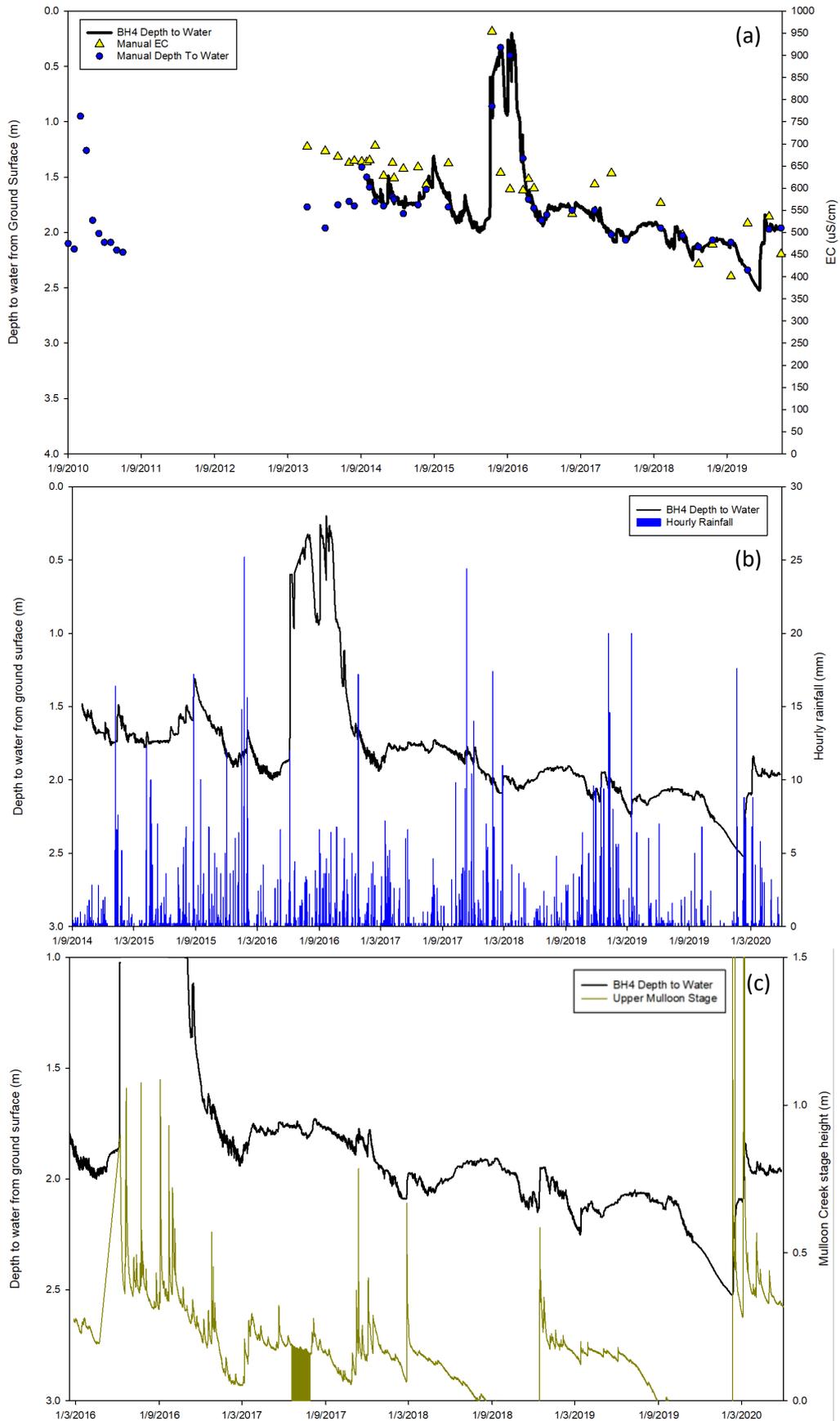


Figure 47. (a) BH4 water level and EC (2010-2020); (b) BH4 water level and rainfall (2014-2020); (c) BH4 water level and stream water level (2016-2020)

Transect B - Borehole 5-1

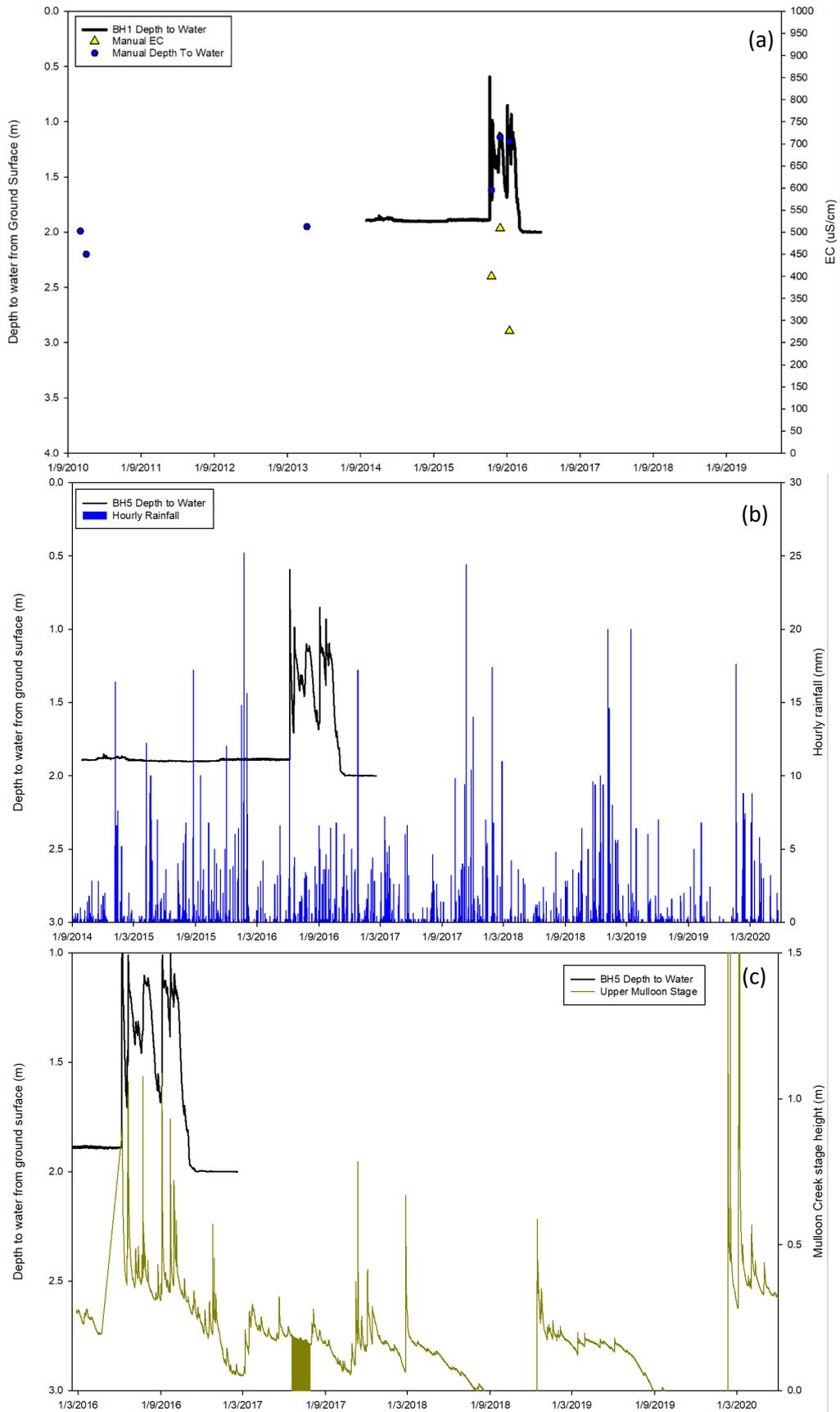


Figure 48. (a) BH5-1 water level and EC (2010-2020); (b) BH5-1 water level and rainfall (2014-2020); (c) BH511 water level and stream water level (2016-2020)



Figure 49. (a) Peter's Pond at Mulloon Home Farm (Image: K. Bradley 2012);
(b) Manual stage for stream water height measurement, Mulloon Creek (Image: Soils for Life 2020)

Groundwater levels are compared with pond water levels and stream water levels measured at manual stages along Mulloon Creek (Figure 49). Borehole 5-2 (3.75m to base of screen) is located on the flood plain immediately west of Mulloon Creek (Figure 46). This borehole has only been continuously monitored since March 2017 (2.50m BGL), but two manual readings were taken in January 2017 (2.25m BGL) and in February 2017 (2.40m BGL) (Figure 50a). Manual groundwater level readings coincide well with continuous readings measured since 2014. Groundwater levels were elevated in January 2017 (2.25m BGL) and winter 2017 (2.40m BGL), with low stands in the intervening periods (March 2017, 3.40m BGL; November 2017, 3.50m BGL). From late summer 2018 to spring 2019, the groundwater level remained relatively steady (2.50m to 2.60m BGL) and then progressively dropped to March 2020 (3.00m BGL) (Figure 50a). Although there was limited recharge over this period, this borehole was responsive after rainfall in November 2017, March 2018, January 2019 and sustained rainfall in March 2020 (Figure 50b), with a groundwater peak in late March 2020 (2.00m BGL), stabilising from April 2020 (2.40m BGL). The rises in groundwater level also coincide with rises in the water level in Mulloon Creek (Figure 50c), but EC remained unchanged. This synchronous response parallels that observed following the sustained rain in March 2020 at borehole 8-2, located upstream in a similar setting.

Borehole 6 (3.20m to base of screen) is located on the flood plain immediately east of Mulloon Creek (Figure 46). Pre-2014 manual readings show elevated groundwater levels in spring 2010 (1.45m BGL) and in spring 2014 (2.05m BGL), but there were limited measurements in the intervening period (Figure 51a). Continuous recording shows a clear peak in late winter through spring 2016 (1.40m BGL) in response to sustained winter rainfall (Figure 51b). Manual groundwater level readings coincide well with continuous readings measured since 2014. The groundwater level dropped progressively, and then more rapidly in March 2017 (2.10m to 2.30m BGL), followed by progressive lowering to March 2020. This borehole was responsive, with a lag, after sustained rainfall in June 2016, and smaller periods of rainfall in November 2017 and March 2018. Groundwater was responsive, with no lag, after rainfall in January 2019 and sustained rains in March 2020 (Figure 51b). The borehole is on the Mulloon Creek proximal alluvial plain. Although early in the monitoring period groundwater levels rose after stream water levels peaked, later in the monitoring period these readings were more synchronous (Figure 51c). This implies that the pattern of elevated groundwater levels likely relates to groundwater movement off the adjacent hills and terrace landscapes, as interflow after sustained rainfall. Still, the response is influenced by elevated stream water levels when the system is wet due to increased pressure head.

Transect B - Borehole 5-2

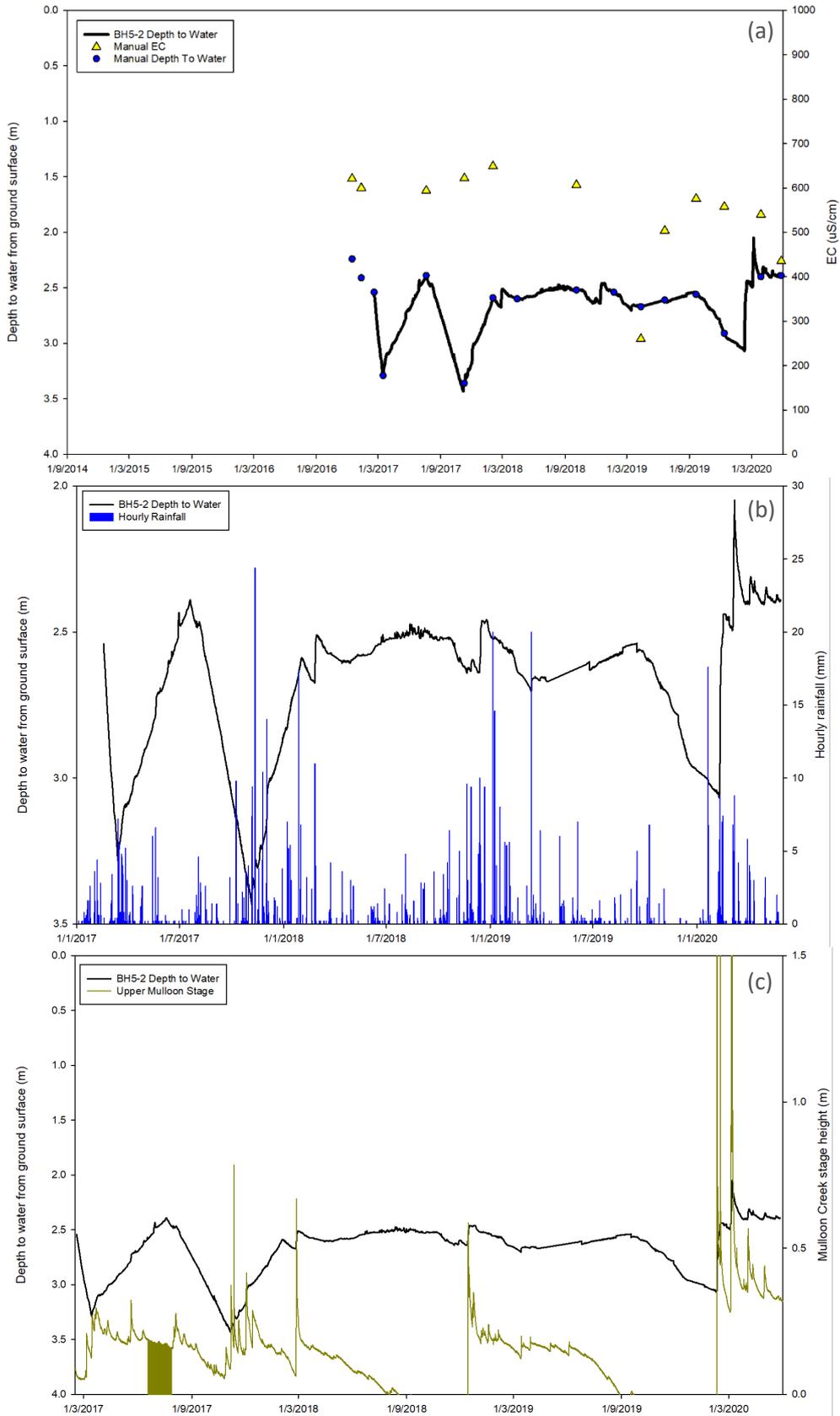


Figure 50. (a) BH5-2 water level and EC (2014-2020); (b) BH5-2 water level and rainfall (2017-2020); (c) BH5-2 water level and stream water level (2017-2020)

Transect B - Borehole 6

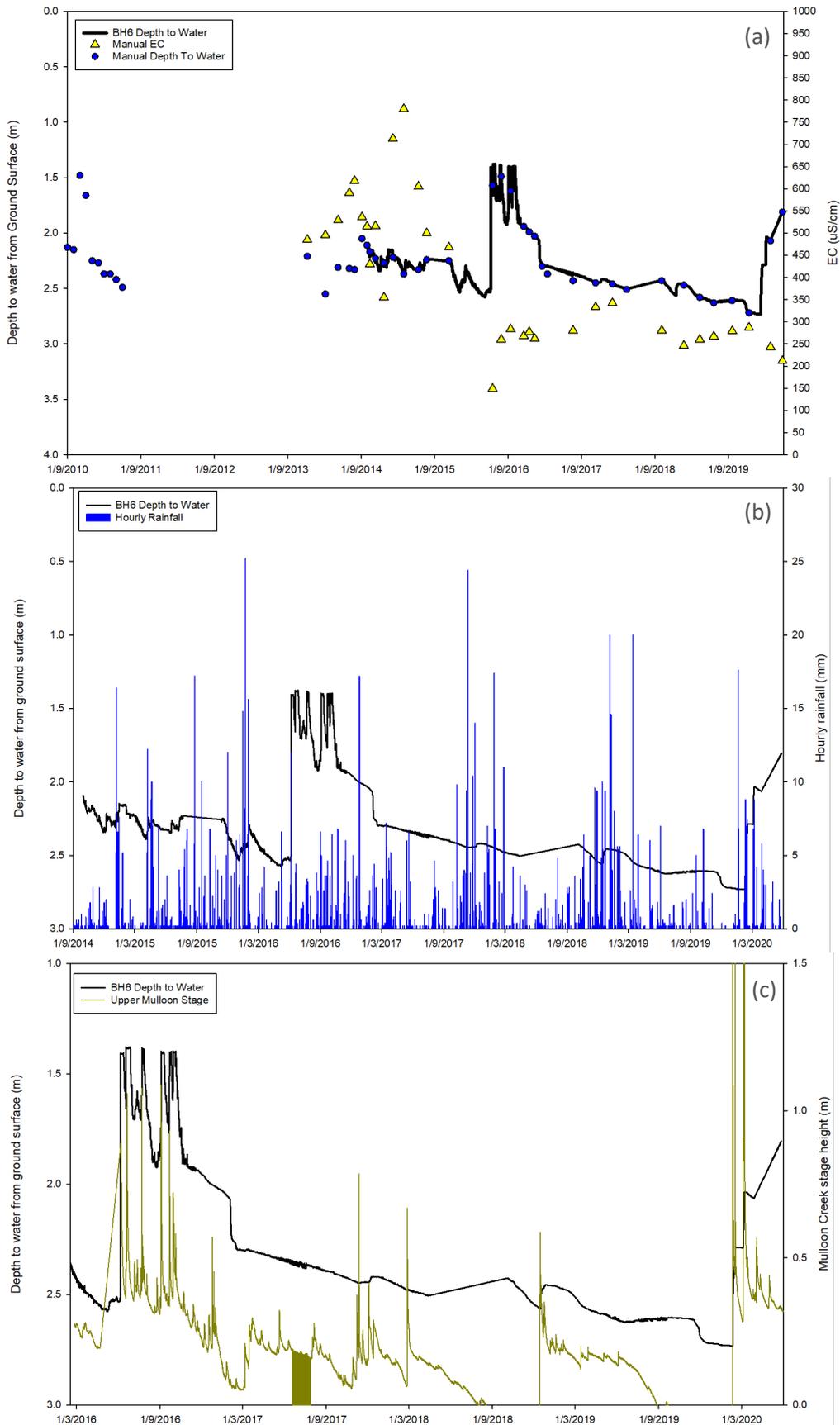


Figure 51. (a) BH6 water level and EC (2014-2020); (b) BH8-2 water level and rainfall (2017-2020); (c) BH6 water level and stream water level (2017-2020)

3.5.2.3 Transect C – Mulloon Home Farm northern west-east transect



Figure 52. Borehole Transect C is a west-east line of boreholes perpendicular to Mulloon Creek, in the northern part of Mulloon Home Farm (after Hickson, 2017, refer to Figure 33).

Borehole 2 (2.60m to base of screen) is located on the flood plain west of Mulloon Creek (Figure 52). Pre-2014 manual readings show elevated groundwater levels in late spring 2010 (0.7m BGL), in spring 2012 (0.80m BGL), late spring 2013 (1.50m BGL) and spring 2014 (1.55m BGL) (Figure 53a). Patterns in this data also reflect the timing of manual sampling. Manual groundwater level readings coincide well with continuous readings measured since 2014. Continuous recording shows elevated groundwater levels in late summer 2015 (1.70m BGL) and spring 2015 (1.40m BGL), with groundwater approaching ground level in late winter (0.40m BGL) and spring 2016 (0.20m BGL) in response to sustained winter rainfall (Figure 53b). The groundwater level dropped rapidly by summer 2017 (2.20m BGL) and remained relatively constant through 2017, then the borehole dried out completely by summer 2018 (2.60m BGL) and remained dry through to 2020 (Figure 53b). This indicates that there was minimal recharge over this period. This borehole was responsive, with a lag, after sustained rainfall in June 2016, smaller periods of rainfall in November 2017, March 2018, January 2019, and sustained rains in March 2020 (Figure 53b). The borehole is on the Mulloon Creek alluvial plain, and throughout the monitoring period, groundwater levels rose after stream water levels peaked (Figure 53c), but EC remained unchanged. This implies that the pattern of elevated groundwater levels likely relates to groundwater movement off the adjacent hills and terrace landscapes, as interflow after sustained rainfall.

Borehole 3-1 (2.50m to base of screen) is located on the flood plain immediately west of Mulloon Creek (Figure 52). This borehole has remained dry apart from clear peaks in late winter (1.25m BGL) and spring 2016 (1.50m BGL) (Figure 54a) after a period of sustained rainfall (Figure 54b). Manual groundwater level readings coincide well with continuous readings measured since 2016. The groundwater level dropped considerably from spring 2016 (1.50m BGL) to late 2016 (2.50m BGL), with the BH3-1 remaining dry until the sensor was removed in March 2017. The borehole is proximal to Mulloon Creek, but there is insufficient data to identify if there is a correlation between groundwater levels and stream water levels (Figure 54c). Both curves reflect the influence of the winter rains in mid-2016, with an immediate (early-mid June) stream response and a delayed (late June/July) groundwater response. The general groundwater pattern parallels that observed at boreholes 8-1 and 5-1 located upstream in a similar setting.

Transect C - Borehole 2

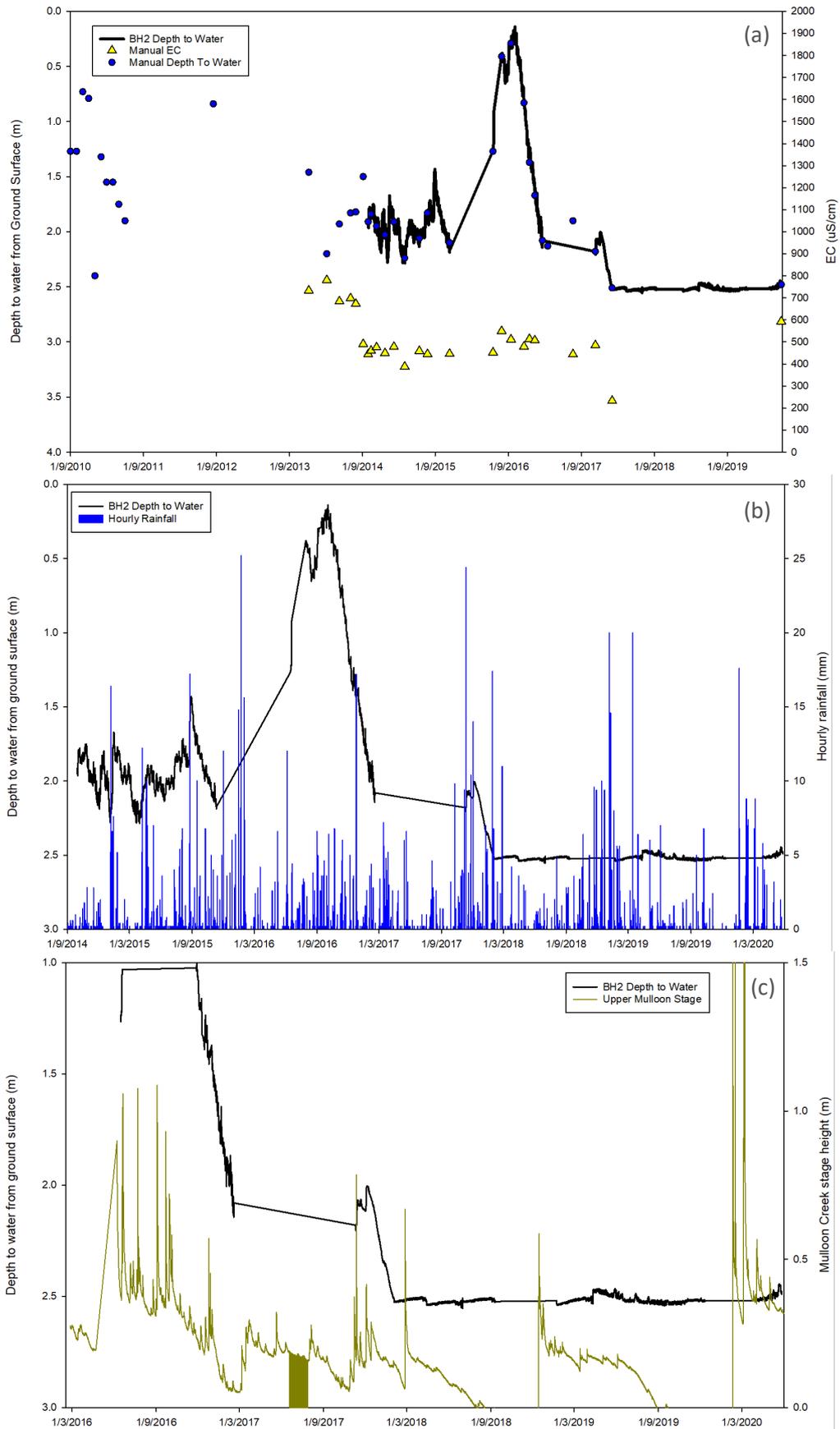


Figure 53. (a) BH2 water level and EC (2010-2020); (b) BH2 water level and rainfall (2014-2020); (c) BH2 water level and stream water level (2016-2020)

Transect C - Borehole 3-1

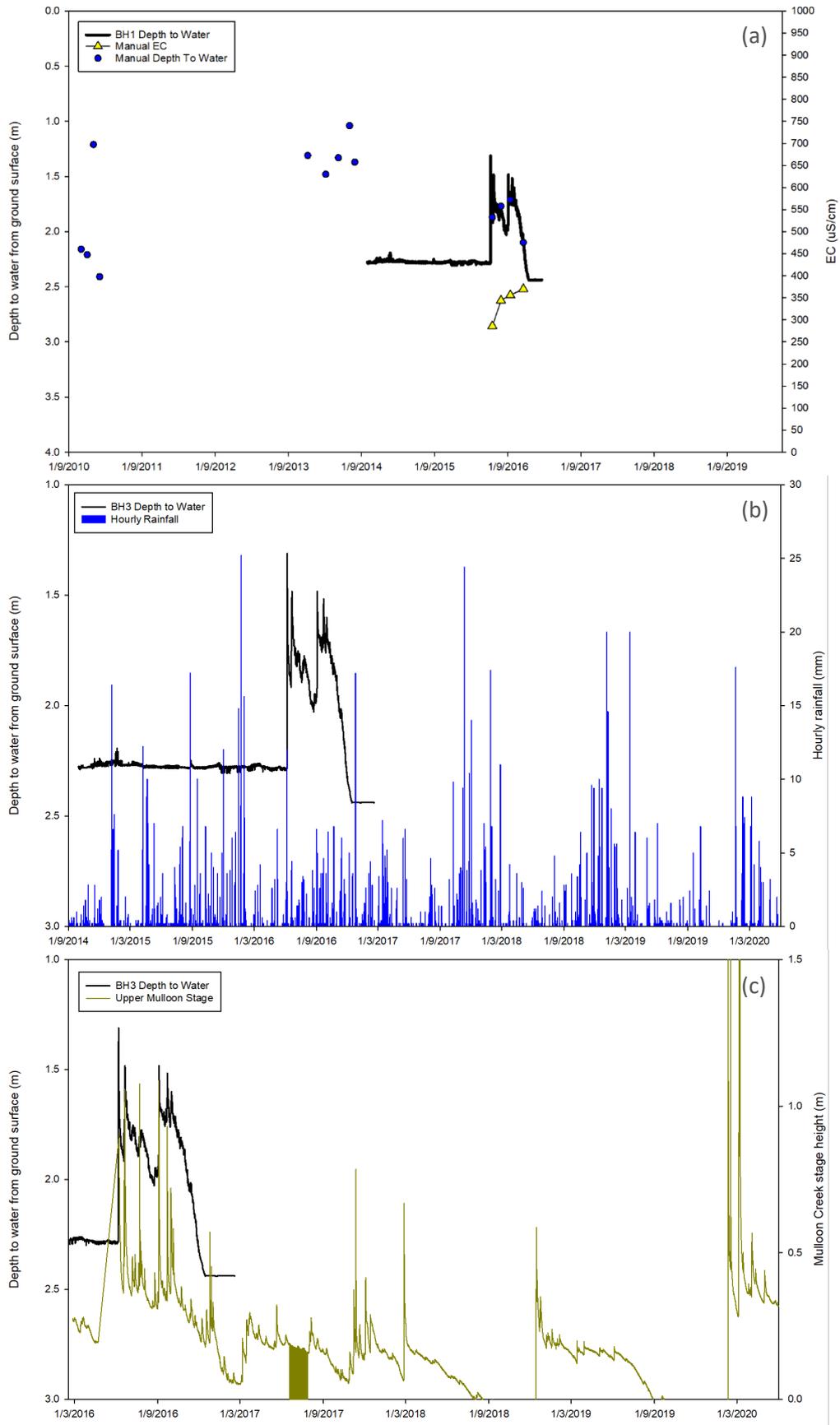


Figure 54. (a) BH3-1 water level and EC (2010-2020); (b) BH3-1 water level and rainfall (2014-2020); (c) BH3-1 water level and stream water level (2016-2020)

Borehole 3-2 (4.30m to base of screen) is located on the flood plain immediately west of Mulloon Creek (Figure 52). This borehole has only been continuously monitored since March 2017 (2.80m BGL), but two manual readings were taken in January 2017 (2.25m BGL) and in February 2017 (2.60m BGL) (Figure 55a). Manual groundwater level readings coincide well with continuous readings measured since 2014. From autumn 2017 to summer 2018, groundwater levels remained steady (2.60m BGL) but dropped rapidly by spring 2018 (3.20m BGL). Groundwater level continued to fall until March 2020 and, although there was limited recharge over this period, this borehole was responsive after rainfall in November 2017, March 2018, January 2019 and sustained rainfall in March 2020 (Figure 55b). The rises in groundwater level also coincide with rises in the water level in Mulloon Creek (Figure 55c), but EC remains unchanged. This synchronous response parallels that observed at borehole 5-2, located upstream in a similar setting.

Borehole 7 (2.70m to base of screen) is located on the lower colluvial slopes of hills east of Mulloon Creek (Figure 52). Pre-2014 manual readings show elevated groundwater levels in late spring 2010 (0.40m BGL), late spring 2013 (1.30m BGL) and spring 2014 (0.75m BGL), but there were limited measurements in the intervening period (spring 2011 to spring 2013) (Figure 56a). Patterns in this data also reflect the timing of manual sampling. Manual groundwater level readings coincide well with continuous readings measured since 2014. Continuous recording shows near-surface groundwater levels in autumn 2014 (0.70m BGL) and spring 2015 (0.20m BGL), with groundwater at ground level in late winter and spring 2016 (0.00m BGL) in response to sustained winter rainfall (Figure 56b). The pattern of elevated groundwater levels in spring at BH7 likely relates to groundwater movement off the adjacent hills as interflow after late winter to early spring rainfall (Figure 56b). The groundwater level dropped rapidly by summer 2017 (2.20m BGL) then rose again in spring 2017 and spring 2018, followed by a progressive drop in water level to winter 2019 (2.10m BGL) when the groundwater level stabilised until (allowing for a base level adjustment) it peaked briefly in late February 2020 (1.75m BGL) (Figure 56b). The borehole is proximal to and east of Mulloon Creek on the lower colluvial slopes. Throughout the monitoring period, groundwater levels rose after stream water levels peaked (Figure 56c). This, together with the pattern of elevated groundwater levels in spring at BH7, likely relates to groundwater movement off the adjacent hills as interflow following winter-to-early-spring rainfall.

Borehole 13 (2.20m to base of screen) is located on the lower colluvial slopes of hills east of Mulloon Creek (Figure 52). Pre-2014 manual readings show elevated groundwater levels in spring 2006 (1.4m BGL). Patterns in this data reflect the timing of manual sampling. Manual groundwater level readings coincide well with continuous readings measured since 2014. Continuous recording shows elevated groundwater levels in autumn (0.75m BGL), spring 2015 (0.25m BGL), and spring 2016 (0.25m BGL) (Figure 57a). The pattern of elevated groundwater levels in spring at BH13 likely relates to groundwater movement off the adjacent hills as interflow after late winter to early spring rainfall (Figure 57b). The groundwater level dropped rapidly by late summer 2017 (2.20m BGL), rose again in spring 2017 (1.75 BGL) and then was dry, apart from small interflow events, to 2020 (Figure 57b). Throughout the monitoring period, groundwater levels rose after stream water levels peaked but when the rain stopped the groundwater level rapidly lowered (Figure 57c). This pattern likely relates to groundwater movement off the adjacent hills as interflow through colluvial gravels after winter to early spring rainfall.

Transect C - Borehole 3-2

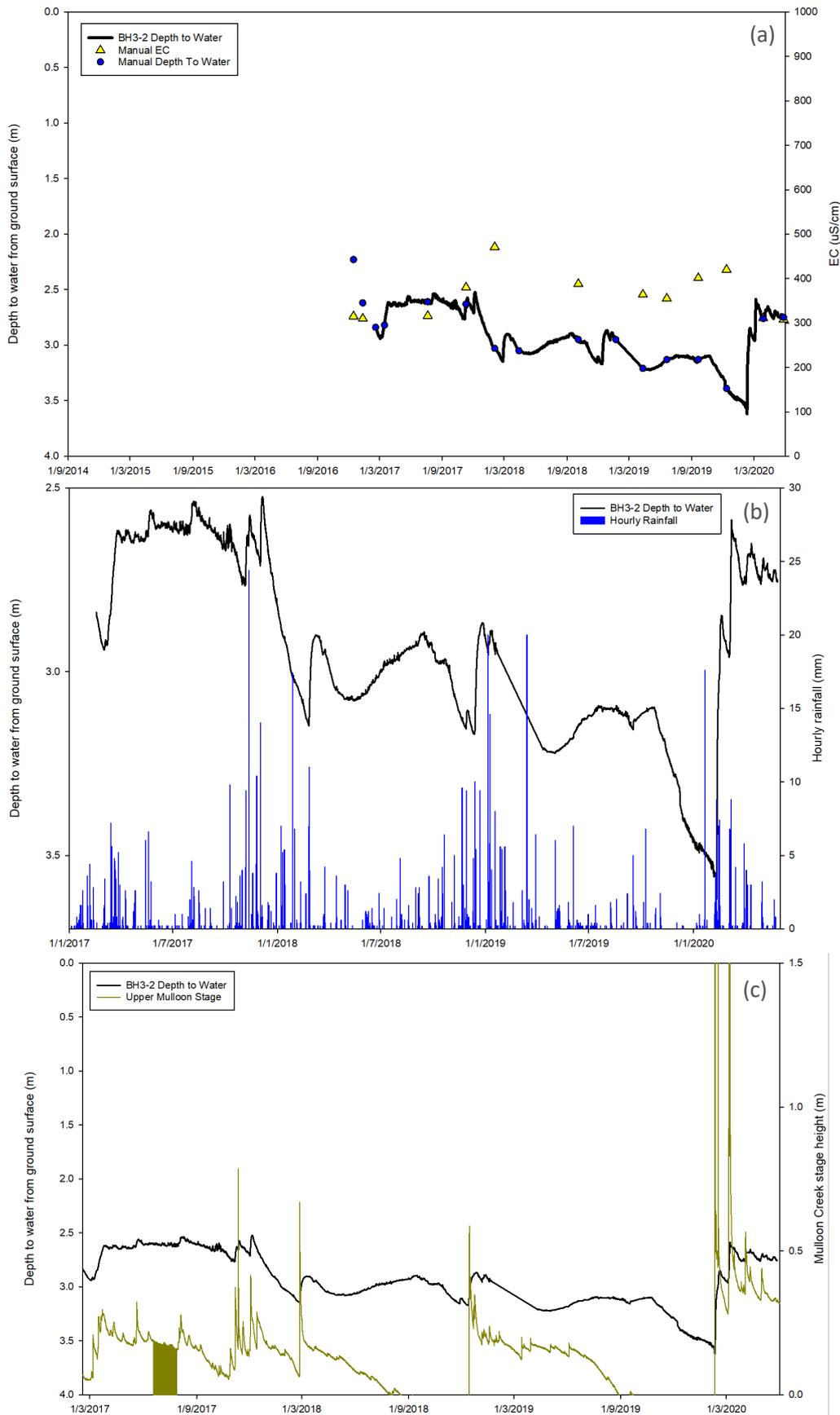


Figure 55. (a) BH3-2 water level and EC (2014-2020); (b) BH3-2 water level and rainfall (2017-2020); (c) BH3-2 water level and stream water level (2017-2020)

Transect C - Borehole 7

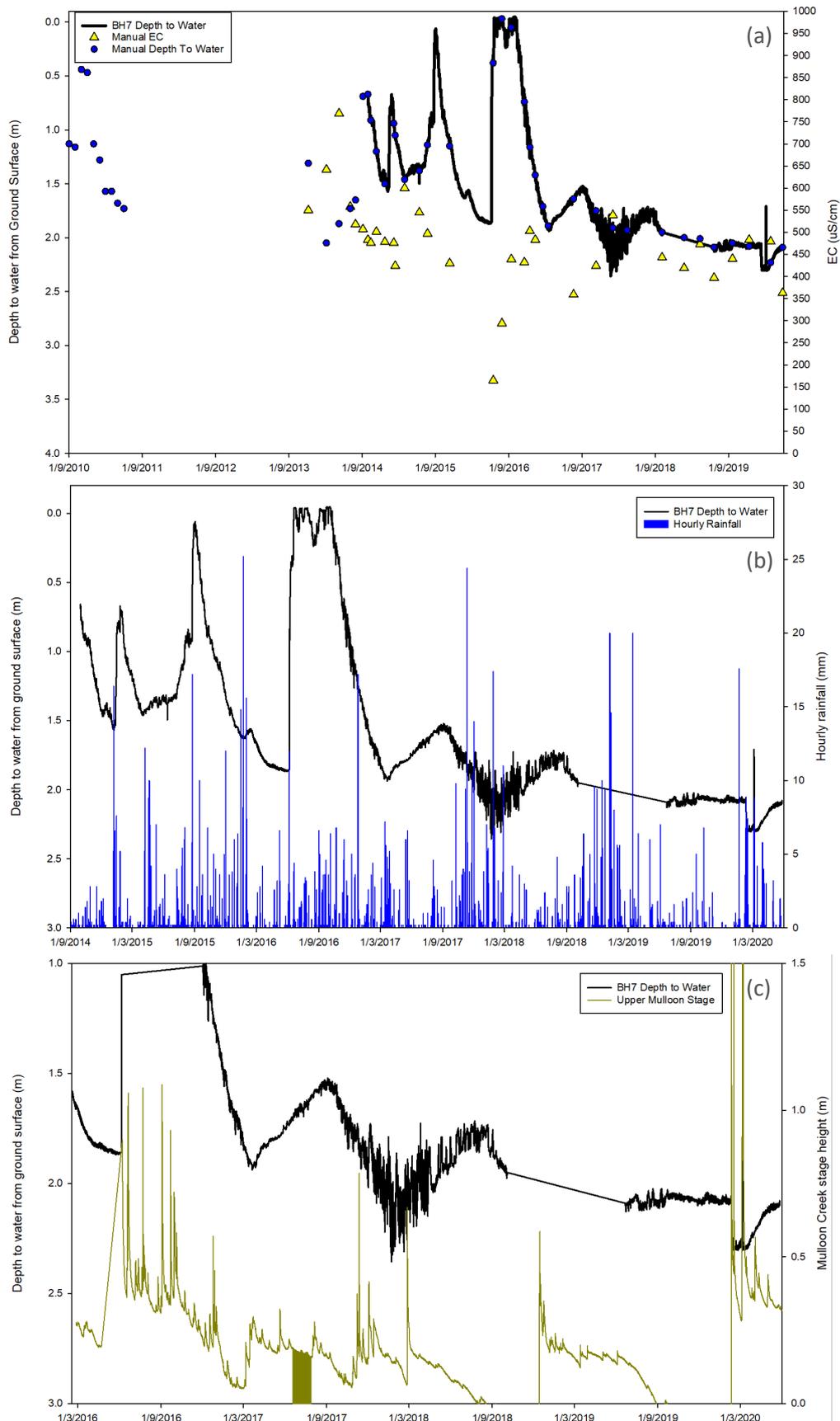


Figure 56. (a) BH7 water level and EC (2010-2020); (b) BH7 water level and rainfall (2014-2020); (c) BH7 water level and stream water level (2016-2020)

Transect C - Borehole 13

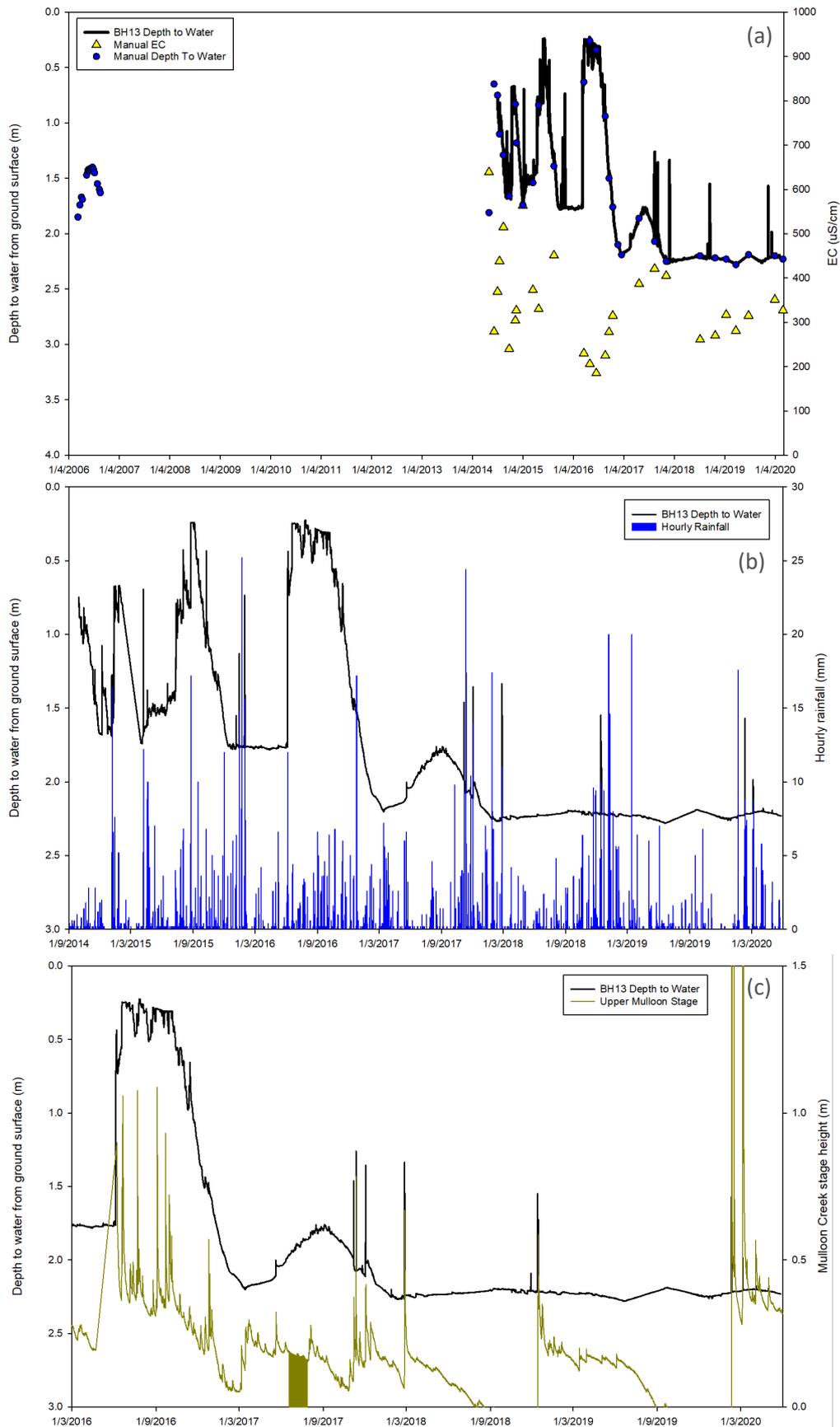


Figure 57. (a) BH13 water level and EC (2006-2020); (b) BH13 water level and rainfall (2014-2020); (c) BH13 water level and stream water level (2016-2020)

3.5.2.4 Northern Boreholes – Mulloon Home Farm north

Borehole 14 (3.90m to base of screen) is a single borehole located on the flood plain immediately west of Mulloon Creek, north of Transect C (Figure 33). This borehole has only been continuously monitored since January 2018 (1.80m BGL). However, manual readings were taken in January and February 2017 (1.90m BGL), in March 2017 (2.10m BGL), in April 2017 (1.90 BGL), in July 2017 (1.80m BGL) and in December 2017 (1.75 BGL) (Figure 58a). Manual groundwater level readings coincide well with continuous readings measured since 2014. From mid- to late summer 2018, groundwater levels dropped (1.70m BGL to 2.30m BGL), rose and dropped again in autumn (1.60m to 2.25m BGL), remained relatively steady (2.10m BGL) from autumn 2018 to autumn 2019, then dropped to 2.50m BGL (Figure 58a). Water level progressively rose to 2.00m BGL by spring 2019, then dropped rapidly to March 2020 (2.80m BGL). This borehole was responsive, with a lag, after sustained rainfall in January 2020, rising to 1.00m BGL in March 2020, then stabilising at 1.75m BGL to the end of the monitoring period (Figure 58b). The rises in groundwater level also coincide with rises in the water level in mid-Mulloon Creek (Figure 58c), but groundwater EC remains elevated. This synchronous response parallels that observed at boreholes 3-2 and 5-2, located upstream in a similar setting, and is likely a pressure response.

Borehole 1 (3.60m to base of screen) is a single borehole located on the flood plain immediately west of Mulloon Creek, north of the weather station (Figure 33). This borehole has been continuously monitored since 2014. Manual readings were taken in September and October 2010 (1.50m BGL), with groundwater rising into the root zone in November (0.4m BGL) and December 2010 (0.55m BGL), then dropping back to 1.5m BGL in January 2011 and continuing to drop until manual readings stopped in June 2011 (1.80m BGL). Manual readings of groundwater level from December 2013 to July 2014 were in the range 1.40m BGL to 1.50m BGL, with a peak in June 2014 (1.1m BGL) and August 2014 (0.6m BGL) (Figure 59a). Manual groundwater level readings coincide well with continuous readings measured since 2014. Groundwater level fluctuates from a 1.50m BGL baselevel (spring 2014 to summer 2015) with peaks in autumn 2015 (0.3m BGL) and spring 2015 (0.3m BGL), then drops to a 1.75 m baselevel (summer 2015-winter 2016) with a peak in autumn 2016 (1.25m BGL). In winter 2016, there was a significant rise in groundwater level (from July 2016, 0.4m BGL to August 2016, 0.15m BGL) that subsided by March 2017 (1.60m BGL), rising again to a peak in winter 2016 (0.7m BGL). This is followed by a declining trend to May 2018 (1.70m BGL), with rainfall event related peaks in September 2017 (1.15m BGL), December 2017 (1.25m BGL) and April 2018 (1.60m BGL). From May 2018 to December 2018, the groundwater level is relatively stable (1.70m BGL) until after a rainfall event related peak in January 2019 (1.5m BGL), when the groundwater level restabilises to 1.80m BGL until October 2019. Groundwater level then drops steadily to January 2020 (2.6m BGL), followed by a rapid rise associated with January 2020 rains, peaking at 1.4m BGL in April 2020 and dropping to 1.75m BGL by the end of the monitoring period (Figure 59b). The rises in groundwater level also coincide with rises in the water level in Mulloon Creek (Figure 59c), but groundwater EC remains elevated. This synchronous response parallels that observed at boreholes 5-2 and 14, located upstream in a similar setting, and is likely a pressure response.

Northern Boreholes - Borehole 14

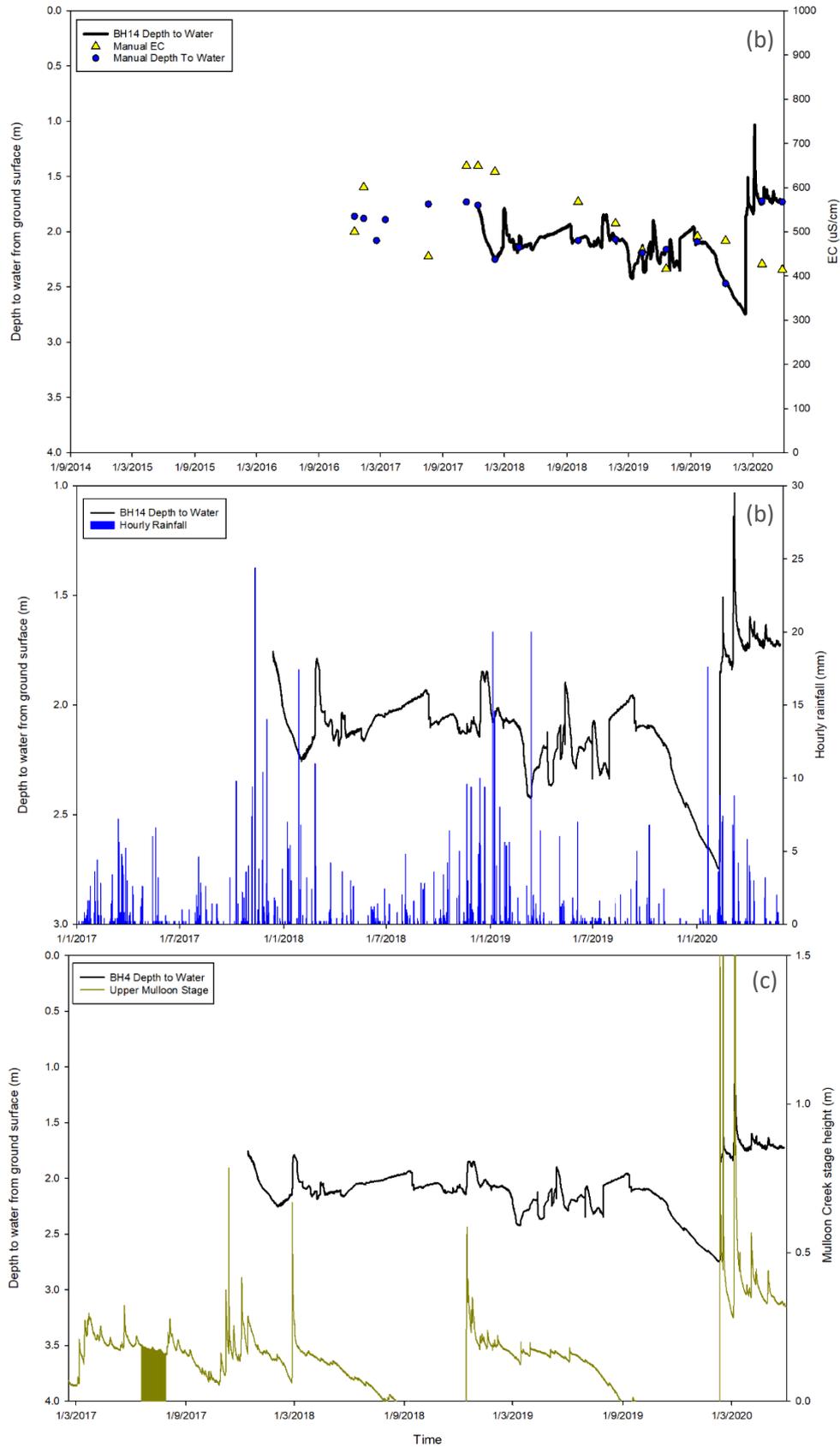


Figure 58. (a) BH14 water level and EC (2014-2020); (b) BH14 water level and rainfall (2017-2020); (c) BH14 water level and stream water level (2017-2020)

Northern Boreholes - Borehole 1

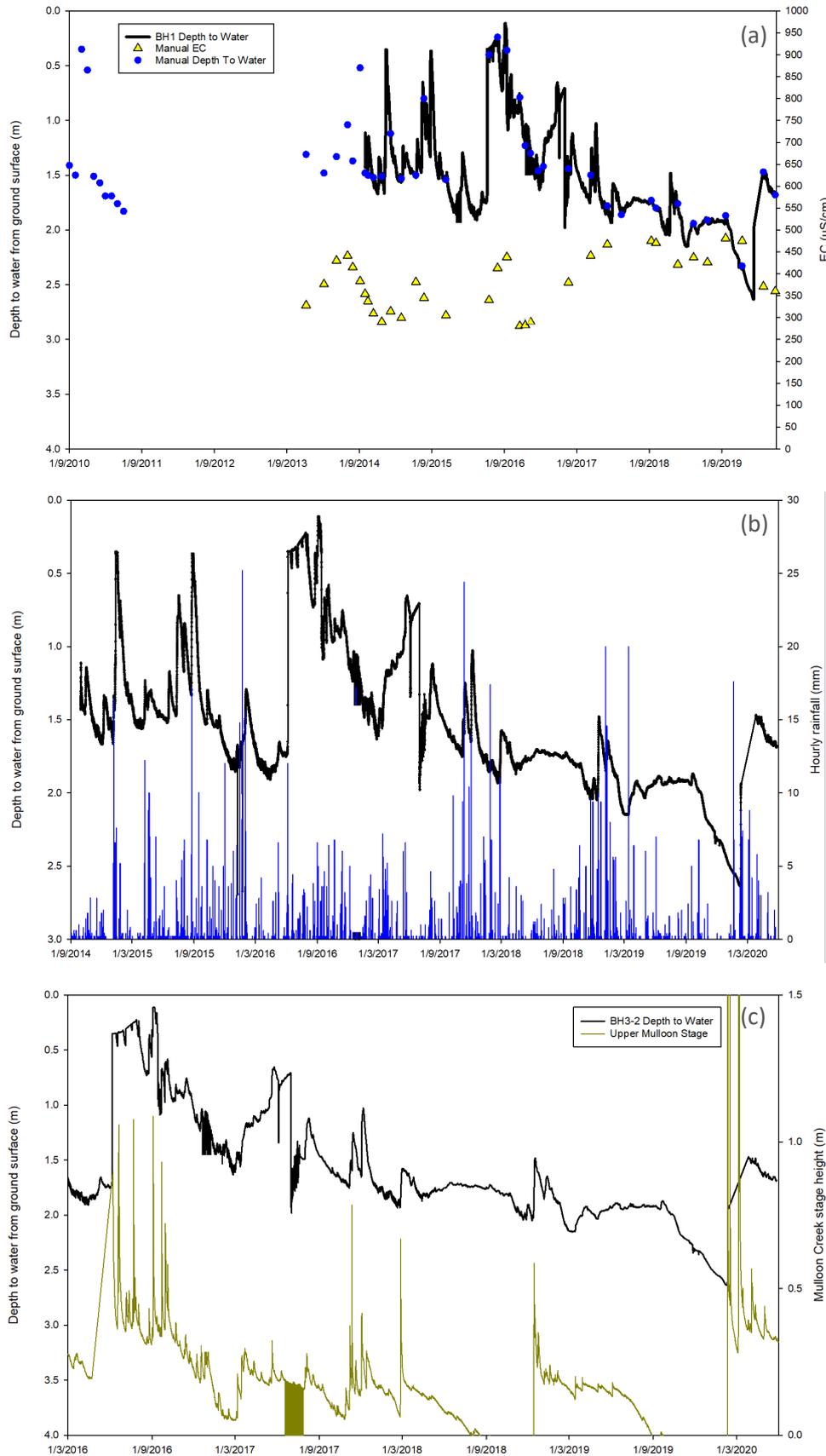


Figure 59. (a) BH1 water level and EC (2010-2020); (b) BH1 water level and rainfall (2014-2020); (c) BH1 water level and stream water level (2016-2020).

3.5.3 Groundwater Electrical Conductivity (EC)

The groundwater electrical conductivity (EC) ranges for the Mulloon Home Farm boreholes are typically relatively low ($\ll 800 \mu\text{S}/\text{cm}$) (Table 6). Water with an EC $< 500 \mu\text{S}/\text{cm}$ is considered fresh (drinkable water), and with an EC $500 \mu\text{S}/\text{cm}$ to $1000 \mu\text{S}/\text{cm}$ is considered brackish (stock water) (Table 2; Mayer et al. 2005). The lowest values ($100\text{-}150 \mu\text{S}/\text{cm}$) were measured in holes on the eastern side of the stream (BH7, BH12), or distal from the stream in the upper part of the alluvial landscape (BH11). The EC values do not vary much in most holes ($< 350 \mu\text{S}/\text{cm}$ difference) with larger ranges for slightly higher relief sites (BH6, BH7, BH13) on the eastern side of the stream, and more distal sites (BH2, BH10, BH11) on the western terraces. Groundwater EC values are consistently higher than those measured in mid-Mulloon Creek ($< 200 \mu\text{S}/\text{cm}$, commonly $< 100 \mu\text{S}/\text{cm}$).

Table 6.

Groundwater electrical conductivity (EC $\mu\text{S}/\text{cm}$) ranges (2014-2020) for Mulloon Home Farm boreholes.

Transect A – southern west-east transect.			
BH11 150-700 $\mu\text{S}/\text{cm}$ Fresh to brackish	BH10 200-600 $\mu\text{S}/\text{cm}$ Fresh to brackish	BH9 200-250 $\mu\text{S}/\text{cm}$ Fresh	BH8-1 250-300 $\mu\text{S}/\text{cm}$ Fresh
BH8-2 300-400 $\mu\text{S}/\text{cm}$ Fresh	BH12 100-250 $\mu\text{S}/\text{cm}$ Fresh		
Transect B – central west-east transect			
BH4 400-700 $\mu\text{S}/\text{cm}$ Fresh to brackish	BH5-1 300-500 $\mu\text{S}/\text{cm}$ Fresh	BH52 450-650 $\mu\text{S}/\text{cm}$ Fresh to brackish	BH6 200-750 $\mu\text{S}/\text{cm}$ Fresh to brackish
Transect C – northern west-east transect			
BH2 250-600 $\mu\text{S}/\text{cm}$ Fresh to brackish	BH3-1 350-400 $\mu\text{S}/\text{cm}$ Fresh	BH3-2 300-400 $\mu\text{S}/\text{cm}$ Fresh	BH7 150-650 $\mu\text{S}/\text{cm}$ Fresh to brackish
BH13 200-600 $\mu\text{S}/\text{cm}$ Fresh to brackish			
Northern Boreholes			
BH14 400-650 $\mu\text{S}/\text{cm}$ Fresh to brackish	BH1 350-500 $\mu\text{S}/\text{cm}$ Fresh		

Groundwater, rainfall and stream water level

Climatically, the sampling period covers the latter part of the Millennium Drought (2006-2010), a wet period (2010-2011), an Interim Drought period (2012-2015), a wet period (2016), the Tinderbox Drought (2017-2019) and the start of the recent wet period (2020). This delivery of water to the mid-Mulloon landscape is further complicated by seasonal weather patterns, typically summer-dominated rainfall, and major storm events, for example, rains associated with east coast low-pressure systems. Changes in groundwater level typically reflect recharge following rain events, with larger responses associated with higher volume and/or more sustained rain events. A number of the mid-Mulloon boreholes are dry for extended periods because of their construction (BH11, BH10, BH9, BH5, BH3, BH2), but they record major events in 2016 and 2020. In several cases, there is a lag of days in boreholes before the recharge is recorded. Boreholes east of Mulloon Creek with steep adjacent slopes (BH12, BH6, BH7, BH13) show a fairly rapid response to rainfall events, but water levels also drop rapidly. This relates to groundwater movement off the adjacent hills as interflow after rainfall. Boreholes

immediately proximal to mid-Mulloon Creek on the floodplain (BH8-2, BH5-2, BH3-2, BH14, BH1) commonly show a synchronous response to an increase in water level in the Creek, and some response is noted in two of the proximal eastern boreholes (BH6, BH7). However, because this response does not correspond with a decrease in electrical conductivity in the groundwater, this is not the result of direct transfer of stream water to the floodplain. This response is a pressure response in boreholes associated with a transient high-stand in the Creek.

3.3.4 Groundwater response to periods of sustained rainfall (2016 and 2020)

In order to evaluate how mid-Mulloon groundwater will respond to large rainfall events in future, it is useful to look in more detail at the major events that occurred during the monitoring period, a large event in mid-2016 (Figure 60) and a series of moderate events in early 2020. One challenge is that these events often overwhelm the monitoring infrastructure when water levels rise rapidly.



Figure 60. Mulloon Creek in flood, June 2016 (TMI, 2016).

Transect A – Mulloon Home Farm southern west-east transect

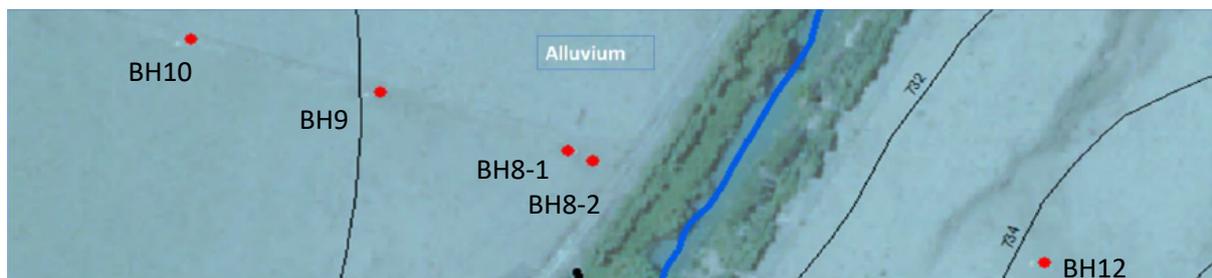


Figure 61. Borehole Transect A is a west-east line of boreholes perpendicular to Mulloon Creek, in the southern part of Mulloon Home Farm (after Hickson, 2017).

Transect A - Sustained Rainfall 2016

Borehole 11 (3.25m to base of screen) is the westernmost borehole in Transect A (Figure 61). When the June 2016 rainfall event commenced, the groundwater level in BH11 rose rapidly from 2.40m BGL to 0.60m BGL (sensor limit). Measurements were recorded at <0.60m BGL

for several days (to 15 June 2016) until sensor failure (Figure 62a). The groundwater EC recorded during this event was 250 μ S/cm.

Borehole 10 (3.60 to base of screen) is located on a fluvial terrace west of Mulloon Creek (Figure 61). Borehole 10 did not have a sensor recording groundwater level during this event (Figure 62b). The groundwater EC recorded during this event was 250 μ S/cm.

Borehole 9 (2.90m to base of screen) is located on the flood plain west of Mulloon Creek (Figure 61). Borehole 9 was dry before the rainfall event and remained dry until mid-July, when the groundwater level rose progressively from 2.90m BGL to 2.00m BGL at the end of June (Figure 62c). The groundwater EC recorded during this event was 1100 μ S/cm.

Borehole 8-1 (2.90m to base of screen) is located on the flood plain immediately west of Mulloon Creek (Figure 61). Borehole 8-1 was dry before the rainfall event and remained dry throughout June (2.90m BGL). This implies that the borehole was not deep enough to receive groundwater during this event (Figure 62d).

Borehole 8-2 (4.80m to base of screen) is located on the flood plain immediately west of Mulloon Creek (Figure 61), but this hole was commissioned after the 2016 rainfall event.

Borehole 12 (3.35m to base of screen) is located on the flood plain, mid-way between the eastern foothills and Mulloon Creek (Figure 61). The borehole was dry before the rain event but responded rapidly, rising from 3.20m BGL to 1.25m BGL (sensor limit) in a day. A week and a half later, the sensor was raised to 0.40m BGL. The groundwater level peaked at 0.6m on 16 June, dropped to 1.3m BGL on 18 June, then rose to 0.40m BGL (sensor limit) on 19 June and remained at <0.40m BGL for the balance of June (Figure 62e). The groundwater EC recorded during this event was 80 μ S/cm.

Transect A - Sustained Rainfall 2020

Most boreholes in this transect (BH11, BH10, BH9, BH8-1) were dry prior to this event and remained dry for the months January to March 2020 (Figure 63a-d).

Borehole 8-2 had a steady groundwater level (4.25m BGL to 4.30m BGL) until early February, then started rising incrementally to 4.10m BGL by the end of March (Figure 63e).

Borehole 12 did not have a sensor recording water level during these events (Figure 63f). Antecedent conditions were extremely dry prior to these rain events.

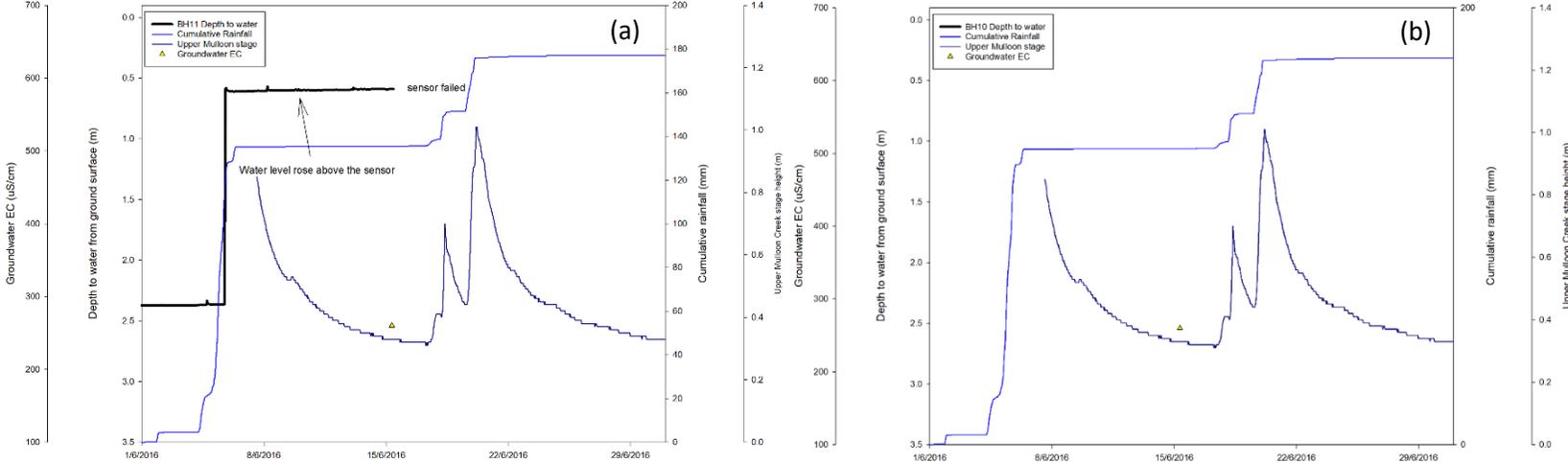


Figure 62. Groundwater Depth (BGL), Cumulative Rainfall, Stream Manual Stage Height, and Groundwater EC from 1 June to 1 July 2016 for Transect A (southern west-east transect): (a) BH11, (b) BH10 at Mulloon Home Farm.

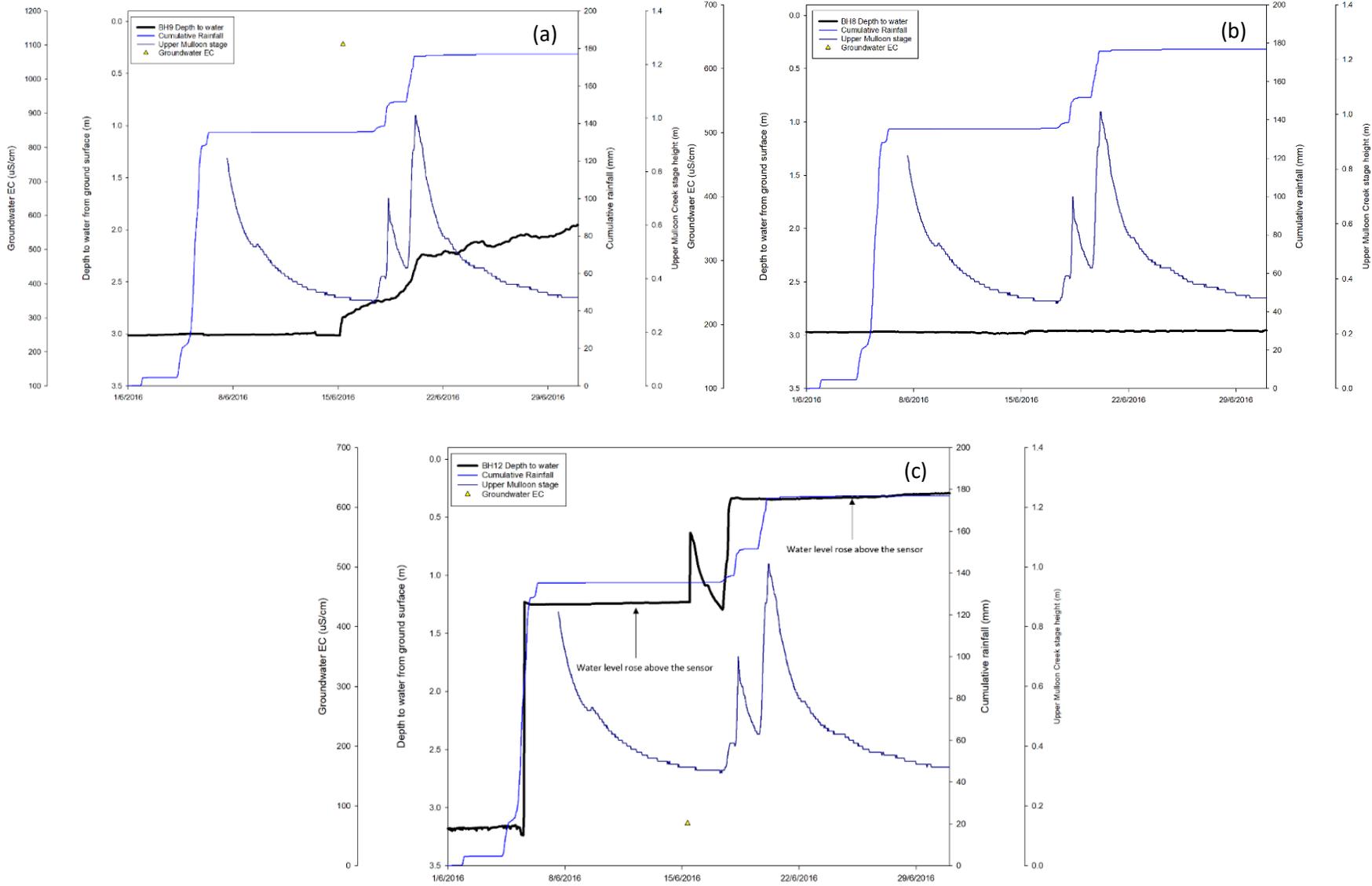


Figure 62. Groundwater Depth (BGL), Cumulative Rainfall, Stream Manual Stage Height, and Groundwater EC from 1 June to 1 July 2016 for Transect A (southern west-east transect): (c) BH9; (d) BH8-1; (e) BH12, at Mulloon Home Farm.

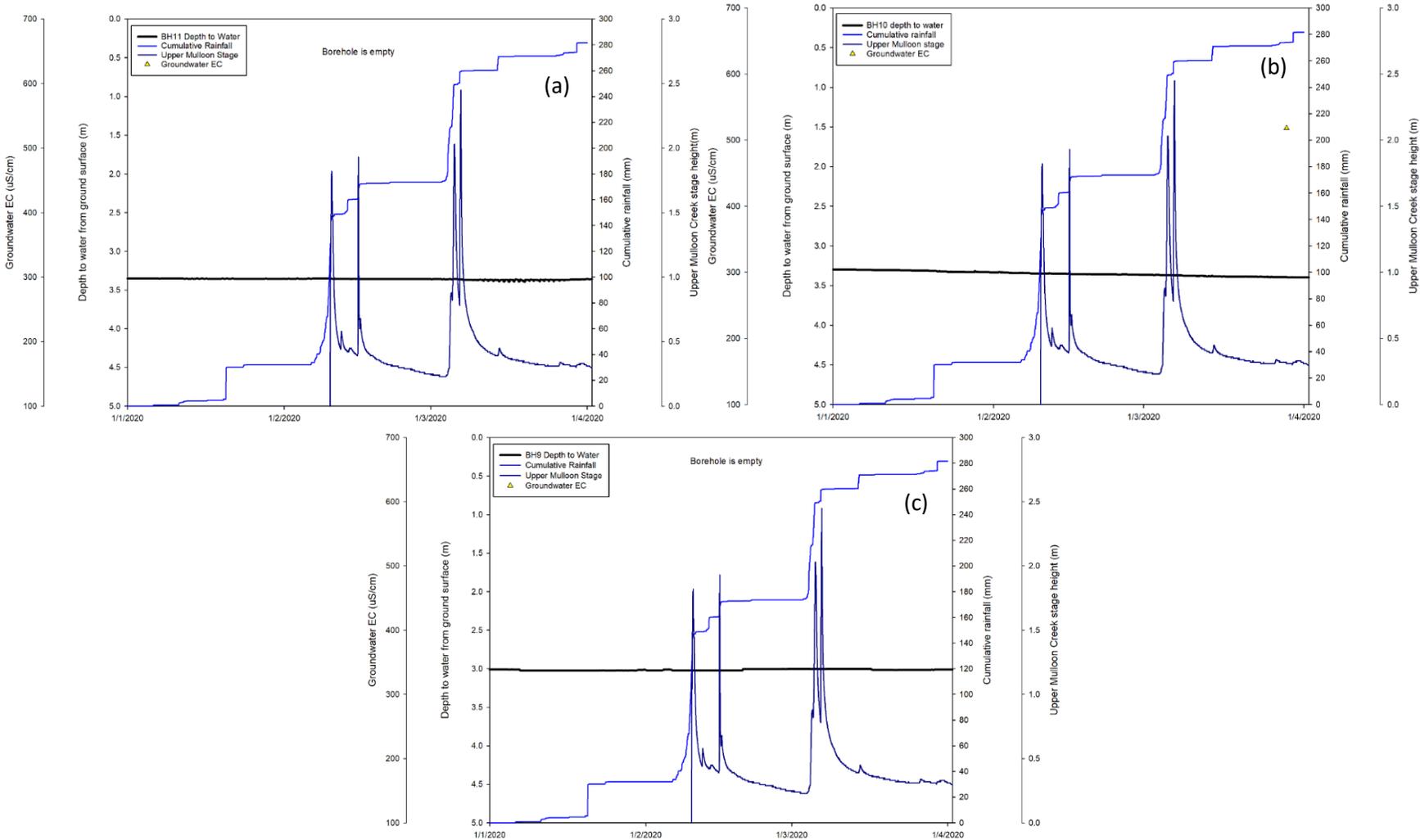


Figure 63. Groundwater Depth (BGL), Cumulative Rainfall, Stream Manual Stage Height, and Groundwater EC from 1 January to 1 April 2020 for Transect A (southern west-east transect): (a) BH11; (b) BH10; (c) BH9, at Mulloon Home Farm.

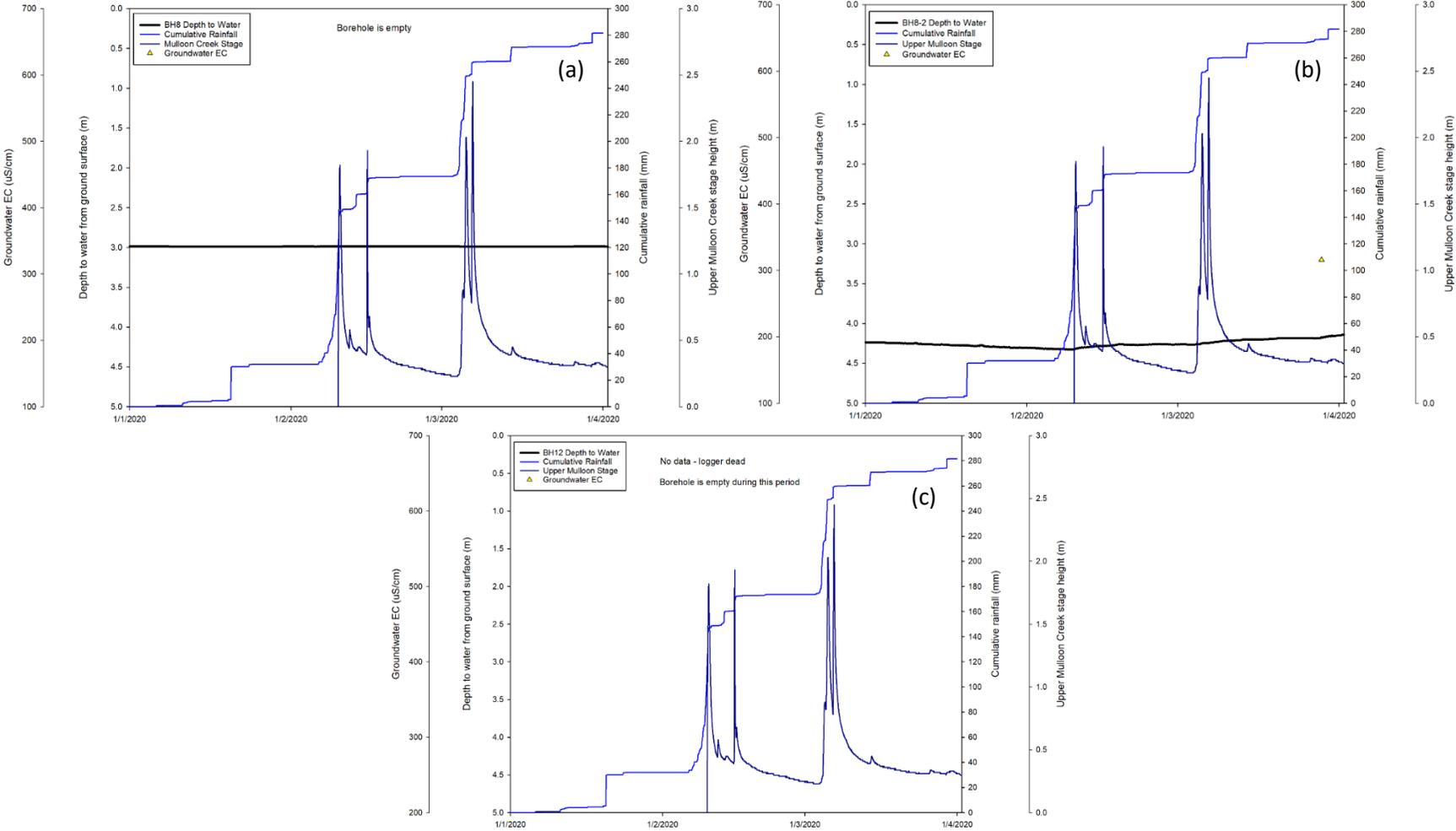


Figure 63. Groundwater Depth (BGL), Cumulative Rainfall, Stream Manual Stage Height, and Groundwater EC from 1 January to 1 April 2020 for Transect A (southern west-east transect): (d) BH8-1, (e) BH8-2, (f) BH12, at Mulloon Home Farm.

Transect B – Mulloon Home Farm central west-east transect



Figure 64. Borehole Transect B is a west-east line of boreholes perpendicular to Mulloon Creek, in the central part of Mulloon Home Farm (after Hickson, 2017, refer to Figure 33).

Transect B – Sustained Rainfall 2016

Borehole 4 (3.40m to base of screen) is the westernmost borehole in Transect B, located in a back-plain flood-runner on the western margin of the alluvial plain (Figure 64). Groundwater level rose rapidly in response to the 5 June event from 1.80m BGL to 0.60m BGL (sensor limit) in one day. The groundwater level remained high (<0.60m BGL) for a week, then dropped to 1.00m BGL over the next week in response to reduced rainfall. Groundwater rose incrementally with the rain event on 18 June (1.00m BGL to 0.80m BGL) and the event on 21 June (0.8m BGL to 0.6m BGL – sensor limit) and remained at <0.60m BGL for the balance of June (Figure 65a). The groundwater EC recorded during this event was 650 μ S/cm.

Borehole 5-1 (2.15m to base of screen) is located on the flood plain immediately west of Mulloon Creek (Figure 64). The hole was dry before the 5 June rain event, but although it rose from 2.00m BGL to 0.60m BGL in a day, it started to subside immediately, dropping to 1.75m BGL by 18 June. The groundwater level rose incrementally in response to the 18 June event (from 1.75m BGL to 1.50m BGL) and the 21 June event (from 1.40m BGL to 1.00m BGL), then slowly lowered to 1.30m BGL by the end of June (Figure 65b). The groundwater EC recorded during this event was 400 μ S/cm.

Borehole 5-2 (3.75m to base of screen) is located on the flood plain immediately west of Mulloon Creek (Figure 64), but this hole was commissioned after the 2016 rainfall event.

Borehole 6 (3.20m to base of screen) is located on the flood plain immediately east of Mulloon Creek (Figure 64). Groundwater level rose rapidly in response to the 5 June event from 2.55m BGL to 1.40m BGL (sensor limit) in one day. The groundwater level remained elevated (<1.40m BGL) for a week, then dropped to 1.70m BGL over the next week in response to reduced rainfall. Groundwater rose incrementally with the rain event on 18 June (1.70m BGL to 1.40m BGL – sensor limit), remained at <1.40m BGL to 27 June, and lowered to 1.60m BGL by the end of June (Figure 65c). The groundwater EC recorded during this event was 150 μ S/cm.

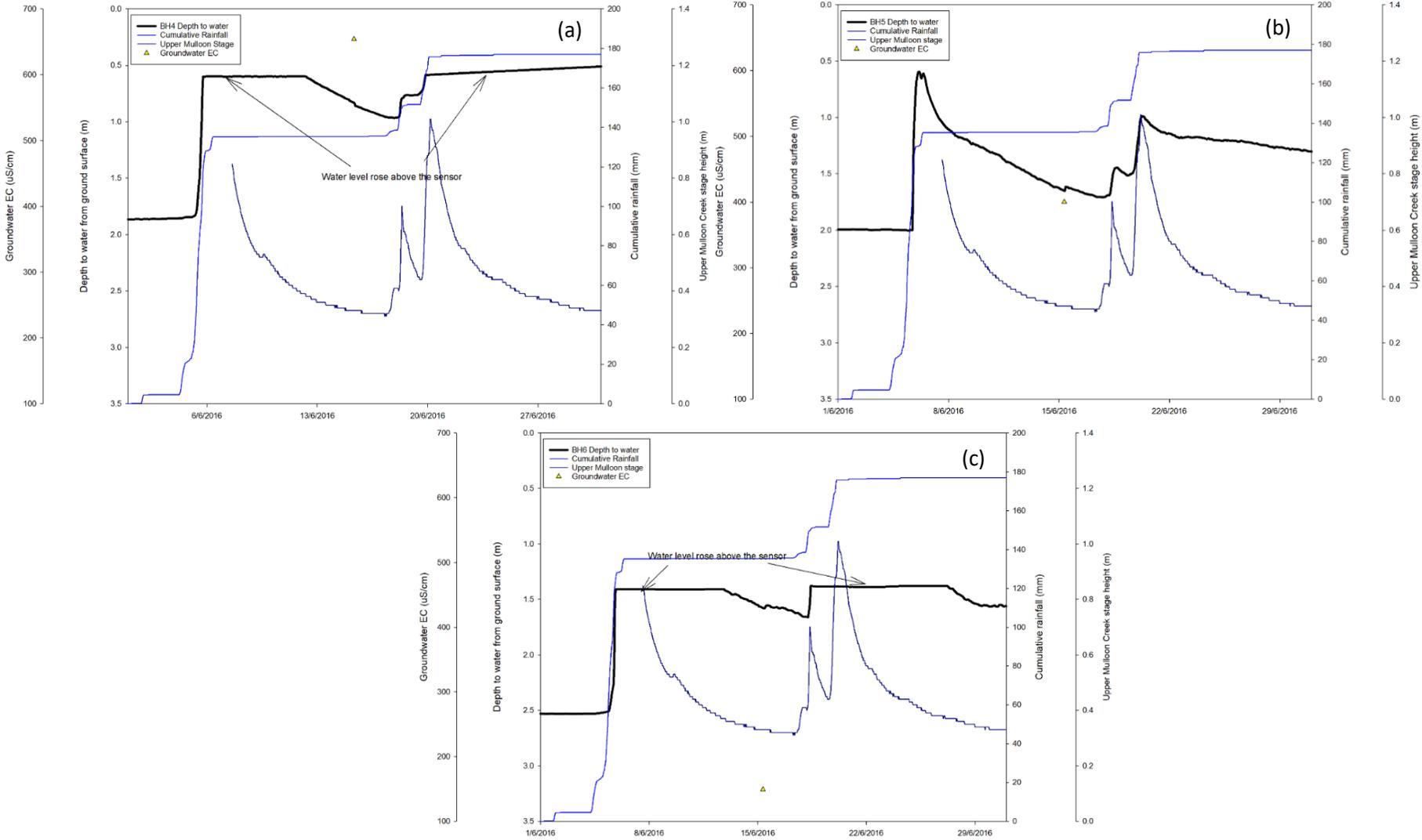


Figure 65. Groundwater Depth (BGL), Cumulative Rainfall, Stream Manual Stage Height, and Groundwater EC from 1 June to 1 July 2016 for Transect B (central west-east transect): (a) BH4, (b) BH5-1, (c) BH6, at Mulloon Home Farm.

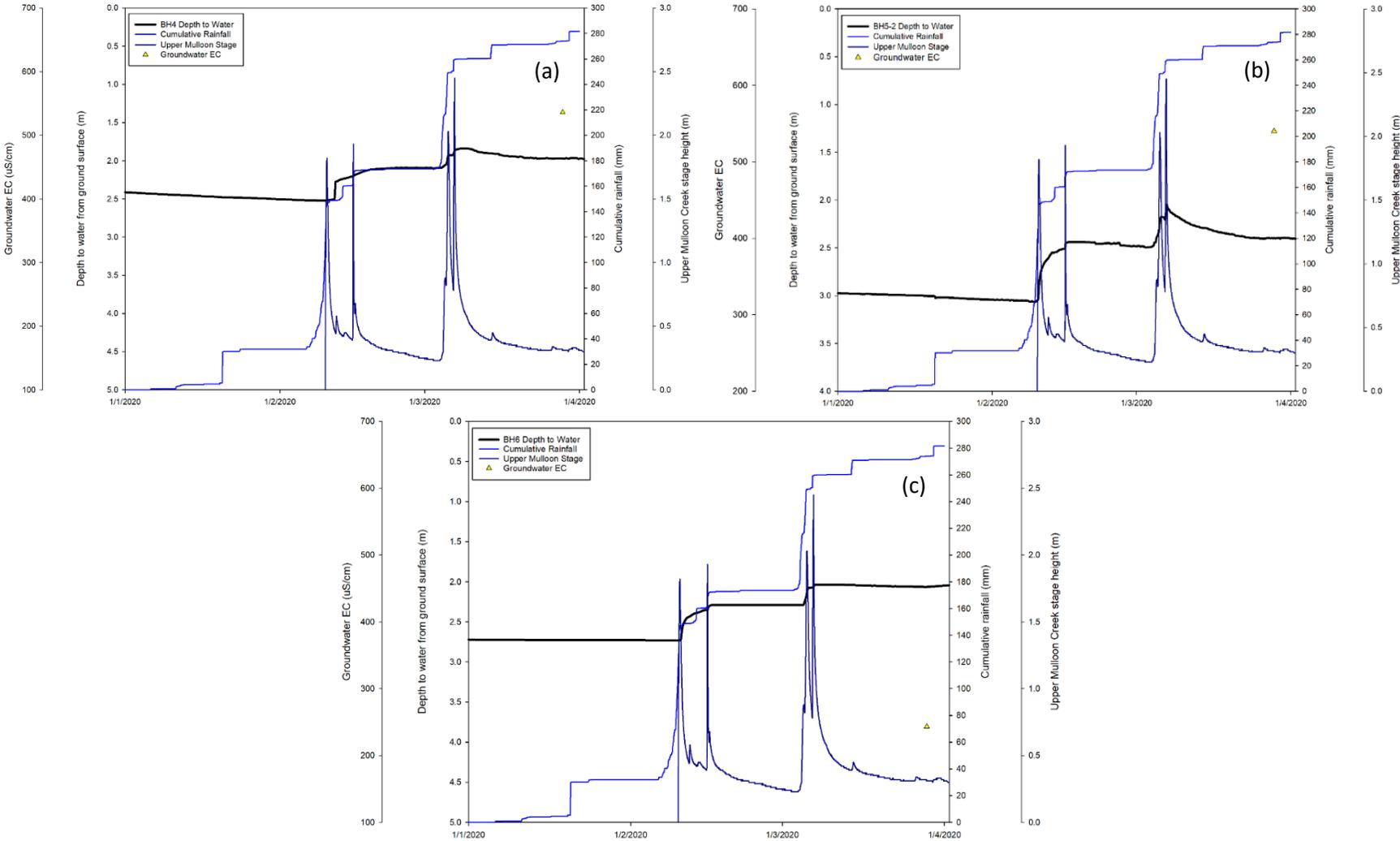


Figure 65. Groundwater Depth (BGL), Cumulative Rainfall, Stream Manual Stage Height, and Groundwater EC from 1 January to 1 April 2020 for Transect B (central west-east transect): (a) BH4, (b) BH 5-2, (c) BH6, at Mulloon Home Farm.

Transect B – Sustained Rainfall 2020

Borehole 4 groundwater level decreased slightly from 1 January to the first rain event in early February (2.50m BGL to 2.40m BGL), but after 2 days rose rapidly to 2.25m BGL, then continued to rise to 2.10m BGL by mid-February and remained at this level until the rain event in early March. Water level rose rapidly, without a lag, in response to the March rainfall events (2.10m BGL to 1.90m BGL), decreasing slightly (1.90m BGL to 2.00m BGL) by the end of March. The groundwater EC recorded during this event was 550 μ S/cm.

Borehole 5-2 groundwater level decreased slightly from 1 January to the first rain event in early February (3.00m BGL to 3.10m BGL) but rose to 2.50m BGL over the next few days in response to the rain event. Groundwater remained at this level until the rain event in early March. Water level rose rapidly in response to the March rainfall events (2.50m BGL to 2.10m BGL), decreasing (2.10m BGL to 2.40m BGL) by the end of March. The groundwater EC recorded during this event was 550 μ S/cm.

Borehole 6 groundwater level was at 2.75m BGL 1 January to the first rain event in early February but rose to 2.40m BGL over the next few days in response to the rain event. Groundwater remained at this level until the rain event in early March. Water level rose in response to the March rainfall events (2.40m BGL to 2.10m BGL), decreasing (2.10m BGL to 2.40m BGL) by the end of March. The groundwater EC recorded during this event was 250 μ S/cm.



Figure 66. Peters Pond in flood 2020, northern Mulloon Home Farm (TMI, 2020).

Transect C – Mulloon Home Farm northern west-east transect



Figure 67. Borehole Transect C is a west-east line of boreholes perpendicular to Mulloon Creek, in the northern part of Mulloon Home Farm (after Hickson, 2017, refer to Figure 33).

Transect C – Sustained Rainfall 2016

Borehole 2 (2.60m to base of screen) is located on the flood plain west of Mulloon Creek (Figure 67). Borehole 2 did not have a sensor recording groundwater level during the first rain event, but elevated levels were recorded, with a 1 day lag, in response to the 18 June event (1.25m BGL to 0.90m BGL), with high levels sustained to the end of June (0.90m BGL to 0.70m BGL) (Figure 68a). The groundwater EC recorded during this event was 650 μ S/cm.

Borehole 3-1 (2.50m to base of screen) is located on the flood plain immediately west of Mulloon Creek (Figure 67). Groundwater level was at 2.30m BGL but rose rapidly, after a 1 day lag, to the 5 June rainfall event (2.30m BGL to 1.25m BGL), then slowly dropped in response to decreased rainfall (1.25 m BGL to 1.90m BGL) until 18 June. Groundwater level rose incrementally in response to the 18 June (1.90m BGL to 1.75m BGL) and 21 June rainfall events (1.75m BGL to 1.60m BGL), then slowly dropped (1.60m BGL to 1.75m BGL) to the end of June (Figure 68b). The groundwater EC recorded during this event was 290 μ S/cm.

Borehole 3-2 (4.30m to base of screen) is located on the flood plain immediately west of Mulloon Creek (Figure 67), but this hole was commissioned after the 2016 rainfall event.

Borehole 7 (2.70m to base of screen) is located on the lower colluvial slopes of hills east of Mulloon Creek (Figure 67). Groundwater level was at 1.70m BGL, but rose rapidly in response to the 5 June rainfall event (1.70m BGL to 0.90m BGL), then continued to rise over the next few days (0.90m BGL to 0.40m BGL), staying at this level until 18 June. Groundwater level rose to the land surface (sensor limit) in response to the 18 June and 21 June rainfall events, then slowly dropped (0.00m BGL to 0.20m BGL) in the final week of June (Figure 68c). The groundwater EC recorded during this event was 150 μ S/cm.

Borehole 13 (2.20m to base of screen) is located on the lower colluvial slopes of hills east of Mulloon Creek (Figure 67). Groundwater level was at 1.75m BGL, but rose rapidly in response to the 5 June rainfall event (1.75m BGL to 0.50m BGL), it then dropped over the next few days (0.50m BGL to 0.75m BGL), rising slightly to 18 June (0.75m BGL to 0.60m BGL). Groundwater level rose to 0.40m BGL (sensor limit) in response to the 18 June rainfall event and stayed at elevated levels (<0.40m BGL) until the end of June (Figure 68d). The groundwater EC recorded during this event was 70 μ S/cm.

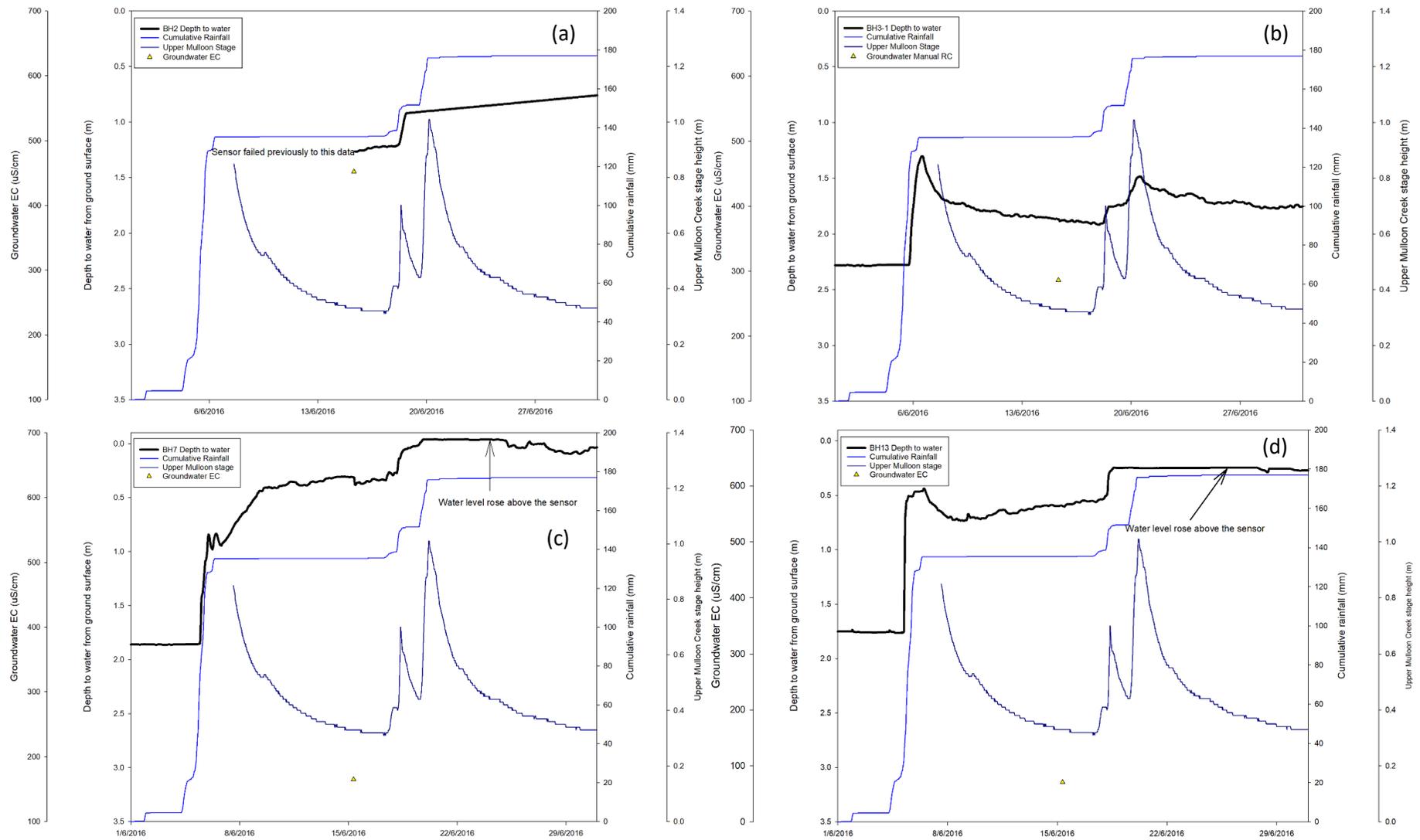


Figure 68. Groundwater Depth (BGL), Cumulative Rainfall, Stream Manual Stage Height, and Groundwater EC from 1 June to 1 July 2016 for Transect C (northern west-east transect): (a) BH2, (b) BH3-1, (c) BH7, (d) BH13, at Mulloon Home Farm.

Transect C – Sustained Rainfall 2020

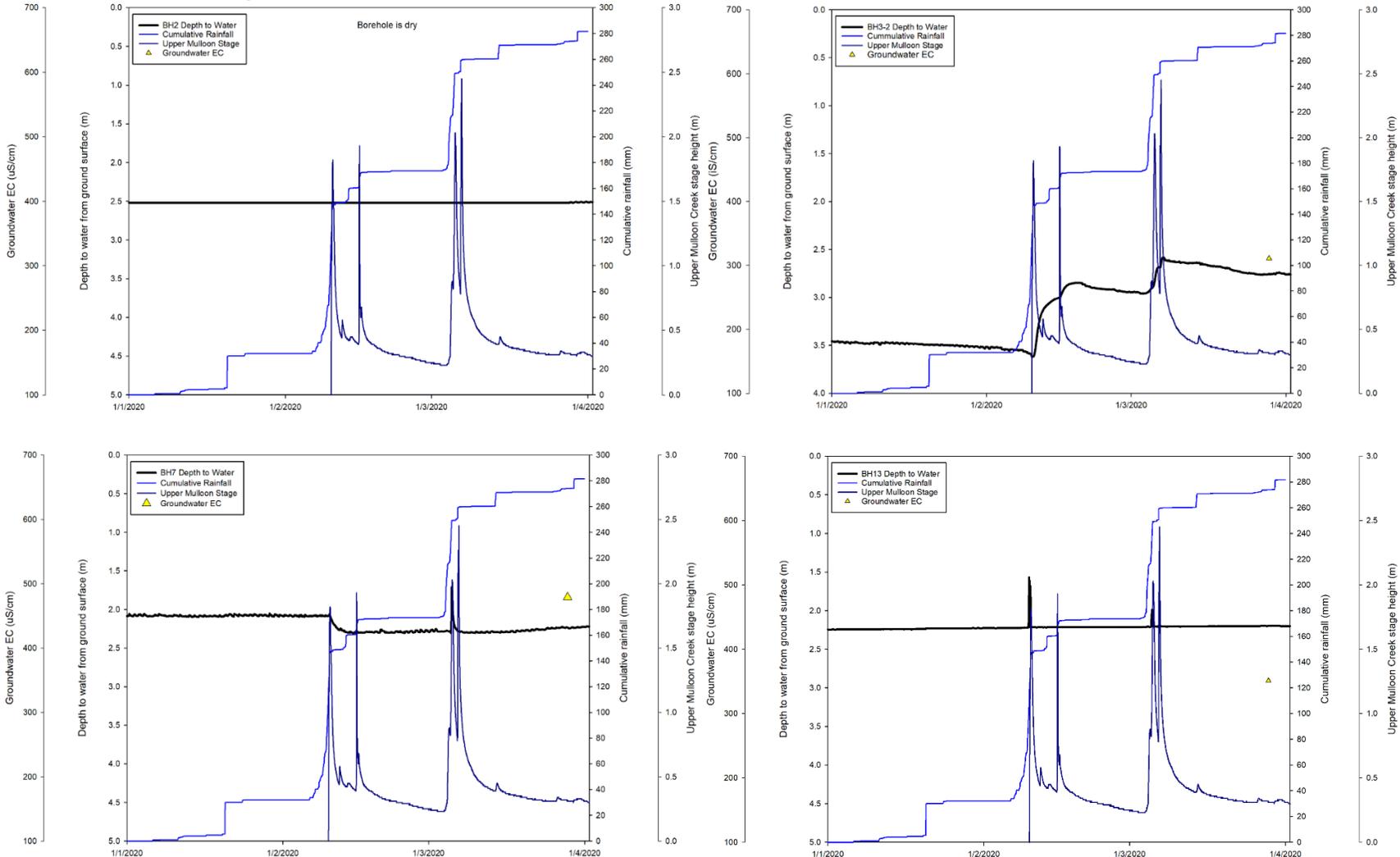


Figure 69. Groundwater Depth (BGL), Cumulative Rainfall, Stream Manual Stage Height, and Groundwater EC from 1 January to 1 April 2020 for Transect C (northern west-east transect): (a) BH2, (b) BH3-2, (c) BH7, (d) BH13, at Mulloon Home Farm

Transect C – Sustained Rainfall 2020

Borehole 2 was dry before this event and remained dry for the months January to March 2020 (Figure 69a).

Borehole 3-2 groundwater level dropped slightly (3.50m BGL to 3.60m BGL) from 1 January to the early February rainfall event, then rose incrementally to the early February (3.60m BGL to 3.10m BGL), mid-February (3.10m BGL to 2.90m BGL) and early March (2.90m BGL to 2.60m BGL) rainfall events. Groundwater level then dropped slightly to the end of March (2.60m BGL to 2.75m BGL) (Figure 69b). The groundwater EC recorded during this event was 300 μ S/cm.

Borehole 7 groundwater level was at 2.10m BGL and dropped to 2.3m BGL after the early February rainfall event, staying at this level until the end of March, apart from a small peak in response to the early March rainfall event (2.30m BGL to 1.60m BGL and back to 2.30m BGL) (Figure 69c). The groundwater EC recorded during this event was 490 μ S/cm.

Borehole 13 was dry prior to this event and remained dry for the months January to March 2020 apart from a small peak in response to the early March rainfall event (2.25m BGL to 1.60m BGL and back to 2.25m BGL) (Figure 69d). The groundwater EC recorded during this event was 350 μ S/cm.

Northern Boreholes – Mulloon Home Farm north**Northern Boreholes - Sustained rainfall in 2016**

Borehole 1 (3.60m to base of screen) is a single borehole located on the flood plain immediately west of Mulloon Creek, north of the weather station (Figure 33). Groundwater level was at 1.75m BGL from 1 June and rose rapidly in response to the 5 June rainfall event (1.75m BGL to 0.40m BGL – sensor limit), staying at elevated levels (<0.40m BGL) until mid-June, then dropping for a few days before the 18 March event (0.40m BGL to 0.60m BGL). Water level rose to <0.40m BGL (sensor limit) and remained at this level to the end of June (Figure 70). The groundwater EC recorded during this event was 340 μ S/cm.

Borehole 14 (3.90m to base of screen) is a single borehole located on the flood plain immediately west of Mulloon Creek, north of Transect C (Figure 33). However, this hole was commissioned after the 2016 rainfall event.

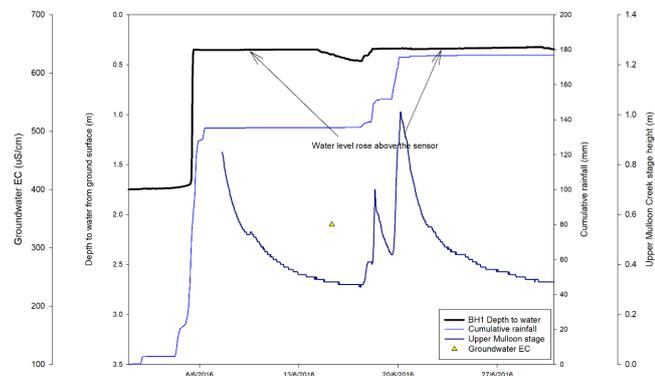


Figure 70. Groundwater Depth (BGL), Cumulative Rainfall, Stream Manual Stage Height, and Groundwater EC from 1 June to 1 July 2020 for Northern Borehole (BH1) at Mulloon Home Farm

Northern Boreholes - Sustained rainfall in 2020

Borehole 1 groundwater level dropped slightly (2.50m BGL to 2.60m) from 1 January and rose rapidly in response to the early February rainfall event (2.60m BGL to 2.00m BGL) before monitoring was lost (sensor not recording). Monitoring resumed toward the end of March with the groundwater level at 1.50m BG, indicating some increase in groundwater level due to the early March rain event (Figure 71a). Consideration of the Borehole 14 data suggests that patterns at these 2 boreholes were likely very similar. The groundwater EC recorded during this event was 350 μ S/cm.

Borehole 14 groundwater level dropped slightly (2.50m BGL to 2.70m) from 1 January and rose rapidly in response to the early February rainfall event (2.70m BGL to 1.80m BGL), rising incrementally again in response to the mid-February rainfall event (1.80m BGL to 1.60m BGL) and the early March rainfall event (1.60m BGL to 1.10m BGL) then decreasing rapidly to 1.50m BGL over the next few days, then slowly to the end of March (1.50m BGL to 1.75m BGL) (Figure 71b). The groundwater EC recorded during this event was 420 μ S/cm.

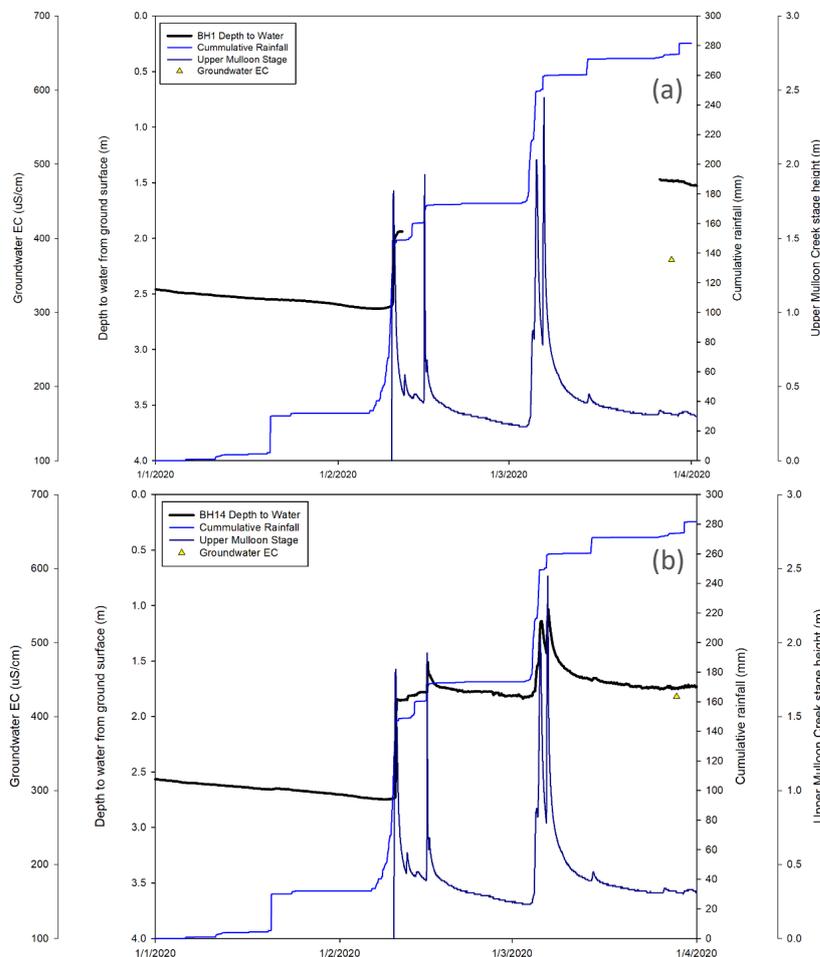


Figure 71. Groundwater Depth (BGL), Cumulative Rainfall, Stream Manual Stage Height, and Groundwater EC from 1 January to 1 April 2020 for Northern Boreholes (a) BH1, (b) BH14, at Mulloon Home Farm

When the mid-2016 sustained rainfall period commenced (15 June 2016), groundwater began to recharge with enhanced flux from the higher parts of the landscape, flowing downhill and northward toward the valley axis (Figure 73). The strongest vector is the groundwater flow from the western hills to the north-east, but patterns in the north suggest flow from the eastern hills as well. Hydraulic gradients are steeper than for the dry period (calculated hydraulic gradient 1% to 0.5% along flow lines in the east and 2% to 0.3% along flow lines in the west), but still indicate slow to very slow groundwater flow. The patterns suggest that groundwater flow is faster on hillslopes and adjacent plains and slower on the central-northern valley floor.

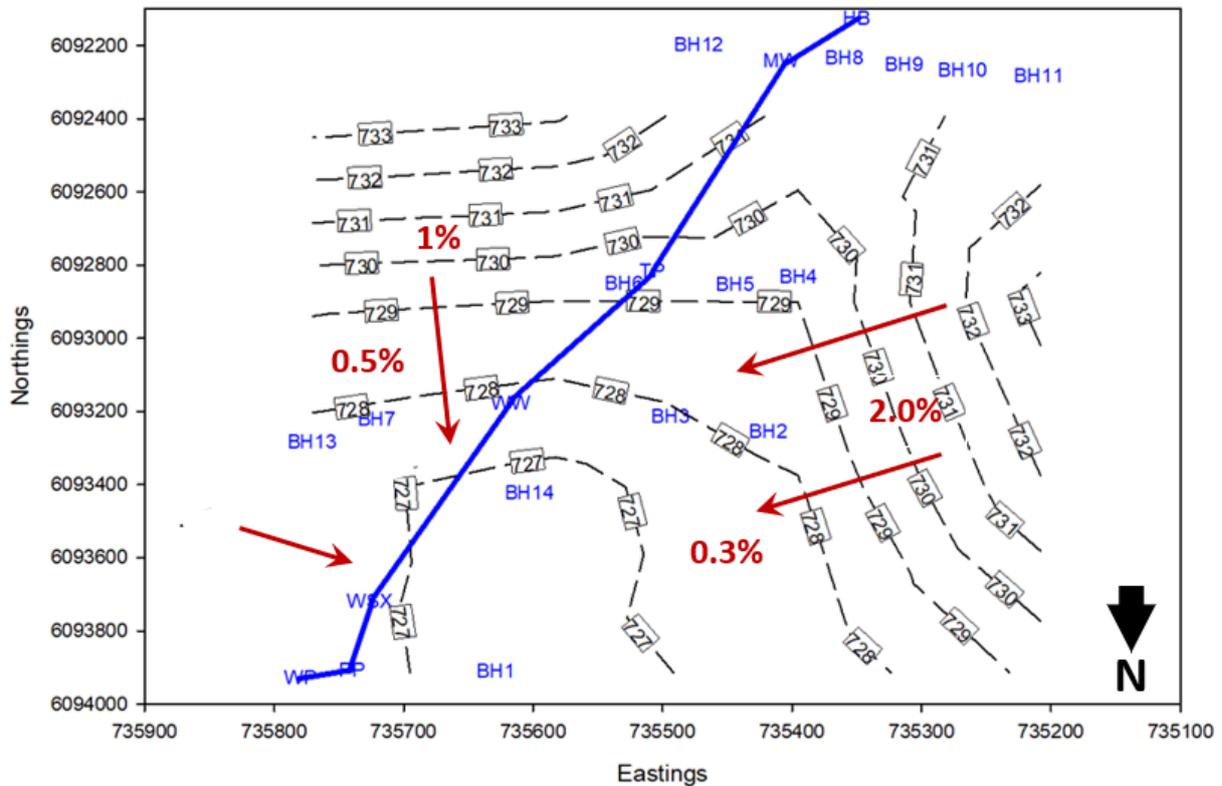


Figure 73. Interpolated potentiometric surface for 15 June 2016 at the Mulloon Home Farm.

Snapshot overview at the start of the groundwater response to the mid-2016 wet period.

The calculated hydraulic gradients are low to very low

(1% to 0.5% along flow line in east; 2% to 0.3% along flow line in west).

The mid-2016 sustained rainfall period occurred in winter (June-July), but the groundwater response to this precipitation input continued through spring. The interpolated potentiometric surface for 13 September 2016 shows the continued influence of groundwater flow from the high parts of the landscape downhill and northward toward the valley axis (Figure 74). There are strong vectors for groundwater flow from the western hills to the east-north-east, and patterns in the north suggest flow from the eastern hills continues. Hydraulic gradients are steeper than at the start of the wet period, but still indicate slow groundwater flow (calculated hydraulic gradient 2% to 1% along flow lines in the east and west). Groundwater flow is faster on hillslopes and adjacent plains and slower on the central-northern valley floor.

By 17 November 2016, the groundwater response is lower in the east with groundwater flow direction and hydraulic gradients similar to those in the dry period (calculated hydraulic gradient 0.3% to 0.2%) (Figure 75). Groundwater flow from the west is still elevated, with a similar flow orientation and low flow rates to those observed in spring.

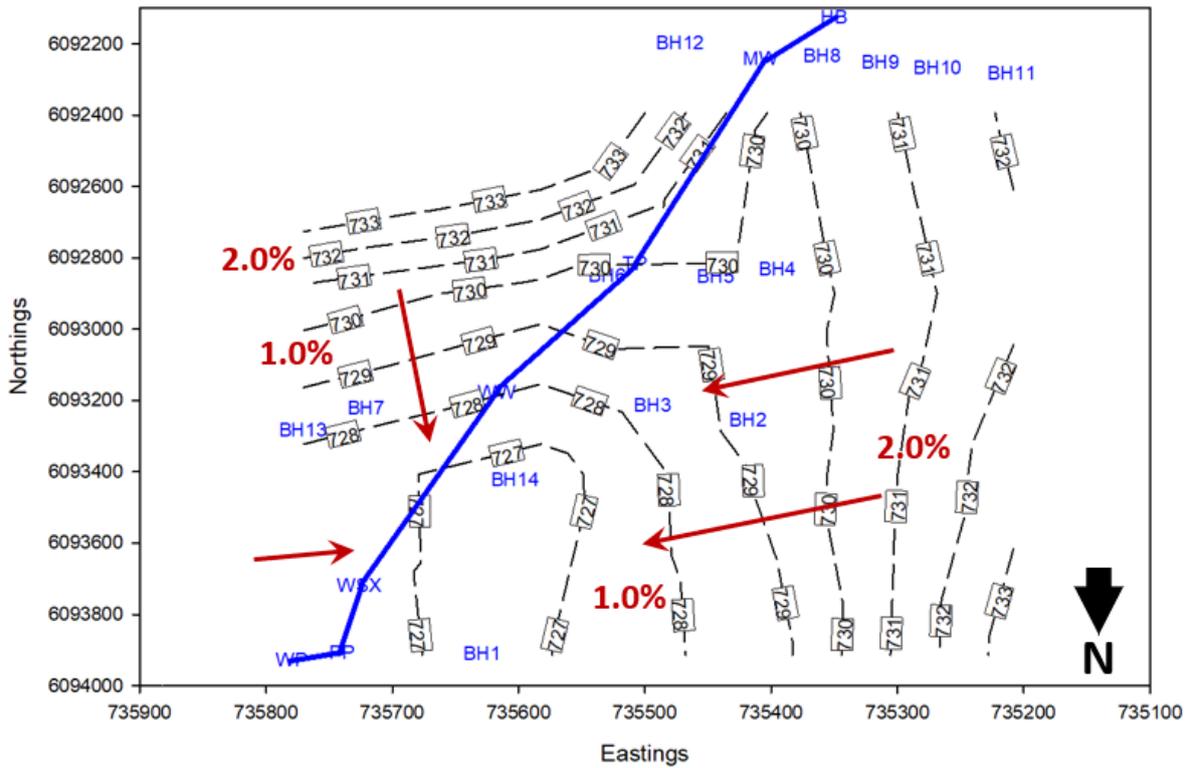


Figure 74. Interpolated potentiometric surface for 13 September 2016 at the Mulloon Home Farm. Snapshot overview in the middle of the groundwater response to the mid-2016 wet period. The calculated hydraulic gradients are low (2% to 1% along flow lines).

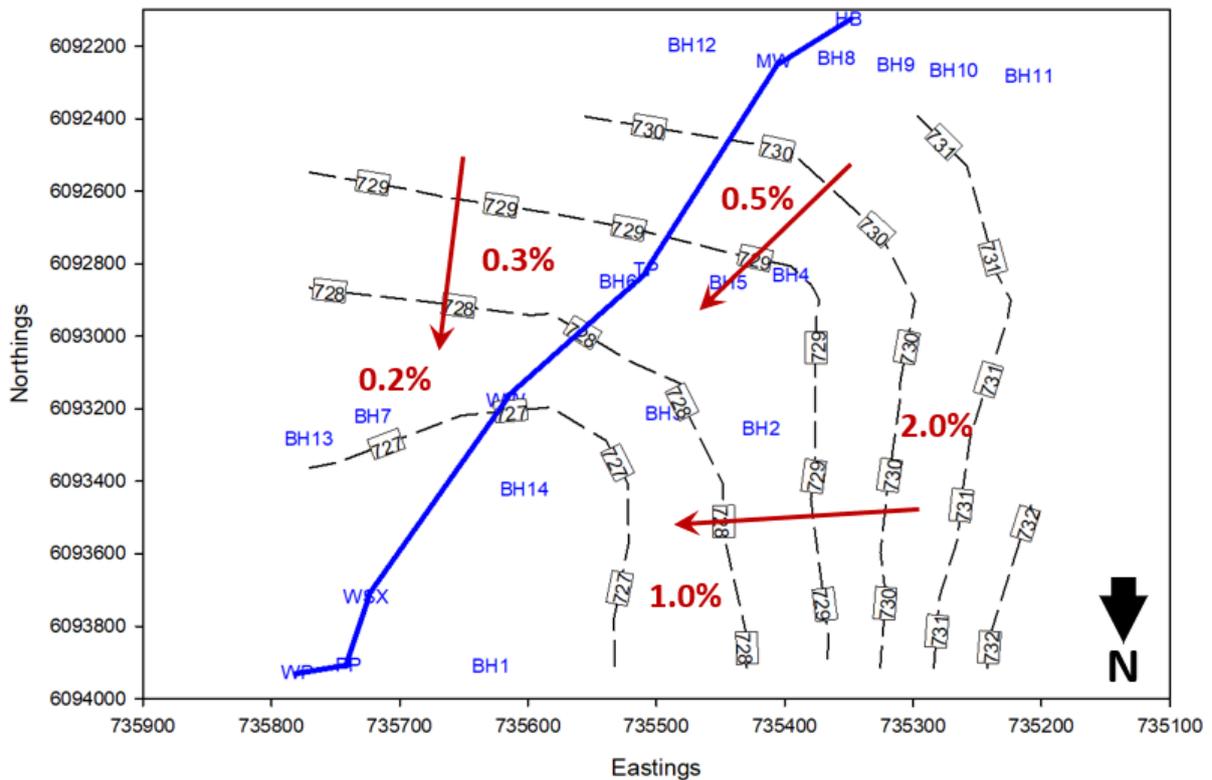


Figure 75. Interpolated potentiometric surface for 17 November 2016 at the Mulloon Home Farm. Snapshot overview in the late stages of the groundwater response to the mid-2016 wet period. The calculated hydraulic gradients are very low in the east but still elevated in the west (0.5% to 0.2% along flow lines in east and south; 2.0% to 1% in the west).

3.3.6 Streamflow

Streamflow was measured from 11 August 2006 to 30 June 2020 at the Black Jackie (BJ) gauging station, where Mulloon Creek enters Mulloon Home Farm, and at the Mid-Mulloon (MM) gauging station, where Mulloon Creek exits (Table 7; Appendix 2). The measured outflow consistently exceeded the inflow, indicating that the stream had a net gain from overland flow and groundwater input as it passed through the Mulloon Home Farm. The volume increase is typically one order of magnitude. Some annual measurements are minimums as events may have been missed when monitored days were $\ll 365$ days. On 2 occasions (2012 and 2016), the water level overtopped the maximum stage height for the rating tables (BJ 1.97m; MM 1.53m) during major flood events.

Table 7. Annual streamflow, salt load and EC: Upper Mulloon (Black Jackie) and Mid-Mulloon gauges

Year	Discharge Upper Mulloon (ML) INFLOW	Salt Load (t)	Flow weighted EC ($\mu\text{S}/\text{cm}$)	¹ Days	Discharge Mid Mulloon (ML) OUTFLOW	Salt Load (t)	Flow weighted EC ($\mu\text{S}/\text{cm}$)	¹ Days
2006	345			143	6,339			143 ²
2007	3,717			358	12,359			358
2008	565			149	12,134			357
2009	1,027			362	4,701			360
2010	9,005			292	25,944			214
2011	30,044			295	31,214			365
2012	33,272			366	33,541			366
2013	127			6	15,615			308
2014	8,688			273	19,825			333
2015	12,966			365	16,817			246
2016	10,343	699 ³	125.0 ³	321	12,131	714	132.0	301
2017	1,285	45	56.7	365	2,770	197	157.5	362
2018	637	43	108.1	365	494	82	294.3	145
2019	372	31	134.8	365	843	214	412.5	278
2020	8,170	527	104.0	182	7,840	631	210.2	182 ⁴

Data from 2006-2013 derived using the original sensor and gauging station offset; new sensor data from 2014-2020

¹Some flow events may have been missed in years with incomplete monitoring ²Monitoring commenced 11 August 2006

³Salt Load and Flow Weighted EC based on 265 days

⁴Monitoring to 30 June 2020

The electrical conductivity (EC) levels of water entering Mulloon Home Farm are low (EC 56.7 $\mu\text{S}/\text{cm}$ to 134.8 $\mu\text{S}/\text{cm}$) indicating the water is fresh (<500 $\mu\text{S}/\text{cm}$; Table 2) (Mayer et al. 2005) (Table 7). A small amount of salt accession takes place as the Mulloon Creek passes

through the Mulloon Home Farm, likely introduced in ‘wet’ deposition as solutes in rain or as ‘dry’ deposition, coupled with windblown or rain-deposited dust (Cattle et al., 2005). The water exiting at Mid-Mulloon gauging station is also fresh (EC 132.0 $\mu\text{S}/\text{cm}$ to 412.5 $\mu\text{S}/\text{cm}$). The largest EC gains measured were in 2018 and 2019, the driest years monitored. The salt load export via Mulloon Creek is only slightly higher than that measured at Black Jackie, and the water passing the Mid-Mulloon gauging station is of high quality (Table 7).

4. DISCUSSION

Precipitation in upland southeast Australia has typically been lower than the historical average from 2003-2020. Decreasing baseflow indices for tableland river systems reflected reduced recharge to groundwater over this period (Zhu et al. 2020). By summer 2019, there was limited or no flow in many of the major southeast Australian river systems for weeks. Farming under these hydrological conditions is extremely challenging, and innovative systems-based regenerative agriculture farming strategies are being championed as a mechanism to address this.

In 2006, a pilot landscape hydration project was initiated at Mulloon Creek Natural Farms, designed to re-establish historic levels of water infiltration and retention (Andrews 2006; Kravcik et al. 2007) and enhance ecological productivity (Johnson and Brierley 2006). Some measurement of weather, landscape, hydrological and hydrogeological parameters was instigated at that time, becoming increasingly rigorous as funding permitted, and in 2014, more systematic monitoring was established at the Home Farm as part of a broader Mulloon Rehydration Initiative (MRI) (Peel et al. 2022). This report compiles all available weather, landscape, hydrological and hydrogeological monitoring in the mid-Mulloon Creek catchment from 2006 to 2020.

Several landscape hydrological strategies have been employed in the Mulloon landscape. However, the foundation of the landscape rehydration program is the establishment of carefully designed and sited in-stream leaky weirs. At the Home Farm, these features modified mid-Mulloon Creek in a manner that paralleled the role of past natural watercourses, including the re-establishment of some chain-of-pond features. Slowing the velocity of the water created conditions that slowed channel incision and bank erosion, improved streambank soil health (hydration) and in-stream water quality, and enabled native vegetation to regenerate, thereby restoring the riparian zone (Figure 76). Measures of floodplain rehydration were equivocal.



Figure 76. Mulloon Creek upstream of Peter’s Pond in 1977 and in 2015 showing invigorated riparian condition after the emplacement of a leaky weir (TMI, 2024).

A subset of the key learnings from this initial project includes:

Recognition that implementation of regenerative agriculture strategies of this kind must be tailored to the climate, landscape and hydrologic setting at the site;

Scientific monitoring and evaluation of existing environmental and agricultural enterprises allows constructive reflection on past practice and informs future planning; and

Monitoring also tests whether the assumed environmental responses to actions in the landscape are really what is happening.

Key Findings

The water in mid-Mulloon Creek is extremely fresh, and the electrical conductivity is typically <100 $\mu\text{S}/\text{cm}$ with EC peaking during periods of high flow after a drier antecedent period in 2016 (290 $\mu\text{S}/\text{cm}$) and 2020 (320 $\mu\text{S}/\text{cm}$).

The establishment of in-stream ponds does not decrease the downstream flow volume with relatively low average flow into the mid-Mulloon Creek catchment (Black Jackie gauge \ll 200 ML/day; daily stage <0.5m) and higher average flow from the mid-Mulloon Creek catchment (Mid-Mulloon gauge 100-300 ML/day; daily stage 0.5-0.75m).

Stream flow velocity is typically low, but high-intensity flood events can overtop the leaky weirs and flow across the flood plain (e.g. major flooding in 2016 and 2020).

Sodic soils in this landscape are susceptible to erosion, so mobilisation of soil/sediment around weirs can destabilise pond systems. Mulloon staff acknowledge this and recognise that ongoing maintenance is essential, especially after flood events.

Bank erosion in mid-Mulloon Creek does not appear to be as severe, and this is attributed to re-establishment of riparian vegetation and overall riparian zone health. Riparian vegetation health has been enhanced, improving bank stability, creating new habitat, and increasing farm productivity (e.g., controlled stock watering sites).

There has been limited measured aggradation of the stream floor (even in ponds) in mid-Mulloon Creek. This limited aggradation is attributed to a relatively low sediment flux from the Mulloon Creek catchment upstream of the study site. Mulloon Creek extends approximately 20km upstream of the study area, but more than 70% of the channel runs through forested rocky terrain on an Ordovician silicified metasedimentary (hard rock) substrate. Except for sediment mobilised post-bushfire in the upper catchment, there is typically low sediment flux into the mid-Mulloon Creek catchment.

The water in mid-Mulloon Creek generally has relatively low turbidity (<20 NTU when flow >25 ML/day) with higher turbidity associated with periods of low flow. Recorded peaks occurred in spring 2016 (40-100 NTU when flow <10.7 ML/day); winter 2017 (60-180 NTU when flow <6.8 ML/day), and winter 2018 (80-500 NTU when flow <2.9 ML/day).

Groundwater flow through fractured rock on boundary ranges and under the valley floor is controlled by secondary porosity (joints, cleavage, faults). Structures associated with the major Mulwaree Fault east of the study area may conduct deeper groundwater beyond the mid-Mulloon Creek catchment divides (local to intermediate groundwater flow system).

Floodplain sediments and soils are dominated by clays with laterally discontinuous sand/gravel lenses typically well below the plant-root zone. The floodplain strata provide preferential groundwater pathways through semi-confined sandy and gravelly intervals, but water is also present in overlying fine-grained floodplain sediments after periods of sustained rainfall.

Mapping of potentiometric surfaces indicates that the net flux of groundwater (and interflow) in regolith-hosted sequences (weathered rock, colluvial and alluvial sediments, soil) is toward the stream from adjacent hills (the local groundwater flow system). Similar patterns of flow from the hills toward the stream were reflected in measured geochemical signatures in west-east borehole arrays in the adjacent lower Mulloon Creek catchment (de Lorenzo, 2021). This indicates that, although some groundwater recharge can occur due to infiltration at the land surface in low-lying areas - especially in wetter periods, most recharge occurs as flow from higher parts of the landscape to low-lying areas.

In the mid-Mulloon Creek catchment, potentiometric surfaces also indicate connectivity along the axis of the valley in floodplain sediments, especially in drier periods. This is consistent with the three-dimensional configuration of sediments in meandering stream floodplain systems, where former channel zone sediments (higher hydraulic conductivity) are buried in finer overbank deposits (lower hydraulic conductivity) in the floodplain sedimentary sequence.

There is little evidence of flow from the stream to the floodplain in the mid-Mulloon Creek catchment. Boreholes immediately proximal to Mulloon Creek (floodplain margin boreholes) show a synchronous water level rise with a rise in stream level associated with large or sustained rain events. However, the EC of the groundwater remains high ($>400 \mu\text{S}/\text{cm}$) relative to stream water EC ($<200 \mu\text{S}/\text{cm}$). The synchronous change in borehole water level indicates a pressure response at the flood plain margin when the stream is at high stand, but does not indicate a net flux of low EC streamwater into the floodplain. These findings support the concept that event-based streamflow can episodically recharge bank storage immediately adjacent to the Creek, but that this storage is reduced once the transient stream high-stand passes. This small-scale localised storage would likely be enhanced in healthy vegetated riparian zones.

These findings also indicate that there is a period where groundwater moving toward the stream might remain in the floodplain due to increased pressure head proximal to the stream as the transient stream high-stand passes, and for a period of time afterwards. Unfortunately, the agricultural value of this phenomenon may be limited, given the rootzone would likely already be wet at this time. However, this observation suggests that groundwater flowing toward the stream in areas where in-stream ponds are at high-stand might cause the same pattern of behaviour, and the egress of groundwater to the stream might take longer in these areas.

Boreholes on the floodplain and in distal settings show an asynchronous response relative to rainfall events (and consequent stream water level rise), reflecting the time it takes for

groundwater to infiltrate at the land surface and reach the monitoring point from the adjacent hills.

Episodic filling of flood-runners on the alluvial plain, associated with major rainfall events causing overbank flooding (measured only at BH4 in the mid-Mulloon Creek catchment), provides an irregular recharge vector to small back-plain semi-confined aquifers.

5. CONCLUSION

Monitoring of weather, landscape, hydrological and hydrogeological parameters (2006-2020) in the mid-Mulloon Creek catchment has provided considerable insight into agriculture-related landscape function and a clearer understanding of hydrological and hydrogeological processes. Ongoing monitoring of this kind is imperative if innovations and decision-making in environmental stewardship, adaptive management and on-farm productivity are to remain evidence-based. The overarching finding of this study is that landscape and hydroscape adaptations must be tailored to the climate, landscape, biotic, hydrologic and hydrogeological setting you are working in.

The net vector for surface and groundwater in the mid-Mulloon Creek catchment is down valley and toward the stream from high relief areas to lower relief areas. Emplacement of leaky weirs forming ponds in Mulloon Creek has greatly enhanced riparian vegetation health and, as a result, stream/riparian biota health and aspects of farm productivity. There is a relationship between transient high-stands in the stream associated with major rainfall events and partitioning of water in bank storage immediately adjacent to the stream. There is likely a feedback loop in which enhanced riparian zone health increases bank storage. Although water velocity generally slowed when leaky weirs were emplaced in Mulloon Creek, there has been limited evidence of stream-bed aggradation in low-velocity zones in the stream at this location. The emplacement of leaky weirs and associated ponds does not induce direct rehydration of the adjacent floodplain with streamwater as was once believed. Direct aquifer connectivity with the stream is very localised, flood plain gravel lenses may be well below the plant root zone, and the geometry of the lenses is likely sub-parallel to the stream. However, when the stream or pond levels are at high-stand, groundwater is retained in the proximal flood plain (pressure head response) for a period after larger or more sustained rainfall events.

Although this study will help constrain a conceptual model for landscape hydrological and hydrogeological processes, a detailed study of the floodplain regolith materials is required in order to better understand hillslope and floodplain processes. Ongoing monitoring across the existing array would be greatly enhanced by a regolith materials study of this kind.

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APPENDIX 1.

BOREHOLE REPORTS

BH 3-2

https://mullooninstitute.org/wp-content/uploads/2026/02/ProfileReport_ProfileId_96262_BH3-2.pdf

BH5-2

https://mullooninstitute.org/wp-content/uploads/2026/02/ProfileReport_ProfileId_96264_BH5-2.pdf

BH8-2

https://mullooninstitute.org/wp-content/uploads/2026/02/ProfileReport_ProfileId_96261_BH8-2.pdf

BH14

https://mullooninstitute.org/wp-content/uploads/2026/02/ProfileReport_ProfileId_96263_BH14.pdf

APPENDIX 2:

Daily Flow (ML/day) at Black Jackie and Mid-Mulloon River Gauges from 2006 to 2020.

(Note some 2016 data was lost because of an extremely large and sustained rain period in June/July.)

